Supplementary Material (ESI) for Soft Matter

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for

Temperature and Redox Responsive Hydrogels from ABA Triblock Copolymers Prepared by RAFT Polymerization

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Materials. *N*,*N*-Dimethylformamide (DMF, Aldrich 99.9%), tris(2-carboxyethyl)phosphine hydrochloride (TCEP-HCl, Calbiochem 100%), ethanol amine (Acros 99%), 1-hexylamine (Alfa Aesar 99%), dithiothreitol (DTT, Acros 99%), glutathione (Acros 98% reduced), potassium hexacyano ferrate(III) ($K_3[Fe(CN)_6]$, Aldrich 99%), toluene (Aldrich 99.5%), tetrahydrofuran (THF, Aldrich 99%), and $CDCl_3$ (Aldrich 99.8 atom% D) were used as received. Prior to use, 1,4-dioxane (Alfa Aesar 99+%), di(ethylene glycol) ethyl ether acrylate (DEGA, Aldrich 90+%) and *N,N*-dimethylacrylamide (DMA, TCI Tokyo Kasei) were passed through basic alumina, *N*-isopropylacrylamide (NIPAM, TCI Tokyo Kasei) was recrystallized (×3) from hexane, 2,2-azobisisobutryonitrile (AIBN, Aldrich 98%) was recrystallized from ethanol. The difunctional chain transfer agent (CTA) 2-(1-carboxy-1-

methylethylsulfanylthiocarbonylsulfanyl)-2-methylpropionic acid (CMP) was donated by Lubrizol Advanced Materials.

Synthesis of PNIPAM macro chain transfer agent (macroCTA). An example RAFT polymerization procedure was as follows. NIPAM (22.00 g, 194.3 mmol), CMP (439.1 mg, 1.555 mmol) and AIBN (12.8 mg, 0.0777 mmol) were placed in a 250 mL side-arm round bottom flask equipped with a magnetic stir bar. After purging the sealed vessel with nitrogen for 90 min, nitrogen-purged 1,4-dioxane (96.9 mL) was added, and the reaction vial was placed in a preheated oil bath at 60 °C. Samples were removed periodically by syringe to determine monomer conversion by ^{1}H NMR spectroscopy and molecular weight by size exclusion chromatography (SEC). The polymerization was quenched after 24 h by cooling and exposing the reaction mixture to air. The resulting PNIPAM (M_n = 21,100 g/mol; M_w/M_n = 1.05) was isolated by precipitating into ether and drying under vacuum. The isolated polymer was then further purified by dialyzing against deionized water and freeze drying.

Chain extension of PNIPAM macroCTA with DMA. PNIPAM macroCTA (2.05 g, 0.0973 mmol) and AIBN (2.0 mg, 0.012 mmol) were placed in a 20 mL vial equipped with a magnetic stir bar. After purging the sealed vial with nitrogen for 20 min, nitrogen-purged toluene (8.72 mL) and DMA (2.50 mL, 24.2 mmol) were added, and the reaction vial was placed in a preheated reaction block at 70 °C. Samples were removed periodically by syringe to determine monomer conversion by ^{1}H NMR spectroscopy and molecular weight by SEC. The polymerization was quenched after 1 h by cooling and exposing the reaction mixture to air**.** The resulting triblock copolymer (M_n = 35,400 g/mol; M_w/M_n = 1.19) was isolated by precipitating into ether and drying under vacuum.

The precipitated polymer was then further purified by dialyzing against deionized water and freeze drying.

