Lecture 5: Chapter 7
Nutrition and Growth

Topics

–Microbial Nutrition
(Amended by Chapter 24, EM)
Microbial Nutrition

• Nutritional requirements

• Sources of nutrients

• Ways to get nutrients
  (Transport mechanisms)
Bacteria are composed of different elements and molecules, with water (70%) and proteins (15%) being the most abundant.

Table 7.2 Analysis of the chemical composition of an *E. coli* cell.

<table>
<thead>
<tr>
<th>Organic Compounds</th>
<th>% Total Weight</th>
<th>% Dry Weight</th>
<th>Elements</th>
<th>% Dry Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proteins</td>
<td>15</td>
<td>50</td>
<td>Carbon (C)</td>
<td>50</td>
</tr>
<tr>
<td>Nucleic acids</td>
<td></td>
<td></td>
<td>Oxygen (O)</td>
<td>20</td>
</tr>
<tr>
<td>RNA</td>
<td>6</td>
<td>20</td>
<td>Nitrogen (N)</td>
<td>14</td>
</tr>
<tr>
<td>DNA</td>
<td>1</td>
<td>3</td>
<td>Hydrogen (H)</td>
<td>8</td>
</tr>
<tr>
<td>Carbohydrates</td>
<td>3</td>
<td>10</td>
<td>Phosphorus (P)</td>
<td>3</td>
</tr>
<tr>
<td>Lipids</td>
<td>2</td>
<td>Not determined</td>
<td>Sulfur (S)</td>
<td>1</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>2</td>
<td>Not determined</td>
<td>Potassium (K)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sodium (Na)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Calcium (Ca)</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Magnesium (Mg)</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Chlorine (Cl)</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Iron (Fe)</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Manganese (Mn), zinc (Zn), molybdenum (Mo), copper (Cu), cobalt (Co), zinc (Zn)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Inorganic Compounds</th>
<th>% Total Weight</th>
<th>% Dry Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>All others</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>
Inorganic nutrients

- Macronutrients
- Micronutrients
- Small molecules and compounds
Macronutrients

Required in millimolar (mM) concentrations

Nathan C. HOPKiNS Café is Mighty good

=> Needed for the synthesis of nucleic acids, proteins, lipids, carbohydrates ... To be assembled to plasma membrane, cell wall ....

Micronutrients

Required in micromolar (µM) concentrations
Mn, Cu, Zn, Mo, Ni, Se, ....
Growth factors

- Essential organic nutrients (amino acid, nitrogenous base, or vitamin that) that cannot be synthesized by the microbe, and must be supplemented if cultured.

==> Essential Amino acids, vitamins
  - For example, many cells cannot synthesize all 20 amino acids so they **must** obtain them from food ("essential amino acids")
Microbial Nutrition

- Nutritional requirements
- **Sources of nutrients**
- Ways to get nutrients
  (Transport mechanisms)
Sources of nutrients

