# CHAPTER 1

Introduction to Olefin Metathesis and Its Applications in Polymer Synthesis

Olefin Metathesis

Olefin metathesis is a metal-catalyzed transformation, which acts on carbon-carbon double bonds and rearranges them via cleavage and reassembly.[1-5] While the reaction itself was discovered in the mid-1950s, its now generally accepted mechanism was not proposed until 1971.[6] According to this mechanism, first introduced by Chauvin, the coordination of an olefin to a metal carbene catalytic species leads to the reversible formation of a metallacyclobutane (Scheme 1.1). This intermediate then proceeds by cycloreversion via either of the two possible paths: 1) non-productive—resulting in the re-formation of the starting materials or 2) product-forming—yielding an olefin that has exchanged a carbon with the catalyst's alkylidene. Since all of these processes are fully reversible (Scheme 1.1), only statistical mixtures of starting materials as well as all of possible rearrangement products are produced in the absence of thermodynamic driving forces.

Scheme 1.1. General mechanism of olefin metathesis.[6]
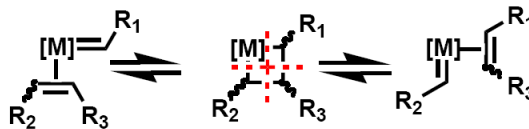
Fortunately for the organic and polymer chemistry communities, the olefin metathesis reaction's thermodynamic equilibrium can be easily influenced. There are two major approaches that are commonly employed to drive the reaction towards the desired products. One tactic is to rely on Le Chatelier's principle by continuously removing one of the products from the reaction system in order to shift the equilibrium in favor of the other product. This method is especially effective in the case of cross metathesis (CM)[7] reactions involving terminal olefins, ring-closing metathesis (RCM)[8,9] and acyclic diene metathesis polymerization (ADMET),[10-14] because the volatile ethylene gas by-product formed in these processes can be easily removed (Scheme 1.2). The other approach capitalizes on the ring strain of cyclic olefins such as cyclooctenes and norbornenes. The energy released during the ring-opening of these compounds is sufficient to drive forward reactions such as ring-opening cross metathesis (ROCM)[15,16]

and ring-opening metathesis polymerization (ROMP)[2,14,17,18] (Scheme 1.2). In addition, in some instances, substrate concentration (which often distinguishes ADMET from RCM) or the catalysts' sensitivity to olefin substitution can also be taken advantage of to influence product selectivity. All of these methods are currently successfully employed in the synthesis of a large variety of small, medium, and polymeric molecules, as well as novel materials.[1-5,19-23]

Scheme 1.2. Types of olefin metathesis reactions.[4]
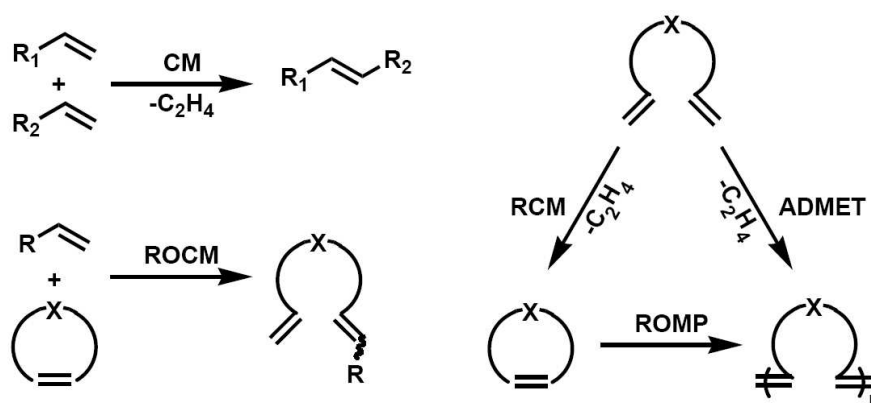
Once an olefin metathesis mechanism consistent with the experimental evidence was established, rational catalyst design became possible. Consequently, several well-defined, single-species catalysts based on different transition metals such as titanium,[24] tungsten,[19,25,26] molybdenum,[19,27] rhenium,[28] osmium,[29] and ruthenium[3,30,31] evolved from the original metathesis-active but ill-defined multi-component mixtures. However, even today, the early transition metal catalysts, although very active, are also sensitive to many functional groups found in organic molecules, as well as moisture and air—a drawback that significantly limits their synthetic applications. For example, as demonstrated in Table 1.1, a metathesis catalyst with a tungsten center will preferentially react with olefins in the presence of esters and amides, but it will ignore all of these functionalities in favor of ketones, aldehydes, alcohols, acids or water.[4] On the other hand, the late transition metal, ruthenium-based catalysts proved to be very tolerant towards polar functional groups and water, albeit at the expense of activity, early in olefin metathesis research.[32] Overall, both Mo and Ru metathesis catalysts gained the most prominence

and popularity due to their versatility, as they provided a good balance between activity and functional group tolerance (Table 1.1). However, only the applications of ruthenium-based catalysts will be discussed in this thesis.