Synthesis of PDEGA macroCTA. An example RAFT polymerization procedure was as follows. CMP (15.0 mg, 0.0530 mmol) was placed in a 20 mL vial equipped with a magnetic stir bar. After purging the sealed vial with nitrogen for 20 min, nitrogen-purged 1,4-dioxane (8.66 mL), DEGA (1.97 mL, 10.6 mmol), and a concentrated solution of AIBN in 1,4-dioxane (0.2 mL, 0.003 mmol) were added, and the vial was placed in a preheated reaction block at 70 °C. Samples were removed periodically by syringe to determine monomer conversion by ^{1}H NMR spectroscopy and molecular weight by SEC. The polymerization was quenched after 2 h by cooling and exposing the reaction mixture to air**.** The resulting PDEGA (M_n = 11,900 g/mol; M_w/M_n = 1.16) was isolated by precipitating into hexanes and drying under vacuum.

Chain extension of PDEGA macroCTA with DMA. PDEGA macro-CTA (246 mg, 0.0207 mmol) was placed in a 20 mL vial equipped with a magnetic stir bar. After purging the sealed vial with nitrogen for 20 min, nitrogen purged DMF (1.50 mL), DMA (0.47 mL, 4.5 mmol), and a concentrated solution of AIBN in DMF (0.30 mL, 0.0023 mmol) were added, and the vial was placed in a preheated reaction block at 70 °C. Samples were removed periodically by syringe to determine monomer conversion by ^{1}H NMR spectroscopy and molecular weight by SEC. The polymerization was quenched after 2.5 h by cooling and exposing the reaction mixture to air. The resulting PDEGA-*b*-PDMA-*b*-PDEGA (M_n = 22,600 g/mol; M_w/M_n = 1.21) was isolated by dialyzing against deionized water and freeze drying.

Trithiocarbonate aminolysis. Aminolysis of the thiocarbonylthio moiety in the macroCTAs, triblock copolymers, and gels were carried out with ethanol amine or hexylamine in water or THF, respectively. Aminolysis of the polymers in solution was accomplished according to the following general procedure. PDEGA-*b*-PDMA-*b*-PDEGA (0.00492 mmol) and TCEP-HCl (3.0 mg, 0.010 mmol) were placed in a vial equipped with a magnetic stir bar, and the sealed contents were purged with nitrogen for 20 min. Nitrogen purged THF (1.13 mL) and hexylamine (52.0 μL, 0.393 mmol) were added, and the reaction vial was placed in a preheated reaction block at 35 °C. After 24 h the vial was opened to air and allowed to cool. Loss of the trithiocarbonate was confirmed by UV-Vis spectroscopy, and molecular weight reduction was observed by SEC. Aminolysis of the triblock copolymer gels was also possible. An example procedure is as follows. A nitrogen-purged solution of PNIPAM-*b*-PDMA-*b*-PNIPAM (0.022 mmol) in water (1.0 mL) was heated in a sealed vial to 40 °C to induce gelation, and ethanol amine (106 μL, 1.74 mmol) was added via syringe. After 1 h, dissolution of the gel was observed to begin, confirming trithiocarbonate cleavage. After 12 h the gel had degraded to a completely liquefied solution.

Oxidation of thiol-terminated polymers. PDEGA-b-PDMA-SH and PNIPAM-b-PDMA-SH diblock copolymers, resulting from aminolysis of the respective triblock copolymers, were oxidized with either CuO or $K_3[Fe(CN)_6]$ via disulfide formation. An example procedure is as follows. Cupric oxide (1.5 mg, 0.020 mmol) was added to a solution of PNIPAM-*b*-PDMA-SH (0.0040 mmol) in deionized water (2.00 mL) in a sealed vial equipped with a magnetic stir bar. The reaction was allowed to stir for 24 h at room temperature before heating to 40 °C to induce gelation. Alternatively, $K_3[Fe(CN)_6]$

(32.9 mg, 0.100 mmol) was added to a solution of PNIPAM-*b*-PDMA-SH (0.0040 mmol) in deionized water (2.00 mL) in a sealed vial equipped with a magnetic stir bar. The reaction was allowed to stir for 24 h at room temperature before heating to 40 ^{o}C to induce gelation.

