Template-Enhanced Ring-Opening Metathesis Polymerization

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ABSTRACT: The template-enhanced ring-opening metathesis polymerization (ROMP) of a norbornene-based thymine monomer was examined. The template, based on diaminopyridine functionalized norbornenes that are designed to recognize thymine substrates with high fidelity, was synthesized via ROMP. The resulting template was used to harness the polymerization of the thymine monomer producing a bis-poly(norbornene) complex. Using ^{1}H NMR spectroscopy, we determined that the polymerization conditions do not disrupt the hydrogen bonding. In addition, the template enhances the rate of the polymerization by inducing an increase in local monomer concentration. To examine whether the polymerization is controlled, we synthesized a solid-supported diaminopyridine template. After the polymerization off this solid-supported template, we extracted the daughter polymer from the support. Detailed analysis of the daughter template proved that the templated polymerization was controlled and that the supported template produces a well-defined daughter polymer.

Introduction

Templation has been the subject of intense investigation since Watson and Crick's discovery that DNA replication involves an elaborate templated synthesis.[1] Nature's employment of template polymerizations for the production of biopolymers ensures monodispersity, reproducibility, and fidelity during the replication of information-rich sequences. An important goal in synthetic polymer chemistry is to both understand and potentially harness Nature's templation strategies to produce abiotic polymers with controlled lengths, tacticities, and sequences. Polymer chemists have studied the effects of templates on various types of polymerization methods including condensation, addition, and chain polymerizations.[2] Arguably the most impressive examples are the use of DNA templated synthesis (DTS)[3] and nucleic acid templated synthesis[4] to either elongate DNA and oligonucleotide strands or polymerize daughter monomers from a predefined DNA sequence.[4c] While DTS provides an attractive platform for the production of monodisperse and even sequence defined polymers, it has thus far been limited to biopolymers. While synthetically templated biopolymers provide insight into and perhaps even rival Nature's complexity, similar strategies for the production of synthetically templated abiotic polymers are still in their infancy. Advances in templation using synthetic polymers would be highly desirable, since they might provide a harness to control and even tune polymer properties. A few examples of influencing polymer properties through templation have recently emerged in the literature in which tacticity[5] and chain organization[6] can be controlled with a template. In addition, template polymerizations appear to be an excellent route to ladder and ladderlike polymers,[7] the properties of which are still not widely understood. Other potential applications include surface-based template polymerizations for the production of intertwined structures and free-standing two-dimensional polymers.[8]

Noncovalent chemistry and molecular recognition are the primary mechanisms by which Nature successfully templates architecturally controlled biopolymers.[9] Nature's mechanisms have undoubtedly inspired the development of template-directed synthesis[10] mediated by molecular recognition and supramolecular self-assembly[11] for the production of topologically interesting small molecules and oligimeric structures. In particular, ring-closing metathesis (RCM)[12] and olefin cross-metathesis (CM)[12b] have been employed extensively in template-directed synthesis. For example, metal−ligand interactions in concert with RCM has been used to prepare porphyrin boxes,[13] macroheterocycles,[14] and calixarene-based multimacrocycles.[15] Templated CM assisted by amide-based hydrogen bonding has been used to generate covalently tethered hydrogen-bonded duplexes,[16] while CM mediated by metal−ligand interactions has been used to form template complementary terpyridine strands.[17] Cross-metathesis and acyclic diene metathesis (ADMET) can even be enhanced by the presence of dialkylammonium and dibenzo[24]crown-8-based templates.[18] Templated olefin metathesis has also resulted in topologically interesting structures such as mechanically interlocked "bundles",[19] catenanes,[14b,c,20] and rotaxanes.[21]

The success of olefin metathesis in small molecule template-directed synthesis is attributed to both functional group tolerance, namely catalyst tolerance toward a wide variety of noncovalent interactions, and the dynamic nature of the metathesis reaction.[22] During templated RCM and CM, both the template recognition event and the covalent bond formation step(s) are reversible, which enables full thermodynamic control[10c] analogous to the proofreading mechanisms of DNA and RNA. Motivated by many small-molecule templated syntheses based on metathesis, we decided to investigate template effects on ring-opening metathesis polymerization (ROMP) since the polymerization of bis-norbornene structures has been shown to be an efficient means for generating bridged polymer architectures.[23] While ROMP is not a dynamic covalent process, it is a highly functional group tolerant process and thus well suited for template polymerizations. In our laboratories, we have shown the compatibility of ROMP with a variety of molecular recognition partners[24] that could potentially be useful in the templation of polymers. In this contribution, we utilize the molecular recognition process between the complementary recognition pair thymine (THY) **1** and diaminopyridine (DAP) **2** (Figure 1). Our design involves the use of a DAP-based

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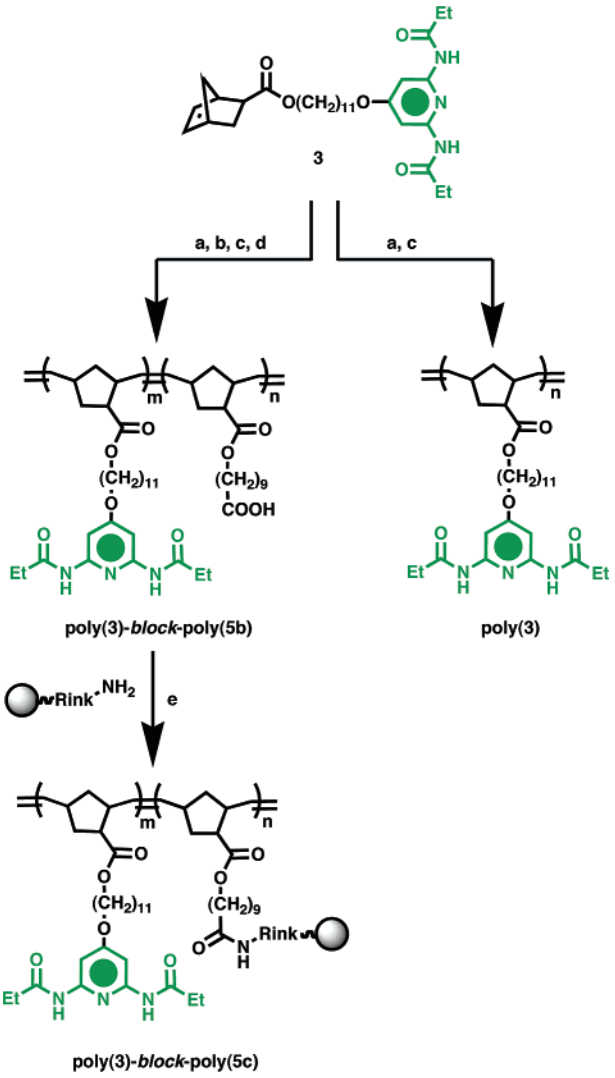
Scheme 1[a] Synthesis of Solution and Solid Support-Based Templates



[a] Reagents and conditions: (a) Grubbs' first-generation catalyst; (b) **4**; (c) ethyl vinyl ether; (d) H_2 Pd/C; (e) Rink amine resin, HATU, DIEA, followed by acetic anhydride.

