BIOL 4640 Study Guide for Exam 2 (Wed 10/28/26): Lecture 17 Envelope Layers: Outer Membrane, Wall, Periplasm, Membrane

Source: Dr. Rowen's lecture slides, in the order of the 2025 Exam 2 study guide outline.
Slide blanks still empty in the notes are filled from the textbook and marked "textbook".
Tags like [L16 p08] give the source page of each line.
Textbook to read (Slonczewski 6e, Textbook page on the site): 3.3 The Envelope and Cytoskeleton (the cell wall); 3.2 Membrane Molecules and Transport (membranes); 4.2 Nutrient Uptake. **Also useful:** 19.1 Archaeal Diversity at a Glance (archaeal lipids, pseudopeptidoglycan).
(teal italics) = plain meaning of the word before it. ⚠ **Do not mix up = a look-alike pair to keep apart.**

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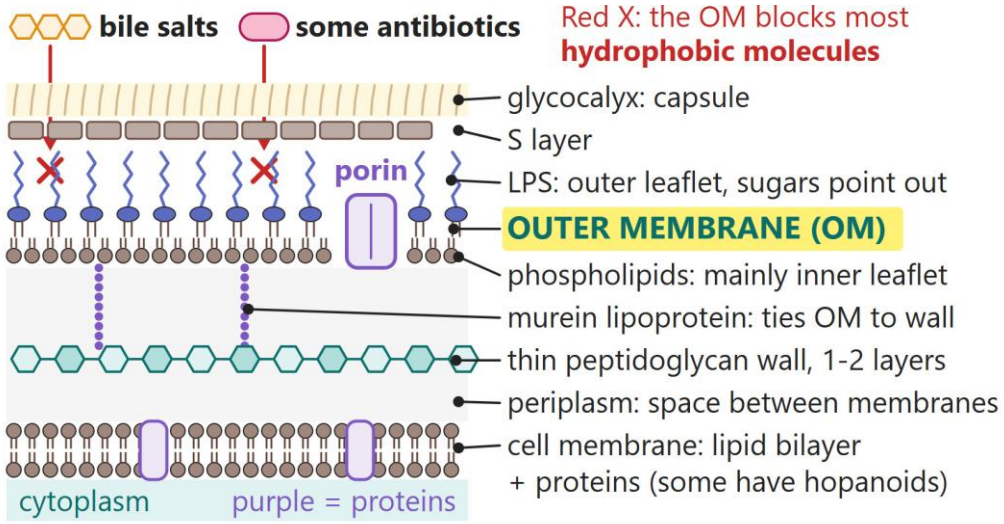
Click a line to jump to it. The PDF side panel (bookmarks) has the same parts as tabs and topics as subtabs.

C. Cell envelope (glycocalyx, outer membrane, cell wall, and cell membrane)

Book: 3.3 The Envelope and Cytoskeleton, Cell Envelope of Bacteria (chapter 3 PDF, p. 49).

Layers outside to inside

Envelope *(layers wrapped around the cell)* **layers**, outside to inside: [L17 p04, L17 p30]



Envelope layers outside to inside, with the outer membrane blocking hydrophobic molecules [L17 p04]

On the figure: Glycocalyx · S layer · LPS · Outer membrane · phospholipids · Periplasm · Cell membrane

Glycocalyx (capsule). [L17 p04, L17 p30]
S layer. [L17 p04, L17 p30]
Outer membrane (**LPS** and **phospholipids**). [L17 p04, L17 p30]
Cell wall (peptidoglycan, pseudopeptidoglycan, teichoic acid, mycolic acids, arabinogalactan). [L17 p04, L17 p30]
Periplasm *(space between the two membranes)*. [L17 p04, L17 p30]
Cell membrane (phospholipids, isoprenoids and hopanoids). [L17 p04, L17 p30]

Peptidoglycan, lysozyme and penicillin

Peptidoglycan *(sugar and peptide mesh of the wall)*: repeats of N-acetyl-glucosamine (NAG) and N-acetyl-muramic acid (NAM).

Lysozyme *(enzyme that cuts wall sugars)*: a defensive enzyme of our body that cleaves the linkage between the sugars in peptidoglycan.

Penicillin: **only** works on growing cells making new wall.

S layer and archaeal envelope

S layer: a protein (or glycoprotein) coating on the outside of the cell wall or membrane *(thin lipid layer)*, seen in some bacteria and archaea *(single cell microbes without a nucleus, their own domain (also called archaeal bacteria))*.

Pseudopeptidoglycan *(archaea version of wall mesh)*: found in the cell wall of some archaeal *(of archaea)* bacteria.

Archaeal envelope: isoprenoid *(branched five carbon repeat fat)* membrane, S layer often present, pseudopeptidoglycan in some, no mycolic acid *(waxy fatty acid of mycobacteria)*.

Envelope differences

Acid-fast *(holds dye despite acid wash)* **envelope**: no outer membrane with phospholipids *(membrane fat with a charged head)* and LPS *(outer membrane sugar and fat coat)*; it has a mycomembrane of mycolic acids (the mycobacterial outer membrane) instead.

Staph vs Gram negative *(thin wall plus outer membrane)* **peptidoglycan**: cross-link amino acids and number of layers differ.

Envelope type	Envelope contents
Gram negative	outer membrane with LPS, thin peptidoglycan (**1-2 layers**), periplasm, cell membrane of phospholipids
Gram positive	thick peptidoglycan (**3-20 layers**), teichoic acids (most **Gram positive**), cell membrane; no outer membrane
Mycobacteria (acid-fast)	peptidoglycan, arabinogalactan, mycolic acids (mycomembrane), cell membrane
Mollicutes (Mycoplasma)	no cell wall
Archaea	pseudopeptidoglycan in some, isoprenoid lipids in the membrane

Table source: [L17 p03, L17 p05, L17 p15, L17 p24, L17 p26, L17 p28, L17 p29, L17 p39]

2. Know role, feature and basic composition of each of these layers (3.3 6e)

Book: 3.3 The Envelope and Cytoskeleton, Proteobacterial Cell Envelope: Gram-Negative (chapter 3 PDF, p. 56).

⚠ **Do not mix up: Mycolic acid *(waxy fatty acid of mycobacteria)* is NOT an archaeal *(of archaea)* feature; archaea *(single cell microbes without a nucleus, their own domain (also called archaeal bacteria))* have isoprenoid *(branched five carbon repeat fat)* membranes *(thin lipid layer)*** and often an S layer.

Layers overview

Outer membrane *(extra membrane outside the wall)* and **periplasm** *(space between the two membranes)* are **Gram negative** *(thin wall plus outer membrane)* layers. [L17 p04]

Gram negative layers in order

Gram negative envelope *(layers wrapped around the cell)* **layers**: outside to inside.

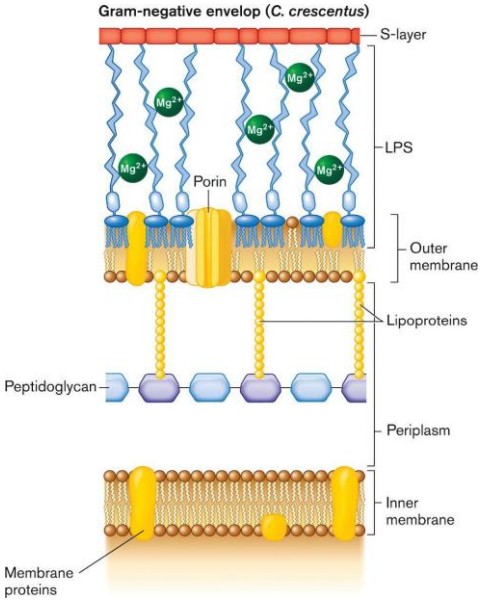
Layer 1: glycocalyx *(sugary coat outside the cell)* or capsule (sugars, proteins or DNA).

Layer 2: outer membrane (lipopolysaccharide, proteins, phospholipids).

Layer 3: periplasm (aqueous compartment between the outer membrane and the **inner membrane**), which holds the thin cell wall *(stiff layer around the cell membrane)*.

Inside layer 3: cell wall (**peptidoglycan**), thin, **1-2 layers**; it sits in the periplasm.

Layer 4: cell membrane (phospholipids and proteins).



Gram negative envelope: LPS, outer membrane, lipoproteins, periplasm, inner membrane [L17 p05]

On the figure: Outer membrane · periplasm · peptidoglycan · inner membrane

Penicillin and the outer membrane

Penicillin: some penicillins are more effective against **Gram positive** *(thick wall, stains purple)* than **Gram negative** bacteria, because some do not pass through the **Gram negative** outer membrane.

Layer	Role	Feature	Composition
Outer membrane	LPS sugars block diffusion of hydrophobic molecules (bile salts, antibiotics, dyes); the membrane blocks hydrophilic molecules except through porins; lipid A induces an inflammatory response	a second membrane beyond the cell membrane, **Gram negative**	LPS (outer leaflet), phospholipids (mainly inner leaflet), porins, murein lipoprotein
Cell wall	structural support and rigidity; prevents lysis in hypotonic conditions; helps determine cell shape	semi-rigid, porous layer beyond the cell membrane; synthesis blocked by some antibiotics	peptidoglycan, pseudopeptidoglycan, teichoic acid, mycolic acid, arabinogalactan
Periplasm	osmotic protection, nutrient transport, redox reactions of the electron transport chain, hydrolysis of nutrients	aqueous compartment between outer and inner membrane, **Gram negative**, own unique proteins	oligosaccharides and a unique set of proteins
Cell membrane	boundary and barrier, regulates what is inside, energy reactions and storage, sensing, lipid synthesis	lipids and proteins, proteins a major component by weight (E. coli: **75%** protein, **25%** phospholipid)	phospholipids, isoprenoids, hopanoids, cardiolipin, proteins

Table source: [L17 p05, L17 p08, L17 p12, L17 p14, L17 p31, L17 p32, L17 p33, L17 p35, L17 p43, L17 p44, L17 p45, L17 p46]

c. Outer membrane

Book: 3.3 The Envelope and Cytoskeleton, Proteobacterial Cell Envelope: Gram-Negative (chapter 3 PDF, p. 56).

