

Chem 466

Lecture #5

01/28/2014

⊗ Quiz #2 $\bar{x} = 4.0$
S.D. = 3.7

⊗ Exam I, Feb. 6, 2014 (next Thursday)

— no office hours Feb. 5

— see Adriana, if have questions
at last moment

⊗ Exam I from previous years will
be posted on course website —
blank exams + answer keys —
TODAY

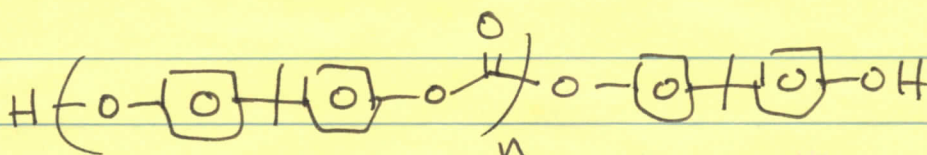
⊗ Chapter 2 problems recommended:

2, 3, 12, 15, 16, 17 — answers to be
posted on website — TODAY

GE Plastics
 sold to SABIC
 in 2007 for \$11.6B

② Polycarbonates

• carbonate linkages along the backbone



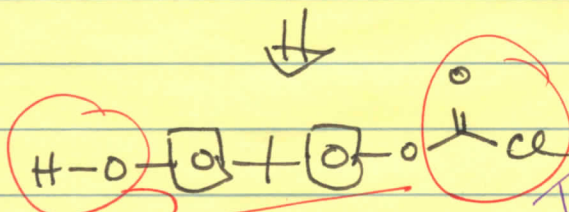
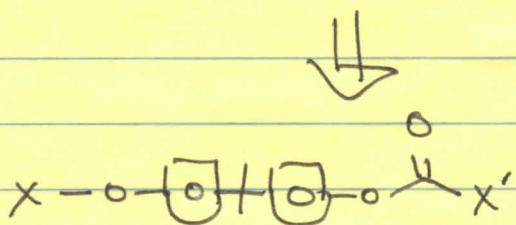
• tradename - Lexan

• developed by Bayer + GE
 in ~1953

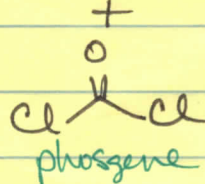
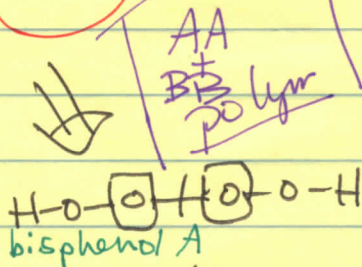
• engineering plastic
 - high transparency
 - high impact resistance (toughness)

• CDs, DVDs, eyeglasses, automotive parts (instrument parts, windshield coating etc), astronaut + football helmets

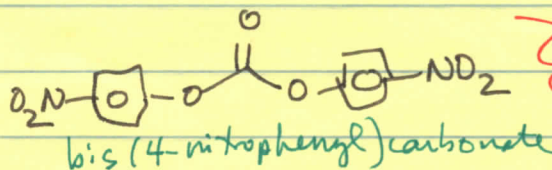
- no longer baby bottles b/c of hydrolytic degradation to bisphenol A (implicated in cancer)



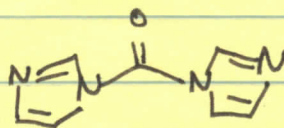
but too reactive



or phosgene alternative:



mech involves transesterification



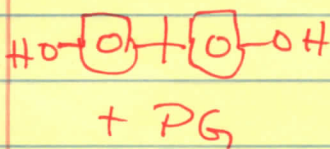
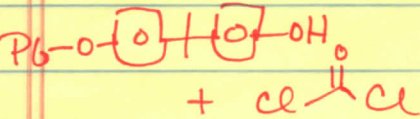
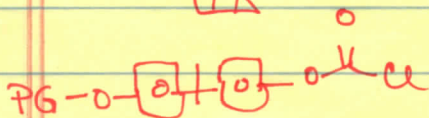
1,1'-carbonyldiimidazole

, among others...

arom-pushing mech (addition, elim, deprot.)