As requirements for growth and metabolism

- Carbon source
- Energy source
- Reductant (electron) source
- Inorganic nutrients (macro- and micronutrients)
- Growth factors
<table>
<thead>
<tr>
<th>Element</th>
<th>Inorganic Environmental Reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>$\text{CO}_2$ in air; $\text{CO}_3^{2-}$ in rocks and sediments</td>
</tr>
<tr>
<td>Oxygen</td>
<td>$\text{O}_2$ in air, certain oxides, water</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>$\text{N}_2$ in air; $\text{NO}_3^-$, $\text{NO}_2^-$, $\text{NH}_4^+$ in soil and water</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Water, $\text{H}_2$ gas, mineral deposits</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>Mineral deposits ($\text{PO}_4^{3-}$, $\text{H}_3\text{PO}_4$)</td>
</tr>
<tr>
<td>Sulfur</td>
<td>Mineral deposits, volcanic sediments ($\text{SO}_4^{2-}$, $\text{H}_2\text{S}$, $\text{S}^0$)</td>
</tr>
<tr>
<td>Potassium</td>
<td>Mineral deposits, the ocean ($\text{KCl}$, $\text{K}_3\text{PO}_4$)</td>
</tr>
<tr>
<td>Sodium</td>
<td>Mineral deposits, the ocean ($\text{NaCl}$, $\text{NaSi}$)</td>
</tr>
<tr>
<td>Calcium</td>
<td>Mineral deposits, the ocean ($\text{CaCO}_3$, $\text{CaCl}_2$)</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mineral deposits, geologic sediments ($\text{MgSO}_4$)</td>
</tr>
<tr>
<td>Chloride</td>
<td>The ocean ($\text{NaCl}$, $\text{NH}_4\text{Cl}$)</td>
</tr>
<tr>
<td>Iron</td>
<td>Mineral deposits, geologic sediments ($\text{FeSO}_4$)</td>
</tr>
<tr>
<td>Manganese, molybdenum, cobalt, nickel, zinc, copper, other micronutrients</td>
<td>Various geologic sediments</td>
</tr>
</tbody>
</table>
Recycling of “bioelements”

- Bioelements – group of **macronutrients** such as carbon, nitrogen, sulfur, phosphorus, oxygen, iron, **and essential building blocks** needed by the cell

- **Biogeochemical cycles** – (re)cycling of essential bioelements (macronutrients) through biotic and abiotic environments
Environmental Microbiology
(Use of knowledge on ecology of microbes)

+ Microbial habitats - microbial communities
+ Microenvironments
  - Physical parameters change rapidly (harsh)
  - Availability and accessibility of nutrients
    - Nutrients are limited (availability)
    - Nutrients are unevenly distributed (availability)
    - Nutrients are competed for (accessibility)
  - How will changes affect growth?
    + Biogeochemical cycling of Carbon and Nitrogen
    + Biodegradation (recycling of persistent recalcitrants)
    + Aquatic and terrestrial habitats
Carbon source
Carbon - the central bioelement

• Autotroph ("self-feeders")
  – Derive carbon solely from CO$_2$

• Heterotroph ("mixed-feeders")
  – Derive carbon from all possible sources, including but NOT solely from CO$_2$
  – Usually diverse organic molecules such as sugars, proteins, lipids and their monomers
Carbon cycle

- Organic reservoir are organisms
- Recycle via carbon fixation (gas -> solid), respiration, and fermentation (solid -> gas), limestone decomposition, and methane production
- Carbon dioxide ($\text{CO}_2$) is main gas phase
- Methane is produced by methanogens
The carbon cycle involves the complex interaction between photosynthesis, respiration, fermentation, and limestone decomposition.
Nitrogen Sources

• Main reservoir is N\textsubscript{2}
• Primary nitrogen source for heterotrophs is proteins, DNA, RNA
• Some bacteria, algae, fungi and plants utilize inorganic nitrogenous nutrients
• Small number can transform N\textsubscript{2} into usable compounds through nitrogen fixation
• Regardless of the initial form, must be converted to NH\textsubscript{3} (the only form that can be directly combined with C to synthesize amino acids and other compounds)
Nitrogen cycle

• Nitrogen gas – most abundant component of the atmosphere

• Four steps
  – Nitrogen fixation \((N_2 \Rightarrow NH_3 \Rightarrow \sim NH_2)\)
  – Assimilation \((NH_3 \Rightarrow \sim NH_2)\)
  – Ammonification \((\sim NH_2 \Rightarrow NH_3)\)
  – Nitrification \((NH_3 \Rightarrow NO_2 \Rightarrow NO_3)\)
  – Denitrification \((NO_3 \Rightarrow NO_2 \Rightarrow NO \Rightarrow N_2)\)
Nitrogen fixation

• Remove nitrogen from the air and convert it into a form usable by organisms
• Soil and water bacteria
  – Azotobacter and Azospirillum
  – Clostridium
  – Cyanobacteria (Anabaena, Nostoc)
• Root nodule (symbiosis)
  – Rhizobium
• Ammonia is the primary product
Root nodules represent a symbiotic relationship, in which rhizobia bacteria fix nitrogen for the plant legume, while the plant legume supplies the bacteria with nutrients.
Plants inoculated with *Rhizobium* bacteria are healthier (ample nitrogen), than plants not inoculated (lack of nitrogen).

