

Lecture 23 (11/10/25)

TODAY

•Reading: Ch7; 251-254, 258-260, 241-250

•Homework: #21, #22

NEXT

Reading: Ch8; 294-296, 263-269
Ch24; 885-890

Homework: #23

Carbohydrates

A. Definition

B. Roles

C. Monosaccharides-Chemistry

1. Chirality

- One or more asymmetric carbons
- Linear and ring forms

2. Derivatives: the chemistry of carbohydrates

- Oxidation
 - C1
 - C6
- Reduction
 - C1/C2
 - Other carbons
- Ester formation
- Amino sugars

3. Polymerization

- The Glycosidic Bond
- Non-covalent bonds in macro-molecular structure
- Disaccharides

D. Oligosaccharides

- Glycoproteins & glycolipids
- O-linked
- N-linked
- Sequence determination-ABO

E. Polysaccharides

- Polymers of glucose
- Polymers of disaccharides

11-11-2025



BU Staff Holiday, not Faculty or Students.

Carbohydrates

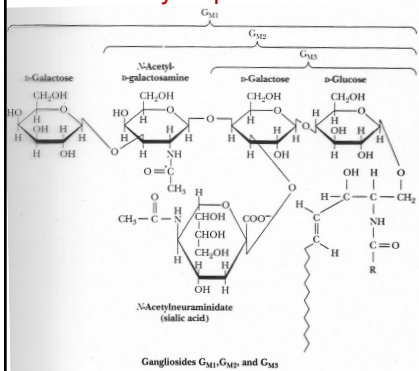
Oligosaccharides

Carbohydrates

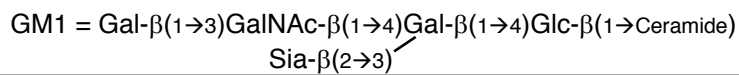
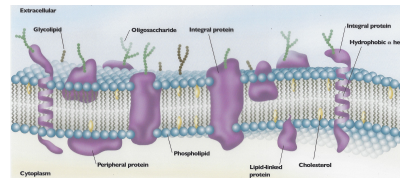
Oligosaccharides:

Here is an oligosaccharide that we will encounter when we study LIPIDS; sphingoglycolipids, or for short:

Glycolipids.



Glycoconjugates: Glycolipids

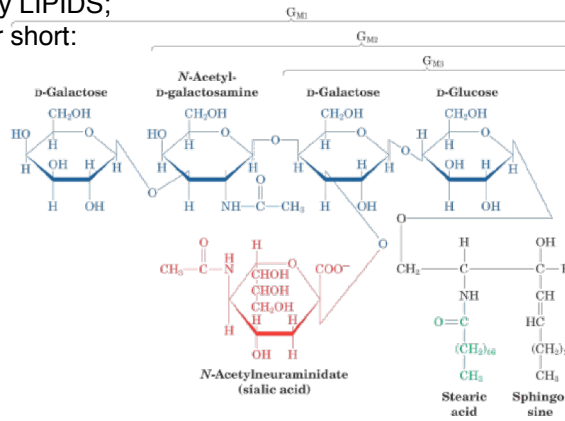
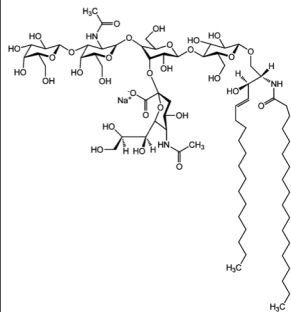


Carbohydrates

Oligosaccharides:

Here is an oligosaccharide that we will encounter when we study LIPIDS; sphingoglycolipids, or for short:

Glycolipids.

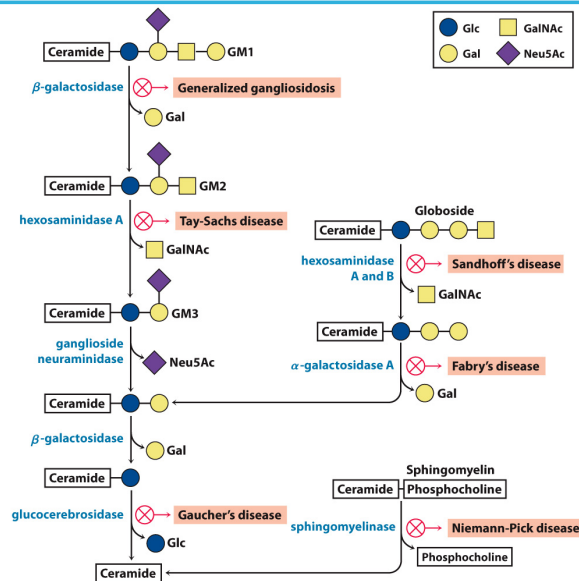


Ganglioside G_{M1} : structural formula with its sphingosine residue in Fischer projection (contain **sialic acid**)

$GM1 = Gal-\beta(1\rightarrow3)GalNAc-\beta(1\rightarrow4)Gal-\beta(1\rightarrow4)Glc-\beta(1\rightarrow$ Ceramide)

$Sia-\beta(2\rightarrow3)$

Dysfunction in Ganglioside Recycling Leads to a Variety of Medical Disorders



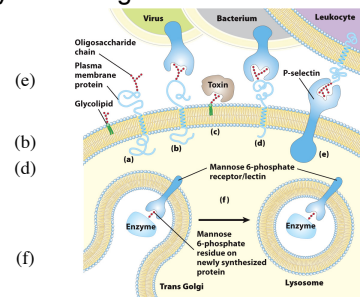
Carbohydrates

Oligosaccharides:

Glycoconjugates: Glycoprotein

When you attach an oligosaccharide to a protein: **Glycoproteins.**

- A protein with small oligosaccharides attached:
 - Carbohydrate is attached via its anomeric carbon to amino acids on the protein.
 - Common connections occur at Ser, Thr, and Asn.
 - About half of mammalian proteins are glycoproteins.
 - Generally, bacteria do not glycosylate their proteins.
 - Carbohydrates play role in **protein-protein recognition**. (a)
 - Viral proteins are heavily glycosylated; this helps **evade the immune system**.
- Proteins whose role is to bind specific carbohydrates/oligosaccharides = **Lectins (or selectins)**
 - Lectins important for many biological functions
 - Recruitment of leukocytes to sites of inflammation
 - Sperm-egg recognition
 - Virus-target cell interaction
 - Attachment of flora (microbiome) in gut
 - Nervous system development
 - Serum-protein turnover (sialic acid)
 - Targeting proteins to lysosomes for degradation (Man)

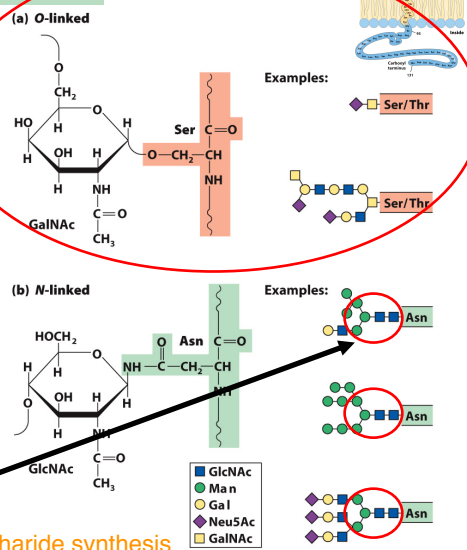


How are these sugars attached?