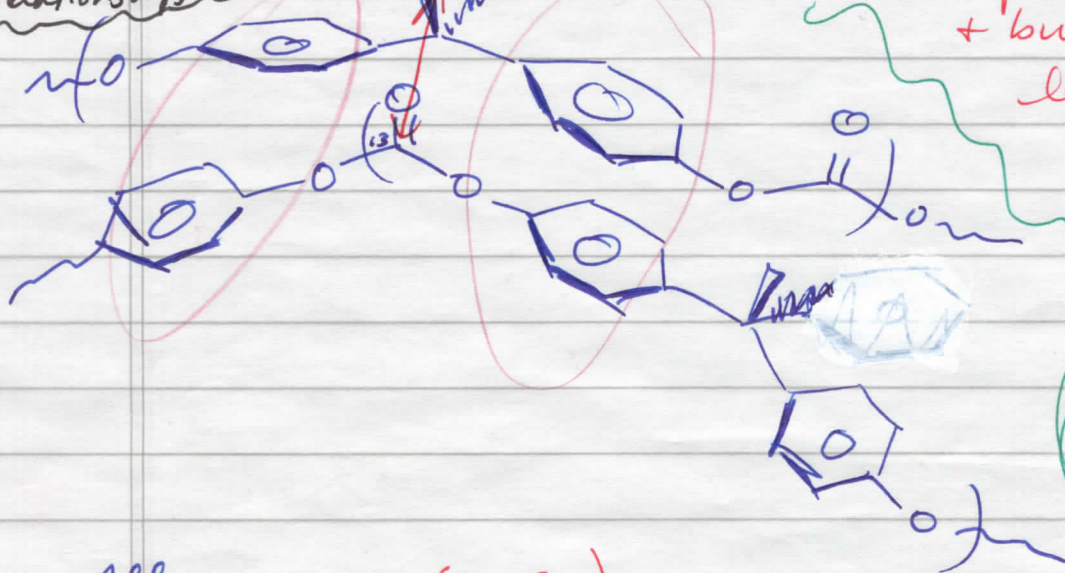
AB monomer route

OKAY FOR SPECIALTY APPS,
 BUT INDUSTRY, TOO EXPENSIVE



⊗ A couple of recent/ongoing advances in polycarbonates:

(1) Fundamental studies of molecular structure - property relationships



see

(et al.)
 D. Stueber, A. K. Mehta,
 Z. Chen, K. L. Woolay + J. Schaefer
 "Local order in polycarbonate glasses by
 ^{13}C $\{^{19}\text{F}\}$ Rotational-echo double-resonance NMR",
 J. Polym. Sci., Part B: Polym. Phys.
 2006, 44, 2760-2775.

(2) Natural product-based polycarbonates

- derived from renewable resources
- potential engineering material/bioengineering materials
- degradation (hydrolytically) regenerate the natural product-based monomers + CO_2

eg. Besset, C.T.; Lonnecker, A.T.; Streff, J.M.; Woolay, K.L.
 "Polycarbonates from the Polyhydroxy Natural Product Quinic Acid", *Macromolecules* 2011, 44, 2512-2517.

see key
 pts. on
 1st page
 article

- Polymers from renewable resources
- Potential engineering materials
- Natural products upon hydrolytic degradation

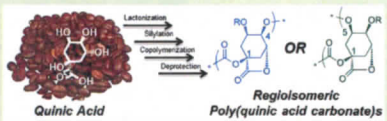
Polycarbonates from the Polyhydroxy Natural Product Quinic Acid

