

Polymers with Multiple Hydrogen-Bonded End Groups and Their Blends

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ABSTRACT: A new strategy for synthesizing well-defined, chain-end-functionalized polymers containing multiple hydrogen-bonding (MHB) groups capable of heterodimerization in both solution and the melt has been developed. Two complementary MHB systems were chosen for initial studies: 2-ureido-4[1H]-pyrimidinone (UPy) and 2,7-diamido-1,8-naphthyridine (Napy) and ATRP initiators containing either UPy or Napy were prepared and shown to produce well-defined (meth)acrylic polymers with the desired MHB functionality present at the chain end. To characterize the effectiveness of the MHB interaction in the melt, blends of chain-end-functionalized linear polymers were cast into films, annealed at various temperatures above T_g , and then quenched, and their structures were analyzed by transmission electron microscopy (TEM) and differential scanning calorimetry (DSC). It was shown that the nature of the hydrogen-bonding group(s) present in the blend has a significant effect on bulk microstructure and thermal behavior, in particular for blends of UPy- and Napy-functional chains.

Introduction

In recent years, significant work has been devoted to the development of polymer materials that can be processed in nontraditional ways, i.e., at low temperature or high pressure. To accomplish this, the material properties must be carefully balanced between mechanical strength and processability. Baroplastics, for example, are block copolymers that display meltlike flow at temperatures below the glass transition of the higher T_g component (depending on the composition) through pressure-induced partial mixing of weakly interacting blocks.^{1,2} Alternately, supramolecular polymers consisting of multiple hydrogen-bonding telechelic oligomers were shown to have highly temperature dependent properties,^{3,4} allowing them to be processed at relatively low temperatures due to the reversible breaking of noncovalent backbone linkages, while at room temperature these linkages are strongly bound, producing an elastic solid.

These examples demonstrate useful strategies to reduce the amount of energy required to process commercially relevant polymers. Our goal is to extend these ideas and provide a versatile, modular, and reversible method for controlling polymer architecture and allow processing of architecturally defined materials at low temperature to give nanoscale morphologies. Multiple hydrogen-bonding (MHB) groups have been designed over the past decade to span a wide range of binding strengths, and their specificity can be controlled through the arrangement of donor and acceptor bonds.⁵ By integrating MHB groups into conventional polymers through functional initiators or monomers, an extremely versatile platform for designing new, low-temperature processable materials can be envisaged. Several groups have recently demonstrated the synthesis of MHB random copolymers^{6–12} or block copolymer-like materials.^{13–17} In the case of MHB block copolymers, as the temperature of the polymer melt is increased, the bonds joining dissimilar

blocks break to generate homopolymers that can then swell the microphase-separated domains and reversibly increase the overall domain spacing as much as 300%.¹⁶

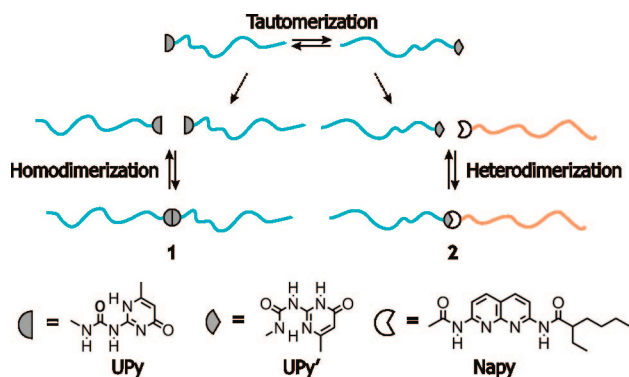
Additionally, polymeric systems utilizing strategically placed reversible binding groups provide potential beyond alternative processing methods. Recent theory^{17,18} indicates that by carefully balancing polymer interactions with the strength and directionality of hydrogen-bonding groups chain-end-functionalized materials have the potential for widely varying structures and properties, all derived from a few simple building blocks. In order to fully take advantage of this potential, however, a model polymer system must be developed that shows the proper balance between phase separation (characterized by the Flory–Huggins χ parameter) and hydrogen-bonding strength at experimentally relevant temperatures. The synthetic strategies reported previously for making end-functional MHB polymers are somewhat limited—the MHB groups are often difficult to synthesize or very bulky for a given binding strength, and attaching them to polymers often requires postpolymerization reactions (and thus uncertainty in the degree of functionalization). The polymers themselves often have broad molecular weight distributions or high T_g s, necessitating melt annealing at temperatures high enough to significantly reduce the strength of the hydrogen bond. Despite these limitations, the incorporation of both homocomplementary^{3,4,6,19} and heterocomplementary^{14,16,20–24} MHB groups at polymer chain ends has been previously demonstrated. In particular, the work of Mather et al.²¹ first demonstrated the incorporation of MHB chain ends through the use of controlled radical polymerization from uracil-functional nitroxide initiators.

Often in studies of MHB end-functional materials the focus has been on oligomers with M_n less than 5000 g/mol. In such cases the MHB end group constitutes a large fraction of the mass of the macromolecule, and it has been shown that not only hydrogen bonding but also phase separation or crystallization of the end groups has a significant influence on the bulk properties of the material.^{25,26} By increasing the molecular weight of the polymer and thereby decreasing the relative contribution of the end group, such complicating factors are

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Scheme 1. Competing Homopolymer and Diblock Copolymer Formation in Blends of End-Functional MHB Polymers

minimized. In order to favor the interaction of dissimilar polymers into block copolymer-like materials, heterocomplementary binding motifs are preferred, if not required, and to compensate for the polymers' tendency to phase separate in the melt (particularly at high molecular weights), the binding strength should be very high.