⚠ **Do not mix up: Murein lipoprotein** ***(protein anchoring outer membrane to wall)*** **links outer membrane** ***(extra membrane outside the wall)*** **to peptidoglycan** ***(sugar and peptide mesh of the wall)*****; porins** ***(channels in the outer membrane)*** **pass only molecules up to 700 daltons** ***(unit of molecule weight)*****.** [L17 p11]

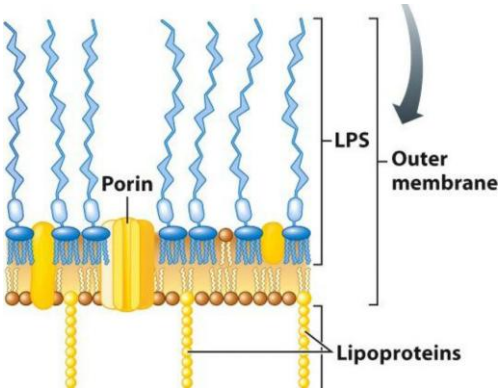
What the outer membrane is

Outer membrane: a second membrane *(thin lipid layer)* beyond the cell membrane *(thin skin around the cell)*. [L17 p05]

Where: found in **Gram negative** *(thin wall plus outer membrane)* bacteria. [L17 p05]

Outer membrane composition: lipopolysaccharide *(outer membrane sugar and fat coat)*, proteins, and phospholipids *(membrane fat with a charged head)*.

Function: inhibits diffusion *(drifting from high to low amount)* of most hydrophobic *(water hating)* molecules (bile salts, some antibiotics); the **LPS** sugars block the hydrophobic molecules, and the membrane itself blocks hydrophilic *(water loving)* molecules, which get through **only** by **porins** (under **700 daltons**). [L17 p05]

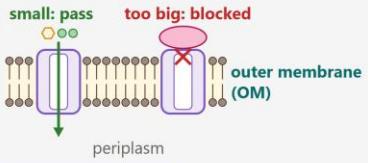


Outer membrane with LPS, porin and lipoproteins [L17 p09]

On the figure: outer membrane · LPS · porins · lipoprotein

Porins: protein channels

outside the cell



MAX 700 daltons

short chains of sugars and amino acids

a few different types

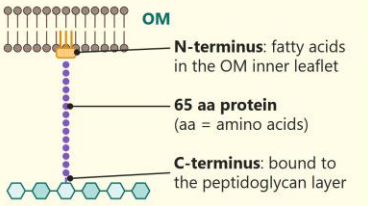
selective for type or size of molecule

E. coli

Protein	Function	Receptor for
OmpF	nonspecific: small molecules	phage T2
OmpC		phage T4
OmpA	specific for peptides	mating pili
LamB	maltose, maltodextrin	phage λ
PhoE	anion-selective channel	none listed

receptor = docking site a phage or pilus binds
phage = virus that infects bacteria
Omp = OM protein; λ = lambda

Murein lipoprotein



Job: LINKS OM TO PEPTIDOGLYCAN

orange = lipid tails; purple = protein

TRAP: these channels do NOT let in molecules of any size; big ones stay out

Porins pass small molecules; murein lipoprotein links outer membrane to peptidoglycan [L17 p10]

On the figure: porins · OmpF · OmpC · OmpA · LamB · PhoE · Murein lipoprotein · 700 daltons

Porins

Porins *(protein channels through the outer membrane)*: a few different types; E. coli has **OmpF**, **OmpC**, **OmpA**, **LamB** and **PhoE**. [L17 p09]

Porin *(water filled channel in outer membrane)* **selectivity**: selective for type or size of molecule. [L17 p09]

Porin size limit: maximum **700 daltons** (short chains of sugars and amino acids). [L17 p09]

In a rich environment, cells down-regulate large porins and express smaller-pore porins, selecting **only** smaller nutrients and avoiding toxins (textbook).

Receptors and phage

Receptor *(docking site on the cell surface)*: a phage *(virus that infects bacteria)* or a mating pilus *(thin hair for sticking or DNA swap)* attaches to its porin receptor. [L17 p10]

Phage *(virus that infects bacteria)*: OmpF, OmpC and LamB are phage receptors *(proteins a signal or virus binds to)*. [L17 p10]

Murein lipoprotein

Murein lipoprotein: a **65** amino acid protein. [L17 p11]

Murein lipoprotein N-terminus: linked to fatty acids in the inner leaflet of the outer membrane. [L17 p11]

Murein lipoprotein C-terminus: linked to the peptidoglycan layer. [L17 p11]

Murein lipoprotein job: links the outer membrane to peptidoglycan. [L17 p11]

A mutant without murein lipoprotein cannot attach its outer membrane to the growing wall, so the outer membrane balloons out where daughter cells separate (textbook).

Component of the outer membrane	Where and what
1) Lipopolysaccharide (LPS)	outer leaflet, sugar chain pointing out
2) Phospholipids	mainly in the inner leaflet
3) Protein channels (porins)	selective for type or size of molecule, maximum size **700 daltons**
4) Murein lipoprotein	**65** amino acid protein linking the outer membrane to peptidoglycan

Table source: [L17 p06, L17 p09, L17 p11]

E. coli porin	Function	Also
OmpF	nonspecific, small molecules	receptor for phage T2
OmpC	nonspecific, small molecules	receptor for phage T4
OmpA	specific for peptides	receptor for mating pili
LamB	porin for maltose, maltodextrin	receptor for phage lambda
PhoE	anion-selective channel	none listed

Table source: [L17 p10]

LPS

Book: 3.3 The Envelope and Cytoskeleton, Proteobacterial Cell Envelope: Gram-Negative (chapter 3 PDF, p. 56).

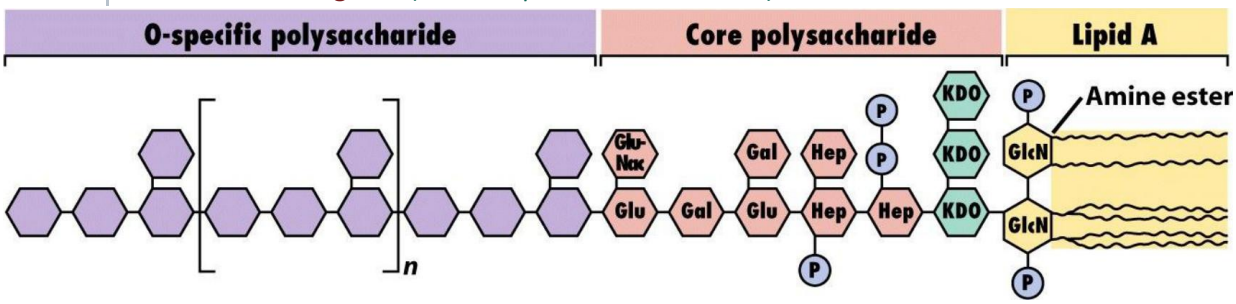
⚠ **Do not mix up: LPS *(outer membrane sugar and fat coat)* polysaccharides *(long chain of sugars)* block diffusion *(drifting from high to low amount)*; lipid A *(toxic fatty part of LPS)* is the part that induces inflammation.** [L17 p08]

What LPS is

LPS (lipopolysaccharide):

Sits in the outer leaflet of the outer membrane *(extra membrane outside the wall)*. [L17 p06, L17 p07]

Found in **Gram negative** *(thin wall plus outer membrane)* bacteria, in the outer membrane. [L17 p07, L17 p08]



LPS in three parts: O-specific polysaccharide, core polysaccharide, lipid A [L17 p07]

On the figure: O-specific polysaccharide · core polysaccharide · lipid A · KDO · Hep · Gal · Glu

LPS structure: three parts, **lipid A**, **core polysaccharide** and **O-specific polysaccharide**. [L17 p07]

LPS sugar chain: points out. [L17 p06, L17 p07]

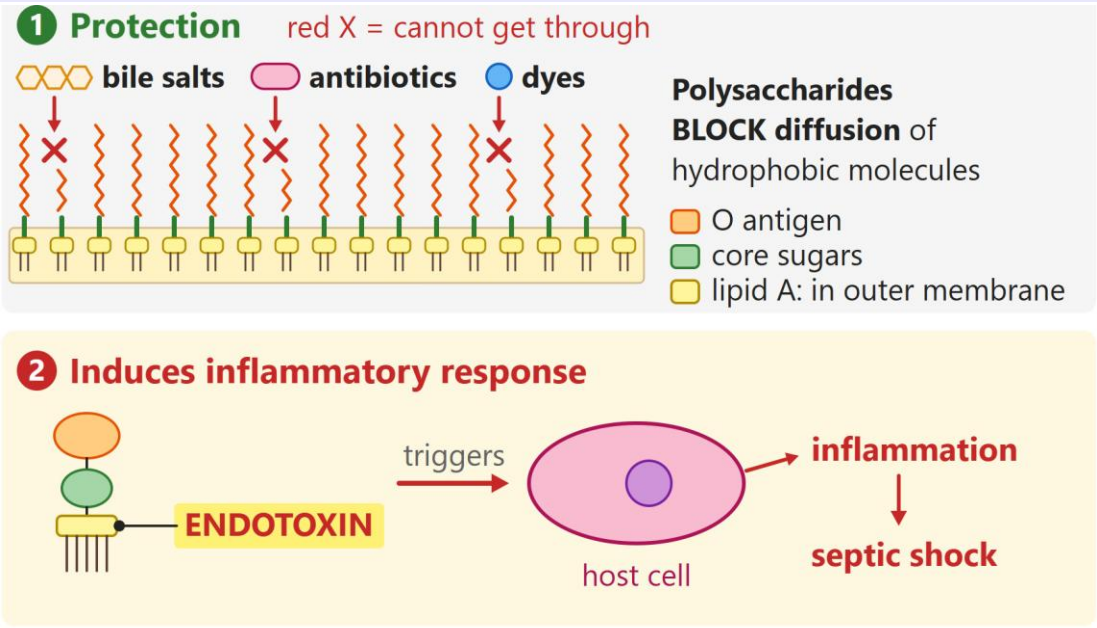
The LPS sugar chains carry negative charges that bind magnesium ions *(charged particle)*, and the ions form ionic cross-links that bridge LPS chains (textbook).

LPS parts

Core polysaccharide sugars: **KDO** *(a core sugar)*, **Hep**, **Gal** and **Glu** *(glucose, not glutamic acid)*. [L17 p07]

O antigen *(the outermost sugar repeat of LPS)*: another name for the **O-specific polysaccharide**. [L17 p08]

Jobs of LPS



Two jobs of LPS: block bile salts, antibiotics and dyes; lipid A triggers inflammation [L17 p08]

On the figure: bile salts · antibiotics · dyes · lipid A · O antigen · Endotoxin

Function of LPS: two jobs. [L17 p08]

LPS job 1, protection: the polysaccharides block diffusion of hydrophobic *(water hating)* molecules (**bile salts**, **antibiotics**, **dyes**). [L17 p08]

LPS job 2: **lipid A** induces an inflammatory response. [L17 p08]

Endotoxin *(toxin built into the cell)* is harmless while the pathogen is intact, but released by a lysed *(broken open)* cell it overstimulates host defenses and can cause potentially lethal shock (textbook).