Table 1.1. Functional group tolerance of olefin metathesis catalysts.[4]

Titanium (Ti)	Tungsten (W)	Molybdenum (Mo)	Ruthenium (Ru)	
Acids	Acids	Acids	*Olefins*	
Alcohols, Water	Alcohols, Water	Alcohols, Water	Acids	Increasing order of reactivity
Aldehydes	Aldehydes	Aldehydes	Alcohols, Water	
Ketones	Ketones	*Olefins*	Aldehydes	
Esters, Amides	*Olefins*	Ketones	Ketones	
Olefins	Esters, Amides	Esters, Amides	Esters, Amides	

Functional group tolerance

The exceptional selectivity of ruthenium for C–C double bonds secured continuous interest for this line of catalysts despite the low activity of the early versions, relative to the molybdenum catalysts of the time. For example, the activity of bis-triphenylphosphine (PPh$_3$) predecessors of catalyst **1** (Figure 1.1) was limited to ROMP of strained monomers, yet the catalyst performed remarkably well in polar media such as alcohols.[32] However, the subsequent replacement of the PPh$_3$ ligands with tricyclohexyl phosphines (PCy$_3$) produced a much more active catalyst **1** ("the 1st generation Grubbs catalyst"), which is capable of cross metathesis of acyclic olefins, while maintaining the stability and high functional group tolerance of earlier ruthenium catalysts.[31,33] Furthermore, the substitution of one of the phosphine ligands for an even more electron-donating N-heterocyclic carbene (NHC) resulted in a series of 2nd generation catalysts, such as **2**[30] and the phosphine-free **3**,[34] which now rival Mo catalysts in activity (Figure 1.1). While both **2** and **3** maintain the excellent selectivity for olefins typical of ruthenium catalysts, they have somewhat slower rates of initiation than the first generation catalysts, limiting their application in polymer synthesis. Alternatively, NHC-catalyst **4**,[35] which bears a bispyridine ligand in place of a phosphine (Figure 1.1), has a

sufficiently rapid initiation rate to promote ROMP of norbornenes with all of the attributes of a living polymerization. Moreover, the continuing emergence of new catalysts serves to further improve the metathesis reaction to be applicable to asymmetric,[36] sterically demanding,[37] or aqueous[38,39] transformations.
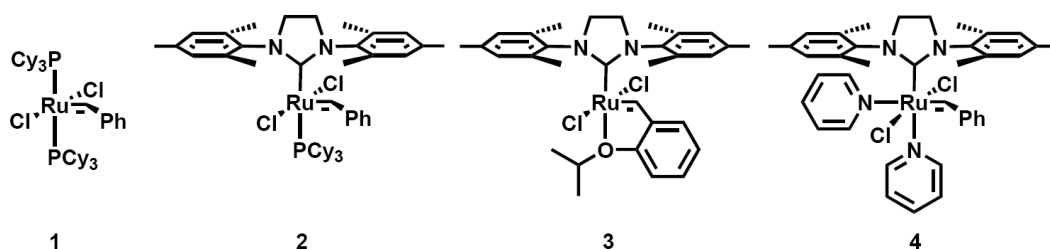

Figure 1.1. Ruthenium-based olefin metathesis catalysts.