Carbohydrates

Oligosaccharides: TWO classes attached to proteins, **O-linked** and **N-linked**

- First, these polymers, unlike any others we have studied, are **BRANCHED**
- Second, like glycolipids, O-linked sugars are attached via an O-glycosidic bond
 - Use a Ser or Thr in the sequence (recall glycophorin)
 - Usually smaller than N-linked
 - Synthesized one at a time by specific glycosyltransferases (specific for sugar, linkage, and chirality)
- Third, N-linked sugars are attached via an N-glycosidic bond
 - Use an Asn
 - The Asn residues are within a 3 AA sequence context: NX^S_T
 - All the same at the core

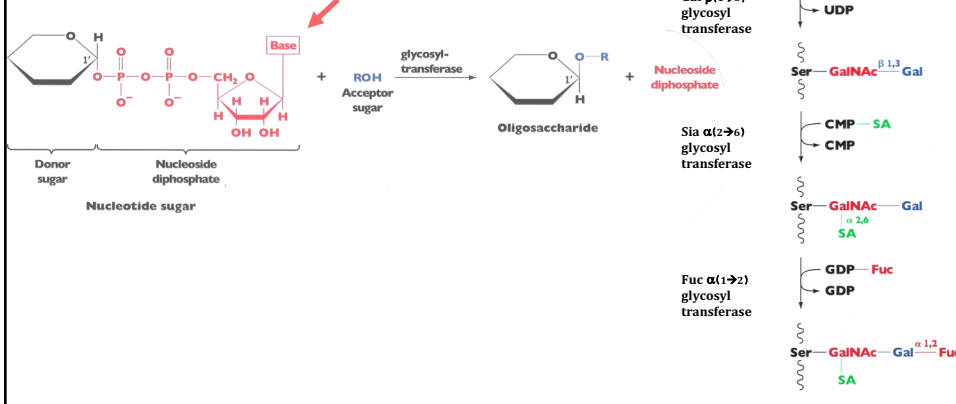
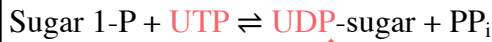


Let's look more closely at O-linked oligosaccharide synthesis

Carbohydrates

Oligosaccharides: O-linked

- Specific glycosyltransferases use “activated” sugars
- Activated by attaching to nucleotides: UDP, CDP, etc.

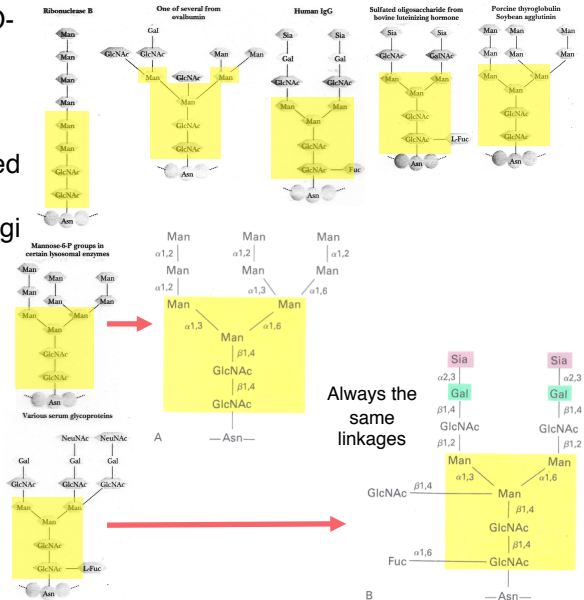


Carbohydrates

Oligosaccharides: N-linked

- Larger, more complex than O-linked
- All have a “Core” containing GlcNAc & Man
- Added as a unit, then modified before adding to Asn groups on proteins; all in the ER/Golgi
- Use an isoprene, called **Dolichol**, to build core
- Examples:

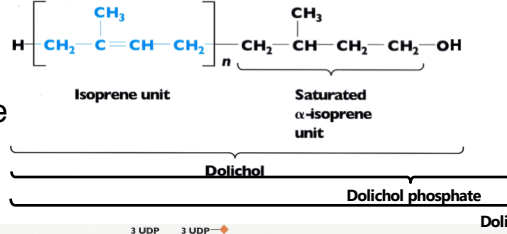
Let's look at this Dolichol & its use in biosynthesis more closely....



Carbohydrates

Oligosaccharides: N-linked

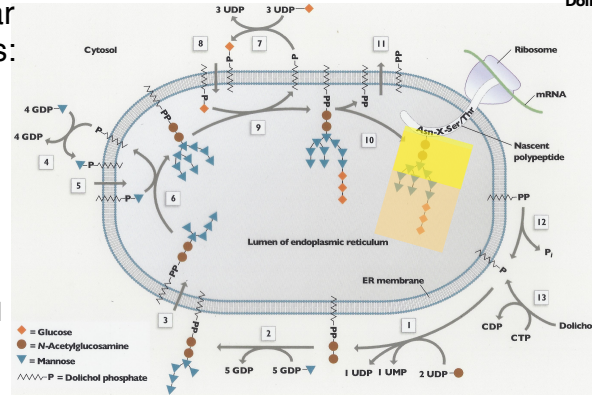
- Activated by attaching two phosphates, one using CTP (step 13)



- Again, uses NDP-sugar precursors:

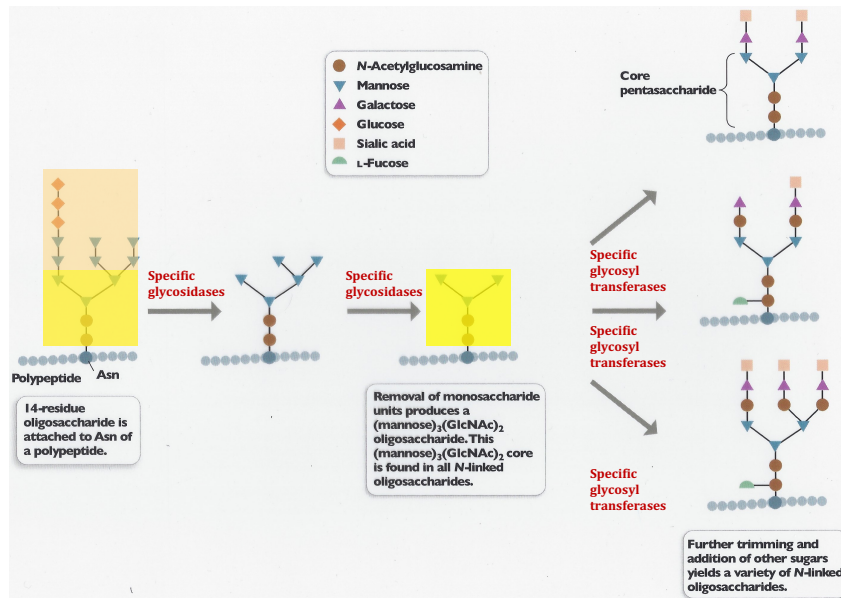
2 UDP-GlcNAc
9 GDP-Man
3 UDP-Glc

- All added to dolichol-PP in cytosol and translocated into ER lumen



Carbohydrates

Oligosaccharides: N-linked



Carbohydrates

Oligosaccharides: Determination of Sequence

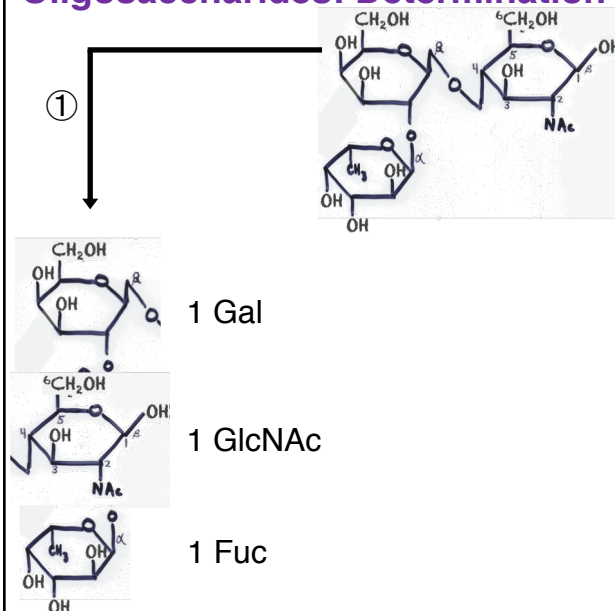
- Whole different problem compared to proteins and nucleic acids.... Its branched!!
- Moreover, a given residue can have several (and stereo-specific) ways of attaching to a neighboring residue.
- Need to use a combination of methods:
 - Chemical
 - Hydrolysis & chromatography to identify sugars
 - Exhaustive methylation & hydrolysis, then chromatography to identify what positions were **not** methylated
 - Biochemical
 - Use of enzymes that stereo-specifically hydrolyze glycosidic bonds (from the non-reducing end)

EXAMPLE: **First**, just like protein sequencing, you need to purify glyco-protein or lipid. Lets say we isolate the glycolipid from a person's RBC's who is O-positive. Treat it with a ceramidase to hydrolyze the lipid from the sugar.

Second, take an aliquot and just hydrolyze (like what was done for amino acid analysis). This gets the composition and stoichiometry.

Carbohydrates

Oligosaccharides: Determination of Sequence

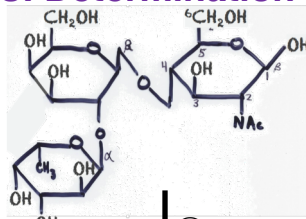


- ① Chemical: Hydrolysis
- ② Chemical: Exhaustive methylation & hydrolysis
- ③ Biochemical: glycosidase

Carbohydrates

Oligosaccharides: Determination of Sequence

- ① Chemical: Hydrolysis
- ② Chemical: Exhaustive methylation & hydrolysis
- ③ Biochemical: glycosidase

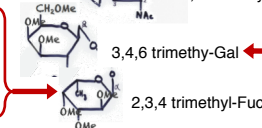


②

①

- Methylation of C1-OH means it's a reducing carbon at the reducing end
- Lack of methylation of C4-OH means it was in glycosidic linkage with another sugar

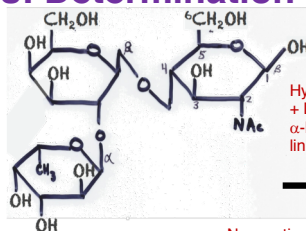
- Again, lack of methylation of C1-OH:
- That all possible hydroxyls are methylated (recall Fuc is a 6-deoxy sugar); this sugar is at a non-reducing end (no other sugars attached to it)



- Lack of methylation of C1-OH means its anomeric carbon was in a glycosidic bond
- Lack of methylation of C2-OH means that it was in glycosidic linkage with another sugar
- This sugar is in the middle

Carbohydrates

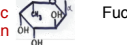
Oligosaccharides: Determination of Sequence



α-glycosidase

③

Hydrolysis yielding only Fuc + Disacc. means there is an α-linkage followed by a β-linkage



β-glycosidase

③

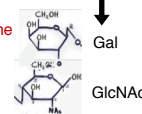
No reaction with the original trisacc. means that there are no sugars in β-linkage at the non-reducing end.

Trisacc. (no reaction)

β-glycosidase

③

Confirmation of the β-linkage at the middle sugar

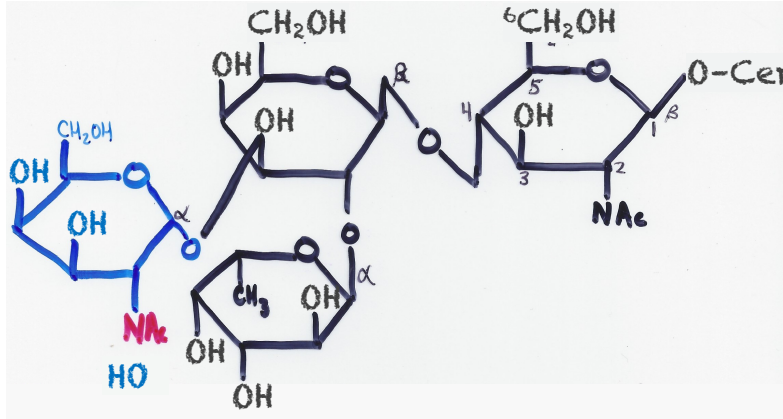


- ① Chemical: Hydrolysis
- ② Chemical: Exhaustive methylation & hydrolysis
- ③ Biochemical: glycosidase

Carbohydrates

Oligosaccharides: Determination of Sequence

- In vertebrates, ganglioside carbohydrate composition determines **blood groups**.