Part	What it is
Lipid A	**4-6** fatty acids attached to a disaccharide of N-acetylglucosamine phosphate; the **endotoxin** *(toxin that causes septic shock)*
Core polysaccharide	branched chain of sugars, same for a species
O-specific polysaccharide	usually a **4-5** sugar repeat; length and composition vary; also contributes to the glycocalyx; sticks out from the outer membrane

Table source: [L17 p07]

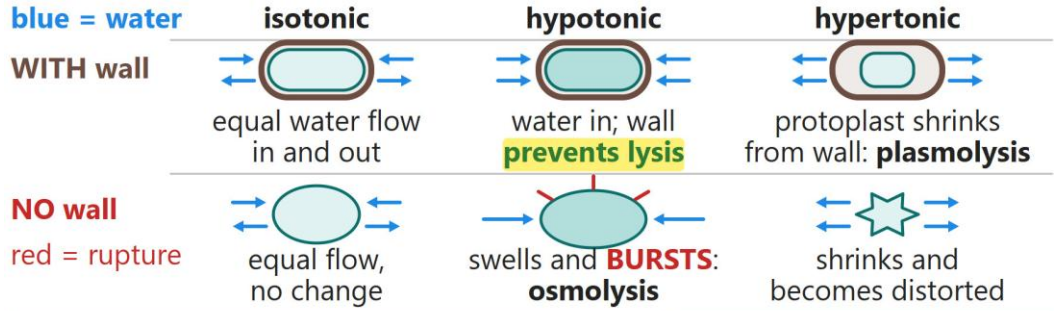
d. Cell Wall: Role

Book: 3.3 The Envelope and Cytoskeleton, The Cell Wall Is a Single Molecule (chapter 3 PDF, p. 43).

⚠ **Do not mix up: Penicillin only kills growing bacteria making new wall; it may fail on Gram negative *(thin wall plus outer membrane)*.**

Cell wall roles

Cell wall: semi-rigid, porous layer beyond the cell membrane
Role: structural support, rigidity; helps determine cell shape
Its synthesis is blocked by some antibiotics



Bacteria: wall components		Plants and fungi
a) peptidoglycan (murein) b) pseudopeptidoglycan c) teichoic acid	d) mycolic acid e) arabinogalactan	**Plants**: **cellulose**, chains of glucose **Fungi**: **chitin**, chains of a modified glucose
most eubacteria: ONE principal component		

TRAP: a walled cell losing water does NOT rupture; it shrinks away from the wall

Cell wall in isotonic, hypotonic and hypertonic water, and wall components [L17 p13]

On the figure: cell walls · hypotonic · peptidoglycan · pseudopeptidoglycan · teichoic acid · mycolic acid · arabinogalactan · cellulose

Cell wall *(stiff layer around the cell membrane)*: a semi-rigid, porous layer beyond the cell membrane *(thin skin around the cell)*. [L17 p12]

Role 1: provides structural support and rigidity. [L17 p12]

Role 2: prevents cells from lysing in **hypotonic** *(low solute outside)* conditions. [L17 p12]

Without a countering wall, osmotic *(about water moving across membranes)* pressure makes a cell burst, which is how penicillin kills bacteria by disrupting wall synthesis. A growing cell keeps opening its wall (autolysins) to insert new units, so when new units cannot be made or cross-linked the wall weakens and the cell bursts (textbook).

Role 3: helps determine cell shape. [L17 p12]

Wall composition

Composition varies, but most eubacteria have one principal component. [L17 p12]

Antibiotics: synthesis of the cell wall is blocked by some antibiotics, such as penicillin and vancomycin *(drug blocking wall building)*, which block cross-bridge formation. [L17 p12]

Components found in bacterial cell walls: **peptidoglycan** (murein), **pseudopeptidoglycan** *(archaea version of wall mesh)*, **teichoic acid** *(charged chains in Gram positive wall)*, **mycolic acid** *(waxy fatty acid of mycobacteria)*, **arabinogalactan** *(chain of arabinose and galactose sugars in the wall)*. [L17 p14]

For comparison, plants use **cellulose** (chains of glucose). [L17 p14]

For comparison, fungi use chitin (chains of a modified glucose). [L17 p14]

Why penicillin may fail

Why penicillin may fail: four reasons treating water with penicillin may not make it safe to drink.

Reason 1:

> The bacteria may not be growing.
> Penicillin **only** kills bacteria that are growing.
> Growing bacteria synthesize new cell wall material.

Reason 2:

> Penicillin may not work against the bacteria causing the illness.
> That type is **Gram negative**.

Reason 3: the bacteria may be resistant.

Beta-lactamase *(enzyme that destroys beta lactam drugs)* cleaves the lactam ring of penicillin, so penicillin can no longer inhibit the transpeptidase (textbook).

Reason 4: you may not reach a high enough concentration.

Condition	Cell with a cell wall	Cell lacking a cell wall
Isotonic	water concentration equal inside and outside, equal diffusion in both directions	rates of diffusion equal in both directions
Hypotonic	net diffusion of water into the cell; swells the protoplast and pushes it tightly against the wall; the wall usually prevents the cell from bursting	water diffuses in, the cell swells and may burst (osmolysis) if no mechanism exists to remove the water
Hypertonic	water diffuses out and the protoplast shrinks away from the wall (plasmolysis)	water diffuses out, the cell shrinks and becomes distorted

Table source: [L17 p13]

1) Peptidoglycan: structure, sugars

Book: 3.3 The Envelope and Cytoskeleton, The Cell Wall Is a Single Molecule (chapter 3 PDF, p. 43).

⚠ **Do not mix up: Gram negative *(thin wall plus outer membrane)* cross-link joins DAP (position 3) directly to D-Ala (position 4); staphylococci use L-Lys and a (Gly)5 bridge instead.** [L17 p19]

What peptidoglycan is

Peptidoglycan (murein): long glycan *(sugar chain)* chains of two alternating sugars. [L17 p15, L17 p16]

Peptidoglycan sugars: repeats of N-acetyl-glucosamine and N-acetyl-muramic acid.

Lysozyme *(enzyme that cuts wall sugars)*: a defensive enzyme of our body that cleaves the linkage between the sugars in peptidoglycan.

Size: one large, interconnected molecule around the outside of the cell. [L17 p15, L17 p16]

Peptide positions in Gram negative

Peptide *(short chain of amino acids)* **of a Gram negative peptidoglycan**: positions counted from the NAM *(the other wall sugar)*. [L17 p19]

Each peptide hangs from an **NAM** (M) sugar of the glycan chain; the cross-link then joins two peptides. [L17 p19]

Position 1: L-Ala. [L17 p19]

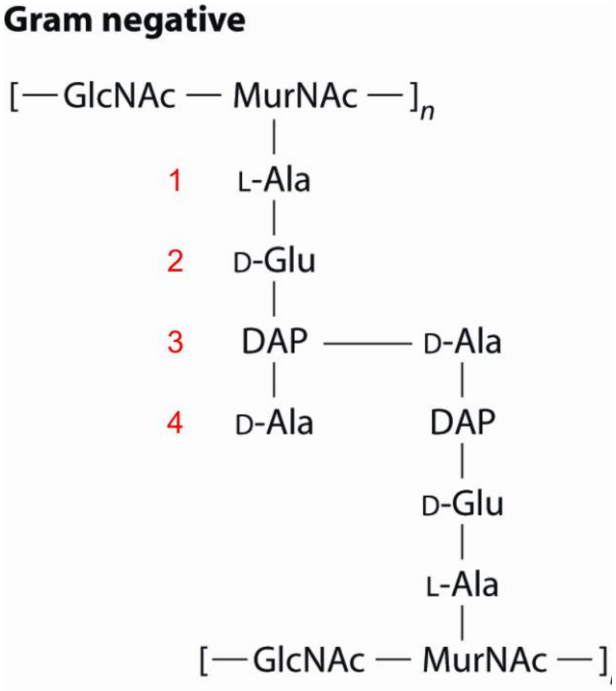
Position 2: D-Glu *(D form of glutamic acid)*. [L17 p19]

Position 3: DAP *(diaminopimelic acid, a modified lysine)*. [L17 p19]

Position 4: D-Ala *(D form of alanine amino acid)*. [L17 p19]

D amino acids sit in positions **2** and **4.** [L17 p19]

D and L *(mirror-image forms of the same amino acid)*: proteins use L-forms, wall peptides have some D-forms. [L17 p17]



Gram negative peptide: L-Ala, D-Glu, DAP and D-Ala with a direct cross-link [L17 p19]

On the figure: L-Ala · D-Glu · DAP · D-Ala

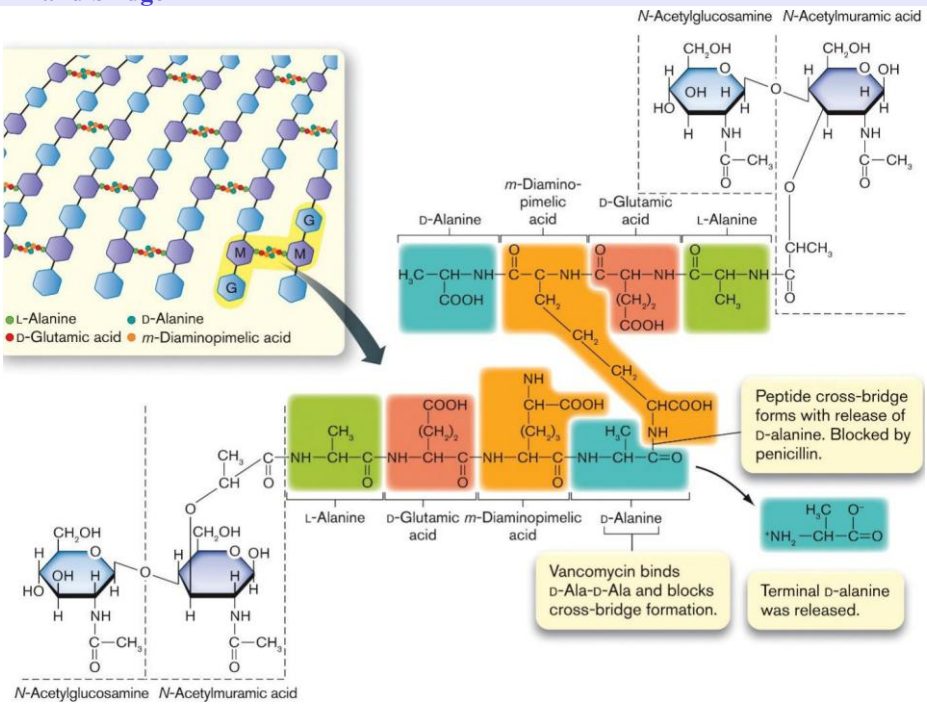
Position 3 varies

Position 3 varies between species. [L17 p21]

Position 3 options: L-alanine, L-homoserine, L-diaminobutyric acid, L-glutamic acid, L-ornithine, L-lysine, or LL-DAP and meso-DAP. [L17 p21]

Other positions: L-alanine at position **1,** D-glutamate at **2,** D-alanine at **4.** [L17 p21]

Cross-link and bridge



Cross-bridge forms with release of D-alanine; blocked by penicillin and vancomycin [L17 p22]

On the figure: Cross-bridge · penicillin · Vancomycin · D-Ala-D-Ala

Cross-link: a peptide of amino acids joins the chains. [L17 p15, L17 p16]

Gram negative cross-link: joins DAP (position **3**) to D-Ala (position **4**) of the neighboring peptide. [L17 p19]

Peptide at cross-linking: starts out with five amino acids. [L17 p22]

5th amino acid: cleaved off when the cross-link is made. [L17 p22]

Cut site: between the two D-alanines. [L17 p22]

Cross-bridge formation releases D-alanine. [L17 p22]

Antibiotics

Antibiotics: many inhibit peptidoglycan synthesis. [L17 p15, L17 p16]

Peptidoglycan is unique to bacteria, and many of its synthesis enzymes bind **penicillin**, so they are called penicillin-binding proteins (textbook).