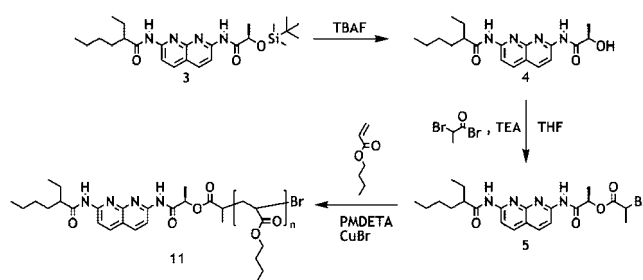
We demonstrate here a general scheme for preparing well-defined, end-functional MHB polymers of controlled molecular weight and chemical composition through atom transfer radical polymerization (ATRP) from strongly associating MHB-functional initiators. ATRP can be used to polymerize of a wide range of monomers including (meth)acrylates, (meth)acrylamides, and styrenics,²⁷ allowing for the trivial variation of the polymer backbone chemistry. For our initial studies we have chosen to focus on the well-characterized 2-ureido-4[1H]-pyrimidinone (UPy) and 2,7-diamido-1,8-naphthyridine (Napy) MHB groups in order to study the effect of directionality on supramolecular polymer assembly and drive supramolecular copolymer formation through their very strong, complementary interaction. UPy forms strong homodimers in solution (K_{eq} 6×10^7 M⁻¹ in CHCl₃, 6×10^8 M⁻¹ in toluene²⁸), but in the presence of Napy, UPy–Napy heterodimers are favored at concentrations above 10^{-5} M.²⁹ As a result, blending of well-defined UPy and Napy monofunctional polymers may lead to the intriguing possibility of competing homopolymer, **1**, and diblock copolymer, **2**, formation.

Results and Discussion

ATRP initiators were synthesized from MHB groups bearing a reactive alcohol group by reaction with commercially available α -bromoacyl bromides. For example, naphthyridine **3** was synthesized according to literature procedures,^{29–31} and the silyl group was subsequently removed using TBAF. The resulting alcohol **4** was reacted with 2-bromopropionyl bromide to give MHB initiator **5**, which was purified by flash chromatography to give a white solid in 87% yield from **3** (Scheme 2).

UPy-functional initiators **8a** and **8b** were synthesized by reacting activated isocytosine **6**³² with ethanolamine and treating the resulting alcohol-functional UPy, **7**, with either 2-bromopropionyl bromide or 2-bromoisobutyryl bromide (Scheme 3). The product, **8a** or **8b**, was recrystallized from ethanol, giving a white solid in 55% or 46% overall yield, respectively.

As the hydrogen bond strength is expected to decrease significantly with temperature, it is important to choose polymers with low T_g s to provide the opportunity to anneal in both the strong (low temperature) and weak (high temperature) binding regimes. Additionally, electron density and/or staining contrast will allow for structural studies by SAXS and TEM, respectively. We have thus chosen to focus on *n*-butyl acrylate (nBA, PnBA, T_g -54 °C) and benzyl methacrylate (bnMA, PbnMA,

Scheme 2. Synthesis of Napy-Functional ATRP Initiator **5 and PnBA–Napy **11****

T_g $+54$ °C), both of which can be polymerized under controlled conditions by ATRP. The aromatic rings of poly(bnMA) can be selectively stained by RuO₄, and although the temperature dependent Flory–Huggins χ parameter has not yet been measured for this system, homopolymers of moderate molecular weight are shown to be immiscible below (Figure 3) by their phase separation on annealing.

Polymerization of nBA from either **5** or **8a** was conducted in bulk at 70 °C using the CuBr/PMDETA system as catalyst,³³ while bnMA was polymerized at room temperature using CuCl/PMDETA³⁴ (Figure 2). Molecular weight distributions were monomodal, and polydispersities were typically in the range of 1.10–1.15. Absolute molecular weights were measured by ¹H NMR by comparing integrations for the characteristic end-group peaks (δ 12.92, 11.91, 10.45, and 5.77 for UPy; δ 8.71, 8.66, 8.43, 8.33, and 5.33 for Napy) with those for the polymer (methylene adjacent to the ester: δ 4.02 for PnBA, δ 4.90 for PbnMA; Figures 1 and 2). Any residual water present in the polymers is expected to affect the melt phase behavior, so all polymers were thoroughly dried after isolation by heating to 50 °C in a vacuum oven over P₂O₅ overnight. For the thin films, anhydrous toluene was used as the casting solvent, and annealing was performed in an atmosphere of dry nitrogen.

Although UPy homodimerization and UPy–Napy heterodimerization have been thoroughly studied in solution, few reports exist of their temperature-dependent behavior in polymer melts. Several reports of UPy end-functional and side-chain-functional polymers indicated that aggregation of multiple dimers occurs in the melt.^{7,19,35} On the basis of rheological characterization, it was shown that the aggregates were disrupted at ~ 80 °C, and a study of polyisoprene stars with UPy groups at the chain ends indicated that associations between stars persist even at a temperature as high as 160 °C. In these cases the MHB groups are contained in a relatively homogeneous polymer melt, rather than at a polymer–polymer interface as expected in blends of different end-functional homopolymers. For our initial studies we considered blends of polymers with molecular weight close to 10 kg/mol and chose three annealing temperatures—65, 80, or 100 °C, each above the T_g of both PbnMA (54 °C) and PnBA (-54 °C). On the basis of prior literature, only at the lowest annealing temperature might the MHB groups be expected to aggregate, and these annealing temperatures and the high molecular weight of the polymers (which reduces the overall concentration of end groups) were chosen to minimize that possibility. The phase structure of the blends at each temperature gives a qualitative indication of the presence or absence of supramolecular diblock copolymers; it is well-known that when added to homopolymer blends, diblock copolymers segregate to the polymer–polymer interface, reducing interfacial tension and the size of phase-separated domains.^{36,37} Comparing the microstructure of the blends by TEM, it is clear that by simply changing the chain end group, the kinetics and structural development are drastically altered. As shown in Figure 3, after 4 days at an annealing temperature as low as 65 °C, the

Scheme 3. Synthesis of UPy-Functional ATRP Initiators 8a and 8b and PbnMA-UPy 9 and PnBA-UPy 10