Reduction of disulfide-linked triblock copolymers. DTT (15.0 mg, 0.0969 mmol) was added to an aqueous solution of PNIPAM-*b*-PDMA-S-S-PDMA-*b*-PNIPAM (0.0019 mmol) in de-ionized water (2.00 mL). The reaction vessel was sealed and allowed to stir at room temperature for 24 h before heating to 40 ^{o}C to yield a micellar solution. Alternatively, reduction was conducted in a similar manner with gluthathione as the reducing reagent.

Analyses. SEC was conducted in 0.05 M LiBr in DMF at 55 °C with a flow rate of 1.0 mL/min (Viscotek VE 2001 GPCmax; Columns: ViscoGel I-Series G3000 and G4000 mixed bed columns: molecular weight range 0 – 60 x 10^3 and 0 – 400 x 10^3 g/mol, respectively) with a Viscotek VE 3580 refractive index detector operating at λ = 660 nm, and molecular weights were determined by conventional calibration with polystyrene standards. ^{1}H NMR spectroscopy was conducted in $CDCl_3$ with a Bruker Avance 400 spectrometer operating at 400 MHz. UV-Vis spectroscopy was conducted with an Ocean Optics USB2000 USB-ISS-UV/VIS spectrophotometer. LCST behavior was investigated by turbidity measurements with a Beckman DU800 spectrophotometer equipped with a Peltier heating device. Data was collected at 1 °C increments with an equilibration time of 16 min between each measurement.

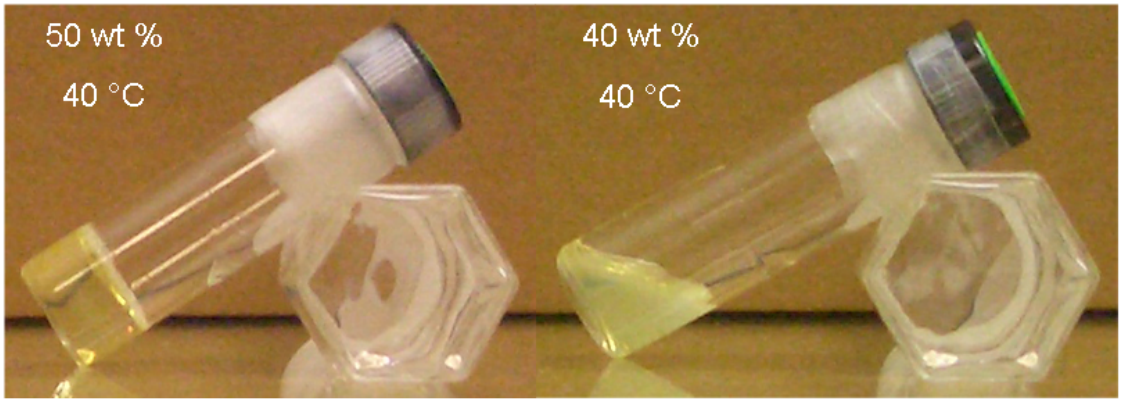

Figure S1. Gel dependence on aqueous solution concentration of $PNIPAM_{102}$-*b*-$PDMA_{123}$-*b*-$PNIPAM_{102}$ (M_n = 35,300 g/mol, M_w/M_n = 1.19) at 40 °C.