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Supporting Information

ABSTRACT: Strategies for the preparation of polycarbonates, derived from natural polyhydroxy monomeric repeat units, were developed for biosourced polycarbonates based on quinic acid. The design and synthesis of regioselectively *tert*-butyldimethylsilyloxy (TBS)-protected 1,4- and 1,5-diol monomers of quinic acid were followed by optimization of their copolymerizations with phosgene, generated in situ from trichloromethyl chloroformate, to yield protected poly(1,4-quinic acid carbonate) and poly(1,5-quinic acid carbonate). The molecular weights reached ca. 7.6 kDa, corresponding to degrees of polymerization of ca. 24, with polydispersities ranging from 2.0 to 3.5, as measured by SEC using tetrahydrofuran as the eluent and with polystyrene calibration standards. Partially because of the presence of the bicyclic backbone, each regioisomeric poly(quinic acid carbonate) exhibited relatively high glass-transition temperatures, 209 °C for poly(1,4-quinic acid carbonate) and 229 °C for poly(1,5-quinic acid carbonate). Removal of the TBS-protecting groups was studied under mild conditions to achieve control over potential competing reactions involving polymer degradation, which could include cleavage of lactones within the repeat units, carbonate linkages, or both between the repeat units. Full deprotection was not achieved without some degree of polymer degradation. The regiochemistry of the monomer showed significant impact on the reactivity during deprotection and also on the thermal properties, with the 1,5-regioisomeric polymer having lower reactivity and giving higher T_g values, in comparison with the 1,4-regioisomer. Each regioisomer underwent a 10–20 °C increase in T_g upon partial removal of the TBS-protecting groups. As the extent of deprotection increased, the solubility decreased. Ultimately, at long deprotection reaction times, the solubility increased and the T_g decreased because of significant degradation of the polymers.



1. INTRODUCTION

Over the past few decades, there has been a significant interest in the preparation of polymers that originate from renewable resources,^{1–4} typically based on carbohydrates and fatty acids to diminish the dependence on petroleum products and also that undergo degradation to reduce landfill accumulation of waste.² An important application of degradable polymers is in biomedicine (e.g., sutures, orthopedic devices,³ tissue engineering,⁴ drug delivery devices,^{5–7} etc.), where incorporation of biocompatibility and biodegradability is imperative. For this purpose, the polymers used are typically of esters,^{8,9} which undergo hydrolysis to afford products containing carboxylic acid and alcohol groups or carbonates,⁷ especially aliphatic carbonates that undergo hydrolytic degradation to give carbon dioxide and alcohols.^{10,11} Beyond these criteria, biodegradable polymeric materials in orthopedic tissue engineering also must possess thermal and mechanical properties and the time of degradation to the needs of the particular application. Polycarbonates, especially those based on bisphenol A, are a foundation material for engineering applications, in general, and we have a keen interest in exploring novel polycarbonates that are derived from renewable resources, may serve as replacements for poly(bisphenol A carbonate), which has been implicated as a toxic and carcinogenic

compound,^{12–15} and may lead to bioresorbable degradation products.

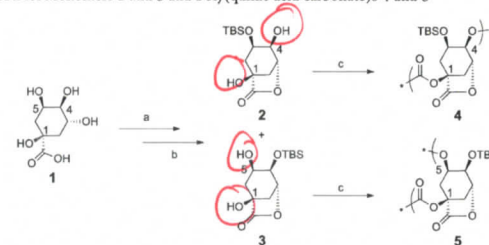
In this context, we have investigated the synthesis of polycarbonates built from a natural monomer, quinic acid, to afford a unique family of biosourced, degradable, engineering polymers: poly(quinic acid carbonate)s. Quinic acid is found in coffee beans and other plants^{16,17} and is known for its growth-promoting properties.^{16,17} is converted to tryptophan and nicotamide by microflora of the gastrointestinal tract,¹⁸ and is also a chiral starting material for pharmaceuticals,²⁰ including Tamiflu. Quinic acid was selected as the starting material because of easy access to a bicyclic diol-monomer by known lactonization and selective silylation,^{21,22} which could lead to materials having high-temperature thermal transitions and strong mechanical properties. Surprisingly, despite its interesting biological activity and its chirality, quinic acid has not been reported as a monomer that can undergo polymerization. This Article reports the design, synthesis, and characterization of *tert*-butyldimethylsilyloxy-protected poly(quinic acid carbonate)s and also includes various attempts for removal of the protecting groups.

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Scheme 1. Syntheses of Diol Monomers 2 and 3 and Poly(quinic acid carbonate)s 4 and 5*



* (a) Amberlyst, benzene/DMF, reflux, 16 h; (b) TBS-Cl, DMAP, NEt₃, DMF, RT, 12 h; and (c) diphosgene, pyridine, RT, 48 h.