Table 1. GPC Data for Template and Daughter Polymers

entry	M_w	M_n	M_w/M_n	*m*	*n*
poly(3)	11800	9150	1.29		20
poly(3)-*block*-poly(5b)	21200	17200	1.23	20	5
poly(3)-*block*-poly(5b)[a]	17900	13800	1.30	20	5
poly(6)	8100	4700	1.73		20
poly(6):(2)	10200	8000	1.28		20
poly(6)[b]	9800	8200	1.19		20

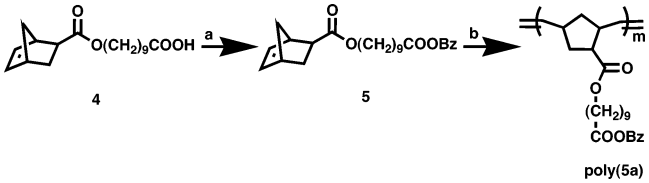
[a] After deprotection. [b] Polymerized from template (at 10 mM in CH_2Cl_2).

poly(norbornene) template that recognizes THY-containing norbornene monomers, followed by the polymerization of the resulting template:monomer complex via ROMP.

Results and Discussion

Template Synthesis. In order to fully understand templated ROMP mediated by DAP:THY interactions, we investigated both solution and solid support-based templates. DAP was chosen as the recognition motif for the polymeric template because the dimerization constant of a polymeric DAP scaffold is lower than the dimerization constant of a THY scaffold, resulting in higher association constants (K_as) for small molecule

Scheme 2[a] Synthesis and Polymerization of Protected Carboxylic Acid Monomer



[a] Reagents and conditions: (a) benzyl alcohol, DCC, DMAP, 12 h, 80%; (b) Grubbs' first-generation catalyst, 2 h, then ethyl vinyl ether.

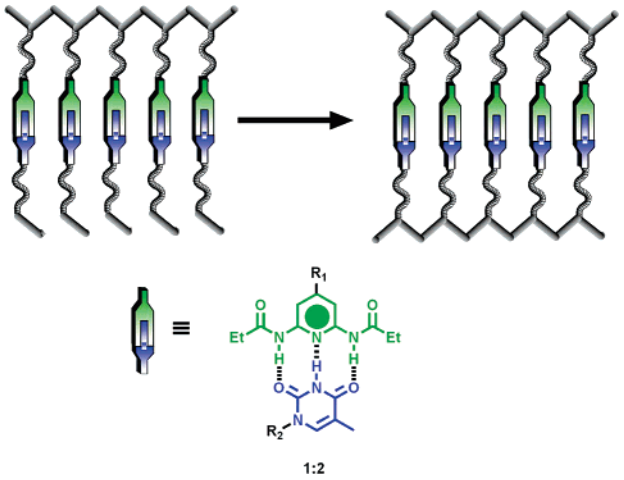


Figure 1. Schematic representation of the template polymerization investigated in this contribution.

THY substrates with DAP polymers relative to K_as for small molecule DAP substrates with THY polymers.[24c,d] The synthesis of the solution-based template is outlined in Scheme 1 and was accomplished by the polymerization of the DAP-based monomer **5** using Grubbs' first-generation catalyst. The polymer characterization data of **poly(3)** are outlined in Table 1. The support-based template synthesis was carried out in close analogy to recent work by Kiessling and co-workers. They demonstrated that the immobilization of poly(norbornene)s onto poly(styrene) resins is more successful when block copolymers consisting of one reactive block are used relative to strategies that utilize reactive polymer end groups.[25] In our case, the reactive block contains a carboxylic acid group that is used to couple the template to the resin. Because of the uncontrolled nature of the polymerization of **4** using Grubbs' first-generation catalyst, the carboxylic acid monomer was protected using a benzyl group through a DCC assisted esterification (Scheme 2). The resulting benzyl protected acid **5** polymerized in a controlled fashion, with molecular weights of the resulting polymers **poly(5a)** linearly dependent on the initiator loading (Supporting Information).

Having demonstrated that monomer **5** can be polymerized in a controlled fashion, block copolymers consisting of both a DAP-based block and a protected carboxylic acid block were synthesized (Scheme 1). DAP-based monomer **3** has previously been found to polymerize in a living fashion[26] and thus was polymerized first. After complete consumption of **3** as evidenced by thin-layer chromatography (TLC), **5** was added to the reaction mixture. The polymerization was terminated upon complete consumption of **5**. Upon hydrogenolysis of the benzyl protecting group, **poly(3)-*block*-poly(5b)** was obtained. The polymer characterization data before and after deprotection of **poly(3)-*block*-poly(5b)** are outlined in Table 1. The resulting block copolymer was coupled to a poly(styrene) Rink amine resin using HATU and DIEA (Scheme 1). Since a 3-fold excess of polymer to resin (based on reactive carboxylic groups) was

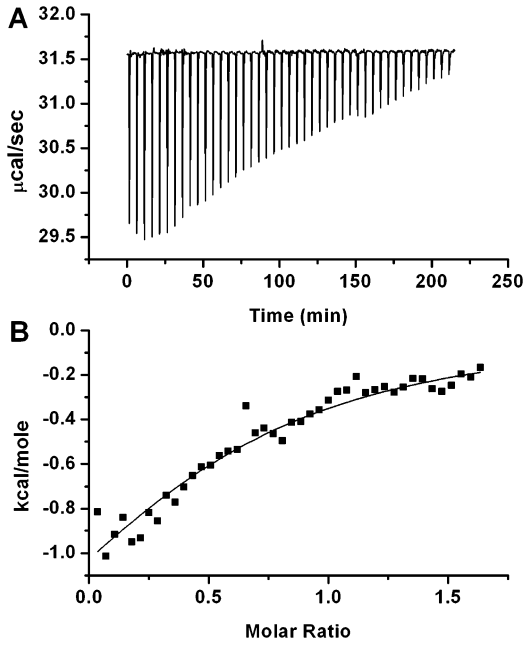


Figure 2. ITC isotherm (A) and titration curve (B) used to calculate binding constant between **6** and **poly(3)**.