![Inoculating legumes seeds with *Rhizobium* bacteria increases the plant’s access to nitrogen.](image)

**Fig. 24.10**

Inoculating legumes seeds with *Rhizobium* bacteria increases the plant’s access to nitrogen.
Ammonification

- Nitrogen containing organic matter is decomposed by soil and water bacteria
- Amino groups and ammonia are produced
- Organisms can assimilate (take up and use) the ammonia
Nitrification

• Soil and water bacteria
• Conversion of ammonia to nitrate
• Two step process
  – Ammonia (NH$_4^+$) to nitrite (NO$_2^-$)
  – Nitrite (NO$_2^-$) to nitrate (NO$_3^-$)
• Nitrate is assimilated by reduction or used as terminal electron acceptor
Denitrification

• Conversion of nitrate (NO$_3^-$) to nitrogen gas (N$_2$) or nitrous oxide (N$_2$O)
• Soil bacteria
Oxygen Sources

- Oxygen is a major component of organic compounds
- Also a common component of inorganic salts
- $\text{O}_2$ makes up 20% of the atmosphere and is dissolved in water (the oceans cover 70% of the Earth’s surface)
Hydrogen Sources

- Hydrogen is a major element in all organic and several inorganic compounds
- Performs overlapping roles in the biochemistry of cells:
  - Maintaining pH
  - Forming hydrogen bonds between molecules
  - Serving as the source of free energy in oxidation-reduction reactions of respiration
Sedimentary cycles

- Sulfur cycle
- Phosphorus cycle
- Other cycles
Phosphorus (Phosphate) Sources

- Main inorganic source of phosphorus is phosphate ($\text{PO}_4^{3-}$)
  - Derived from phosphoric acid
  - Found in rocks and oceanic mineral deposits
- Key component in nucleic acids
- Also found in ATP
- Phospholipids in cell membranes and coenzymes
Phosphorus cycle

- Phosphorous is part of DNA, RNA and ATP
- Inorganic phosphate is central
  - Mineral reservoir – sedimentation (rock)
- Phosphate rock is converted by sulfuric acid (*Thiobacillus*-sulfur cycle) into soluble phosphate
- Soluble \( \text{PO}_4^{2-} \) is primary source for autotrophs
- Organic \( \text{PO}_4^{2-} \) is primary source for heterotrophs
- Decomposers return organic to soluble phosphate
Sulfur Sources

• Widely distributed throughout the environment in mineral form
• Essential component of some vitamins
• Amino acids- methionine and cysteine
Sulfur cycle

- Sulfur - rocks, oceans, lakes, and swamps
- Forms of sulfur
  - Hydrogen sulfide (H₂S)
  - Elemental sulfur (S)
  - Thiosulfate (S₂O₃)
  - Sulfate (SO₄)
- Cycled mostly by bacteria – *Thiobacillus*
  - Associated with phosphorus cycle
- Plants and microbes assimilate sulfate
- Animals obtain sulfur from amino acids
Other Nutrients Important in microbial Metabolism

- Potassium: protein synthesis and membrane function
- Sodium: certain types of cell transport
- Calcium: stabilizer of cell walls and endospores
- Magnesium: component of chlorophyll and stabilizer of membranes and ribosomes
- Iron: important component of cytochrome proteins
- Zinc: essential regulatory element for eukaryotic genetics, and binding factors for enzymes
- Cooper, cobalt, nickel, molybdenum, manganese, silicon, iodine, and boron: needed in small amounts by some microbes but not others (micronutrients)
Energy source
Nutritional Type