Penicillin blocks the cross-bridge. [L17 p22]

The transpeptidase *(enzyme making wall cross bridges)* that cross-links the peptides is the target of penicillin (textbook).

Vancomycin *(drug blocking wall building)* binds **D-Ala-D-Ala** and blocks cross-bridge formation. [L17 p22]

Vancomycin binding the terminal D-Ala-D-Ala prevents release of the terminal D-alanine, so the cross-bridge cannot form (textbook).

Feature	Content
Sugar 1	N-acetyl-glucosamine (GlcNAc, NAG or G)
Sugar 2	N-acetylmuramic acid (MurNAc, NAM or M)
Sugar linkage	beta-**1**-**4** between the alternating sugars
Cross-link	by a peptide of amino acids (two linked peptides); sequence varies
Amino acids	most contain some D-amino acids (proteins use L-forms)

Table source: [L17 p17, L17 p18]

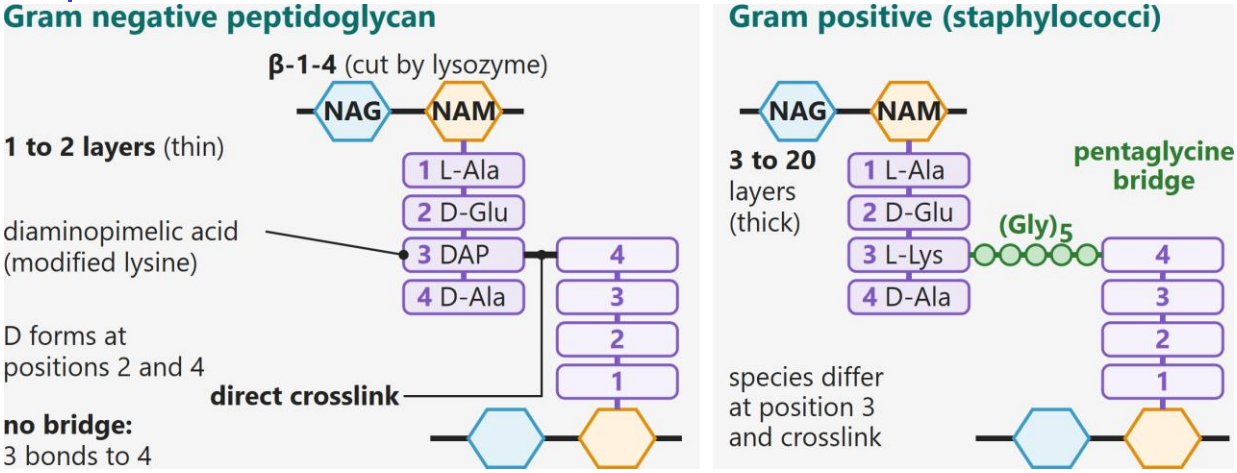
- **Know how it differs in Gram negative vs Gram positive**

  Book: 3.3 The Envelope and Cytoskeleton, Cell Envelope of Bacteria (chapter 3 PDF, p. 49); 3.3 The Envelope and Cytoskeleton, Firmicute Cell Envelope: Gram-Positive (chapter 3 PDF, p. 52).

  ⚠ **Do not mix up: Staph vs Gram negative *(thin wall plus outer membrane)***: cross-link amino acids and layers differ, sugars do not.

Side by side comparison

Gram positive *(thick wall, stains purple)* **example** is the staphylococci. [L17 p15, L17 p19, L17 p20]



Gram negative, staphylococcal and archaeal peptidoglycan: layers, position 3 and cross-link [L17 p20]

On the figure: DAP · L-Lys · (Gly)5 · pentaglycine

Gram positive wall: thicker, with more layers.

Layers differ: **3-20** in **Gram positive** versus **1-2** in **Gram negative**. [L17 p15, L17 p23]

Staph vs Gram negative: the amino acids in the peptide *(short chain of amino acids)* cross-link differ.

Position 3 differs: **L-Lys** in **Gram positive** versus **DAP** *(special amino acid in wall peptide)* in **Gram negative**. [L17 p19, L17 p20, L17 p23]

Cross-link differs: **(Gly)5** bridge versus direct DAP to D-Ala *(D form of alanine amino acid)*. [L17 p19, L17 p20, L17 p23]

(Gly)5 is **pentaglycine** *(five glycines in a row)*. [L17 p20]

What stays the same

Sugars and sugar linkage: the same in staph and **Gram negative**.

Evidence for a Gram positive envelope

Evidence for a Gram positive envelope *(layers wrapped around the cell)*: techniques or experiments that support it.

Evidence:

TEM showing a thick peptidoglycan *(sugar and peptide mesh of the wall)* layer and no outer membrane *(extra membrane outside the wall)*.

Isolate teichoic acid *(charged chains in Gram positive wall)* from the wall.

Sensitivity to a penicillin more effective on **Gram positive**.

No growth on selective media for **Gram negative**.

Genome lacking genes for LPS *(outer membrane sugar and fat coat)*, outer membrane and periplasmic *(in the space between the two membranes)* proteins.

Genome having genes for teichoic acid synthesis.

Feature	Gram negative	Gram positive (staphylococci)
Thickness	thinner, **1-2 layers**	**3-20 layers**
Position 1 and 2	L-Ala, D-Glu	L-Ala, D-Glu
Position 3 of the peptide	DAP	L-Lys
Position 4	D-Ala	D-Ala
Cross-link	direct: DAP (position **3**) to D-Ala (position **4**)	bridge of five glycines: L-Lys to (Gly)**5** to D-Ala
Sugars and linkage	NAG and NAM, beta-**1-4**	NAG and NAM, beta-**1-4** (same)
Other wall layers	outer membrane outside the thin wall; the wall sits in the periplasm	teichoic acids found in most **Gram positive** bacteria

Table source: [L17 p05, L17 p15, L17 p19, L17 p20, L17 p26]

▸ 2) Pseudopeptidoglycan: how it differs from peptidoglycan

Book: 19.1 Archaeal Diversity at a Glance (chapter 19 PDF, p. 5).

⚠ Do not mix up: Pseudopeptidoglycan *(archaea version of wall mesh)* has NAT *(archaeal wall sugar)*, beta-1-3 links, all L-amino acids; Gram negative *(thin wall plus outer membrane)* has NAM *(the other wall sugar)*, beta-1-4. [L17 p24]

Where it is found

Pseudopeptidoglycan:

> Found in some archaeal *(of archaea)* bacteria. [L17 p24]
> Is not in **Gram positive**, **Gram negative** or mycobacteria *(waxy walled bacteria)* walls.

Its features

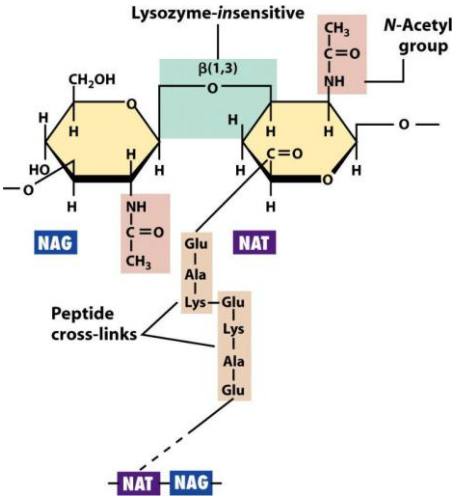
Pseudopeptidoglycan sugars: N-acetyl-glucosamine (**NAG**) and N-acetyltalosaminuronic acid (**NAT**). [L17 p24]

Layers: can have many. [L17 p24]

Sugar linkage: beta-**1-3.** [L17 p24]

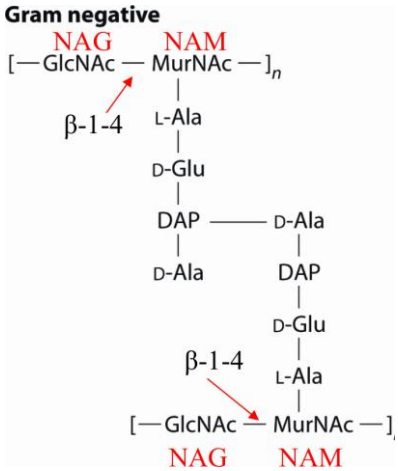
Cross-link: peptide *(short chain of amino acids)* made of all L-amino acids (Glu, Ala and Lys). [L17 p24]

Pseudopeptidoglycan is **lysozyme-insensitive** *(not cut by wall cutting enzyme)*. [L17 p24]



Pseudopeptidoglycan: NAG and NAT, beta 1,3 link, lysozyme insensitive, peptide cross-links [L17 p24]

On the figure: NAG · NAT · lysozyme-insensitive



Gram negative peptidoglycan: NAG and NAM with beta-1-4 links, for comparison [L17 p25]

On the figure: NAG · NAM · Gram negative

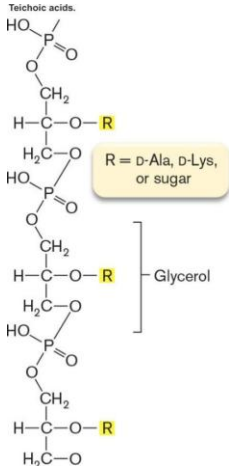
Feature	Gram negative peptidoglycan	Pseudopeptidoglycan
Sugars	NAG and NAM	NAG and NAT (N-acetyltalosaminuronic acid)
Sugar linkage	beta-**1**-**4**	beta-**1**-**3**
Peptide	D-amino acids (D-Glu, D-Ala) and DAP	all L-amino acids
Layers	**1**-**2**	can have many layers
Lysozyme	linkage between the sugars is cut by lysozyme	lysozyme-insensitive

Table source: [L17 p15, L17 p19, L17 p24, L17 p25]

3) Teichoic acids

Book: 3.3 The Envelope and Cytoskeleton, Firmicute Cell Envelope: Gram-Positive (chapter 3 PDF, p. 52).