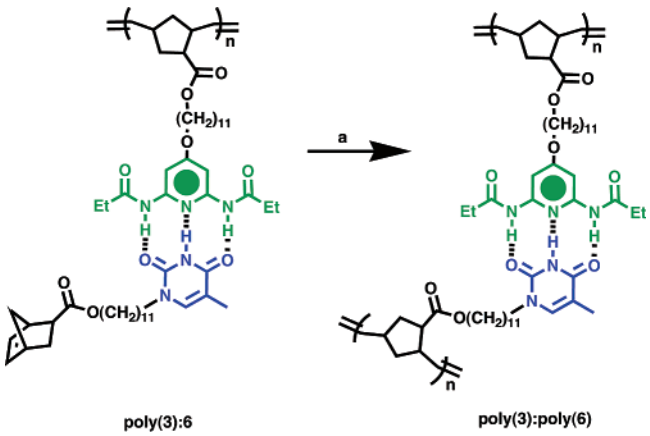
used, quantitative polymer attachment was achieved. Evidence of polymer attachment could be determined visually, as the color of the resin retained the dark brown polymer color after repeated washes. Additionally, a negative ninhydrin test indicated that surface amine reactive groups were consumed. Any residual amine groups were capped following the addition of acetic anhydride.

Template Polymerizations. Our hypothesis was that the DAP:THY interactions would be particularly suited for template polymerizations since the binding constant for this interaction is sufficiently high to result in an increase in local monomer concentrations, while low enough to allow for sufficient flexibility to retain full solubility of the noncovalently cross-linked polymers during the template polymerization. To determine the binding constant of monomer **6** with template **poly(3)**, isothermal titration calorimetry (ITC) was performed (Figure 2). The K_a for the hydrogen-bonding event was found to be $1.5 \times 10^3 \pm 483\ M^{-1}$, which is consistent with the binding constant for similar small molecule THY substrates with polymeric DAP receptors.[24g]

Once it was established that the THY-based monomer **6** had a sufficiently high association constant with template **poly(3)**, the solution-based template polymerization (Scheme 3) was studied. As a benchmark and control experiment, a nontemplated polymerization analogue was also investigated (Scheme 4). For the nontemplated polymerization, the small molecule DAP-based compound **2** was added to monomer **6** to (a) reduce the dimerization behavior of this monomer, which ordinarily prevents a controlled polymerization in nonpolar solvents (vide infra), and (b) mimic the templation polymerization experiment as close as possible by having the same functional groups present in solution during the polymerization.

Detailed ^{1}H NMR spectroscopic studies were performed to monitor the templated polymerization in situ (Figure 3). The amide proton resonances originating from **poly(3)** and the imide proton resonance originating from **6** and **poly(6)** are diagnostic signals for identifying the presence (or absence) of the hydrogen-bonded complex.[24a,d] Signals originating from the amide protons present in the hydrogen-bonded complex **poly(3):6** appear at 9.25 ppm, while the imide proton resonates downfield at 11.44

Scheme 3[a] **Solution-Based Templated Polymerization**

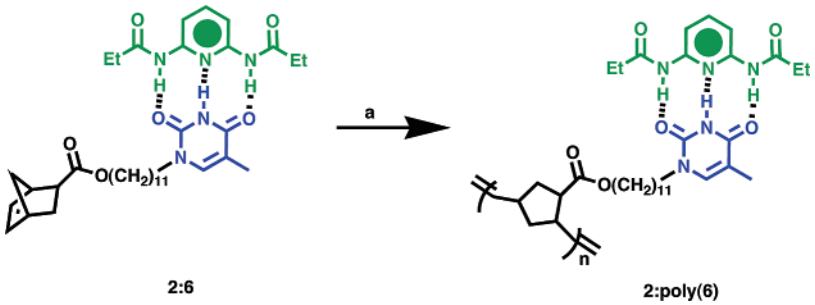


[a] Reagents and conditions: (a) Grubbs' first-generation catalyst, $CDCl_3$ followed by ethyl vinyl ether.

ppm. The presence of these signals provides good evidence for the presence of a polymeric DAP:THY hydrogen-bonded complex, since the uncomplexed amide proton resonance typically appears around 8 ppm, while the complexed amide proton resonates downfield past 9 ppm in $CDCl_3$.[24d] Furthermore, the uncomplexed imide proton typically resonates at or upfield of 10 ppm, while the complexed analogue resonates downfield of 10.4 ppm,[24d] although the precise location of this proton usually depends on the ratio of DAP to THY present in the mixture.[24a] The ^{1}H NMR spectra (Figure 3) in conjuction with the ITC results (Figure 2) provide sufficient evidence to conclude that a hydrogen-bonding complex between the polymeric DAP receptor (**poly(3)**) and THY monomer (**6**) is present. Once the presence of the hydrogen-bonded complex was established, the important question to address was whether the hydrogen-bonded species resides unaffected during the templated polymerization. Thus, we recorded ^{1}H NMR spectra at different intervals during a sample polymerization. We found that the nature of the hydrogen-bonded complex does not appear to be affected by the formation of the polymer:polymer complex (**poly(3):poly(6)**) and that the hydrogen-bonded species is not disrupted by the polymerization conditions. Both the amide proton resonance and the imide proton resonance remain at 9.25 and 11.44 ppm, respectively, throughout the polymerization (Figure 3). Additionally, the ^{1}H NMR spectra clearly show the complete consumption of monomer **6** over time. The olefinic proton resonance originating from monomer **6** at 6.15 ppm disappears while the signal corresponding to the olefin-containing polymer at 5.28 ppm increases throughout the polymerization (Figure 3).

We then investigated the kinetics of the template polymerization in detail to determine whether or not the polymer-based template (**poly(3)**) could enhance the rate of polymerization. Such a phenomenon has been observed before during ionic and hydrogen-bond-based free-radical template polymerizations.[2] Furthermore, kinetic enhancements are also seen during many examples of DTS and nucleic acid-based templated polymerizations; in some cases, the template is *required* for polycondensation to ensue at dilute concentrations.[4b] We studied kinetics of both templated polymerizations and nontemplated polymerization analogues at 10, 50, and 100 mM using ^{1}H NMR spectroscopy. Our hypothesis, based on many examples of DTS, was that the greatest template effect would be observed at the lowest concentration. In this case, 10 mM was the lowest concentration we investigated, since concentrations below 10 mM resulted in errors in the rate constants originating from

Scheme 4[a] Nontemplated Polymerization Control Experiment



[a] Reagents and Conditions: (a) Grubbs' first generation catalyst, $CDCl_3$ followed by ethyl vinyl ether.