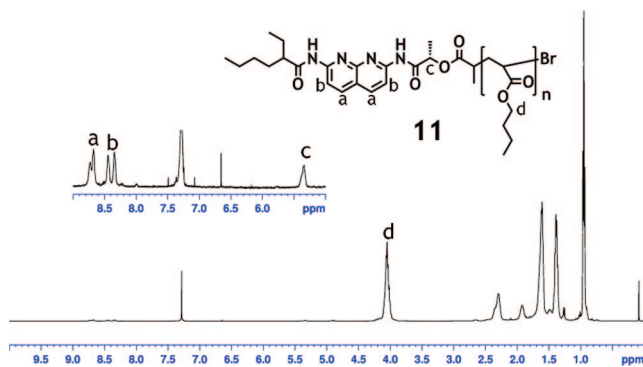
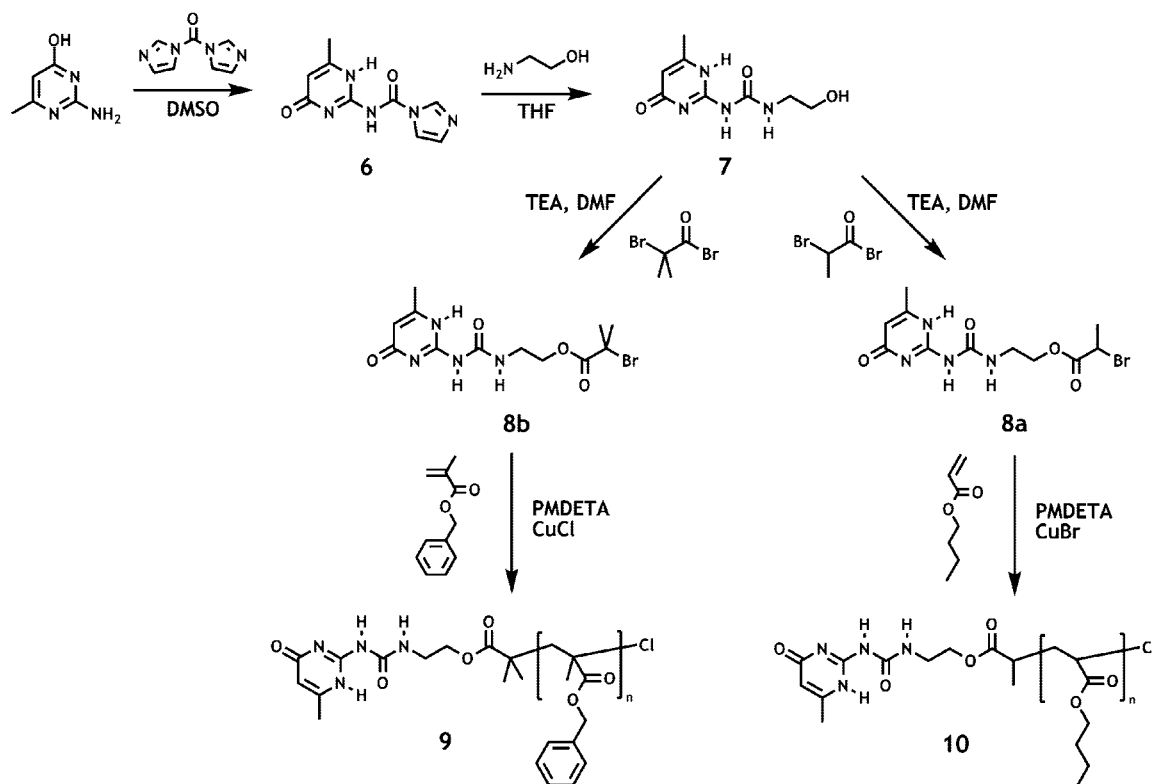


Figure 1. 500 MHz ^1H NMR spectrum of PbnMA-Napy **11** in CDCl_3 ; M_n of 8.8×10^3 was calculated by comparing integrations for peaks c and d.

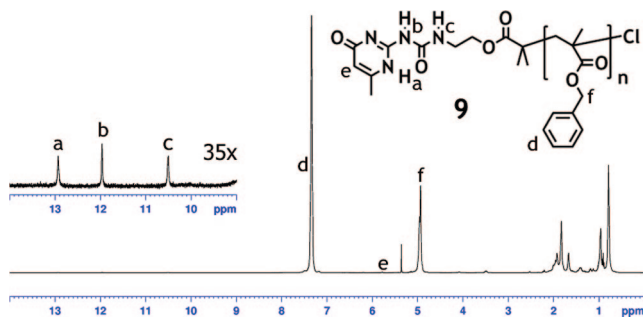


Figure 2. 500 MHz ^1H NMR of PbnMA-UPy **9** in CD_2Cl_2 ; M_n of 10.2×10^3 was calculated by comparing integrations for peaks e and f.

nonfunctional blend is macroscopically phase separated with domains of $\sim 20 \mu\text{m}$ observed optically. With a single MHB end group at the end of each homopolymer this phase separation is significantly suppressed. For the blend of UPy-PbnMA and

UPy-PnBA, annealing at either 65 or 80 $^\circ\text{C}$ for 4 days produces domains of $\sim 1 \mu\text{m}$ by TEM, while annealing at 100 $^\circ\text{C}$ results in macroscopic phase separation after only 3 h. In direct contrast, blending of homopolymers containing directional, complementary UPy and Napy groups results in no phase-separated features observable by either optical microscopy or TEM even after prolonged annealing (7 days at 100 $^\circ\text{C}$).

These microscopy results suggest the formation of supramolecular block copolymers in the bulk or at the interfaces of polymer blends leading to a significant reduction in phase separation with analysis by DSC providing additional support (Figure 4). Clear T_g s near 50 $^\circ\text{C}$ (PbnMA) and -50 $^\circ\text{C}$ are observed in blends PbnMA 10k/PnBA 8K and PbnMA-UPy 10K/PnBA-UPy 10K (measured on second heating after one cycle from -75 to 100 $^\circ\text{C}$ at 10 $^\circ\text{C}/\text{min}$) but not in blend PbnMA-UPy 10K/PnBA-Napy 8K, suggesting that the UPy/Napy blend has few large regions of PbnMA-UPy and implying that it consists of some fraction of supramolecular diblocks. A reference covalent diblock copolymer was also synthesized via “click” coupling^{38–40} with composition 8.1K PbnBA, 8.5K PbnMA. Because “click” coupling has been shown to be high yielding and tolerant of a wide variety of functional groups, this strategy allows for the synthesis of well-defined block copolymers from easily characterized starting blocks and thus a direct comparison between MHB blends, homopolymer blends, and covalent diblock copolymers with nearly the same composition and molecular weights. DSC characterization of the covalent diblock copolymer gave very similar results to those for the UPy/Napy blend.