⚠ **Do not mix up: Teichoic acids *(charged chains in Gram positive wall)* link to peptidoglycan *(sugar and peptide mesh of the wall)*; lipoteichoic *(teichoic acid anchored in membrane)* acid links to membrane *(thin lipid layer)* lipids.** [L17 p27]



Teichoic acid: glycerol phosphate chain with R group of D-Ala, D-Lys or sugar [L17 p26]

On the figure: Teichoic acids · glycerol · R

What teichoic acids are

Teichoic acids:

> Polyanionic *(many negative charges)* polymers *(long chains of repeating units)* of **glycerol** *(three carbon fat backbone)* phosphate *(PO4 group)* or ribitol *(five carbon sugar alcohol)* phosphate; each phosphate group carries a negative charge.
> Are modified with amino acids (**R**): R is D-Ala *(D form of alanine amino acid)*, D-Lys or a sugar. [L17 p26]

Where seen: most **Gram positive** *(thick wall, stains purple)* bacteria. [L17 p26]

Watch out: The envelope *(layers wrapped around the cell)* summary list says teichoic acid is in some **Gram positive** walls (most versus some). [L17 p26]

Composition varies, so they can be used for identification. [L17 p26]

Placement

Placement: run through the peptidoglycan. [L17 p27]

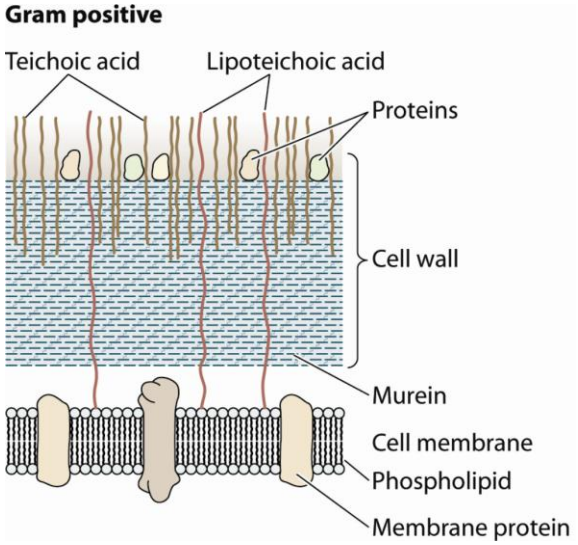
Lipoteichoic acid: linked to lipids in the membrane. [L17 p27]

Teichoic acid can also be linked to peptidoglycan. [L17 p27]

Teichoic acids run through the peptidoglycan. [L17 p27]

Roles

Role 1: regulation of cell shape and cell division. [L17 p27]



Gram positive wall with teichoic acid and lipoteichoic acid through the murein [L17 p27]

On the figure: Teichoic acids · lipoteichoic acid · cell wall

Role 2: affects antibiotic resistance. [L17 p27]

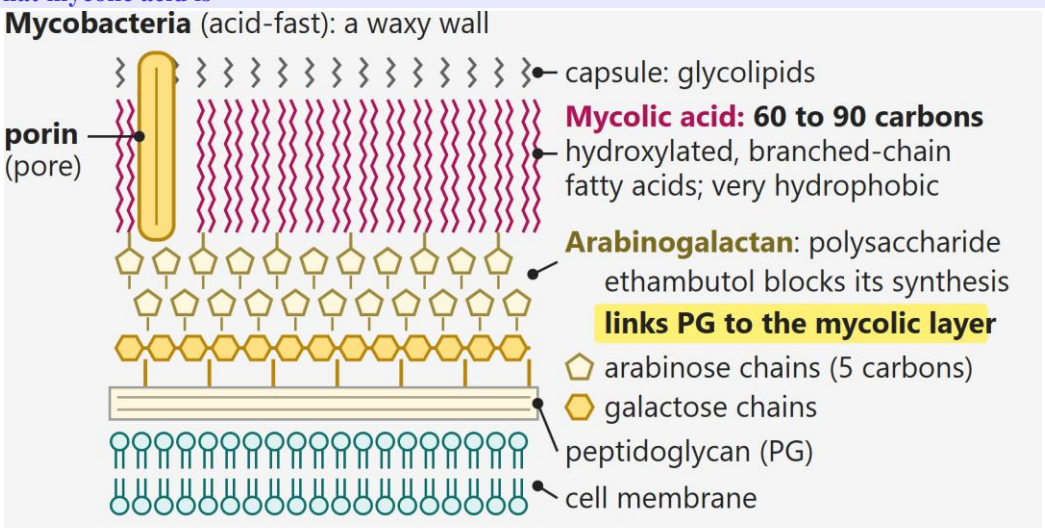
Role 3: integrity of the **cell wall** *(stiff layer around the cell membrane)*. [L17 p27]

4) Mycolic acids

Book: 3.3 The Envelope and Cytoskeleton, Mycobacterial Cell Envelope (chapter 3 PDF, p. 63).

⚠ **Do not mix up: Acid-fast** ***(holds dye despite acid wash)*** **envelope** ***(layers wrapped around the cell)*** **has a mycolic acid** ***(waxy fatty acid of mycobacteria)*** **layer but NOT an outer membrane** ***(extra membrane outside the wall)*** **with LPS** ***(outer membrane sugar and fat coat)***.

What mycolic acid is



Mycolic layer: blocks diffusion of most molecules, even nutrients
makes cells resist acids, bases, antibiotics and dehydration
Found in mycobacteria; archaea lack it

TRAP: mycobacteria do NOT have an LPS outer membrane

Mycolic acid, arabinogalactan and thin peptidoglycan in the acid fast wall [L17 p28]

On the figure: Mycolic acids · arabinogalactan · Ethambutol · porins · hydrophobic · galactose · arabinose

Mycolic acid: complex hydroxylated *(with OH groups added)*, branched-chain fatty acids. [L17 p28]

Mycolic acid carbons: elevated carbon numbers, **60-90 carbons**. [L17 p28]

Mycolic acid is very **hydrophobic** *(water hating)*. [L17 p28]

Found in Mycobacteria *(waxy walled bacteria)*. [L17 p28]

Linked to **arabinogalactan** *(chain of arabinose and galactose sugars in the wall)* sugars. [L17 p28]

Role of mycolic acid

Role:

Blocks diffusion *(drifting from high to low amount)* of most molecules including nutrients.

Makes cells resistant to acids, bases, antibiotics and dehydration. [L17 p28]

Arabinogalactan

Arabinogalactan:

Polysaccharide *(long chain of sugars)* in the Mycobacteria cell wall *(stiff layer around the cell membrane)*.

Has chains of **arabinose** (**5 carbons**) and chains of **galactose**.

Is linked to peptidoglycan *(sugar and peptide mesh of the wall)* and mycolic acid. [L17 p29]

Arabinogalactan synthesis: inhibited by some antibiotics used against mycobacteria. [L17 p29]

Ethambutol: blocks arabinan *(five carbon sugar chain)* synthesis (the arabinose chains of arabinogalactan). [L17 p29]

Mycobacteria and the acid-fast envelope

Mycobacteria are **Gram positive** **actinomycetes** *(a group of Gram positive bacteria)* with an acid-fast envelope. [L17 p03]

Mycolic acids *(waxy fatty acids of mycobacteria)* provide the basis for acid-fast staining, in which cells retain the dye carbolfuchsin (textbook).

Acid-fast envelope:

Has peptidoglycan.

Also has arabinan-galactan sugars and mycolic acid.

Also has a phospholipid *(membrane fat with a charged head)* bilayer *(two layers)* membrane *(thin lipid layer)*.

Has NO outer membrane containing phospholipids and LPS; its outer layer is the mycomembrane of mycolic acids, called the mycobacterial *(about waxy walled bacteria)* outer membrane.

Wall layers inside to outside

Mycobacterial envelope layers, inside to outside (**peptidoglycan** through the **mycomembrane** form the cell wall core): [L17 p29]

Layer 1: cell membrane *(thin skin around the cell)*. [L17 p29]

Wall layer 2: peptidoglycan. [L17 p29]

Wall layer 3: **galactan** *(chain of galactose sugars)*. [L17 p29]

Wall layer 4: **arabinan**. [L17 p29]

Wall layer 5: mycomembrane of mycolic acids. [L17 p29]

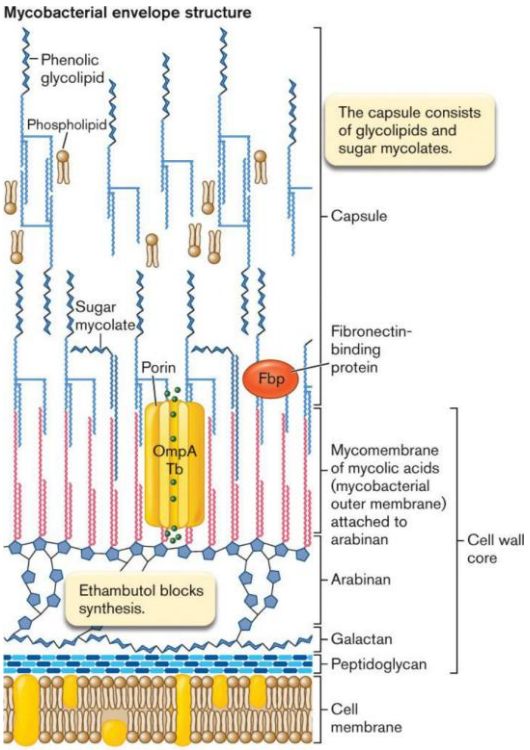
Mycomembrane of mycolic acids (mycobacterial outer membrane), attached to arabinan, with a porin *(water filled channel in outer membrane)*. [L17 p29]

Layer 6: **capsule** *(firm sugar coat outside the cell)* of glycolipids and **sugar mycolates**. [L17 p29]