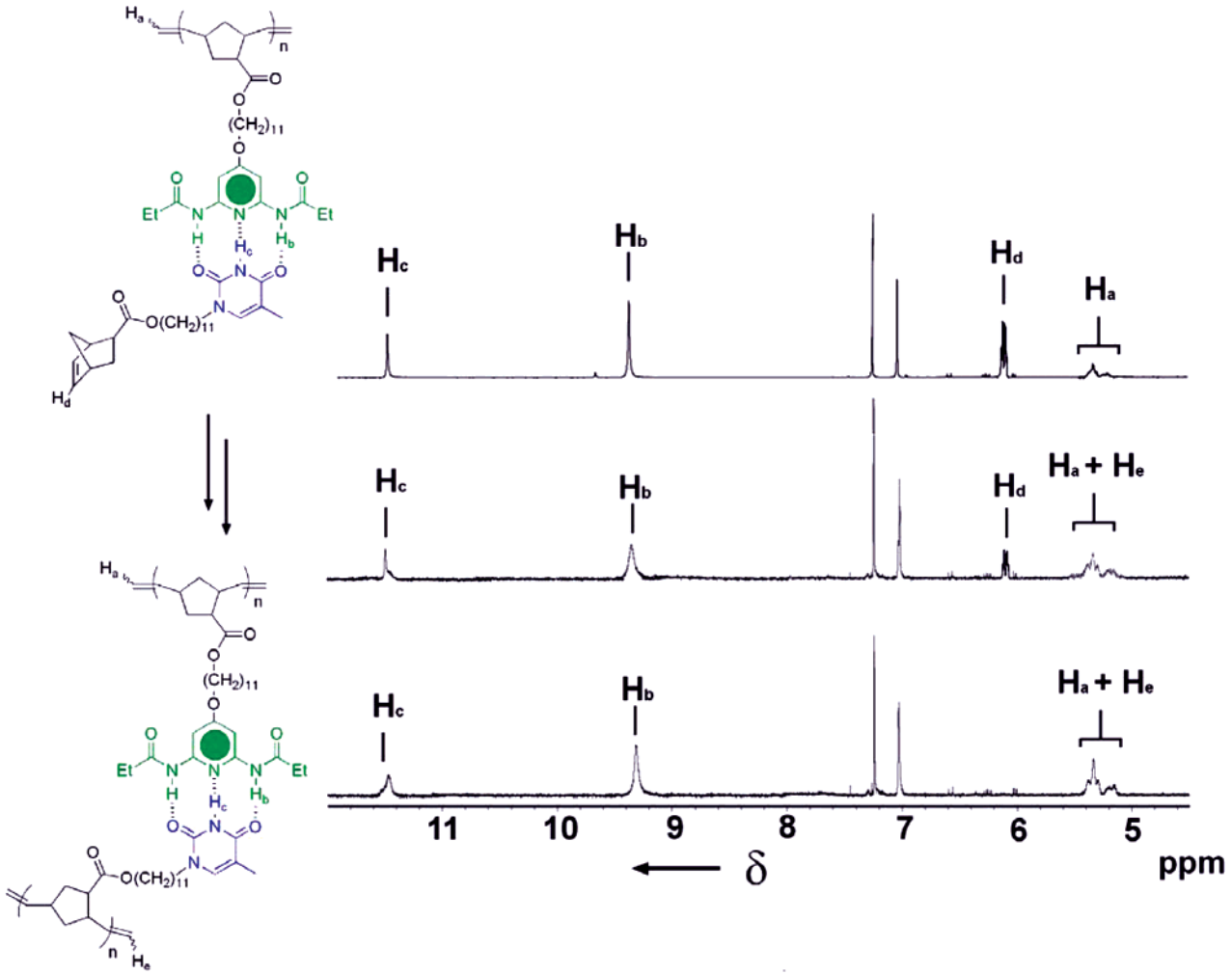


Figure 3. Stacked plot of partial ^{1}H NMR spectra (10 mM, $CDCl_3$, 298 K) and corresponding peak assignments displaying the polymerization progress of monomer **6** bound to template **poly(3)** in situ.

baseline noise that were too high to properly assess the data. In order to compare templated and nontemplated analogues, we chose to use a small molecule DAP substrate (**2**) to protect the THY monomer **6** during the nontemplated polymerization. We assumed that this would ensure the comparison of truly analogous systems, since THY monomer **6** has been shown to aggregate due to self-dimerization of polymer chains in nonpolar solvents at moderate degrees of polymerization (DP > 50).[24a]

Pseudo-first-order rate constants (k_{obs}) for the polymerization (in $CDCl_3$) of monomer **6** bound to template **poly(3)** or protected with small molecule **2** were measured by monitoring the decrease in peak height of the signal originating from the monomeric olefin protons. In the solution-based polymerization examples with or without a template (Schemes 3 and 4), exponential decreases in monomer concentrations were observed, indicating that the polymerizations follow expected pseudo-first-order kinetics, in which all cases reached 100% conversion (Figures 4−6). The greatest rate enhancement was observed at 10 mM, the most dilute concentration studied. An approximate 3-fold increase in the rate constant was observed when the template was used relative to the nontemplated analogue (Table 2). A result that was not entirely expected was observed at higher concentrations. The effect of the template seems to decrease exponentially as concentration decreases (Figure 7). At 10 mM, a 3-fold template enhancement effect was observed, while at 50 mM, the enhancement was only 2-fold, and at 100 mM, no enhancement was observed. These results suggest that at high dilution a local concentration

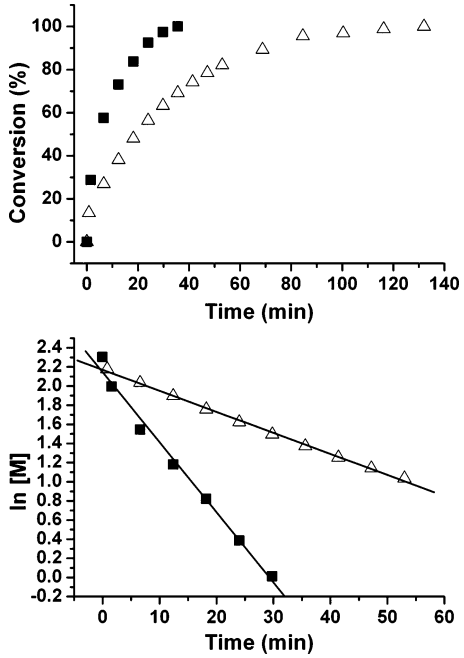


Figure 4. Polymerization kinetics at 10 mM ($CDCl_3$, 298 K): plot of conversion vs time (top) and corresponding first-order kinetics plot (bottom) for the polymerization of **2:6** (Δ) and **poly(3):6** (■).