L-Fuc $\alpha(1\rightarrow2)$ -D-Gal $\beta(1\rightarrow4)$ D-GlcNAc β -Ceramide O blood group

D-Gal $\alpha(1\rightarrow3)$
 D-GalNAc $\alpha(1\rightarrow3)$

B blood group

A blood group

Glycoconjugates: Analysis

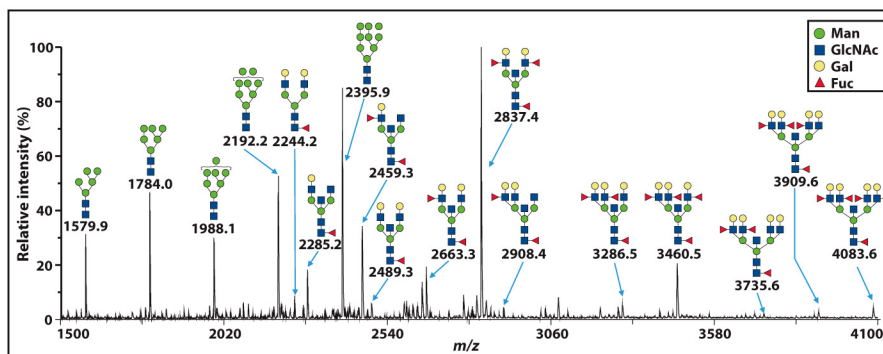


Figure 7-39
Lehninger Principles of Biochemistry, Seventh Edition
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Carbohydrates

Polysaccharides

Carbohydrates

Polysaccharides

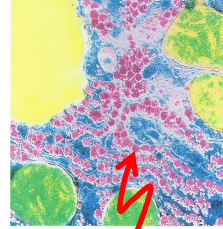
- The majority of natural carbohydrates are usually found as large polymers.
- These polysaccharides can be:
 - homopolysaccharides (one monomer unit)
 - heteropolysaccharides (multiple monomer units)
 - linear (one type of glycosidic bond)
 - branched (multiple types of glycosidic bonds)
- Polysaccharides do not have a defined molecular weight.
 - This is in contrast to proteins because, unlike proteins, no template is used to make polysaccharides.
 - Polysaccharides are often in a state of flux; monomer units are added and removed as needed by the organism.

Carbohydrates

Polysaccharides: **Polymers of Glucose**

Homopolymers of Glucose:

- Starch
- Glycogen
- Cellulose
- Chitin



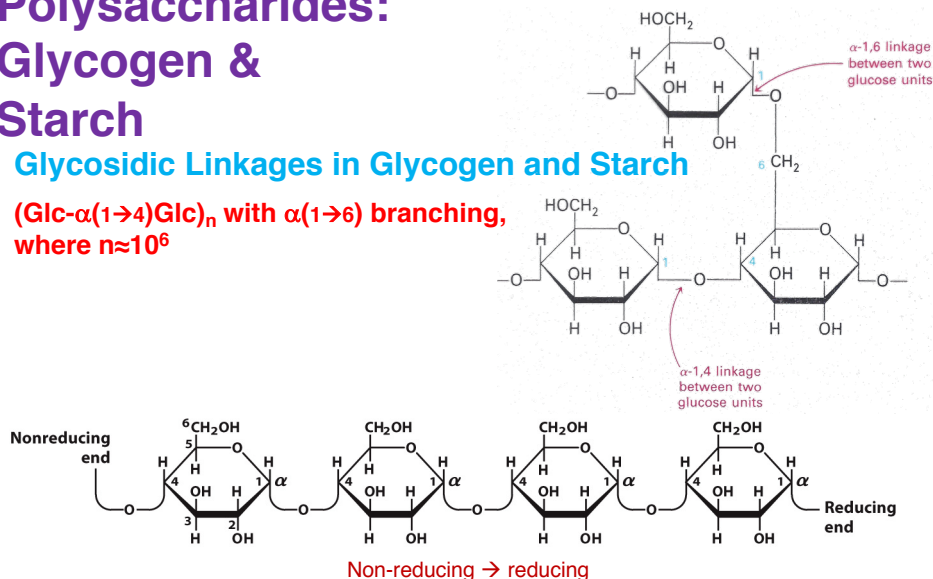
- Glycogen and Starch are the main **storage polysaccharides** for energy.
 - Glycogen and starch are insoluble due to their high molecular weight and often form **granules** in cells.
 - Molecular weight reaches several millions ($\sim 200 \times 10^6$) (can see in microscope).
- Glycogen is a branched homopolysaccharide of **glucose**.
 - Glucose monomers form $\alpha(1 \rightarrow 4)$ linked chains.
 - There are branch points with $\alpha(1 \rightarrow 6)$ linkers every 8–12 residues.
- Starch is a mixture of two homopolysaccharides of **glucose**.
 - **Amylopectin** is like glycogen, but the branch points ($\alpha(1 \rightarrow 6)$ linkages) occur every 24–30 residues.
 - **Amylose** is an unbranched polymer of $\alpha(1 \rightarrow 4)$ linked residues.

Carbohydrates

Polysaccharides: Glycogen & Starch

Glycosidic Linkages in Glycogen and Starch

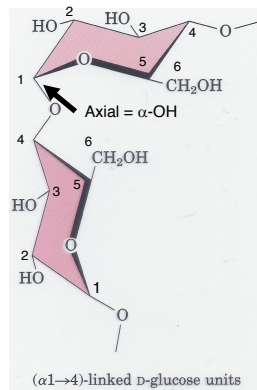
(Glc- $\alpha(1 \rightarrow 4)$ Glc) $_n$ with $\alpha(1 \rightarrow 6)$ branching, where $n \approx 10^6$



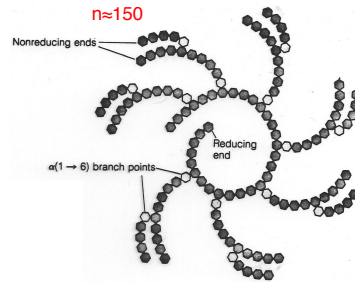
Carbohydrates

Polysaccharides: Glycogen & Starch

I_2



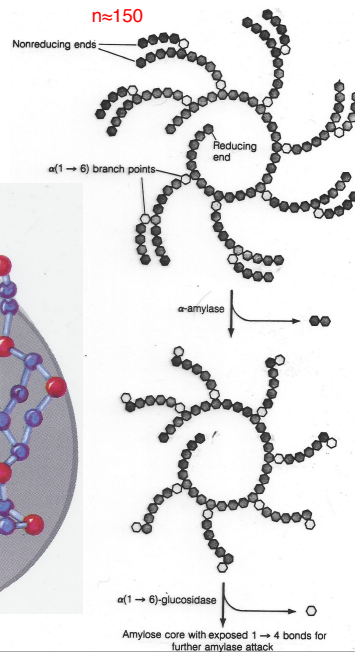
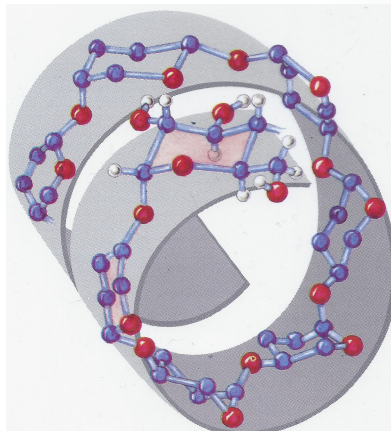
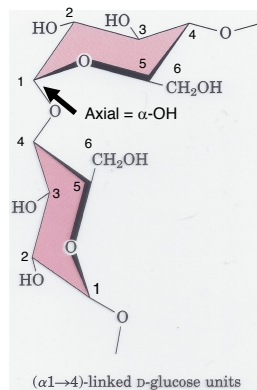
- Granules contain enzymes that synthesize and degrade these polymers.
- Glycogen and amylopectin have **one** reducing end but **many nonreducing ends**.
- Enzymatic processing occurs simultaneously in many nonreducing ends.