• Phototrophs

• Chemo-organo-trophs
  - Chemo-organo-trophs
  – Chemo-litho-trophs
Autotrophs and Their Energy Sources

- **Photoautotrophs**
  - Photosynthetic
  - Form the basis for most food webs

- **Chemoautotrophs**
  - Chemoorganooxidizing autotrophs: use organic compounds for energy and inorganic compounds as a carbon source
  - Chemoorganooxidizing autotrophs: rely totally on inorganic minerals
    - **Methanogens** (Arbacia) - use hydrogen gas to produce methane and to fix carbon dioxide
    - **Nitrifying bacteria** - produce nitrite/nitrate from ammonia to fix carbon dioxide
Photo-trophs

• Derive their energy from sunlight.
  – Transform light energy into chemical energy.
• They usually get their carbon from CO$_2$.
• They are primary producers
  (of organic matter for heterotrophs).

• Oxygenic Phototrophs are the primary producers of oxygen
  – Ex. Algae, Cyanobacteria (also non-microbes: plants)

• Anoxygenic Phototrophs do not produce oxygen
  – Ex. Green and purple bacteria
Chemo-organo-trophs

- Derive energy and electrons from bonds in organic compounds.
  - Chemoorganoheterotrophs - derive carbon from organics
    - Saprobes (saprotrophs, saprophytes)
    - decomposers of plant litter, animal matter, and dead microbes
    - Parasites
      - Need at least temporary association (on or in) with a host
  - Chemoorganoaototrophs - derive carbon solely from CO$_2$
    - rare
Chemo-litho-trophs

• Derive their energy and electrons only from inorganic compounds
  – Chemo-litho-autotrophs - derive carbon solely from CO$_2$
    • (Use neither sunlight nor organics)

  – Chemo-litho-heterotrophs - derive carbon NOT solely from CO$_2$
    • (can be organics or organics and CO$_2$)
Methanogens are an example of a chemolithoautotroph.

Energy source: Hydrogen gas - $\text{H}_2$
Carbon source: $\text{CO}_2$ (formate, acetate)

Fig. 7.1 Methane-producing archaea
Summary of the different nutritional categories based on carbon and energy source.

<table>
<thead>
<tr>
<th>Category</th>
<th>Energy Source</th>
<th>Carbon Source</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autotroph</td>
<td>Nonliving environment</td>
<td>CO₂</td>
<td>Photosynthetic organisms, such as algae, plants, cyanobacteria</td>
</tr>
<tr>
<td>Photoautotroph</td>
<td>Sunlight</td>
<td>CO₂</td>
<td>Only certain bacteria, such as methanogens, deep sea vent bacteria</td>
</tr>
<tr>
<td>Chemoautotroph</td>
<td>Simple inorganic chemicals</td>
<td>CO₂</td>
<td></td>
</tr>
<tr>
<td>Heterotroph</td>
<td>Other organisms or sunlight</td>
<td>Organic</td>
<td>Purple and green photosynthetic bacteria</td>
</tr>
<tr>
<td>Photoheterotroph</td>
<td>Sunlight</td>
<td>Organic</td>
<td>Protozoa, fungi, many bacteria, animals</td>
</tr>
<tr>
<td>Chemoheterotroph</td>
<td>Metabolic conversion of the nutrients from other organisms</td>
<td>Organic</td>
<td></td>
</tr>
<tr>
<td>Saprobe</td>
<td>Metabolizing the organic matter of dead organisms</td>
<td>Organic</td>
<td>Fungi, bacteria (decomposers)</td>
</tr>
<tr>
<td>Parasite</td>
<td>Utilizing the tissues, fluids of a live host</td>
<td>Organic</td>
<td>Various parasites and pathogens; can be bacteria, fungi, protozoa, animals</td>
</tr>
</tbody>
</table>
Important (Energy) Limitation

- **Energy is not (re)cycled**
- As energy is transferred from producer to consumer, large amounts of energy are lost in the form of heat
- Amount of energy available decreases at each successive trophic level
- Fewer individuals can be supported by remaining available energy
Organization of the Biosphere

• Biosphere
  – Terrestrial – biomes
  – Aquatic

• Ecosystem
  – Hydrosphere
  – Lithosphere
  – Atmosphere

• Communities
• Populations
• Habitats
• Niche
The different levels of organization in an ecosystem, which ranges from the biosphere to the individual organism.