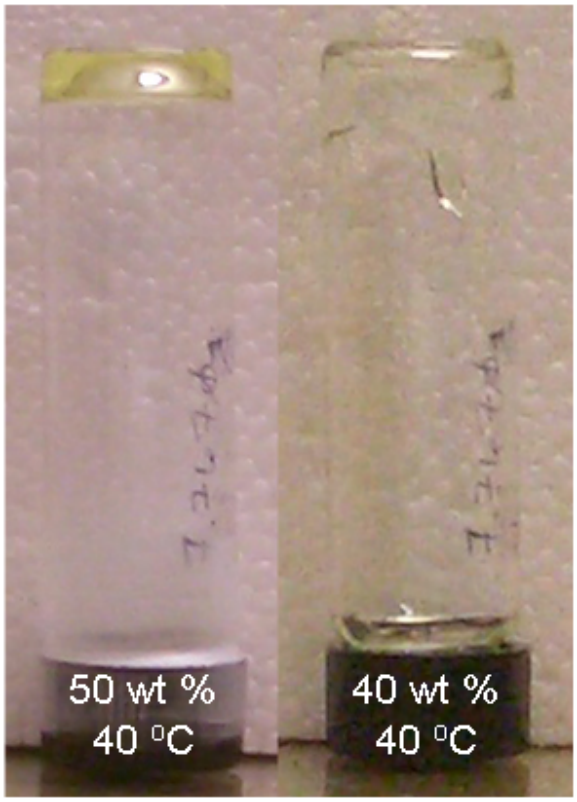

Figure S2. Gel dependence on aqueous solution concentration of $PDEGA_{32}$-*b*-$PDMA_{106}$-*b*-$PDEGA_{32}$ (M_n = 22,600 g/mol, M_w/M_n = 1.21) at 40 °C.