Capsule components: **phenolic glycolipid**, phospholipid, sugar mycolate and **fibronectin-binding protein** (**Fbp**). [L17 p29]

Wall layers outside to inside

Mycobacterial wall layers, outside to inside: **porins** *(channels in the outer membrane)* and surface proteins, **acyl lipids**, mycolic acid, arabinogalactan, **lipoarabinomannan**, peptidoglycan, **PIM**, cytoplasmic membrane. [L17 p28]



Mycobacterial envelope: capsule, mycomembrane, arabinan, galactan, peptidoglycan, membrane [L17 p29]

On the figure: **capsule** · **phenolic glycolipid** · **sugar mycolates** · **Fbp** · **arabinan** · **galactan** · **peptidoglycan** · **mycomembrane**

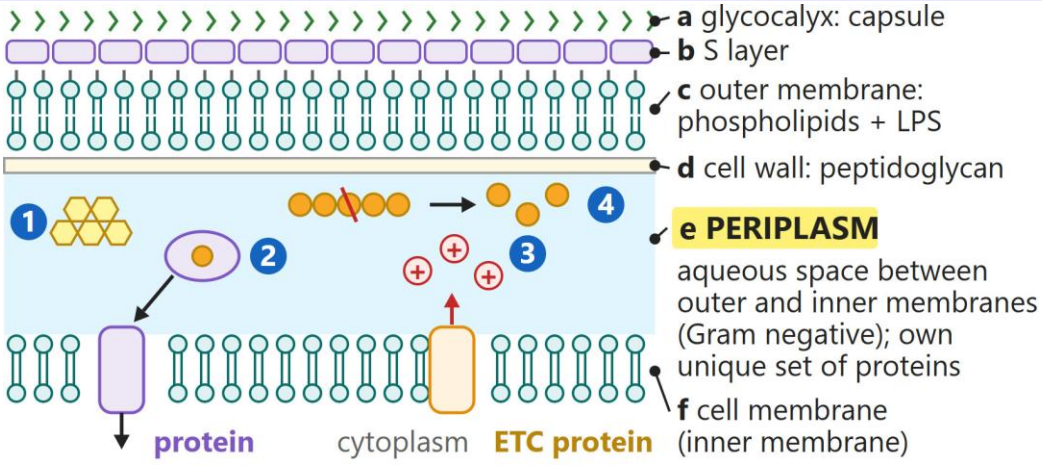
Mycolic acid is not archaeal

Mycolic acid: not part of the archaeal *(of archaea)* envelope.

e. Periplasm

Book: 3.3 The Envelope and Cytoskeleton, Proteobacterial Cell Envelope: Gram-Negative (chapter 3 PDF, p. 56).

What the periplasm is



Main Functions

1 osmotic protection: holds oligosaccharides
2 transport: binding proteins bring solutes (food) to membrane transporters
3 oxidation-reduction reactions of the electron transport chain; stores H+ ions
4 hydrolysis: cuts nutrients (red slash) into subunits small enough to import

TRAP: the periplasm is NOT outside the cell; it lies inside the envelope

Periplasm between the outer and inner membranes, with its four functions [L17 p31]

On the figure: periplasm · outer membrane · inner membrane · Peptidoglycan · unique set of proteins

Periplasm *(space between the two membranes)*: the aqueous compartment between the **outer membrane** *(extra membrane outside the wall)* and the **inner membrane** *(the skin around the cytoplasm)*. [L17 p31]

Where: **Gram negative** *(thin wall plus outer membrane)* bacteria. [L17 p31]

Periplasm contains its own **unique set of proteins**. [L17 p31]

The outer membrane prevents passage of proteins and other macromolecules, so the periplasm is a separate membrane-enclosed compartment (textbook).

Peptidoglycan (murein) layer: sits inside the periplasm. [L17 p31]

Gram positive contrast

Gram positive *(thick wall, stains purple)* **strain**: lacks genes for periplasmic *(in the space between the two membranes)* proteins.

#	Main function of the periplasm
1	osmotic protection: contains oligosaccharides
2	transport of nutrients: proteins bind solutes (food) and carry them to inner membrane transporter proteins
3	oxidation-reduction reactions of the electron transport chain; stores H+ ions
4	hydrolysis of nutrients into smaller subunits that can be transported into the cytoplasm

Table source: [L17 p32]

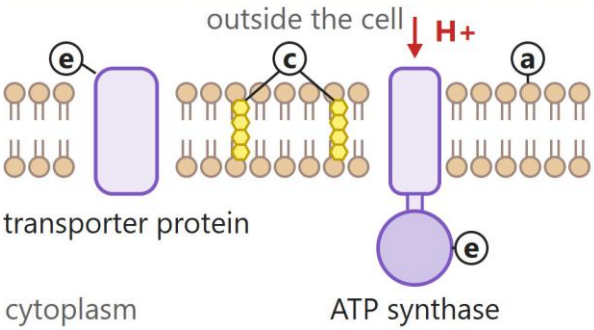
f. Cell membrane (3.2 6e)

Book: 3.2 Membrane Molecules and Transport (chapter 3 PDF, p. 24).

⚠ **Do not mix up: E. coli membrane** ***(thin lipid layer)*** **is 75% protein, 25% phospholipid** ***(membrane fat with a charged head)*** **by weight, with no sterol** ***(stiff ring shaped fat)*****.** [L17 p33]

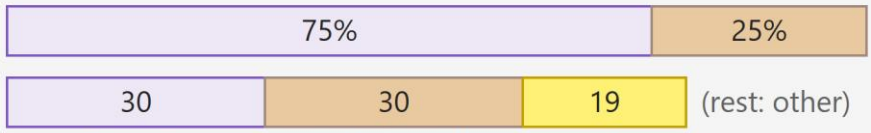
What the cell membrane is

Cell membrane = lipids + proteins; it is the boundary and barrier



Components:
a Phospholipids: most bacteria
b Isoprenoids: archaea
c Hopanoids: similar to sterols
d Cardiolipin
e Proteins:
largest component by weight

% by weight (E. coli membrane)



Bars: purple = protein, tan = phospholipid, yellow = sterol;
E. coli has no sterol; for comparison

TRAP: lipid is NOT the main component by weight in bacteria

Cell membrane of lipids and proteins; protein is 75% of E. coli membrane [L17 p33]

On the figure: lipids · proteins · E. coli · myelin · sterol · 75% · 25%

Cell membrane *(thin skin around the cell)*: composed of **lipids** and **proteins**. [L17 p33]

Cell membrane proteins: a major component by weight. [L17 p33]

Cell membrane is a boundary and a barrier. [L17 p33]

Membrane makeup compared

E. coli membrane: **75%** protein and **25%** phospholipid by weight. [L17 p33]

Human myelin sheath *(fatty covering of nerves)*: **30%** protein, **30%** phospholipid and **19%** sterol (cholesterol). [L17 p33]

E. coli membrane: no sterol. [L17 p33]

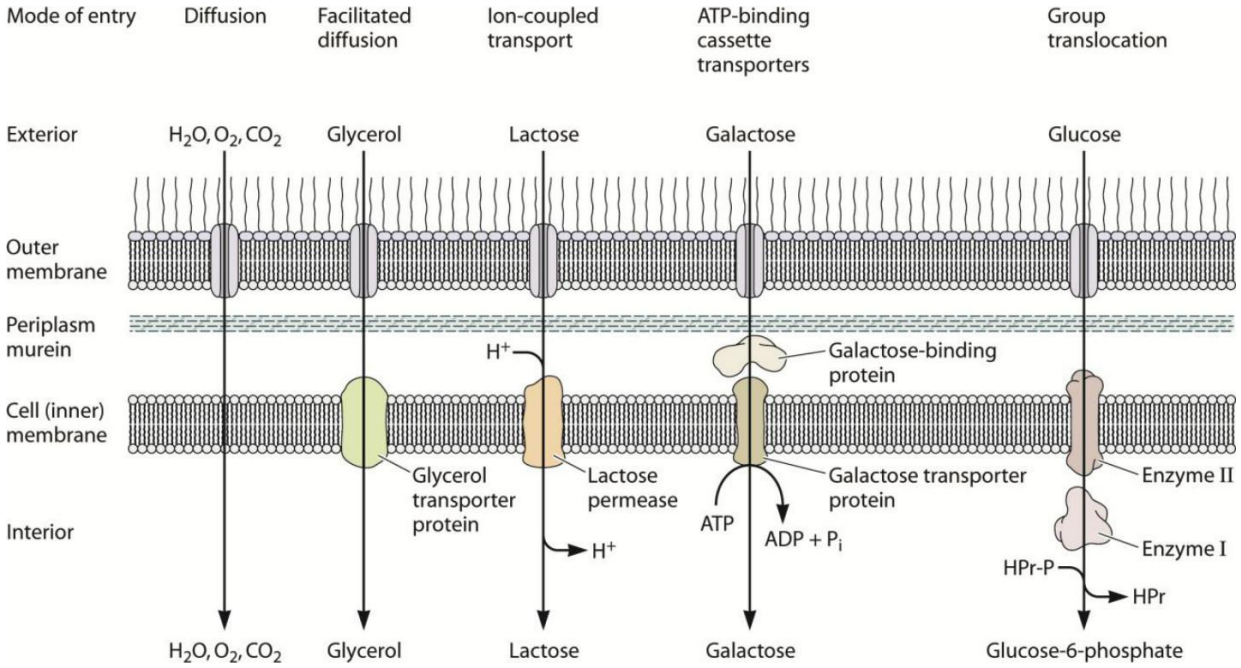
Modes of entry

Modes of entry across a **Gram negative** *(thin wall plus outer membrane)* envelope *(layers wrapped around the cell)*: five in all. [L17 p34]

Mode 1: diffusion (H_2O, O_2, CO_2). [L17 p34]

Mode 2: facilitated diffusion (glycerol). [L17 p34]

Mode 3: ion-coupled transport (lactose enters with H+). [L17 p34]



Five modes of entry across the Gram negative envelope [L17 p34]

On the figure: diffusion · facilitated diffusion · ion-coupled transport · ATP-binding cassette transporters · group translocation

Energy released as an ion *(charged particle)* moves down its concentration gradient *(gradual change in amount)* drives a second molecule against its gradient (textbook).

Mode 4: ATP-binding cassette *(protein part)* transporters (galactose). [L17 p34]

A substrate-binding protein delivers the solute to the channel, then ATP *(cell energy molecule)* hydrolysis *(breaking with water)* signals the channel to open to the cytoplasm (textbook).