One specific example of the improved reactivity of 2nd generation ruthenium catalysts, such as **2** and **3**, is their ability to react with electron-deficient α,β-unsaturated carbonyls, which are inert to **1**. As a result, excellent cross metathesis selectivity can be achieved in the reactions with such substrates.[40,41] While both types of catalysts will successfully homodimerize "easy," electron-rich, unsubstituted olefins, such as terminal aliphatic alkenes, even the active NHC-catalysts have very limited ability, if any, to cross a pair of "difficult," electron-deficient olefins, such as acrylates. Nevertheless, unlike **1**, NHC-catalysts will promote selective cross metathesis between an "easy" and a "difficult" olefin. Therefore, a mixture of compounds, each functionalized with either a terminal alkene or an acrylate, will produce homodimers of the "easy" alkenes exclusively when exposed to **1**, and mixed "easy"-"difficult" cross products when exposed to **2** or **3** (Scheme 1.3). Importantly, although homodimerization of "easy" olefins occurs in the presence of either **2** or **3**, the disubstituted, electron-rich product of this cross is still qualified as "easy" and can proceed through secondary metathesis with acrylates and the NHC-catalyst to form a thermodynamically more stable cross product. In fact, this cross metathesis selectivity of 2nd generation ruthenium catalysts has already been creatively exploited in the synthesis of small molecules,[42] macrocycles,[43] and alternating A,B polymers.[44]

Scheme 1.3. Selectivity of 1st and 2nd generation ruthenium catalysts.
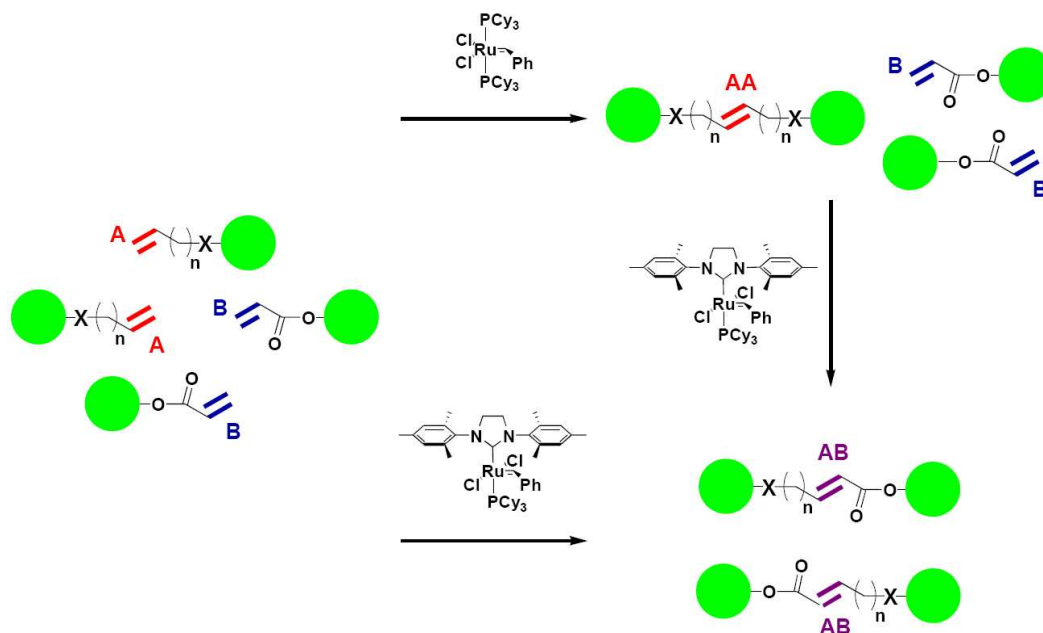
Polymer Synthesis Applications of Olefin Metathesis

Olefin metathesis is a versatile reaction that is becoming an increasingly important tool in the synthesis of small molecules, preparation of natural products, and construction of polymers. Furthermore, recent advances in the development of very active, yet stable catalysts now allows for the facile preparation of various functionalized polyalkenes,[1] alternating block-copolymers,[44] and even telechelic[45] polymers. The two synthetic approaches to olefin metathesis polymerizations are acyclic diene metathesis and ring opening metathesis reactions, each of which requires a different set of considerations for successful polymerization.

ADMET

Traditionally, acyclic diene metathesis is considered to be a step-growth[46] polycondensation-type polymerization reaction, which makes strictly linear chains from unconjugated dienes.[10-14] As such, ADMET requires very high monomer conversion rates to produce polymer chains of considerable size. Therefore, the more active 2nd generation catalysts such as **2** and **3** are usually better suited for ADMET than bisphosphine ones.[12] Since the loss of ethylene is the main driving force behind the cross metathesis of terminal