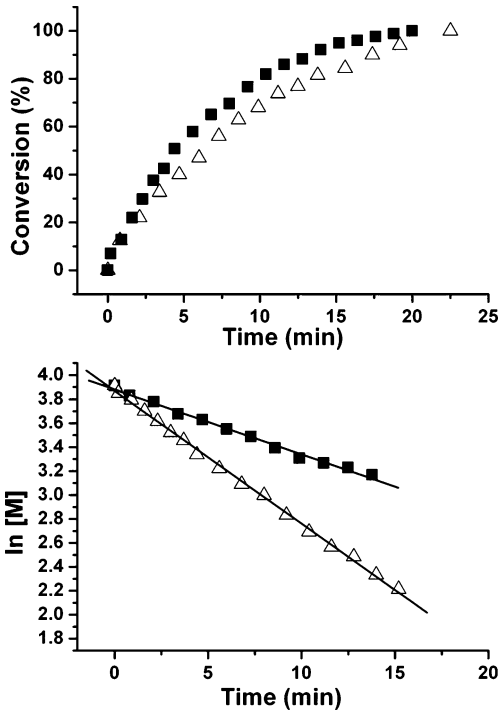


Figure 5. Polymerization kinetics at 50 mM ($CDCl_3$, 298 K): plot of conversion vs time (top) and corresponding first-order kinetics plot (bottom) for the polymerization of **2:6** (Δ) and **poly(3):6** (■).

enhancement induced by the template is sufficient to speed up the rate of polymerization. At higher concentrations, however, this effect probably still exists yet has little effect on the observed kinetics of the polymerization. Thus, at concentrations approaching 100 mM, the bulk solution molarity seems to dictate the rate of polymerization rather than any local concentration effects induced by the template.

Several control experiments were carried out to verify our hypothesis. First, it is plausible that the template prevents the *slowing* of the polymerization by reducing the aggregation behavior of monomer **6** rather than actually *speeding* up the

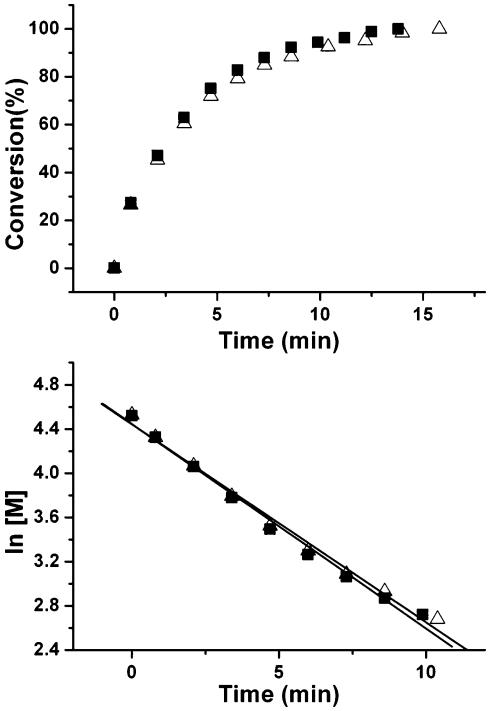


Figure 6. Polymerization kinetics at 100 mM ($CDCl_3$, 298 K): plot of conversion vs time (top) and corresponding first-order kinetics plot (bottom) for the polymerization of **2:6** (Δ) and **poly(3):6** (■).

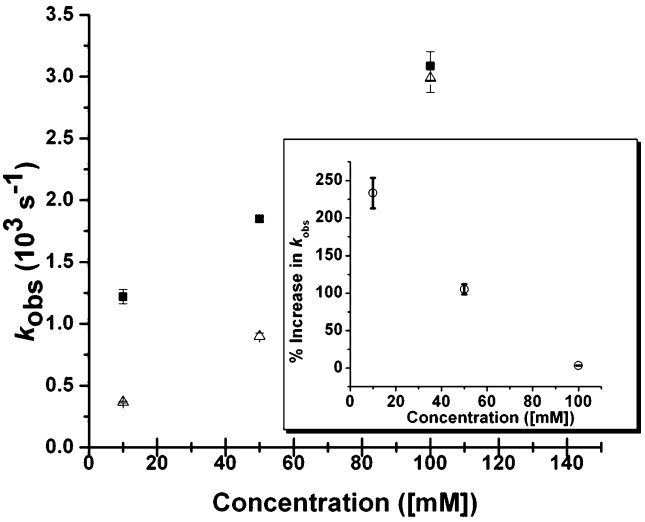
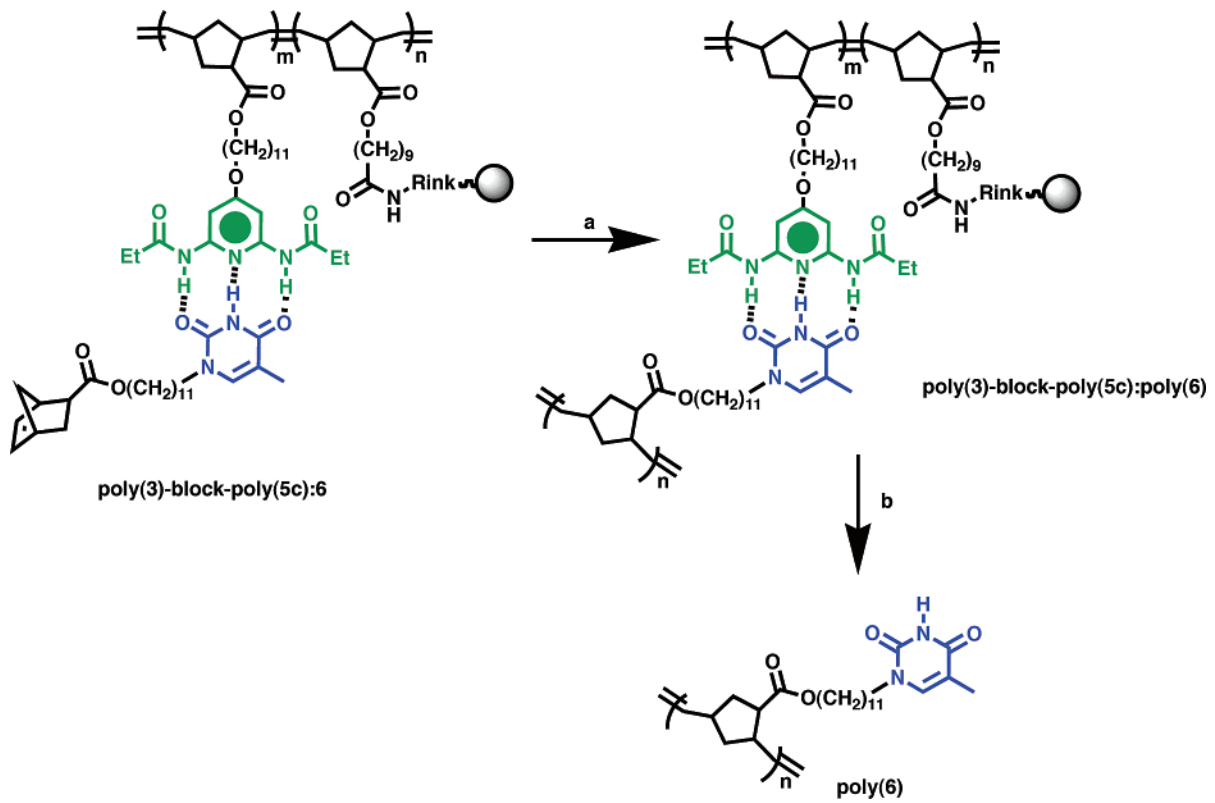