These results suggest that blends of end-functional MHB homopolymers contain some supramolecular diblock copolymer which serves as a compatibilizer and provides thermal tunability to the blend microstructure. As UPy groups have the ability to strongly homodimerize, in UPy-UPy blends three different types of higher molecular weight polymer can be created by the bonding of chain ends: diblock copolymer, PbnBA ho-

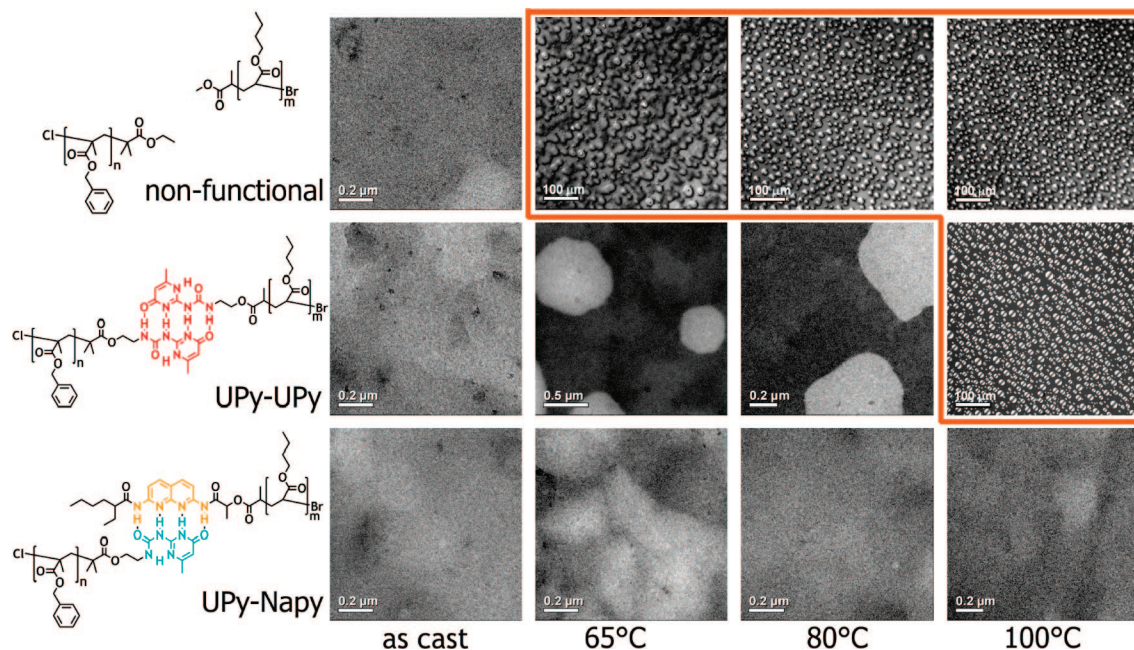


Figure 3. Microstructure of supramolecular blends annealed at various temperatures; annealing time was 4 days for all samples except UPy-UPy at 100 °C (3 h) and UPy-Napy 100 °C (7 days). Structure was observed by TEM except for those outlined in orange (optical microscopy).

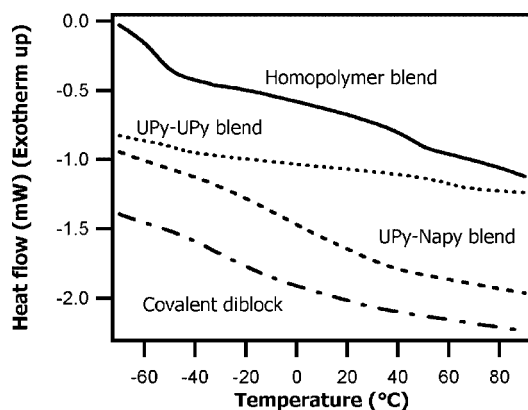


Figure 4. DSC traces (second heating) of supramolecular blends, showing T_g s near -50 °C (PnBA) and $+50$ °C (PbnMA) for nonfunctional homopolymer and UPy-UPy blends. No T_g is evident for the UPy-Napy blend or covalent diblock copolymer. Traces have been vertically shifted for clarity.

mopolymer ($2\times$ original molecular weight), and PbnMA homopolymer ($2\times$ original molecular weight). Additionally, immiscibility of the homopolymers results in phase separation (which would be enhanced by the presence of higher molecular weight homopolymer) and the physical separation of the MHB end groups, making them inaccessible for the formation of diblocks except when localized to the interfaces (which is energetically unfavorable). The relative amount of diblock is thus expected to be less than in the UPy-Napy system, where heterodimerization (and therefore diblock formation) is favored which was clearly demonstrated through nanoscale blending studies.²⁹ Since the supramolecular diblocks serve as surfactants to stabilize the polymer-polymer interfaces, the retardation of phase separation and decrease in the size of phase separated domains provides evidence that interaction between the end groups is taking place.

However, it may be the case that these block copolymers form first in solution at room temperature and are primarily active in preventing large-scale phase separation by impeding the coalescence of small droplets in the melt. It has been

Table 1. Molecular Weight Characterization of MHB End-Functional Polymers, Homopolymers, and Block Copolymer

sample		M_n (^1H NMR, g/mol)	M_n (SEC, g/mol)	PDI	chain end
9	P(bnMA)-UPy	10200	8900	1.20	UPy
10	P(nBA)-UPy	10700	5900	1.14	UPy
11	P(nBA)-Napy	8800	8000	1.14	Napy
15	P(bnMA)		8200	1.15	
16	P(nBA)		9900	1.10	
14	P(bnMA)-yne		8500	1.11	alkyne
13a	P(nBA)-N ₃		8100	1.11	azide
12	P(nBA- <i>b</i> -bnMA)		15200	1.16	

repeatedly demonstrated that very small areal densities of block copolymers are very effective in retarding droplet coalescence.⁴¹⁻⁴⁴ In this regard our small-angle X-ray scattering experiments have failed to detect the scattering one would expect from a significant amount of a separate disordered block copolymer phase. In addition, attempts to detect directly the assembly of deuterium-labeled PbnMA-UPy/PnBA-Napy block copolymers at the interface between PnBA/PbnMA bilayers on silicon using dynamic secondary ion mass spectrometry (dSIMS) after annealing these bilayers at temperatures above 65 °C have so far failed. (In these experiments only a small volume fraction of the labeled PnBA-Napy and PbnMA-UPy in higher molecular weight homopolymer bilayers was examined.)