2. EXPERIMENTAL SECTION

2.1. Instrumentation. The ¹H NMR (300 and 500 MHz) and ¹³C NMR (75 and 125 MHz) spectra were obtained on either a Varian Mercury 300 MHz or an Inova 500 MHz spectrometer using the solvent as internal reference. Glass transition (T_g) temperatures were measured by differential scanning calorimetry on a Mettler Toledo DSC822* apparatus (Mettler Toledo, Columbus, OH) with a heating rate of 20 °C/min. The T_g was taken as the midpoint of the inflection tangent upon the third heating scan. Thermogravimetric analysis was performed under a N₂ atmosphere using a Mettler Toledo model TGA/SDTA851* apparatus with a heating rate of 10 °C/min. Gel permeation chromatography (GPC) measurements were conducted on two different systems, both equipped with a Waters Chromatography (Milford, MA) model 1515 isocratic pump, a model 2414 differential refractometer, and a three-column set of Polymer Laboratories (Amherst, MA) Styragel columns (PL_{gel} 5 μ m Mixed C, 500 Å, and 10⁴ Å, 300 \times 7.5 mm columns) for the tetrahydrofuran system or a three-column set of Waters Chromatography Styragel columns (HR 2, HR 4E, and HR4, 300 \times 7.8 mm columns) for the dimethylformamide system. The systems were equilibrated at 35 °C in THF or 70 °C in DMF, which served as the polymer solvent and eluent (flow rate set to 1.00 mL/min). Polymer solutions were prepared at a known concentration (ca. 3 mg/mL), and an injection volume of 200 μ L was used. Data collection and analyses were performed with Precision Acquire software and Discovery 32 software, respectively (Precision Detectors). The differential refractometer was calibrated with standard polystyrene materials (SRM 706 NIST) for the tetrahydrofuran system and poly(ethylene glycol) for the dimethylformamide system. The infrared measurements were obtained with a Shimadzu IR Prestige, FTIR spectrophotometer equipped with an ATR accessory.

2.1. Materials. Quinic acid 1 (Alfa Aesar, 98%), trichloromethyl chloroformate (Alfa Aesar, 98%), Amberlyst (Sigma Aldrich, 15-ion-exchange resin), dimethylaminopyridine, triethylamine (Sigma Aldrich, >99%), *tert*-butyldimethylsilyl chloride (Alfa Aesar, 97%), and boron trifluoride diethyl etherate (Alfa Aesar, >98%) were used as received. Pyridine was distilled over potassium hydroxide, tetrahydrofuran, and dimethylformamide were dried through columns (J. C. Meyer Solvent Systems). (1R,3R,4S,5R)-5-*tert*-Butyldimethylsilyloxy-1,4-dihydroxy-cyclohexane-1,3-carbolactone 2, (1R,3R,4S,5R)-4-*tert*-butyldimethylsilyloxy-1,4-dihydroxy-cyclohexane-1,3-carbolactone 3, and calcium sulfonate resin were synthesized as previously described.^{21–23}

2.2. General Procedure of the Copolymerization between Diol Quinic Acid 2 or 3 and Trichloromethyl Chloroformate. Trichloromethyl chloroformate was added to a cold (0 °C) solution of diol quinic acid in pyridine (600 g/L) under nitrogen three times over ca. 10 min. Caution! Trichloromethyl chloroformate is highly toxic by

inhalation and ingestion; use of respiratory mask is required. After 48 h at room temperature, a saturated solution of sodium bicarbonate was added until no further emission of carbon dioxide was observed. The residue was diluted with dichloromethane; the organic layer obtained was washed with a 10% solution of hydrochloric acid, then dried with magnesium sulfate, filtered, and concentrated under reduced pressure. The crude polymer was dissolved in dichloromethane, followed by precipitation in cold methanol to afford the desired polymer as a white solid.