Carbohydrates

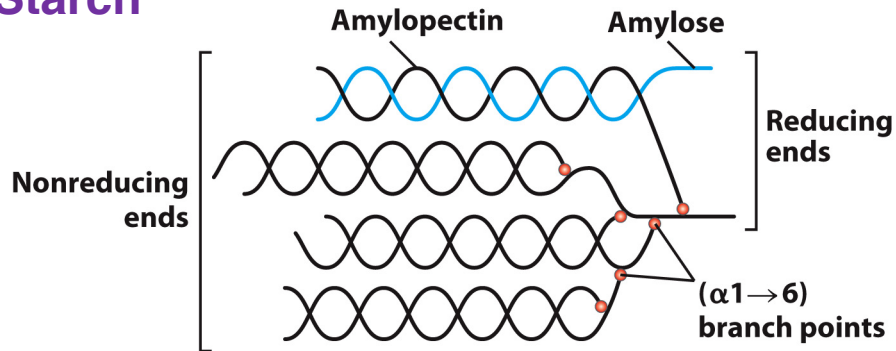
Polysaccharides: Glycogen & Starch

I_2



Carbohydrates

Polysaccharides: Glycogen & Starch



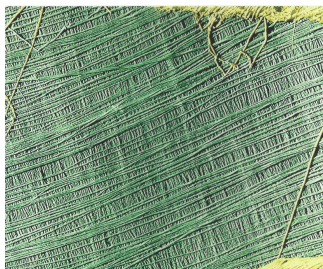
Mixture of **Amylose** and **Amylopectin** in Starch

Carbohydrates

Polysaccharides: Homopolymers of Glucose:

- Starch
- Glycogen
- Cellulose

- Cellulose is a **linear** homopolysaccharide of **glucose**.
 - Glucose monomers form $\beta(1 \rightarrow 4)$ linked chains (no branching).
 - **Hydrogen bonds** form between adjacent monomers.
 - There are additional H-bonds between chains.
 - Structure is now tough and water insoluble.
 - It makes up almost 50% of plant mass; in cell walls.
 - Cotton is nearly pure fibrous cellulose.



Carbohydrates

Polysaccharides:

Homopolymers of Glucose:

- Starch
- Glycogen
- Cellulose
- Chitin

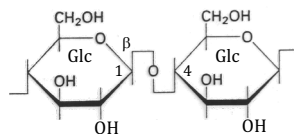


- Chitin is a linear homopolysaccharide of *N*-acetylglucosamine (GlcNAc).
 - *N*-acetylglucosamine monomers form $\beta(1 \rightarrow 4)$ -linked chains.
 - forms extended fibers that are similar to those of cellulose
 - hard, insoluble, cannot be digested by vertebrates
 - structure is tough but flexible, and water insoluble
 - found in cell walls in mushrooms and in exoskeletons of insects, spiders, crabs, and other arthropods

Carbohydrates

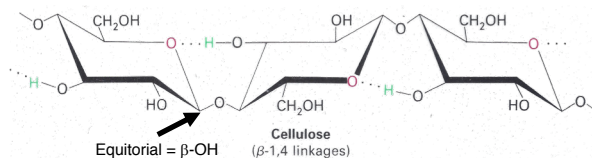
Polysaccharides:

Cellulose & Chitin

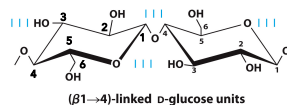


Glycosidic Linkages in Cellulose & Chitin

(Glc- $\beta(1 \rightarrow 4)$ Glc)_n with NO branching,
n $\approx 10^4$



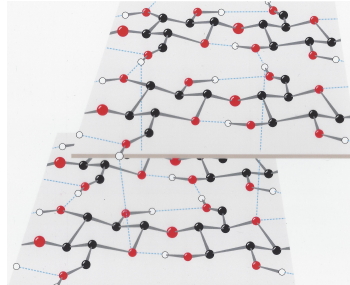
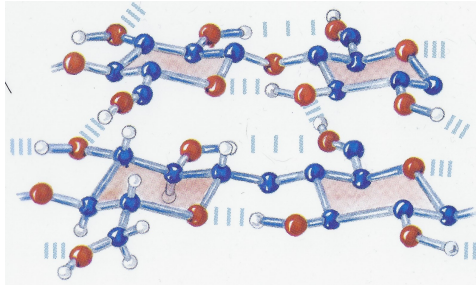
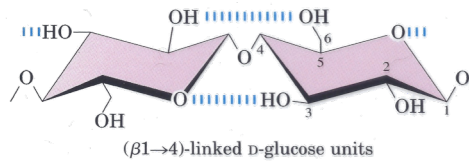
Notice that each chair is alternatively flipped



THE most abundant biological molecule in the world: ~300 trillion kg

Carbohydrates

Polysaccharides: Cellulose & Chitin



- The fibrous structure and water insolubility make cellulose a difficult substrate to act upon.
- Most animals cannot use cellulose as a fuel source because they lack the enzyme to hydrolyze β(1→4) linkages (β-Amylase or cellulase).
- Fungi, bacteria, and protozoa secrete **cellulase**, which allows them to use wood as source of glucose.
- **Ruminants and termites** live symbiotically with microorganisms that produce cellulase and are able to absorb the freed glucose into their bloodstreams.
- Cellulases hold promise in the fermentation of biomass into biofuels.

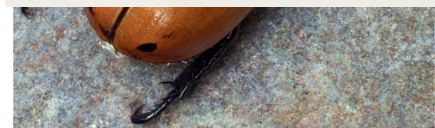


Carbohydrates

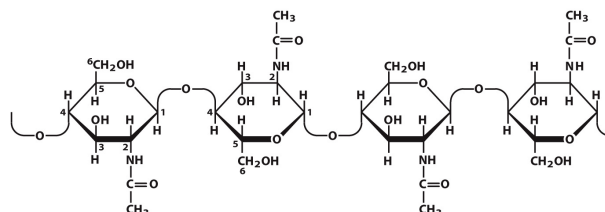
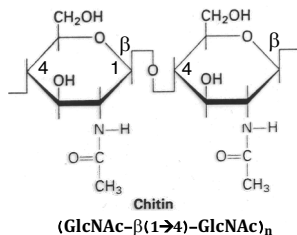
Polysaccharides: Cellulose & Chitin



A Sally lightfoot crab. The exoskeleton of this arthropod is rich in chitin, one of the most abundant biopolymers on earth.