Thus, we suspect that the fraction of PbnMA-UPy/PnBA-Napy block copolymer in the annealed blends is low, possibly due to a lower K_{assoc} in the polymer system, and it is necessary that we directly measure K_{assoc} for the UPy and Napy functional polymers to compare with small molecule analogues. These experiments are in progress, and the results will be reported separately.

Conclusions

By the introduction of MHB functionalities at a single chain end of linear homopolymers, supramolecular systems have been obtained that show a direct correlation between structure and properties. Bulk blending experiments clearly demonstrate that their phase behavior is controlled by the specificity of the MHB

group with self-complementary UPy–UPy groups leading to a slight compatibilization while complementary UPy–Napy groups result in a dramatic retardation of phase separation. Blending of benzyl methacrylate and *n*-butyl acrylate homopolymers containing a single UPy and Napy group, respectively, gives a stable nanostructured material even after annealing at 100 °C for 7 days, which suggests the dynamic presence of some amount of supramolecular diblock copolymer at the blend interfaces. We are currently investigating the broader phase space of this family of polymers, including molecular weight effects, detailed temperature and composition behavior, and alternative architectures.

Experimental Section

General Methods. All synthetic procedures were performed under an inert atmosphere of dry argon unless stated otherwise. Analytical TLC was performed on commercial Merck Plates coated with silica gel GF254 (0.24 mm thick). Silica gel (32–63 μ m, 220–400 mesh) for flash chromatography was purchased from Bodman Industries. ^1H NMR (500 MHz) and ^{13}C NMR (125 MHz) were performed on a Bruker AVANCE500 spectrometer at room temperature. Proton chemical shifts are reported in ppm downfield from tetramethylsilane (TMS). The following splitting patterns are designated as s, singlet; d, doublet; t, triplet; q, quartet; b, broad; m, multiplet; and dd, double doublet. Carbon chemical shifts are reported downfield from TMS using the resonance of the deuterated solvent as the internal standard.

Size exclusion chromatography was carried out at room temperature on a Waters chromatograph connected to a Waters 410 differential refractometer and six Waters Styragel columns (five HR-5 μ m and one HWM-20 μ m) using THF as eluent (flow rate: 1 mL/min). A Waters 410 differential refractometer and a 996 photodiode array detector were employed. The molecular weights of the polymers were calculated relative to linear polystyrene standards. Fourier transformed infrared spectroscopy was performed using a Perkin-Elmer Spectrum One spectrometer equipped with a Universal ATR accessory. Spectra are the sum of 16 scans acquired at a resolution of 4 cm^{-1} . Matrix-assisted laser desorption/ionization mass-time-of-flight (MALDI-TOF) data were obtained at the Technical University of Eindhoven using a PerSeptive Biosystems Voyager-DE PRO spectrometer using an acid α -cyanohydroxycinnamic acid (CHCA) or a neutral 2-[(2*E*)-3-(4-*tert*-butylphenyl)-2-methylprop-2-enylidene]malononitrile (DCTB) matrix. Elemental analysis was performed at the Technical University of Eindhoven on a Perkin-Elmer 2400 series II CHNS/O analyzer. The reported values are the average of two measurements.

Transmission electron micrographs were acquired on a FEI Tecnai G2 Sphera microscope operating at an accelerating voltage of 200 kV. Optical micrographs were acquired on a Nikon Optiphot-100S microscope. Differential scanning calorimetry data were acquired on a TA Instruments Q2000 modulated DSC at a heating rate of 5 °C/min. Data presented are from the second heating after a single cycle from –75 to 100 °C.

Materials. 7-Amino-[1*H*]-2-oxo-1,8-naphthyridine was prepared as reported by Newkome et al.³⁰ 7-(2-Ethylhexanoylamino)-2-oxo-1,8-naphthyridine and 7-(2-ethylhexanoylamino)-2-chloro-1,8-naphthyridine were prepared as reported by Ligthart et al.²⁹ 7-(2-(*tert*-Butyldimethylsilyloxy)propanoylamino)-2-(2-ethylhexanoylamino)-1,8-naphthyridine (**3**) was prepared as reported by Meijer et al.³¹ 2-(1-Imidazolylcarbonylamino)-6-methyl-4-[1*H*]-pyrimidinone (**6**) was prepared as reported by Meijer et al.³² Tris[2-(dimethylamino)ethyl]amine (Me₆TREN) was prepared as reported by Queffelec et al.⁴⁵ 2-Propynyl 2-bromo-2-methylpropanoate was synthesized according to Luedtke et al.⁴⁶ Tetrahydrofuran was dried using a Pure Solv-MD solvent purification system from Advanced Technology. *n*-Butyl acrylate (nBA) and benzyl methacrylate (bnMA) were

purified by passing over neutral alumina. All other chemicals were obtained from Aldrich and used as received.

1-(2-Hydroxyethyl)-3-(6-methyl-4-oxo-1,4-dihydropyrimidin-2-yl)urea, 7. To a stirred suspension of 2-(1-imidazolylcarbonylamino)-6-methyl-4-[1*H*]-pyrimidinone (**6**) (20 g, 91.2 mmol) in DMF (450 mL) was added ethanolamine (8.36 g, 139 mmol) at room temperature. After 2 h, the mixture became homogeneous, and 1.5 L of acetone was added to triturate the product. The white solid was filtered and rinsed with water and then acetone. After drying under vacuum, the product **7** was obtained as a white powder (16.3 g) in 84% yield. ^1H NMR (CDCl_3): δ = 8.19 (br, 1H), 5.73 (s, 1H), 3.46 (t, 2H, J = 15 Hz), 3.22 (t, 2H, J = 15 Hz), 3.05 (b, 1H), 2.10 (s, 3H) ppm. FTR-IR (ATR): ν = 3508, 3484, 3052, 2939, 2881, 1703, 1661, 1578, 1519, 1443, 1234, 1057 cm^{-1} . Anal. Calcd for $\text{C}_8\text{H}_{12}\text{N}_4\text{O}_3$: C 45.28, H 5.7, N 26.4; found: C 45.22, H 5.52, N 27.14 (%). MALDI-TOF-MS (CHCA matrix) (m/z): calcd: 213.10 ($\text{M} + \text{H}^+$); found: 213.16 ($\text{M} + \text{H}^+$), 235.16 ($\text{M} + \text{Na}^+$).