Synthesis of 4. The general procedure for copolymerization was applied to a solution of diol quinic acid 2 (500 mg, 1.73 mmol) in pyridine (850 μ L) and trichloromethyl chloroformate (207 μ L, 1.73 mmol) to obtain a white solid (462 mg, 85%). ¹H NMR (CDCl₃, 300 MHz): δ 5.13 (bs, 1H, H-4), 4.78–4.92 (m, 1H, H-3), 4.07 (bs, 1H, H-5), 2.19–3.17 (m, 4H, H-2, H-6), 0.83–0.92 (m, 9H, (CH₃)₃CSi), 0.04–0.09 (m, 6H, (CH₃)₂Si). ¹³C NMR (CDCl₃, 75 MHz): δ 170.5–170.8 (CO-lactone), 150.0–153.3 (CO-carbonate), 78.1–78.4 (C1), 73.3–73.7 (C3), 70.5–71.7 (C4), 65.6–65.8 (C5), 36.9–37.1 (C6), 33.2–34.0 (C2), 25.4–25.6 ((CH₃)₃CSi), 17.7–18.0 ((CH₃)₂CSi), 5.3–5.0 ((CH₃)₂Si). IR ν_{max}/cm^{-1} : 3104–2758, 1803, 1746, 1240, 124, 1033, 843, 777. T_g = 209 °C. (T_d)_{5%} = 284 °C; (T_d)_{10%} = 384 °C; 284–420 °C, 89% mass loss; 11% mass remaining at 500 °C.

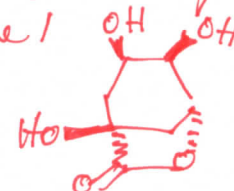
Synthesis of 5. The general procedure for copolymerization was applied to a solution of diol quinic acid 3 (500 mg, 1.73 mmol) in pyridine (850 μ L) and trichloromethyl chloroformate (207 μ L, 1.73 mmol) to obtain a white solid (462 mg, 85%). ¹H NMR (CDCl₃, 300 MHz): δ 4.76–4.77 (m, 1H, H-5), 4.67 (bs, 1H, H-3), 4.37 (bs, 1H, H-4), 3.00–3.15 (m, 1H, H-2), 2.62–2.69 (m, 1H, H-2), 2.26–2.34 (m, 2H, H-6), 0.83–0.92 (m, 9H, (CH₃)₃CSi), 0.04–0.09 (m, 6H, (CH₃)₂Si). ¹³C NMR (CDCl₃, 75 MHz): δ 170.6–170.7 (CO-lactone), 149.7–152.8 (CO-carbonate), 78.1–78.5 (C1), 76.1–76.4 (C3), 71.9–72.7 (C5), 64.5 (C4), 32.7–33.0 (C2, C6), 25.5 ((CH₃)₃CSi), 17.9 ((CH₃)₂CSi), 5.1 ((CH₃)₂Si). IR ν_{max}/cm^{-1} : 3096–2272, 1803, 1746, 1227, 1060, 832, 776. T_g = 225 °C. (T_d)_{5%} = 302 °C, (T_d)_{10%} = 373 °C; 302–416 °C, 92% mass loss; 8% mass remaining at 500 °C.

2.3. General Procedure of the Removal of the TBS-Protecting Group. Boron trifluoride diethyl etherate was added to a solution of protected poly(quinic acid carbonate) in anhydrous tetrahydrofuran at different temperatures. After different durations, Amberlyst H⁺ (15 times the mass of protected poly(quinic acid carbonate)) and calcium sulfonate resin (15 times the mass of protected poly(quinic acid carbonate)) were added to the reaction, and the mixture was stirred for 2 h at the same temperature as the reaction occurred. The resins were removed by filtration and rinsed twice with tetrahydrofuran. The filtrate was concentrated under reduced pressure; then, the residue was

- quinic acid, natural product
- cyclization + protection rxns afford monomers of Δ regiochem.

- separation of 2 \rightarrow prep of 2 polycarbonates of Δ regiochem.