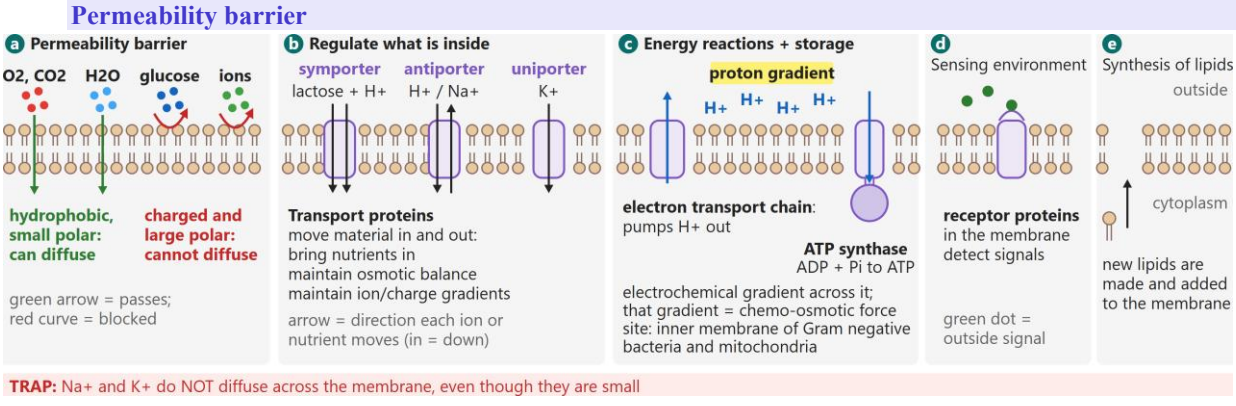
Mode 5: **group translocation** (glucose enters as glucose-**6**-phosphate). [L17 p34]

Group translocation attaches a group such as phosphate *(PO4 group)* to the nutrient during transport, so the unmodified solute always moves down its gradient (textbook).

▸ Role, function

Book: 3.2 Membrane Molecules and Transport, Molecules Cross the Cell Membrane (chapter 3 PDF, p. 35).

⚠ Do not mix up: Hydrophobic *(water hating)* and small polar molecules diffuse; charged and large polar molecules cannot. [L17 p43]



Five membrane functions: barrier, regulate, energy, sensing, lipid synthesis [L17 p43]

On the figure: Permeability barrier · Hydrophobic · proton gradient · chemo-osmotic force · ATP synthase · receptor proteins · synthesis of lipids

Function a, permeability barrier: **hydrophobic** and small polar molecules can diffuse through membranes *(thin lipid layer)*. [L17 p43]

Cannot diffuse: charged and large polar molecules. [L17 p43]

Ions *(charged particle)* such as Na+ and K+ are charged and cannot diffuse through the membrane (impermeable). [L17 p43]

Regulating the inside

Function b, regulate what is inside the cell: transport nutrients in. [L17 p44]

Function b:

- Maintain osmotic *(about water moving across membranes)* balance.
- Maintain ion and charge gradients *(gradual change in amount)*. [L17 p44]

Energy reactions

Function c, energy reactions and storage: an electrochemical gradient is created across the membrane. [L17 p45]

Function c: electron transport chain. [L17 p45]

Electron transport: the **reductant** is the electron **donor** and the **oxidant** is the electron **acceptor**. [L17 p45]

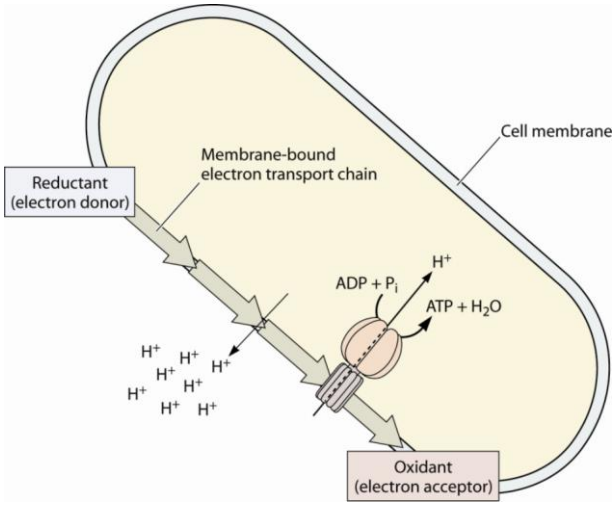
Electron transport chain *(chain of carriers in the membrane)* **pumps H+ out** across the membrane, which builds the **proton gradient**. [L17 p45]

Function c:

- Proton gradient (**chemo-osmotic force**).
- Synthesis of ATP *(cell energy molecule)*. [L17 p45]

ATP synthase *(enzyme that makes ATP)*: **ADP** *(used up energy molecule)* **+ Pi** to ATP (+ H2O); Pi is inorganic phosphate *(PO4 group)*. [L17 p45]

Function c happens across the inner membrane *(the skin around the cytoplasm)* in **Gram negative** *(thin wall plus outer membrane)* bacteria and mitochondria. [L17 p45]



Electron transport chain pumps H+ out; ATP synthase makes ATP from ADP + Pi [L17 p45]

On the figure: reductant · oxidant · electron transport chain · ADP + Pi · H+

Sensing the environment

Function d: sensing the environment (**receptor proteins** in the membrane). [L17 p46]

Receptors *(proteins a signal or virus binds to)* for attractants *(chemical that pulls cells in)* sit in the cell membrane *(thin skin around the cell)*. [L17 p46]

Chemotaxis *(moving toward or away from chemicals)*: **counterclockwise** (**CCW**) rotation of the flagella *(whip tails that spin)* moves the cell toward an attractant. [L17 p46]

Lipid synthesis

Function e: **synthesis of lipids**. [L17 p46]

Molecule type	Examples	Permeability
Hydrophobic molecules	O2, CO2, N2	freely permeable
Small, uncharged polar molecules	H2O, glycerol	slightly permeable
Large, uncharged polar molecules	glucose, sucrose	impermeable
Ions	H+, Na+, HCO3-, Ca2+, Cl-, Mg2+, K+	impermeable

Table source: [L17 p43]

Carrier type	What it does	Example
Symporter	two solutes in the same direction; Lac permease moves H+ together with lactose	Lac permease (lactose and H+ together); phosphate symporter; sulfate symporter
Antiporter	two like charged ions, opposite directions	sodium-proton antiporter
Uniporter	one solute, one direction	potassium uniporter (K+)

Table source: [L17 p44]

Components (types of lipids, etc) observed in bacteria

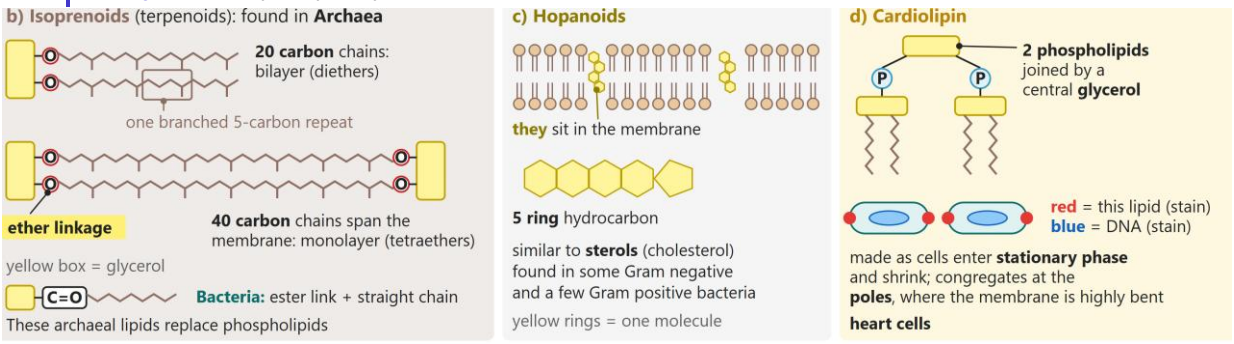
Book: 3.2 Membrane Molecules and Transport, Membrane Lipids (chapter 3 PDF, p. 24).

⚠ **Do not mix up: Archaea *(single cell microbes without a nucleus, their own domain (also called archaeal bacteria))* use isoprenoid *(branched five carbon repeat fat)* lipids; bacteria use phospholipids *(membrane fat with a charged head)*; hopanoids *(five ring cholesterol like fat)*** are 5 ring hydrocarbons similar to sterols (cholesterol).

Five components

Components of the cell membrane *(thin skin around the cell)*: five, a to e. [L17 p35]

Component a: phospholipids, in most bacterial cells. [L17 p35]



TRAP: archaeal membrane lipids are NOT ester-linked to glycerol (they are ether-linked)

Isoprenoids in archaea, hopanoids in the membrane, cardiolipin at the poles [L17 p36]

On the figure: isoprenoids · Archaea · hopanoids · sterols · Cardiolipins · poles · stationary phase

Component b: isoprenoids (found in Archaea). [L17 p35]

Component c: hopanoids. [L17 p35]

Component d: cardiolipin *(double phospholipid joined by glycerol)*. [L17 p35]

Component e: proteins. [L17 p35]

Lipid differences

Ways membrane components differ:

Lipids: archaea have isoprenoid lipids while bacteria have phospholipids.

Fatty acid chains: more or less saturated, changing with temperature.

Hopanoids and cardiolipin

Hopanoids (sterol-like molecules): some bacteria have them; like sterols in eukaryotes, they fit between fatty acid chains and stabilize the membrane (textbook).

Cardiolipins: other bacteria have them; made in bacterial cells entering stationary phase, when cell size decreases.

Cardiolipin (diphosphatidylglycerol) gathers at the cell poles. [L17 p41]

Cardiolipin has a narrow head group and wide fatty acid group, thought to form concave domains that stabilize the curve of the polar membrane (textbook).

DAPI *(dye that stains DNA)* stains the **DNA** *(cell genetic instruction molecule)*; in the same cells, cardiolipin shows at the poles. [L17 p41]

LPS and proteins

LPS *(outer membrane sugar and fat coat)*: **Gram negative** *(thin wall plus outer membrane)* bacteria can have it in the outer membrane *(extra membrane outside the wall)*.

Membrane proteins differ between species and conditions.