Paul Whitten/Science Source



Carbohydrates

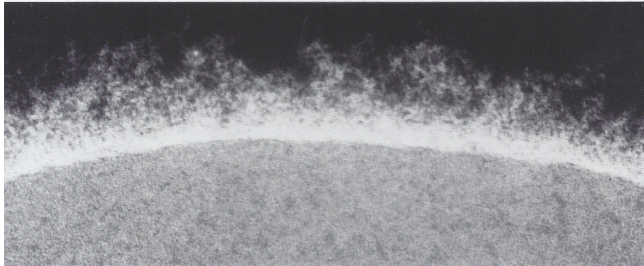
Polysaccharides: Polymers of Disaccharides

First, need to describe the Extracellular Matrix (ECM)

- Material outside the cell in most animal cells
- Strength, elasticity, and physical barrier in tissues (varies tremendously)
- Main components
 - proteoglycans
 - collagen & elastin fibers

• Proteoglycans

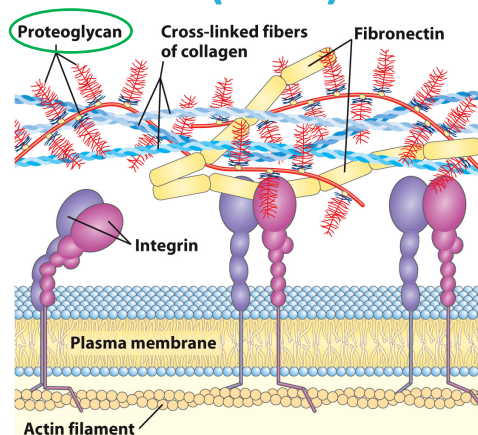
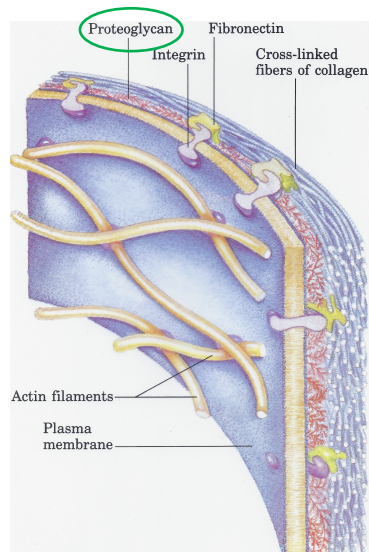
- Different **glycosaminoglycans** are O-linked to the “core protein.”
- Linkage from anomeric carbon of xylose to serine hydroxyl
- Our tissues have many different core proteins; **aggrecan** is the best studied.



Carbohydrates

Polysaccharides: Polymers of Disaccharides

Extracellular Matrix (ECM)



Carbohydrates

Polysaccharides: Polymers of Disaccharides Glycosaminoglycans

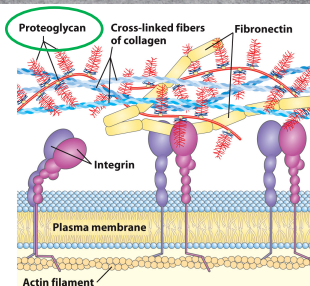
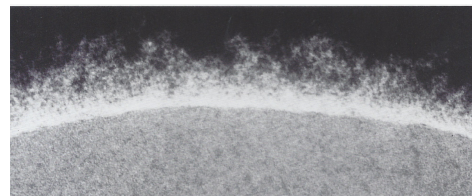
(the carbohydrate part of proteoglycans)

- Linear polymers of repeating disaccharide units (sugarX-sugarY)_n
- One monomer (sugarX) is either sugar acid or Gal
 - uronic acids (C6 oxidation)
 - Most have sulfate esters
- One monomer (sugarY) is either:
 - N-acetyl-glucosamine (GlcNAc) or N-acetyl-galactosamine (GalNAc)
 - Also sulfate esters
- Extended hydrated molecule
 - Negatively charged
 - minimizes charge repulsion
- Forms meshwork with fibrous proteins to form extracellular matrix
 - connective tissue
 - lubrication of joints
- Form huge ($M_r > 2 \cdot 10^8$) noncovalent aggregates (Hyaluronan and Aggrecan).
 - They hold a lot of water (1000× its weight) and provide lubrication.
 - Very low friction material
 - Covers joint surfaces: articular cartilage
 - reduced friction & load balancing

Carbohydrates

Polysaccharides: Polymers of Disaccharides Extracellular Matrix (ECM)

- Main components
 - proteoglycans
 - collagen & elastin fibers
- Proteoglycans
 - Different glycosaminoglycans are O-linked to the “core protein.”
- ECM is a barrier for tumor cells seeking to invade new tissues.
 - Some tumor cells secrete heparinase that degrades ECM.
- Cosmetics

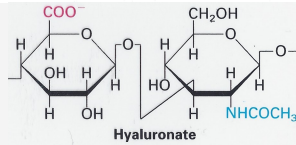


Carbohydrates

Polysaccharides: Polymers of Disaccharides Glycosaminoglycans

Major components of the polysaccharide portion of mucopolysaccharides (proteoglycans)

	Usual molecular weight of polysaccharide chain	Component sugars	Location of sulfate	Linkage	Major Source
Hyaluronic acid ^a	1 - 3 x 10 ⁶	<i>N</i> -acetylglucosamine glucuronic acid	-	β-(1→4) β-(1→3)	synovial fluid, vitreous humor of the eye, umbilical cord, cock's comb



^aThe attachment of hyaluronic acid to protein has not been demonstrated unequivocally.

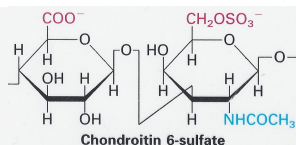
^bThis linkage of *L*-iduronic acid, identical to the β-linkage of *D*-glucuronic acid. However, iduronic acid is of the *L* rather than *D* configuration, which results in this bond being designated as α rather than β.

Carbohydrates

Polysaccharides: Polymers of Disaccharides Glycosaminoglycans

Major components of the polysaccharide portion of mucopolysaccharides (proteoglycans)

	Usual molecular weight of polysaccharide chain	Component sugars	Location of sulfate	Linkage	Major Source
Chondroitin 4-sulfate (chondroitin sulfate A)	2 - 5 x 10 ⁴	<i>N</i> -acetylgalactosamine glucuronic acid	4	β-(1→4) β-(1→3)	human cartilage, aorta
Chondroitin 6-sulfate (chondroitin sulfate C)	2 - 5 x 10 ⁴	<i>N</i> -acetylgalactosamine glucuronic acid	6	β-(1→4) β-(1→3)	heart valves



^aThe attachment of hyaluronic acid to protein has not been demonstrated unequivocally.