Figure 7. Rate constant dependence on concentration for templated (square) and nontemplated (diamond) polymerizations. The corresponding inset plot displays the percent increase in k_{obs} induced by the polymeric template at varying concentrations.

polymerization by inducing a local concentration effect, especially since aggregation behavior of monomer **6** has been observed when attempts were made to polymerize monomer **6** with a desired DP of greater than 50 (in CH_2Cl_2).[24a] This aggregation behavior would presumably be mitigated by protecting the THY moiety with the corresponding DAP (**2**) substrate, but it is possible that aggregation might still exist in competition with the protecting group, since we are considering an equilibrium process. Thus, we examined the polymerization of unprotected monomer **6** at varying concentrations in the hopes of quantifying how large of an effect aggregation might have on the rate constant. To our surprise, unprotected monomer **6** does not visibly aggregate at low concentrations (10−100 mM), and no effect on the rate constant was observed relative to the rate constant observed for the polymerization of **2:6** (Table 2

Scheme 5[a] Support-Based Template Polymerization



[a] Reagents and conditions: (a) Grubbs' first-generation catalyst, CH_2Cl_2 followed by ethyl vinyl ether; (b) DMF.

and Supporting Information). Monomer **6** only tends to aggregate as initiator loading is decreased with desired DPs of greater than 50. It is important to note that when aggregation is observed while trying to polymerize monomer **6** with higher DPs, the polymerization only tends to proceed to around 50% conversion. Thus, these results indicate that the rate constants for the nontemplated analogue polymerizations of monomer **6** are not hampered by aggregation. Most importantly, these data provide strong evidence that the template is not an aggregation suppressant but rather an inducer of a local concentration increase.

The role of the polymer backbone during the template polymerization might also be important since the template is based on a poly(olefin) and ROMP is used as the polymerization method. While we predicted that the polymer backbone would not interfere with subsequent template polymerizations since the first-generation Grubbs catalyst is active primarily toward strained olefins, we nevertheless carried out control experiments in which monomer **2:6** was polymerized in the presence of poly(norbornene) (DP = 20; M_w = 2000; M_n = 1850; PDI = 1.08). The rate constants measured were independent of the presence of the control polymer (Table 2 and Supporting Information). These results support the conclusion that the poly(olefin) backbone is not a nuisance during the polymerization, and if minimal backbiting is occurring, that this has no noticeable effect on k_{obs}.

Next, we investigated the nature and the control of the templated polymerization. Since the daughter polymer (**poly(6)**) formed could not be easily separated from **poly(3)**, we utilized the support-based template **poly(3)-*block*-poly(5c)** (Scheme 5). Once monomer **6** was completely polymerized from the support-based template, DMF was added to the reaction mixture to break up the hydrogen-bonded complex and to remove the daughter polymer (**poly(6)**) from the resin. The resulting polymer could then be analyzed by GPC and compared to its nontemplated analogues. The homopolymerization of monomere **6** in nonpolar solvents (CH_2Cl_2, $CHCl_3$) results in a rather uncontrolled polymerization with the formation larger molecular weight species (Figure 8, Table 1). Our kinetic studies indicate that aggregation is not a problem during the polymerization of monomer **6** with DP < 50, so this is probably not a contributing factor to the uncontrolled polymerization. It is possible, however, that monomer **6** may interfere with the catalyst in some way, and this interference may not have been detectable during our ^{1}H NMR spectroscopy studies. Another factor may be the solubility of monomer **6** in CH_2Cl_2. Under dilute conditions, the limited solubility of monomer **6** in CH_2Cl_2 did not have a noticeable effect on the kinetics of the polymerization, but this still could potentially have an effect on the control of the polymerization. These are merely assumptions, however, as the exact reason why monomer **6** polymerizes in an uncontrolled fashion is not fully understood. Nevertheless, the addition of a small molecule DAP substrate (**2**) to monomer **6** clearly allows for a more controlled polymerization (Figure 8, Table 1). The resulting polymer has a lower polydisperity

Table 2. Kinetic Data for Template Polymerizations and Control Polymerizations

entry	concn (mM)	k_{obs} (10^3 s^{-1})
2:6	10	0.37 ± 0.01
poly(3):6	10	1.22 ± 0.06
6	10	0.36 ± 0.01
2:6 + p(NBE)	10	0.41 ± 0.02
2:6	50	0.90 ± 0.03
poly(3):6	50	1.85 ± 0.02
6	50	0.82 ± 0.04
2:6 + p(NBE)	50	0.91 ± 0.02
2:6	100	2.99 ± 0.12
poly(3):6	100	3.09 ± 0.12
6	100	2.67 ± 0.09
2:6 + p(NBE)	100	2.65 ±0.06

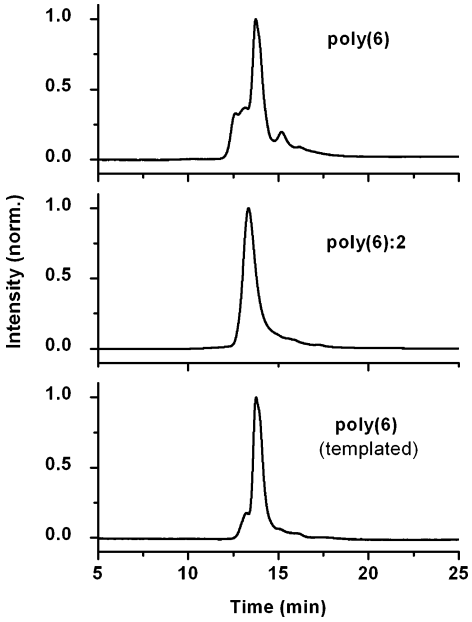


Figure 8. GPC traces of **poly(6)** without any template (a), **poly(6)** in the presence of **2** (b), and **poly(6)** released from the template.