- diol monomers afford linear polymers
- trifol from (a) of Scheme 1 is being studied for prep. of xlinked network polys

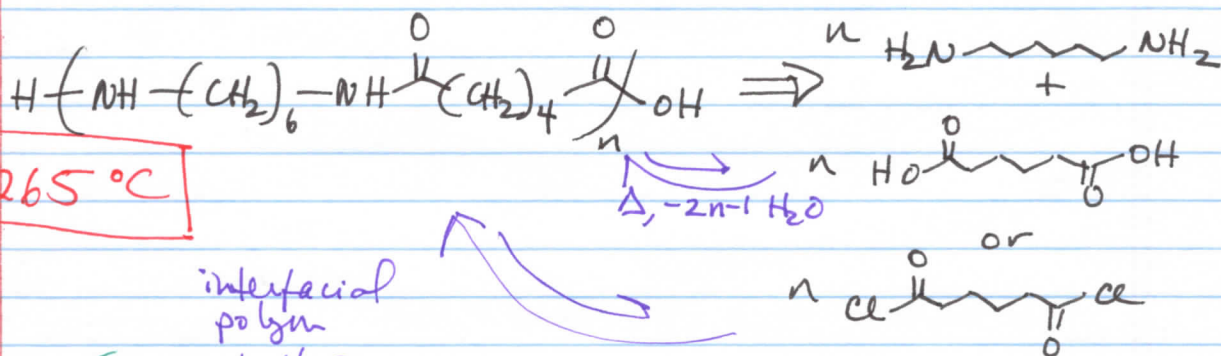


③ Polyamides

(a) aliphatic polyamides

e.g. Nylon 6,6

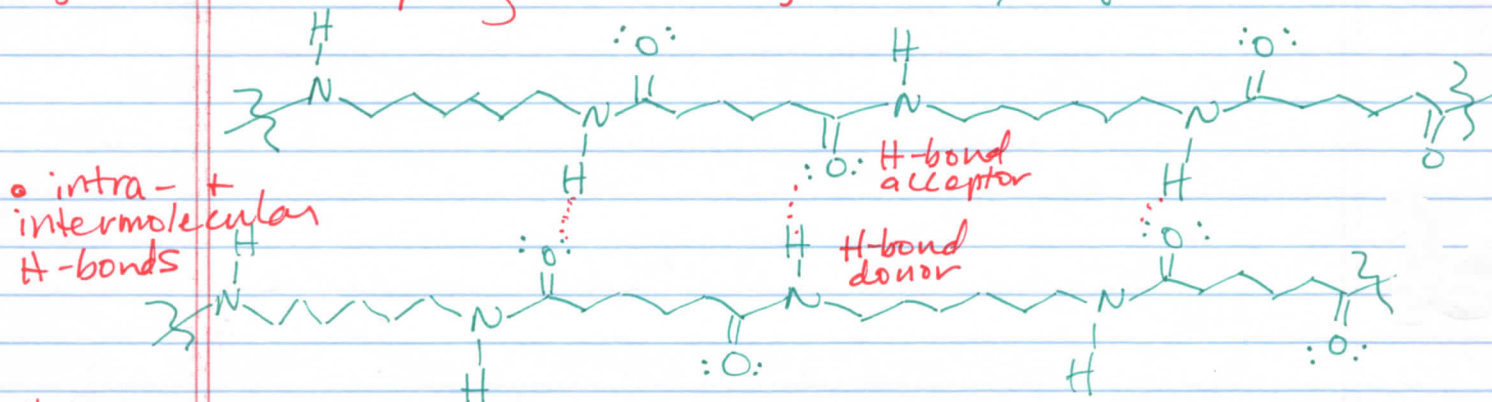
(see ppt slides from earlier lecture)



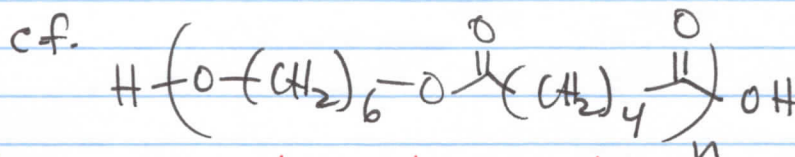
$T_m = 265^\circ\text{C}$

interfacial
polym
+ H_2O
- $2n \text{ HCl}$

• good chain-chain packing for xtablization + reinforcement



• H-bonds strengthen intra- + inter-chain attractions, acting as pseudo xlinks (supramolecularly)