2-(3-(6-Methyl-4-oxo-1,4-dihydropyrimidin-2-yl)ureido)ethyl 2-Bromopropanoate, 8a. A solution of **7** (5.00 g, 23.6 mmol) and triethylamine (2.62 g, 25.9 mmol) in tetrahydrofuran (20 mL) was cooled to 0 °C, after which 2-bromopropionyl bromide (5.04 g, 23.6 mmol) was added dropwise via a syringe. The solution was stirred for 4 h. Water (50 mL) was added to the mixture, which was extracted with dichloromethane. The organic fraction was washed with saturated NaHCO_3 (3 \times 15 mL) and with 1 M HCl (3 \times 15 mL). The organic layer was dried over MgSO_4 and evaporated to dryness. The resulting solid was purified by recrystallization from ethanol, giving the product as a white solid in 55% yield (4.50 g). ^1H NMR (CDCl_3): δ = 12.94 (br, 1H), 11.92 (br, 1H), 10.45 (br, 1H), 5.78 (s, 1H), 4.28 (t, 2H, J = 5 Hz), 3.56 (t, 2H, J = 5 Hz), 2.28 (s, 3H), 1.82 (d, 3H, J = Hz), 1.61 (s, 3H) ppm. ^{13}C NMR (CDCl_3): δ = 172.8, 170.4, 156.9, 154.4, 148.4, 106.9, 64.3, 40.1, 38.8, 21.7, 19.0 ppm. FTR-IR (ATR): ν = 2953, 1739, 1701, 1660, 1575, 1523, 1444, 1248, 1145 cm^{-1} . Mp 173 °C. Anal. Calcd for $\text{C}_{11}\text{H}_{15}\text{BrN}_4\text{O}_4$: C 38.06, H 4.36, N 16.14; found: C 37.61, H 4.08, N 16.09. MALDI-TOF-MS (CHCA matrix) (m/z): calcd: 347.04 ($\text{M} + \text{H}^+$); found: 347.12 ($\text{M} + \text{H}^+$), 369.09 ($\text{M} + \text{Na}^+$).

2-(3-(6-Methyl-4-oxo-1,4-dihydropyrimidin-2-yl)ureido)ethyl 2-Bromo-2-methylpropanoate, 8b. A solution of **7** (5.00 g, 23.6 mmol) and triethylamine (2.62 g, 25.9 mmol) in tetrahydrofuran (20 mL) was cooled to 0 °C, after which bromoisobutyl bromide (5.42 g, 23.6 mmol) was added dropwise via a syringe. The solution was stirred for 4 h. Water (50 mL) was added to the mixture, which was extracted with dichloromethane. The organic fraction was washed with saturated NaHCO_3 (3 \times 15 mL) and with 1 M HCl (3 \times 15 mL). The organic layer was dried over MgSO_4 and evaporated to dryness. The resulting solid was purified by recrystallization from ethanol, giving the product as a white solid in 63% yield (5.36 g). ^1H NMR (CDCl_3): δ = 12.91 (br, 1H), 11.91 (br, 1H), 10.45 (br, 1H), 5.74 (s, 1H), 4.27 (t, 2H, J = 6 Hz), 3.54 (t, 2H, J = 6 Hz), 2.19 (s, 3H), 1.89 (s, 6H), 1.52 (s, 3H) ppm. ^{13}C NMR (CDCl_3): δ = 172.8, 171.6, 156.9, 154.5, 148.3, 106.8, 64.2, 55.9, 38.6, 30.7, 19.0 ppm. FTR-IR (ATR): ν = 2932, 1726, 1694, 1659, 1591, 1523, 1436, 1310, 1244, 1157, 1102 cm^{-1} . Mp 184 °C. Anal. Calcd for $\text{C}_{12}\text{H}_{17}\text{BrN}_4\text{O}_4$: C 39.90, H 4.74, N 15.51; found: C 39.94, H 4.52, N 15.70. MALDI-TOF-MS (CHCA matrix) (m/z): calcd: 361.05 ($\text{M} + \text{H}^+$); found: 361.10 ($\text{M} + \text{H}^+$), 383.08 ($\text{M} + \text{Na}^+$).

2-Ethyl-N-(7-((*S*)-2-hydroxypropanamido)-1,8-naphthyridin-2-yl)hexanamide, 4. A solution of 7-(2-(*tert*-butyldimethylsilyloxy)propanoylamino)-2-(2-ethylhexanoylamino)-1,8-naphthyridine (**3**) (1.40 g, 3.26 mmol) in tetrahydrofuran (15 mL) was cooled to 0 °C, and 1 M tetrabutylammonium fluoride in THF (3.68 mL, 3.68 mmol) was added dropwise and stirred for 2 h. Dichloromethane (15 mL) was added to the mixture, which was washed with 1 M citric acid (3 \times 15 mL). The organic layer was dried over MgSO_4 , concentrated, and purified by column chromatography using chloroform as the eluent to give the product as a white solid in 89% yield (0.94 g). ^1H NMR (CDCl_3): δ = 9.43 (br, 1H), 8.46 (dd, 2H, J_1 = 12 Hz, J_2 = 9 Hz), 8.21 (br, 1H), 8.13 (dd, 2H, J_1

= 9 Hz, $J_2 = 4$ Hz), 4.52 (q, 1H, $J = 7$ Hz), 3.41 (br, 1H), 2.25 (tt, 4H, $J_1 = 9$ Hz, $J_2 = 5$ Hz), 1.3–1.8 (m, 11H), 0.98 (t, 3H, $J = 7$ Hz), 0.88 ppm (t, 3H, $J = 7$ Hz). ^{13}C NMR (CDCl_3): $\delta = 175.4, 173.8, 153.9, 153.3, 139.1, 139.0, 118.6, 113.7, 113.2, 69.0, 51.1, 32.4, 29.8, 26.1, 23.7, 21.1, 13.9, 12.0$. FTR-IR (ATR): $\nu = 3316, 2960, 2925, 2874, 1705, 1663, 1609, 1545, 1502, 199, 1383, 1288, 1187, 1125\text{ cm}^{-1}$. MALDI-TOF-MS (CHCA matrix) (m/z): calcd 358.20; obs: 359.15 ($M + H^+$). Anal. Calcd for $\text{C}_{19}\text{H}_{26}\text{N}_4\text{O}_3$: C 63.67, H 7.31, N 15.63; found: C 63.62, H 7.33, N 15.63.