olefins, the efficient removal of this volatile gas from the reaction vessel is also crucial. Consequently, although olefin metathesis with ruthenium catalysts is, in general, very mild and does not require stringent air removal, ADMET greatly benefits from conditions which promote the diffusion and expulsion of ethylene (i.e., higher reaction temperatures, application of vacuum, and rigorous stirring). In addition, the use of concentrated or even neat solutions of monomers is usually helpful to polycondensation reactions but, in the case of ADMET, a very viscous solution might be detrimental to efficient stirring and ethylene removal. Furthermore, as a consequence of the poor molecular weight control of step-growth reactions, the polydispersity index (PDI) of polymers obtained by this method is usually quite large. However, an important advantage of ADMET is that it allows a large variety of monomers to be polymerized since terminal olefins are quite easy to install. Many functional groups and moieties of interest can be incorporated into such polymers directly through monomer design, due to the excellent tolerance of ruthenium catalysts.

ROMP

Ring opening metathesis polymerization exhibits very different reaction kinetics from the ADMET approach to polymeric materials. ROMP is a chain-growth type polymerization which relies on monomer ring strain and, thus, it can be efficiently controlled by catalyst loading. The equilibrium molecular weight of the resulting polymer chains is, therefore, essentially independent of the extent of conversion. Moreover, a variety of olefin metathesis catalysts effect ROMP and sufficiently fast initiating ones can even lead to a living polymerization of appropriately chosen monomers. For example, the polymerization of norbornenes with the fast initiating bispyridine species **4** produces well-defined polymers with PDIs close to 1.0.[47] The employment of these strained, bi-cyclic alkenes as monomers ensures that both depolymerization via competing RCM and chain fragmentation via "back-biting" of the catalyst into the growing chain are significantly suppressed. However, the limited availability of suitable monomers is the main disadvantage of this method. Although a variety of backbones can be created through monomer functionalization, such alterations sometimes negatively affect the ring strain and, thus, success of ROMP.

Summary and Thesis Research

Olefin metathesis is a mild, yet powerful, method for carbon-carbon bond formation. Although metathesis is mediated by a variety of metals, ruthenium-based catalysts demonstrate unprecedented functional group, air, and moisture tolerance and greatly expand the scope of this reaction. Furthermore, recent advances in catalyst development have produced a variety of well-defined and very active catalysts, some of which are tuned for specific applications. This progress has allowed for new and creative uses of olefin metathesis in the preparation of novel synthetic products.

With so many olefin metathesis catalyst options at hand, a number of factors, most importantly the nature of the substrate, need to be considered for each specific application in order to fully realize the potential of this chemical transformation. For example, in the case of polymerization via ADMET, the pool of monomers can be practically unlimited if a very active and stable species such as phosphine-free **3** is chosen as the catalyst. On the other hand, when polymerizing via ROMP, any ruthenium catalyst can produce satisfactory results, if the monomer of choice has sufficient ring strain. In addition, to achieve "living polymerization" with ruthenium catalysts, the use of fast-initiating **4** and norbornene-based monomers are required. However, despite certain limitations, ADMET and ROMP together provide a bottomless toolbox for the synthesis of polymeric materials.

Notably, even well-established materials such as polyethylene (PE) can benefit from the advances in olefin metathesis. This polymer is already one of the largest-volume polymers produced world-wide, with more than 22 billion pounds made yearly in the United States alone.[48] The demand for this plastic is driven by a stunning range of desirable properties provided by the simplest polymeric backbone imaginable. Furthermore, all of the diversity in physical properties (crystallinity, mechanical strength, and thermal stability) stems from the different architecture of the individual polymeric chains, specifically chain branching and chain size, rather than variations in chemical composition.[48,49] Therefore, the synthesis and study of polymers with different structural design and a variety of molecular weights is important for promoting a better

understanding of structure-property relationships and, consequently, broadening the applications of polymeric materials.[50]

In spite of the progress in polymer synthesis techniques, some important chain architectures remain inaccessible for PE with current synthetic methods. For example, both coordination and, to some extent, radical polymerization of α-olefins currently employed in industry allow for very good statistical control over the number and length of branches along the chain backbone, but these reactions cannot produce absolutely linear PE or place branches of exact desirable length at precise locations along the polymer chain. In contrast, ROMP of cyclooctene or cyclooctadiene, followed by hydrogenation of the resulting internal alkenes, can effortlessly accomplish the perfectly linear polymerization; ADMET of a diene with a desired side chain can ensure precise branching.[50] Finally, today's state of the art olefin metathesis catalysts and methods also allow the synthesis of cyclic[51] and, potentially, hyperbranched PE (Scheme 1.4).