^bThis linkage of *L*-iduronic acid, identical to the β-linkage of *D*-glucuronic acid. However, iduronic acid is of the *L* rather than *D* configuration, which results in this bond being designated as α rather than β.

Carbohydrates

Polysaccharides: Polymers of Disaccharides Glycosaminoglycans

Major components of the polysaccharide portion of mucopolysaccharides (proteoglycans)					
	Usual molecular weight of polysaccharide chain	Component sugars	Location of sulfate	Linkage	Major Source
Dermatan sulfate (chondroitin sulfate B)	2 - 5 x 10 ⁴	N-acetylgalactosamine iduronic acid glucuronic acid	4	β-(1→4) α-(1→3) ^b β-(1→3)	skin, blood vessels, heart valves

Dermatan sulfate

^aThe attachment of hyaluronic acid to protein has not been demonstrated unequivocally.

^bThis linkage of L-iduronic acid, identical to the β-linkage of D-glucuronic acid. However, iduronic acid is of the L rather than D configuration, which results in this bond being designated as α rather than β.

Carbohydrates

Polysaccharides: Polymers of Disaccharides Glycosaminoglycans

Major components of the polysaccharide portion of mucopolysaccharides (proteoglycans)					
	Usual molecular weight of polysaccharide chain	Component sugars	Location of sulfate	Linkage	Major Source
Heparin	1 - 3 x 10 ⁴	glucosamine glucuronic acid iduronic acid	3,6,N 2	α-(1→4) β-(1→4) α-(1→4) ^b	lung, mast cells
Heparan sulfate (heparitin sulfate)	2 - 10 x 10 ³	glucosamine N-acetylglucosamine glucuronic acid iduronic acid	N ? 3,6 2	α-(1→4) β-(1→4) α-(1→4) ^b	blood vessels, cell surfaces

Heparin

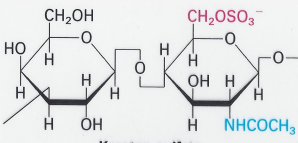
^aThe attachment of hyaluronic acid to protein has not been demonstrated unequivocally.

^bThis linkage of L-iduronic acid, identical to the β-linkage of D-glucuronic acid. However, iduronic acid is of the L rather than D configuration, which results in this bond being designated as α rather than β.

Carbohydrates

Polysaccharides: Polymers of Disaccharides Glycosaminoglycans

Major components of the polysaccharide portion of mucopolysaccharides (proteoglycans)

	Usual molecular weight of polysaccharide chain	Component sugars	Location of sulfate	Linkage	Major Source
 Keratan sulfate					
Keratan sulfate	5 - 20 x 10 ³	N-acetylglucosamine galactose	6 6	β-(1→3) β-(1→4)	cornea of the eye, nucleus pulposus, cartilage

^aThe attachment of hyaluronic acid to protein has not been demonstrated unequivocally.

^bThis linkage of L-iduronic acid, identical to the β-linkage of D-glucuronic acid. However, iduronic acid is of the L rather than D configuration, which results in this bond being designated as α rather than β.

Carbohydrates

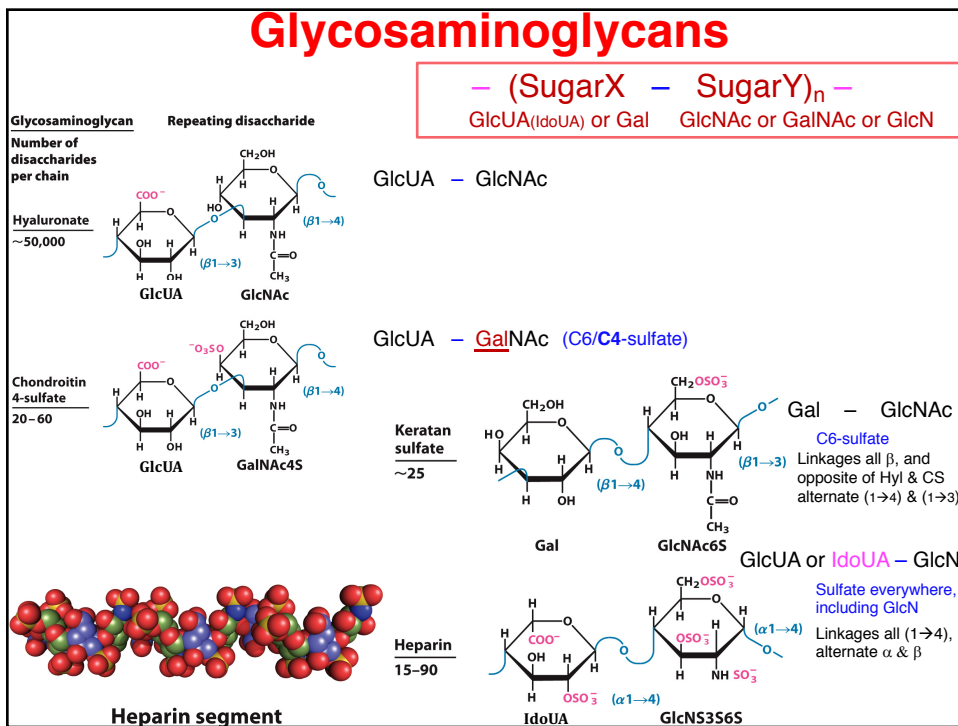
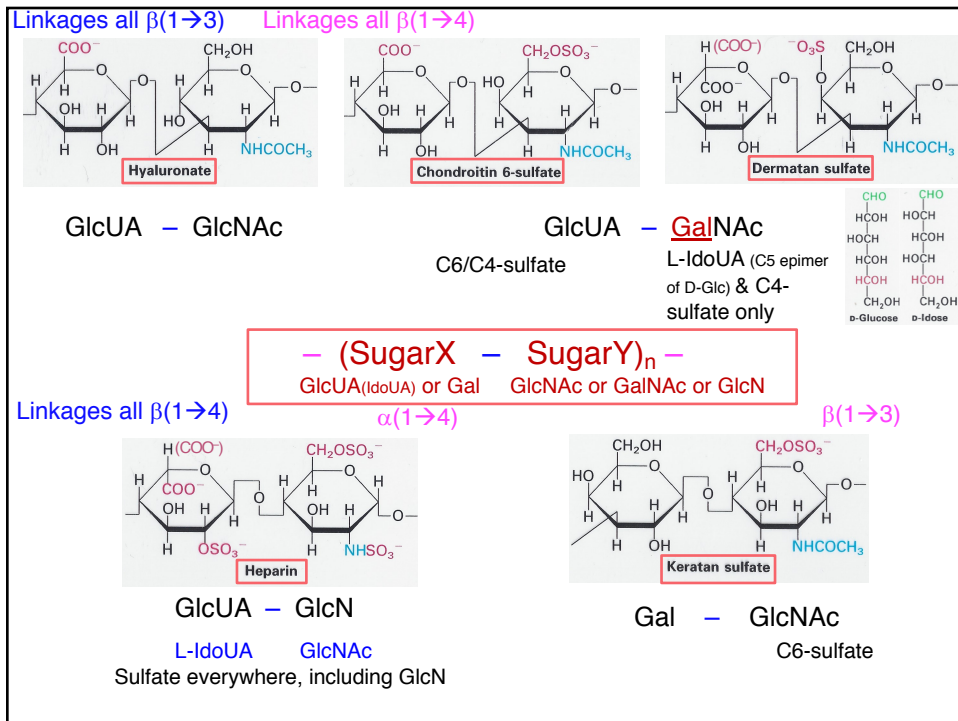
Polysaccharides: Polymers of Disaccharides Glycosaminoglycans