(2*S*)-1-(7-(2-Ethylhexanamido)-1,8-naphthyridin-2-ylamino)-1-oxopropan-2-yl 2-Bromopropanoate, **5**. A solution of 2-ethyl-N-(7-((*S*)-2-hydroxypropanamido)-1,8-naphthyridin-2-yl)hexanamide, **4** (1.00 g, 2.79 mmol), and triethylamine (0.295 g, 2.92 mmol) in tetrahydrofuran (5 mL) was cooled to 0 °C, after which 2-bromopropionyl bromide (1.37 g, 6.35 mmol) was added dropwise via a syringe. The solution was stirred for 4 h. Dichloromethane (15 mL) was added to the mixture, which was washed with saturated NaHCO_3 (3 \times 15 mL) and with 1 M HCl (3 \times 15 mL). The organic layer was dried over MgSO_4 and evaporated to dryness. During purification, two diastereomers were separated by column chromatography eluting with 80/20 hexanes/ethyl acetate. These two products were analyzed (^1H NMR is listed for both below) but were recombined for polymerizations because the second stereocenter loses all stereochemical information upon abstraction of the bromine atom. The final product was a white solid, which is a mixture of the two diastereomers (1.25 g, 91%). ^1H NMR (CDCl_3): $\delta = 9.95$ (b, 1H), 8.55 (dd, 1H, $J_1 = 9$ Hz, $J_2 = 3$ Hz), 8.50 (b, 1H), 8.44 (d, 1H, $J = 9$ Hz), 8.15–8.19 (m, 2H), 5.77 (m, 1H), 4.55 (1H, q, $J = 7$ Hz), 2.32 (m, 1H), 1.94 (d, 3H, $J = 7$ Hz), 1.5–1.8 (m, 11H), 0.99 (t, 3H, $J = 6$ Hz), 0.89 ppm (m, 3H). ^1H NMR (CDCl_3) for alternate diastereomer: $\delta = 9.69$ (b, 1H), 8.55 (dd, 1H, $J_1 = 9$ Hz, $J_2 = 3$ Hz), 8.50 (b, 1H), 8.44 (d, 1H, $J = 9$ Hz), 8.15–8.19 (m, 2H), 5.68 (m, 1H), 4.55 (1H, q, $J = 7$ Hz), 2.32 (m, 1H), 1.94 (d, 3H, $J = 7$ Hz), 1.5–1.8 (m, 11H), 0.99 (t, 3H, $J = 6$ Hz), 0.89 ppm (m, 3H). ^{13}C NMR (CDCl_3): $\delta = 175.7, 169.5, 169.2, 154.2, 153.7, 153.4, 139.3, 139.0, 118.6, 114.0, 71.8, 50.7, 39.3, 32.2, 29.7, 26.0, 22.8, 21.4, 17.7, 14.2, 11.9$ ppm. FTR-IR (ATR): $\nu = 2931, 2873, 1706, 1685, 1607, 1542, 1499, 1389, 1311, 1134\text{ cm}^{-1}$. Anal. Calcd for $\text{C}_{22}\text{H}_{29}\text{BrN}_4\text{O}_4$: C 53.56 H 5.92 N 11.36. Found: C 53.13, H 5.70 N 11.35. MALDI-TOF-MS (CHCA matrix) (m/z): calcd: 493.15 ($M + H^+$); found: 494.13 ($M + H^+$) 515.08 (MNa^+).

UPy End-Functional Poly(benzyl methacrylate), $P(\text{bnMA})_n$ -UPy, **9**. Benzyl methacrylate (bnMA) polymerizations were conducted at room temperature according to a previous method.³⁴ Benzyl methacrylate (2.5 g, 14.2 mmol), UPy initiator **8b** (100 mg, 0.28 mmol), PMDETA (9.6 mg, 0.55 mmol), and THF (2.5 g) were combined in a Schlenk flask and subjected to three freeze–pump–thaw cycles. CuCl (27 mg, 0.28 mmol) was added under flowing nitrogen, and the flask evacuated and backfilled with nitrogen twice. The flask was then sealed and stirred in a room temperature water bath for 10 min before exposing to air and diluting with THF. The reaction mixture was passed over neutral alumina to remove the copper, concentrated, and precipitated into hexanes to give $P(\text{bnMA})_n$ -UPy, $M_n 8.9 \times 10^3$, PDI 1.20 (THF GPC). ^1H NMR (CD_2Cl_2): $\delta = 12.89, 11.92, 10.43, 7.30, 5.74, 4.89, 1.83, 1.59, 0.92, 0.75$ ppm; $M_n 10.2 \times 10^3$.

UPy End-Functional Poly(*n*-butyl acrylate), $P(\text{nBA})_n$ -UPy, **10**. *n*-Butyl acrylate (nBA, 1.1 g, 8.6 mmol), UPy initiator **8a** (30 mg, 0.086 mmol), PMDETA (30 mg, 0.172 mmol), and THF (1.1 g) were combined in a Schlenk flask and subjected to three freeze–pump–thaw cycles. CuBr (12 mg, 0.086 mmol) was added under flowing nitrogen, and the flask evacuated and backfilled with nitrogen twice. The flask was then sealed and placed in a 70 °C oil bath for 3 h before exposing to air and diluting with THF. The reaction mixture was passed over neutral alumina to remove the copper, concentrated, and precipitated into cold hexanes to give $P(\text{nBA})_n$ -UPy, $M_n 5.9 \times 10^3$, PDI 1.14. ^1H NMR (CD_2Cl_2): $\delta =$

12.92, 11.91, 10.45, 5.77, 4.02, 2.26, 1.89, 1.60, 1.37, 0.94 ppm; $M_n 10.7 \times 10^3$.