Scheme 1.4. Olefin metathesis routes to polyethylene of different architectures.
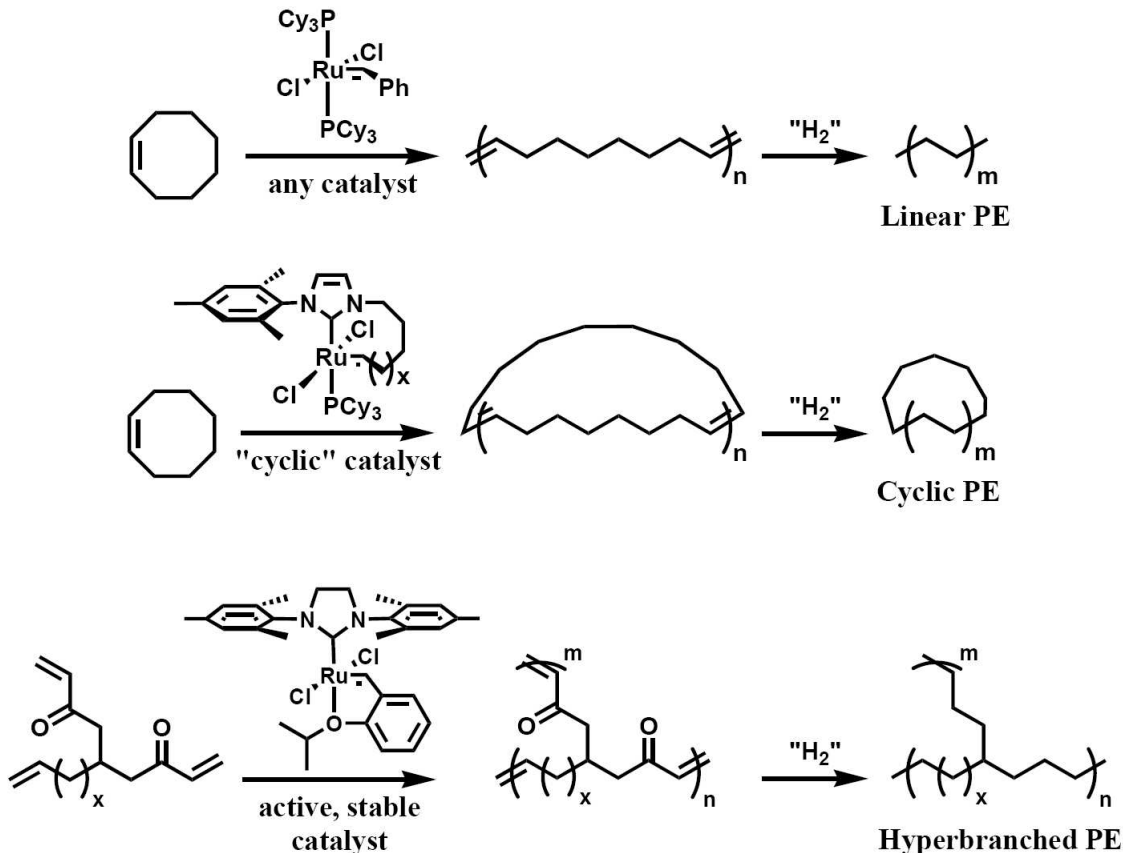
This thesis explores the application of ruthenium catalyzed olefin metathesis in the synthesis of polymers with nonlinear architectures. The hyperbranched and cyclic polymers described herein are made possible by means of either judicious substrate or catalyst design (Scheme 1.4). The fact that both of these polymeric architectures can be extended to the synthesis of polyethylene further demonstrates the power of olefin metathesis as a synthetic tool because neither cyclic[51] nor truly hyperbranched PE[52] is currently available via any other method.

Chapter 2 of this thesis describes the method for the synthesis of hyperbranched polymers via ADMET of specially designed, yet very simple monomers. Chapter 3 explores the post-synthetic functionalization of these polymers by secondary olefin metathesis and probes their potential application as substrate carriers. Chapter 4 investigates the molecular weight control of this polymerization technique (effects of the catalyst loading, reaction time, end-capping, and multifunctional core molecules). Chapter 5 of this thesis summarizes the recent developments in the synthesis and study of cyclic polymers and catalysts. In addition, Appendix 1 outlines the extension of the hyperbranched ADMET polymerization methodology towards the synthesis of hyperbranched polyethylene.

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