index (PDI) (1.28) than the analogue polymer formed without the addition of the THY additive, which has a PDI of 1.73 (Table 1). Likewise, the polymer formed from the support based template **poly(3)-*block*-poly(5c)** has a PDI of 1.19. Such a narrow PDI indicates a controlled polymerization, and the GPC results indicate a monomodal distribution of molecular weights. A small amount of high molecular polymer is present according to the GPC results (Figure 8). However, significantly less high molecular weight polymer is formed during the templated polymerization relative to the homopolymerization of **6** (Figure 8). It is clear from these results that the support-based template does not interfere with the polymerization, a satisfactory result since we did not see the evidence of cross-linking at dilute conditions. Furthermore, upon washing with DMF, a solvent that is able to disrupt the hydrogen bonds between the template and the daughter polymer, thereby releasing the daughter polymer, polymer was recovered. On the basis of initial monomer loading to the supported template, we found that 96% of the resulting polymer was recovered after the DMF wash. This rules out the possibility of higher molecular weight species being retained on the template after the wash. Our results from the supported template experiments indicate that the template is capable of providing an environment in which monomer **6** can polymerize in a controlled fashion. However, when the small molecule protecting group (DAP **2**) is used, similar results are obtained. Thus, the supported template does not appear to be significantly advantageous over the small molecule **2** in providing a controlled polymerization environment.

We also investigated the effect of the template on the degree of polymerization (DP) of the daughter polymer and found no relationship between the DP of the template with the DP of the daughter polymer. Rather, the DP was based on initiator loading. Regardless of the DP of the template, the initiator loading was the only factor that seemed to affect the DP of the daughter polymer. Although relationships between template DP and daughter DP have been observed during radical polymerizations,[27] these results cannot be generalized and applied to our system. The observed control during the support-based template polymerization is most likely the result of the protection of the thymine moiety, analogous to the effect of the small molecule DAP (**2**) protecting group. Another possibility, however, is that the template speeds up the polymerization such that catalyst death is minimized, and the larger molecular weight species are not produced, a result that we have previously observed during the polymerization of similar monomers.[26]

Conclusion

Template polymerizations are of great interest because they mimic the impressive polymerization techniques found in Nature, thereby allowing for a high degree of control during the polymerization, and might permit for the realization of applications to which templated polymers are key. Most of the prior studies on templated polymerizations, however, deal with uncontrolled polymerization methods that have difficulties separating the daughter polymer from the template. In this contribution, we present that both a controlled polymerization method can be performed from a polymeric template and the daughter polymer can be separated from a support-based template easily. We find that a polymeric template enhances both polymerization kinetics under dilute conditions and the control of the resulting polymerization. These results are satisfactory for our next challenge to apply templated ROMP to materials applications, such as surface-templated polymerizations or polymerizations from nanoparticle assemblies.

Experimental Section

Materials. Grubbs' first-generation catalyst was purchased from Aldrich. *N*,*N*′-Dicyloclohexylcarbodiimide (DCC) and (dimethylamino)pyridine (DMAP) were purchased from Alfa Aesar. Benzyl alcohol was purchased from Alfa Aesar and distilled prior to use. 2-(7-Aza-1*H*-benzotriazole-1-yl)-1,1,3,3-tetramethyluronium hexafluorophosphate (HATU) was purchased from Oakwood Products (West Columbia, SC). Rink Amide AM Resin (200−400 mesh, 0.71 mmol/g) was purchased from Novabiochem. Ethyl vinyl ether (stabilized) and dry *N*,*N*-dimethylformamide (DMF) were purchased from Acros Organics. Palladium on carbon powder (5%), 50% water wet, was purchased from Aldrich. $CHCl_3$ purchased from Fischer was dried ($CaCl_2$), distilled, and degassed prior to use. CH_2Cl_2 purchased from Fischer was dried via passage through copper oxide and alumina columns. Compounds **3**,[26] **4**,[24f] and **6**[24a] were synthesized according to literature procedures. *N*-Diisopropylethylamine purchased from Avocado Research Chemicals was distilled over CaH prior to use.

Methods. Reactions were carried out under an argon atmosphere unless otherwise noted. Thin-layer chromatography (TLC) was performed on Silica XHL TLC glass backed plates (Sorbent Technologies). Column chromatography was performed on premium R_f grade silica gel (Sorbent Technologies, 40−75 μm). Nuclear magnetic resonance (NMR) spectra were recorded using a 500 MHz Bruker DRX spectrometer (^{1}H NMR: 500 MHz; ^{13}C NMR: 125 MHz) or a 300 MHz Varian Vx 300 spectrometer (^{1}H NMR: 300 MHz; ^{13}C NMR: 75 MHz). Spectra were referenced from the residual proton resonance of the deuterated solvent. Chemical shifts are reported as parts per million (ppm) downfield from the signal origination of Me_4Si as an internal standard for ^{1}H and ^{13}C NMR spectroscopy. Kinetic experiments for polymerizations were conducted using ^{1}H NMR spectroscopy (298 K) by monitoring the decay in proton resonances originating from monomer. The peak heights were subsequently fitted to a decreasing exponential function (pseudo-first order) from which rate constants were extrapolated. Gel permeation chromatography (GPC) analyses were carried out using a Shimadzu pump, a Shimadzu UV detector with THF or DMF as the eluants, and a set of American Polymer Standards columns (100, 1000, 100 000 Å linear mixed bed). The flow rate used for all the measurements was 1 mL/min. All GPC measurements were calibrated using poly(styrene) standards and were carried out at room temperature. M_w, M_n, and PDI represent weight-average molecular weight, number-average molecular weight, and the polydispersity index, respectively. Isothermal titration calorim-

etry was performed on a Microcal VP-ITC isothermal calorimeter using degassed $CHCl_3$ as the solvent with a cell concentration of 1 mM and a syringe (titrant) concentration of 10 mM.

Monomer 5. Carboxylic acid monomer **4** (100 mg, 0.325 mmol), benzyl alcohol (35 mg, 0.325 mmol), DCC (74 mg, 0.358 mmol), and DMAP (cat.) were dissolved in dry CH_2Cl_2, and the reaction mixture was refluxed overnight. The precipitate was filtered off, and the solvent was removed using rotary evaporation under reduced pressure. The resulting oil was purified using column chromatography (hexanes/EtOAc = 9:1) to give a clear oil (120.5 mg, 93%). ^{1}H NMR ($CDCl_3$): δ = 7.37 (m, 5H), 6.12 (m, 2H), 5.12 (s, 2H), 4.08 (t, J = 6.7 Hz, 2H), 3.01 (m, 1H), 2.98 (m, 1H), 2.35 (t, J = 7.6 Hz, 2H), 2.22, (m, 1H), 1.81−0.90 (m, 18H). ^{13}C NMR ($CDCl_3$): δ = 174.0, 171.1, 140.3, 136.0, 135.9, 128.5, 128.0, 127.3, 70.3, 68.9, 50.6, 48.3, 43.0, 34.2, 31.3, 30.2, 29.5, 29.1, 29.0, 28.6, 25.4, 24.7. Anal. Calcd for $C_{25}H_{34}O_4$: C, 75.34; H, 8.60. Found: C, 75.59; H, 8.74.