Major components of the polysaccharide portion of mucopolysaccharides (proteoglycans)

	Usual molecular weight of polysaccharide chain	Component sugars	Location of sulfate	Linkage	Major Source
Hyaluronic acid ^a	1 - 3 x 10 ⁶	N-acetylglucosamine glucuronic acid	-	β-(1→4) β-(1→3)	synovial fluid, vitreous humor of the eye, umbilical cord, cock's comb
Chondroitin 4-sulfate (chondroitin sulfate A)	2 - 5 x 10 ⁴	N-acetylgalactosamine glucuronic acid	4	β-(1→4) β-(1→3)	human cartilage, aorta
Chondroitin 6-sulfate (chondroitin sulfate C)	2 - 5 x 10 ⁴	N-acetylgalactosamine glucuronic acid	6	β-(1→4) β-(1→3)	heart valves
Dermatan sulfate (chondroitin sulfate B)	2 - 5 x 10 ⁴	N-acetylgalactosamine iduronic acid glucuronic acid	4	β-(1→4) α-(1→3) ^b β-(1→3)	skin, blood vessels, heart valves
Heparin	1 - 3 x 10 ⁴	glucosamine glucuronic acid iduronic acid	3,6,N 2	α-(1→4) β-(1→4) α-(1→4) ^b	lung, mast cells
Heparan sulfate (heparitin sulfate)	2 - 10 x 10 ³	glucosamine N-acetylglucosamine glucuronic acid iduronic acid	N ? 3,6 2	α-(1→4) β-(1→4) α-(1→4) ^b	blood vessels, cell surfaces
Keratan sulfate	5 - 20 x 10 ³	N-acetylglucosamine galactose	6 6	β-(1→3) β-(1→4)	cornea of the eye, nucleus pulposus, cartilage

^aThe attachment of hyaluronic acid to protein has not been demonstrated unequivocally.

^bThis linkage of L-iduronic acid, identical to the β-linkage of D-glucuronic acid. However, iduronic acid is of the L rather than D configuration, which results in this bond being designated as α rather than β.



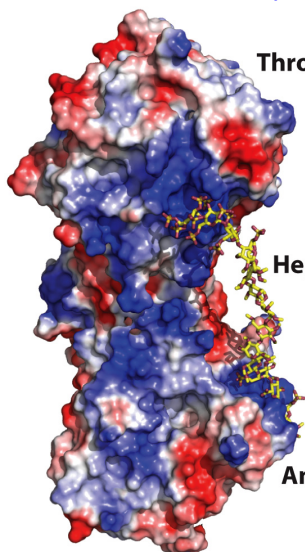
Carbohydrates

Polysaccharides: **Proteoglycans** = Polymers of Disaccharides (glycosaminoglycans) + proteins
a.k.a. - mucopolysaccharides

- Some integral membrane proteins are proteoglycans.
 - syndecans
- Other integral membrane proteins are receptors for extracellular proteoglycans.
 - Integrins (which then interact with Actin)
- These proteins link cellular cytoskeleton to the ECM and transmit signals into the cell to regulate:
 - cell growth
 - cell mobility
 - apoptosis
 - wound healing
- In chondrocytes, huge amounts of cartilage proteoglycans are produced (Aggrecan)
 - Resilience
 - Plasticity
 - Cushioning
 - Due to reversible hydration
- Heparin is linear polymer, 3–40 kDa.
 - Heparan sulfate is heparin-like polysaccharide but attached to proteins.
 - Highest density of negative-charge of any biomolecule
 - Prevent blood clotting by activating protease-inhibitor antithrombin III
 - Binding to various cells regulates development and formation of blood vessels.
 - Modulates growth and development by binding growth-factor receptors
 - Important role in cancer metastasis
 - Can also bind to viruses and bacteria and decrease their virulence

Carbohydrates

Polysaccharides: **Proteoglycans** = Polymers of Disaccharides (glycosaminoglycans) + proteins
a.k.a. - mucopolysaccharides



Thrombin

Heparin

Prevent blood clotting by activating protease inhibitor antithrombin III to bind and inactivate Thrombin.

Heparin

Without Heparin, the anti-thrombin will dissociate from thrombin, which then can perform the proteolysis that initiates the blood clotting cascade of events.

Antithrombin

TABLE 7-2 Structures and Roles of Some Polysaccharides				
Primer	Type ^a	Repeating unit ^b	Size (number of monosaccharide units)	Roles/significance
Starch				
Amylose	Homo-	($\alpha 1 \rightarrow 4$) Glc, linear	50–5,000	Energy storage: in plants
Amylopectin	Homo-	($\alpha 1 \rightarrow 4$) Glc, with ($\alpha 1 \rightarrow 6$) Glc branches every 24–30 residues	Up to 10 ⁶	
Glycogen	Homo-	($\alpha 1 \rightarrow 4$) Glc, with ($\alpha 1 \rightarrow 6$) Glc branches every 8–12 residues	Up to 50,000	Energy storage: in bacteria and animal cells
Cellulose	Homo-	($\beta 1 \rightarrow 4$) Glc	Up to 15,000	Structural: in plants, gives rigidity and strength to cell walls
Chitin	Homo-	($\beta 1 \rightarrow 4$) GlcNAc	Very large	Structural: in insects, spiders, crustaceans, gives rigidity and strength to exoskeletons
Peptidoglycan	Hetero-; peptides attached	4)Mur2Ac($\beta 1 \rightarrow 4$) GlcNAc($\beta 1$)	Very large	Structural: in bacteria, gives rigidity and strength to cell envelope
Hyaluronan (a glycosaminoglycan)	Hetero-; acidic	4)GlcA ($\beta 1 \rightarrow 3$) GlcNAc($\beta 1$)	Up to 100,000	Structural: in vertebrates, extracellular matrix of skin and connective tissue; viscosity and lubrication in joints

^aEach polymer is classified as a homopolysaccharide (homo-) or heteropolysaccharide (hetero-).
^bThe abbreviated names for the peptidoglycan, agarose, and hyaluronan repeating units indicate that the polymer contains repeats of this disaccharide unit. For example, in peptidoglycan, the GlcNAc of one disaccharide unit is ($\beta 1 \rightarrow 4$)-linked to the first residue of the next disaccharide unit.