Napy End-Functional Poly(*n*-butyl acrylate), $P(\text{nBA})_n$ -Napy, **11**. *n*-Butyl acrylate (nBA, 1.95 g, 15.2 mmol), Napy initiator **3** (150 mg, 0.3 mmol), and Me₆TREN (57 mg, 0.3 mmol) were combined in a Schlenk flask and subjected to three freeze–pump–thaw cycles. CuBr (44 mg, 0.3 mmol) was added under flowing nitrogen, and the flask was evacuated and backfilled with nitrogen twice. The flask was then sealed and placed in a 70 °C oil bath for 30 min before exposing to air and diluting with THF. The reaction mixture was passed over neutral alumina to remove the copper, concentrated, and precipitated into cold hexanes to give $P(\text{nBA})_n$ -Napy, $M_n 8.0 \times 10^3$, PDI 1.14. ^1H NMR (CDCl_3): $\delta = 8.71, 8.66, 8.43, 8.33, 5.33, 4.88, 4.02, 2.33, 1.91, 1.60, 1.38, 0.94$ ppm; $M_n 8.8 \times 10^3$.

Covalent Diblock Copolymer, $P(\text{nBA}-b\text{-bnMA})$, **12**. A covalent diblock copolymer was synthesized by a combination of ATRP and click coupling. Azide-terminated PnBA was synthesized as follows. *n*-Butyl acrylate (10 g, 78.1 mmol), methyl 2-bromopropionate (72.4 mg, 0.43 mmol), and PMDETA (150 mg, 0.87 mmol) were combined in a Schlenk flask and subjected to three freeze–pump–thaw cycles. CuBr (63 mg, 0.43 mmol) was added under flowing nitrogen, and the flask was evacuated and backfilled with nitrogen twice. The flask was then sealed and placed in a 70 °C oil bath for 5 h before exposing to air and diluting with THF. The reaction mixture was passed over neutral alumina to remove the copper, concentrated, and precipitated into cold hexanes to give $P(\text{nBA})_n$ -Br, **13**, $M_n 1.0 \times 10^4$, PDI 1.11. The purified polymer was combined with a 4-fold excess of NaN_3 in DMF and stirred at room temperature overnight. DMF was removed under vacuum, and the polymer was redissolved in DCM (100 mL) and washed with water (3 \times 50 mL). The organic layer was dried over NaSO_4 , filtered, concentrated, and precipitated into cold methanol to yield $P(\text{nBA})_n$ -N₃, **13a**. ^1H NMR (CDCl_3): $\delta = 4.02, 2.28, 1.91, 1.60, 1.37, 0.93$ ppm.

Alkyne-terminated PbnMA was synthesized as follows. Benzyl methacrylate (5 g, 28.4 mmol), 2-propynyl 2-bromo-2-methylpropanoate (32.3 mg, 0.16 mmol), and PMDETA (54.7 mg, 0.32 mmol) were combined in a Schlenk flask and subjected to three freeze–pump–thaw cycles. CuCl (15.8 mg, 0.16 mmol) was added under flowing nitrogen, and the flask was evacuated and backfilled with nitrogen twice. The flask was then sealed and stirred in a room temperature water bath for 10 min before exposing to air and diluting with THF. The reaction mixture was passed over neutral alumina to remove the copper, concentrated, and precipitated into hexanes to give $P(\text{bnMA})_n$ -yne, $M_n 1.1 \times 10^4$, PDI 1.15, **14**. ^1H NMR (CDCl_3): $\delta = 7.30, 4.93, 4.60, 1.83, 1.59, 0.95, 0.77$ ppm.

$P(\text{nBA})_n$ -N₃ (2.68 g, 0.27 mmol), $P(\text{bnMA})_n$ -yne (1 g, 0.089 mmol), and PMDETA (15.4 mg, 0.089 mmol) were dissolved in DMF (10 mL) and subjected to three freeze–pump–thaw cycles. CuBr (12.9 mg, 0.089 mmol) and Cu(0) (12.9 mg, 0.20 mmol) were added under flowing nitrogen. The flask was sealed and stirred at room temperature overnight. DMF was removed under vacuum, and the crude mixture was redissolved in THF and precipitated into hexanes to give $P(\text{nBA}-b\text{-bnMA})$, **12**, $M_n 2.1 \times 10^4$, PDI 1.10. ^1H NMR (CDCl_3): $\delta = 7.29, 4.90, 4.05, 2.30, 1.90, 1.80, 1.62, 1.34, 0.97, 0.76$ ppm; 55 mol % nBA.

Poly(benzyl methacrylate), $P(\text{bnMA})_n$, **15**. Benzyl methacrylate (5 g, 28.4 mmol), ethyl 2-bromo-2-methylpropanoate (55 mg, 0.28 mmol), and PMDETA (98 mg, 0.57 mmol) were combined in a Schlenk flask and subjected to three freeze–pump–thaw cycles. CuCl (28 mg, 0.28 mmol) was added under flowing nitrogen, and the flask was evacuated and backfilled with nitrogen twice. The flask was then sealed and stirred in a room temperature water bath for 10 min before exposing to air and diluting with THF. The reaction mixture was passed over neutral alumina to remove the copper, concentrated, and precipitated into hexanes to give $P(\text{bnMA})_n$, $M_n 8.2 \times 10^3$, PDI 1.15 (THF GPC).

Poly(*n*-butyl acrylate), $P(\text{nBA})_n$, **16**. *n*-Butyl acrylate (nBA, 5 g, 39.1 mmol), methyl 2-bromopropionate (65 mg, 0.39 mmol), and PMDETA (135 mg, 0.78 mmol) were combined in a Schlenk flask

and subjected to three freeze–pump–thaw cycles. CuBr (57 mg, 0.39 mmol) was added under flowing nitrogen, and the flask was evacuated and backfilled with nitrogen twice. The flask was then sealed and placed in a 70 °C oil bath for 3 h before exposing to air and diluting with THF. The reaction mixture was passed over neutral alumina to remove the copper, concentrated, and precipitated into cold hexanes to give P(nBA), M_n 9.9×10^3 , PDI 1.10 (THF GPC).

Sample Preparation. Solutions for spin-casting consisted of 3 wt % total polymer in toluene with a 1:1 molar ratio of end groups (no excess UPy- or Napy-functional polymer). Thin films ~100 nm thick for optical microscopy were spun on silicon wafers, and films ~100 nm thick for TEM were spun on salt (NaCl) crystals. All samples were annealed under nitrogen for 4 days unless otherwise noted. TEM samples were stained with RuO₄ (which selectively stains PbnMA) for 15 min and floated onto copper grids for imaging.

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