Fig. 24.2 Levels of organization in an ecosystem
Energy and nutrient flow

• Food chain
• Producers
• Consumers
• Decomposers
• Limitation
• Ecological interactions
Food chain

• Energy pyramid
  – Begins with a large amount of usable energy and ends with a smaller amount of usable energy

• Trophic (feeding) levels
  – The number of organisms that are producers, consumers and decomposers
An example of the trophic and energy pyramid.

Fig. 24.3 A trophic and energy pyramid.
The roles, description of their activities, and types of microorganisms involved in the ecosystem.

Table 24.1 The major roles of microorganisms in ecosystems.

<table>
<thead>
<tr>
<th>Role</th>
<th>Description of Activity</th>
<th>Examples of Microorganisms Involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary producers</td>
<td>Photosynthesis</td>
<td>Algae, cyanobacteria, sulfur bacteria</td>
</tr>
<tr>
<td></td>
<td>Chemosynthesis</td>
<td>Chemolithotrophic bacteria in thermal vents</td>
</tr>
<tr>
<td>Consumers</td>
<td>Predation</td>
<td>Free-living protozoa that feed on algae and bacteria; some fungi that prey upon nematodes</td>
</tr>
<tr>
<td>Decomposers</td>
<td>Degradation of plant and animal matter and wastes</td>
<td>Soil saprobes (primarily bacteria and fungi) that degrade cellulose, lignin, and other complex macromolecules</td>
</tr>
<tr>
<td></td>
<td>Mineralization of organic nutrients</td>
<td>Soil bacteria that reduce organic compounds to inorganic compounds such as CO₂ and minerals</td>
</tr>
<tr>
<td>Cycling agents for biogeochemical cycles</td>
<td>Recycling compounds containing carbon, nitrogen, phosphorus, sulfur</td>
<td>Specialized bacteria that transform elements into different chemical compounds to keep them cycling from the biotic to the abiotic and back to the biotic phases of the biosphere</td>
</tr>
<tr>
<td>Parasites</td>
<td>Living and feeding on hosts</td>
<td>Viruses, bacteria, protozoa, fungi, and worms that play a role in population control</td>
</tr>
</tbody>
</table>
Producer

• Fundamental energy source
• Drives the trophic pyramid
• **Autotrophs** - produce organic carbon compounds by fixing inorganic carbon
• **Photosynthetic organisms**
  – Cyanobacteria
  – Algae (and Plants)

• **Lithotrophs** (oxidize reduced inorganics)
Consumers

• Feed on other living organisms
• Obtain energy from organic substrate bonds (break bonds = release energy)
  – Ex. Animals, protozoa, some bacteria and fungi
  – Function at several levels
    • Primary, secondary, tertiary and quaternary consumers
A simple example of the different levels of a consumer.

Fig. 24.4 Food chain
Decomposer

- Saprobotes - inhabit all levels of the food pyramid
- Primarily bacteria
- Reduce organic matter into inorganic minerals and gases
- Mineralization - cycled decomposed material back into the ecosystem and global biogeochemical cycles
Trophic patterns can be complex, as many producers and composers are involved.