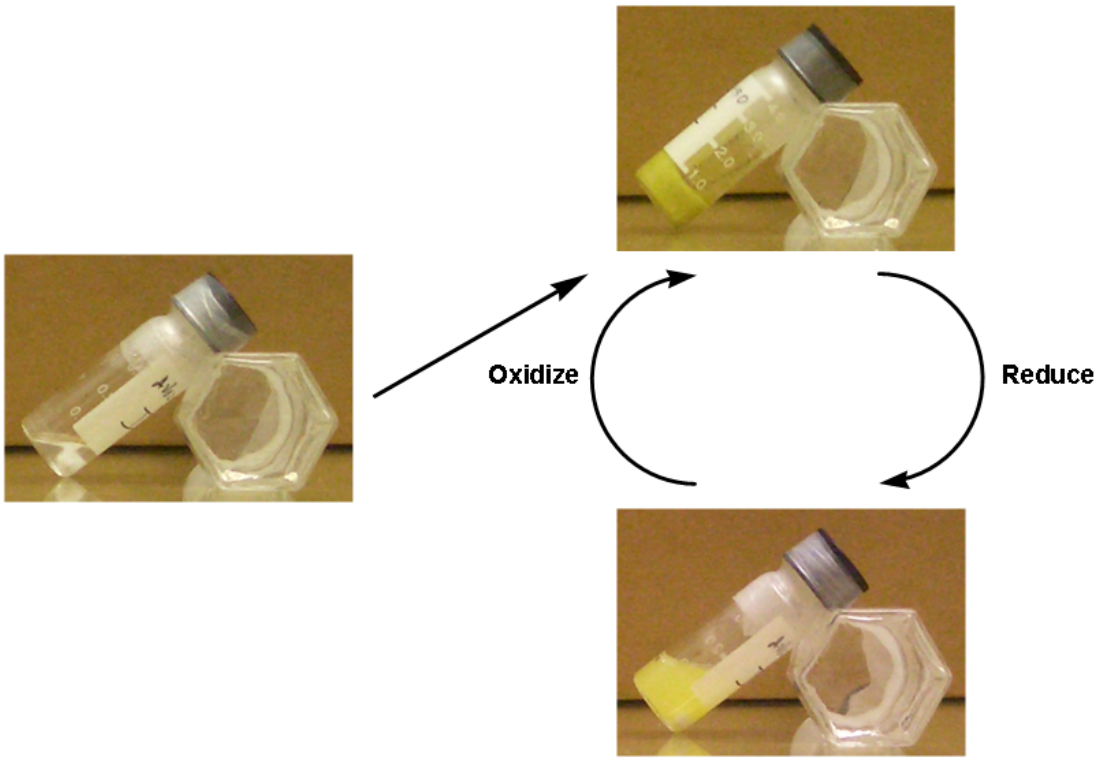

Figure S3. Reversible aqueous self-assembly and gelation of a 50 wt.% solution of PDEGA$_{32}$-*b*-PDMA$_{53}$-SH (M_n = 11,900 g/mol) at 40 °C. Oxidation was conducted with [PDEGA$_{32}$-*b*-PDMA$_{53}$-SH]/[K_3[Fe(CN)$_6$]] = 1/25, 40 °C, 24 h. Reduction was conducted with [PDEGA$_{32}$-*b*-PDMA$_{53}$-S-S-PDMA$_{53}$-*b*- PDEGA$_{32}$]/[DTT] = 1/50, 40 °C, 24 h.

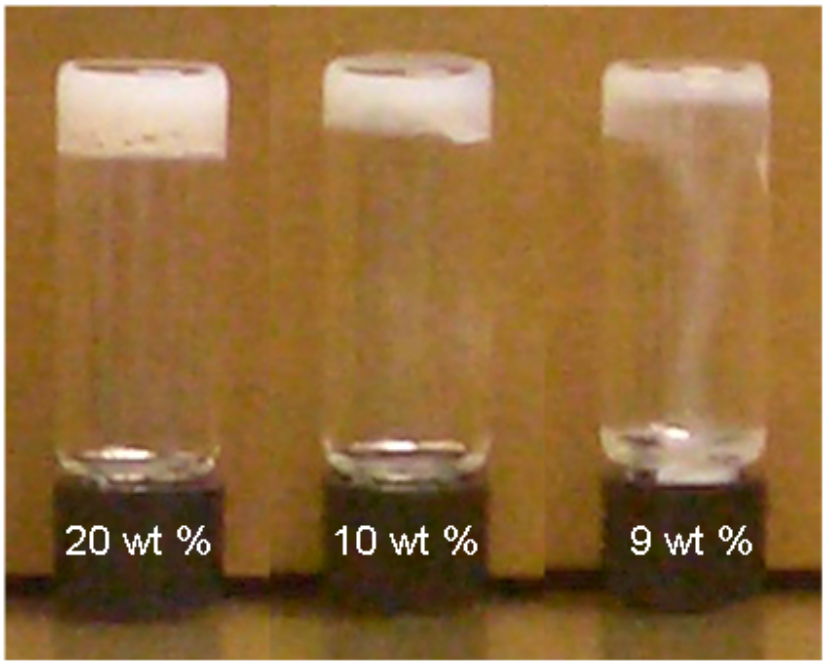

Figure S4. Gel dependence on aqueous solution concentration of $PNIPAM_{112}$-*b*-$PDMA_{824}$-*b*-$PNIPAM_{112}$ at 40 °C.

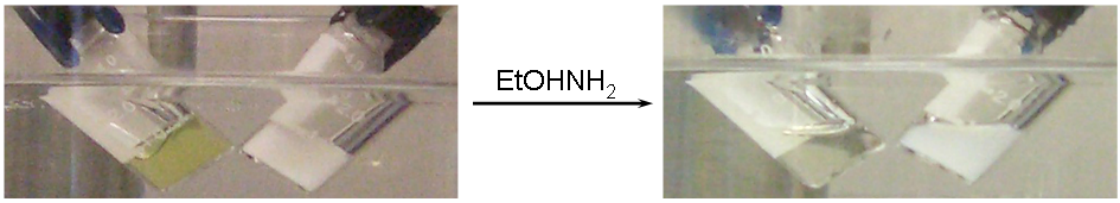

Figure S5. Direct ABA hydrogel degradation via ethanol amine. (left vial: $PNIPAM_{102}$-*b*-$PDMA_{123}$-*b*-$PNIPAM_{102}$, right vial: $PNIPAM_{112}$-*b*-$PDMA_{824}$-*b*-$PNIPAM_{112}$) at 55 °C after 0 minutes (left image) and after 12 h (right image).