Phospholipid types

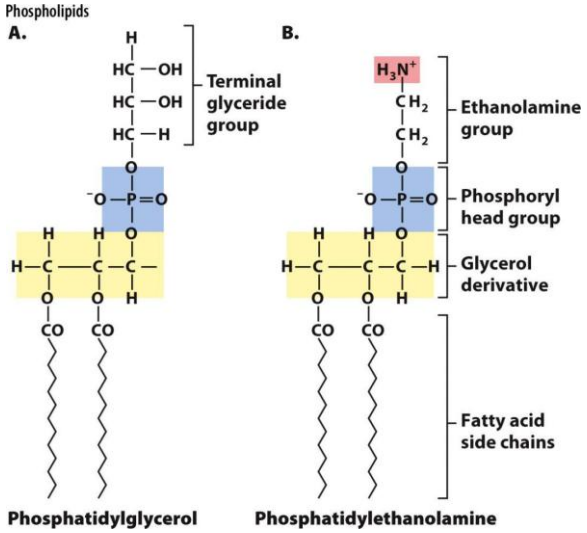
Phospholipid types vary: the head group varies, and the fatty acid chains vary in length and number of double bonds.

Phosphatidylethanolamine:

> A phospholipid; the polar head group is **ethanolamine**.
>
> Is joined through the phosphoryl group to glycerol *(three carbon fat backbone)*, with two fatty acid tails. [L17 p36]

Phosphatidylglycerol:

> Its polar head is a **terminal glyceride group** on the **phosphoryl head group**.
>
> Also has a **glycerol derivative** and two **fatty acid side chains**. [L17 p36]



Phosphatidylglycerol and phosphatidylethanolamine: head groups, glycerol derivative, fatty acid side chains [L17 p36]

On the figure: **Phosphatidylethanolamine** · **Phosphatidylglycerol** · **ethanolamine** · **terminal glyceride group** · **phosphoryl head group** · **glycerol derivative** · **fatty acid side chains**

Component	Description	Where
Phospholipids	glycerol with ester linkages to two fatty acids and a phosphoryl head group; head group varies; fatty acid chains vary in length and number of double bonds	most bacterial cells
Hopanoids	**5** ring hydrocarbon similar to sterols (cholesterol)	membrane of some **Gram negative** and a few **Gram positive** bacteria
Cardiolipin	**2** phospholipids linked by a glycerol; made in cells entering stationary phase when cell size decreases; congregates at the poles where the membrane is highly bent	bacteria; also some other organisms (heart cells)
Membrane proteins	largest component by weight; many transport material in and out of the cell	in the cell membrane

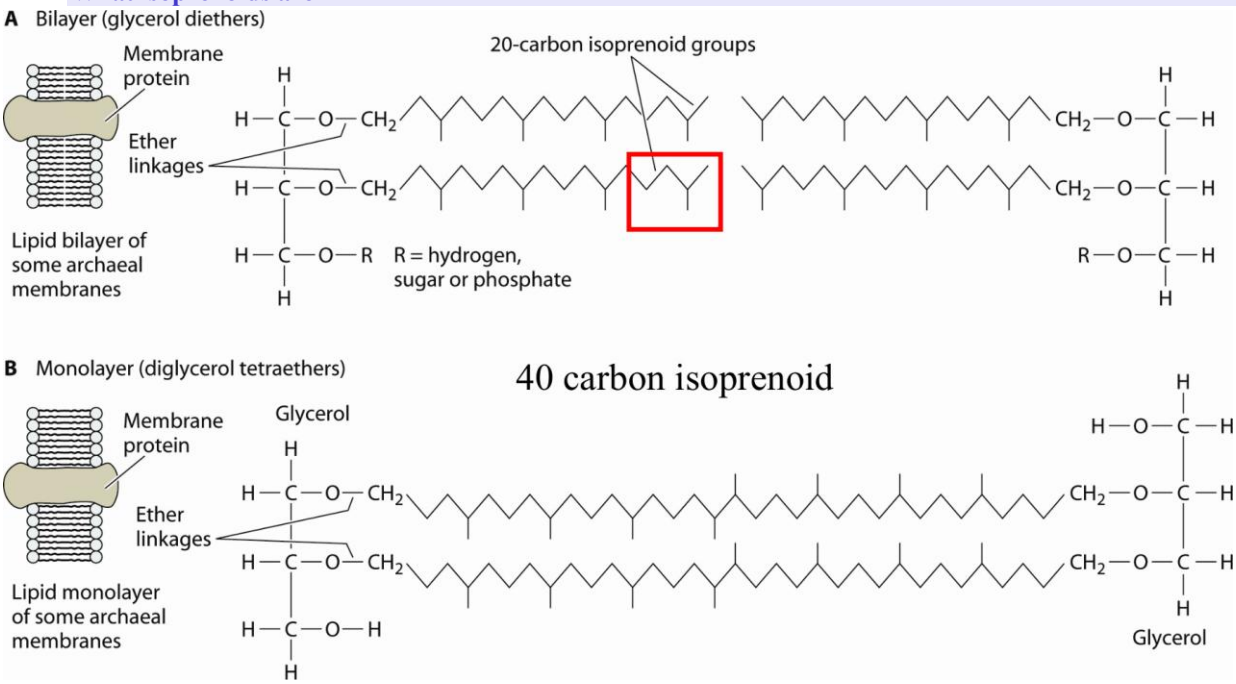
Table source: [L17 p35, L17 p36, L17 p40, L17 p41, L17 p42]

▸ **Components observed in Archaea and how different? Isoprenoids**

Book: 3.2 Membrane Molecules and Transport, Membrane Lipids (chapter 3 PDF, p. 24).

⚠ **Do not mix up: Isoprenoids *(branched five carbon repeat fats)* link to glycerol *(three carbon fat backbone)* by ether *(C O C bond)* bonds (Archaea); phospholipids *(membrane fat with a charged head)* use ester *(bond of acid and alcohol)* bonds.** [L17 p39]

What isoprenoids are



Archaeal lipids: ether linked isoprenoids as a bilayer or a monolayer [L17 p39]

On the figure: ether linkage · glycerol diethers · diglycerol tetraethers · bilayer · monolayer · glycerol

Isoprenoids: **20** or **40 carbon** terpenoids. [L17 p39, L17 p36]

Isoprenoid *(branched five carbon repeat fat)* **units**: branched **5 carbon** repeats. [L17 p39, L17 p36]

Isoprenoids link to **glycerol** via **ether linkage** *(a C-O-C bond instead of the ester bond of phospholipids)*. [L17 p39, L17 p36]

Found in Archaea *(single cell microbes without a nucleus, their own domain (also called archaeal bacteria))*. [L17 p39, L17 p36]

Ether bonds are much more stable than ester bonds, which hydrolyze easily in water, so some archaea grow at higher temperatures (textbook).

Archaeal membranes

Archaeal *(of archaea)* **cell membrane** *(thin skin around the cell)*: made of isoprenoids instead of phospholipids.

Archaeal isoprenoid lipids: **20 carbon glycerol diethers** form a **bilayer** *(two layers)*; **40 carbon diglycerol tetraethers** form a **monolayer** *(one layer)*; the head group R can be hydrogen, sugar or phosphate *(PO4 group)*. [L17 p36, L17 p39]

Feature	Bacterial phospholipid	Archaeal isoprenoid lipid
Hydrocarbon	fatty acid chains	**20** or **40 carbon** isoprenoid chains with branched **5 carbon** repeats
Link to glycerol	ester linkage	ether linkage

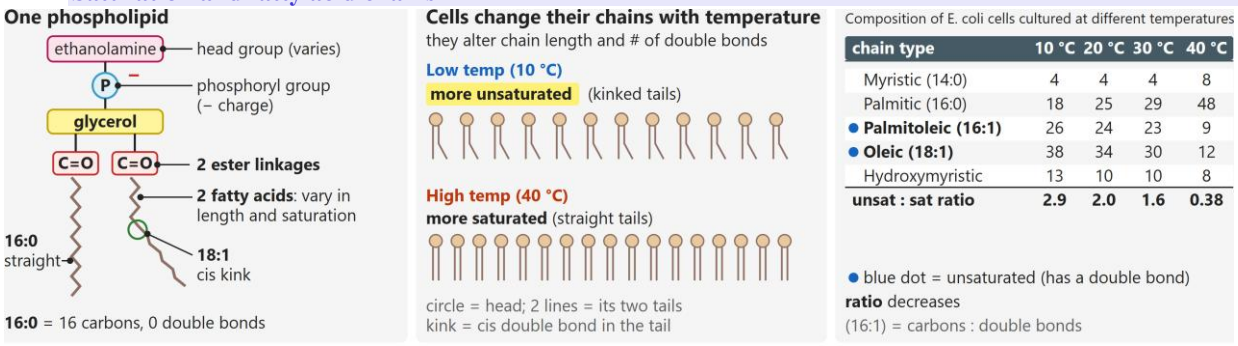
Table source: [L17 p36, L17 p39]

▸ **How types of fatty acids present change in response to temperature?**

Book: 3.2 Membrane Molecules and Transport, Membrane Lipids (chapter 3 PDF, p. 24).

⚠ **Do not mix up: Cold: more unsaturated fatty acids (ratio 2.9 at 10 C); warm: more saturated palmitic acid.** [L17 p37]

Saturation and fatty acid chains



TRAP: cold does NOT raise the saturated share; it lowers it (unsaturated chains take over in the cold)

Straight saturated and kinked unsaturated tails; E. coli fatty acids at four temperatures [L17 p37]

On the figure: cis · unsaturated · saturated · 16:0 · 18:1 · 2.9 · 0.38 · palmitic

Saturation is the number of double bonds: a **saturated** chain has none, and each double bond makes it more **unsaturated**. [L17 p37]

Unsaturated tail: has a **cis double bond** *(C=C with both chain parts on the same side)* that bends (kinks) the tail; a saturated tail has no double bond and stays straight. [L17 p37]

Response to temperature

Temperature response: bacteria alter the chain length and saturation of phospholipid *(membrane fat with a charged head)* fatty acids. [L17 p37]

Kinked unsaturated chains pack less closely than straight chains, so the membrane *(thin lipid layer)* is more fluid and works better at low temperature (textbook).

E. coli results

E. coli: fatty acid composition changes with growth temperature. [L17 p37]

Cold: unsaturated fatty acids (**16:1** and **18:1**, with double bonds) are more abundant. [L17 p37, L17 p38]

Warm: saturated **palmitic** acid (**16:0**) rises as temperature rises. [L17 p37, L17 p38]

Unsaturated to saturated ratio: **2.9** at **10** C and **0.38** at **40** C. [L17 p37, L17 p38]

Fatty acid (percent of total)	10 C	20 C	30 C	40 C
Myristic 14:0	4	4	4	8
Palmitic 16:0 (saturated)	18	25	29	48
Palmitoleic 16:1	26	24	23	9
Oleic 18:1	38	34	30	12
Hydroxymyristic	13	10	10	8
Ratio unsaturated to saturated	2.9	2.0	1.6	0.38

Table source: [L17 p37, L17 p38]