General Procedure for the Synthesis of Poly(3) and Poly-(5a). The desired amount of monomer was weighed into a glass vial with a rubber septum cap, placed under an argon atmosphere, and dissolved in anhydrous, degassed CH_2Cl_2. A stock solution of the catalyst (in the corresponding solvent) was prepared, and the desired volume was added to the polymerization vessel. Upon complete polymerization, ethyl vinyl ether was added to quench the polymerization. The polymer was isolated and purified by repeated precipitations into MeOH.

Poly(3). All analytical data are consisted with previously published results.[47]

Poly(5a). ^{1}H NMR ($CDCl_3$): δ = 7.37 (m, 5H), 5.39 (m, 2H), 5.12 (s, 2H), 4.08 (t, J not resolved, 2H), 2.80−2.60 (m, 2H), 2.36 (t, J = 7.7 Hz, 2H), 1.90−1.20 (m, 18H). ^{13}C NMR ($CDCl_3$): δ = 174.3, 170.1, 140.3, 137.0, 134.0, 133.1, 130.2, 128.5, 128.0, 127.3, 70.3, 67.6, 50.3, 48.0, 43.0, 34.2, 30.3, 30.2, 29.3, 29.1, 28.9, 28.6, 24.9, 24.3.

Poly(3)-*block*-poly(5b). Monomer **3** (44 mg, 0.083 mmol) was dissolved in anhydrous, degassed CH_2Cl_2. Grubbs' first-generation catalyst (3.45 mg, 0.004 mmol) was added in a solution of CH_2Cl_2. The polymerization was monitored by TLC. Upon complete disappearance of **3**, **5** (8.3 mg, 0.021 mmol) was added as a solution in CH_2Cl_2. Upon complete consumption of **5**, the polymerization was terminated with ethyl vinyl ether. The polymer was isolated and purified by successive precipitations in cold methanol (50 mg, 96%). ^{1}H NMR ($CDCl_3$): δ = 7.80 (br m, 2H), 7.45 (m, 2H), 7.36 (m, 5H) 5.27 (m, 4H), 5.10 (s, 2H), 4.05 (m, 6H), 2.80 (m, 2H), 2.21 (m, 23H) 1.80−1.11 (m, 40H). ^{13}C NMR ($CDCl_3$): δ = 176.2, 173.9, 172.8, 169.3, 150.7, 136.3, 133.9, 128.8, 128.4, 96.3, 68.7, 66.3, 64.8, 49.8, 47.8, 42.1, 36.5, 34.5, 31.0, 29.7, 29.5, 29.1, 28.9, 27.2, 26.5, 26.1, 25.1.

The resulting polymer was dissolved in THF/MeOH = 3:1 and hydrogenated for 24 h to remove the benzyl protecting group using H_2 over Pd/C (60 psi). The reaction mixture was filtered over celite, and the solvent was removed using rotary evaporation under reduced pressured to yield **poly(3)-*block*-poly(5b)** as a light brown glassy solid (40 mg, 80%). ^{1}H NMR ($CDCl_3$): δ = 11.20, (br s, 1H), 7.80 (br m, 2H), 7.45 (m, 2H), 5.27 (m, 4H), 5.10 (s, 2H), 4.05 (m, 6H), 2.75 (m, 2H) 2.21 (m, 23H) 1.80−1.11 (m, 40H). ^{13}C NMR ($CDCl_3$): δ = 176.2, 173.9, 172.8, 169.3, 150.7, 136.3, 133.9, 96.3, 68.7, 66.3, 64.8, 49.8, 47.8, 42.1, 36.5, 34.5, 31.0, 29.7, 29.5, 29.1, 28.9, 27.2, 26.5, 26.1, 25.1.

Resin-Supported Poly(3)-*block*-poly(5c). Rink amide AM resin (121 mg, 0.71 mmol/g, 0.086 mmol) was added to a fritted filter equipped coupling vessel and swelled in CH_2Cl_2 for 45 min followed by DMF for 10 min with shaking using a WS180° Shaker (Glas-Col). The resin was subsequently washed with MeOH and DMF. Piperidine (20% in DMF, 1 mL) was added to remove the Fmoc protecting group. The mixture was agitated for 10 min, and the resin was thoroughly washed with CH_2Cl_2, MeOH, and DMF. A ninhydrin test indicated the presence of free amine groups. **Poly-(3)-*block*-poly(5b)** (3 equiv, 135.5 mg, 0.258 mmol), HATU (130 mg, 0.344 mmol), and DIEA (0.05 mL) were added to the resin as solutions in DMF, and the coupling vessel was shaken overnight. The resin was filtered and washed thoroughly with DMF, MeOH, and CH_2Cl_2. A negative ninhydrin test indicated the consumption of surface amine groups. Residual amine groups were capped with acetic anhydrid. The resin-supported polymer was dried under high vacuum for 24 h.

Solution-Based Template Polymerization for Poly(3):Poly-(6). **Poly(3)** was dissolved in CH_2Cl_2 or $CDCl_3$ followed by the addition of **6**. The concentration of **6** was kept at 10 mM. The mixture was sonicated for 30 min to ensure complete dissolution followed by the addition of Grubbs' first-generation catalyst. The polymerization was monitored by ^{1}H NMR spectroscopy. Upon complete conversion, the polymerization was quenched with ethyl vinyl ether. The resulting polymer:polymer complex **poly(3):poly-(6)** was isolated by precipitation into cold MeOH.

Support-Based Template Polymerization for Poly(3)-*block*-poly(5c):Poly(6). Resin-supported **poly(3)**-*block*-**poly(5c)** was swelled in CH_2Cl_2 for 45 min. Monomer **6** was then added to the vessel, and the mixture was shaken for 1 h to ensure complete complexation. Then, Grubbs' first-generation catalyst was added, the polymerization was allowed to proceed for 6 h, and the polymerization was terminated with ethyl vinyl ether. The resin was washed with CH_2Cl_2 and subsequently with DMF to remove the daughter polymer (**poly(6)**, 96%). Analytical data for **poly(6)** are consistent with previous reported values.[47]

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Supporting Information Available: Supporting text including polymer characterization for monomer **5** and kinetic plots for control nontemplated polymerizations. This material is available free of charge via the Internet at http://pubs.acs.org.

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