$T_m = 60^\circ\text{C}$

• good chain-chain packing + xtablization

but,

• lacking H-bonding

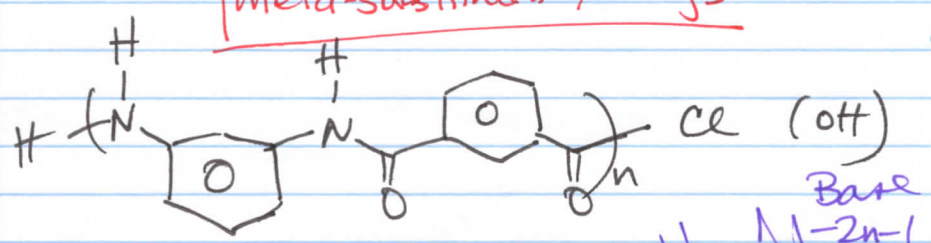
↑ rigidity, ↑ $T_m + T_g$

draw amide resonance

made w/ Nomex® + Kevlar®
 'ove' glove demo
 also silicone grip - chem to discuss later

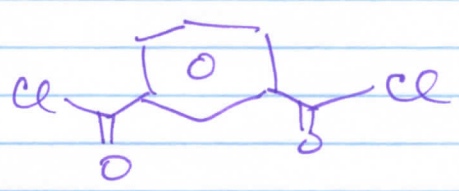
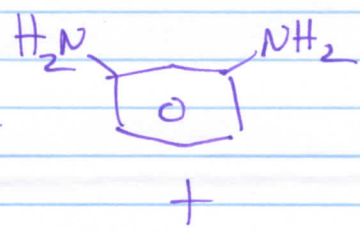
(b) polyamides

meta-substituted Ar rings



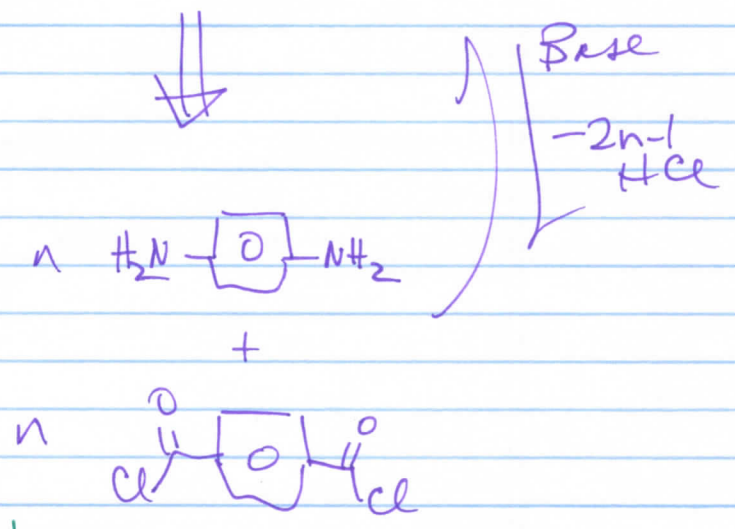
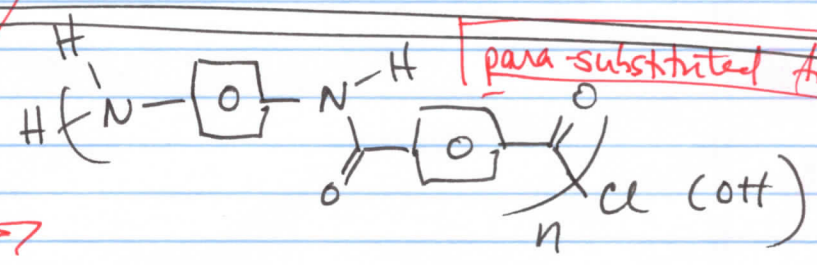
- Tradename - Nomex (DuPont, 1960's)
- Fireproof
 - doesn't melt, burn or transmit heat
 - $T_{decomp} > 500^\circ\text{C}$
- used as fiber
 - woven into oven gloves, clothing for fire fighters, etc.

- no aliphatic groups
- rigid, stable Ar rings
- H bonds via amides



↑ rigidity
 ↑ $T_m + T_g$
 ↑ T_{decomp}

para-substituted Ar rings



- Tradename - Kevlar (DuPont, 1965)
- similar properties to Nomex but para-substituted Ar rings give enhanced chain-chain packing, oligomer, liquid crystalline properties & higher strength
- uses - bullet-proof vests, fabrics in armored vehicles, etc.