Fig. 24.5 Food web
Ecological interactions

• **Symbiosis** (“living together”)
  – Commensalism (“eating at the same table”)
  – Co-metabolism (“simultaneous metabolism of 2 compounds”)
  – Syntrophy (“eating together”)
  – Synergism (“working together”)
  – Parasitism (“one benefits on the expense of another one”)

• **Antagonism** (“working against one another”)
  – Competition (“striving against one another”)
  – Predator (“hunting and killing prey”)
  – Scavengers (“consuming dead material, cleaning up”)

Microbial Nutrition

• Nutritional requirements

• Sources of nutrients

• Ways to get nutrients (Transport mechanisms)
Transport mechanisms

- Passive transport
  - Diffusion
    - Osmosis
  - Facilitated Diffusion
    - Carriers, Channels

- Active transport

- Endocytosis
Representation of a saprobe (saprotroph) and its mode of action.

Fig. 7.2 Extracellular digestion in a saprobe with a cell wall.

(a) Walled cell is a barrier.

(b) Enzymes are transported outside the wall.

(c) Enzymes hydrolyze the bonds on nutrients.

(d) Smaller molecules are transported across the wall into the cytoplasm.
Diffusion

• Net movement of molecules from a high concentrated area to a low concentrated area
• No energy is expended (passive)
• Concentration difference and permeability affect movement of solute (molecule in solution)
A cube of sugar will diffuse from a concentrated area into a more dilute region, until an equilibrium is reached.

Fig. 7.5 Diffusion of molecules in aqueous solutions
Osmosis

- Diffusion of water through a permeable but selective membrane

- Water moves toward the area with higher solute concentrations
Osmotic Relationships

• The osmotic relationship between cells and their environment is determined by the relative concentrations of the solutions on either side of the cell membrane

• **Isotonic:** The environment is equal in solute concentration to the cell’s internal environment
  – No net change in cell volume
  – Generally the most stable environment for cells

• **Hypotonic:** The solute concentration of the external environment is lower than that of the cell’s internal environment
  – Net direction of osmosis is from the hypotonic solution into the cell
  – Cells without cell walls swell and can burst

• **Hypertonic:** The environment has a higher solute concentration than the cytoplasm
  – Will force water to diffuse out of a cell
  – Said to have high osmotic pressure
Representation of the osmosis process.

Fig. 7.3 Osmosis, the diffusion of water through a selectively permeable membrane
Adaptations to Osmotic Variations in the Environment

• Example: fresh pond water- hypotonic conditions
  – Bacteria: cell wall protects them from bursting
  – Amoeba: a water (or contractile) vacuole that moves excess water out of the cell

• Example: high-salt environment- hypertonic conditions
  – Halobacteria living in the Great Salt Lake absorb salt to make their cells isotonic with the environment
Cells with- and without cell walls, and their responses to different osmotic conditions (isotonic, hypotonic, hypertonic).

Fig. 7.4 Cell responses to solutions of differing osmotic content.
Facilitated diffusion

• Transport of polar molecules and ions across the membrane
• No energy is expended (passive)
• Channel and carrier proteins facilitate the binding and transport
  – Specificity
  – Saturation
  – Competition
Representation of the facilitated diffusion process.

Fig. 7.6 Facilitated diffusion
Active transport

• Transport of molecules requires use of energy (active)
• Outcome is movement uphill a gradient

• Ex. Permeases and protein pumps transport sugars, amino acids, organic acids, phosphates and metal ions.
• Ex. Group translocation transports and modifies specific sugars
Endocytosis

• Substances are taken, but are not transported through the membrane.
• Requires energy (active)
• Common for eukaryotes
• Ex. Phagocytosis, pinocytosis
Example of the permease, group translocation, and endocytosis processes.

Fig. 7.7 Active transport
Summary of the transport processes in cells.

<table>
<thead>
<tr>
<th>General Process</th>
<th>Nature of Transport</th>
<th>Examples</th>
<th>Description</th>
<th>Qualities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive</td>
<td>Energy expenditure is not required.</td>
<td>Diffusion</td>
<td>A fundamental property of atoms and molecules that exist in a state of random motion</td>
<td>Nonspecific Brownian movement</td>
</tr>
<tr>
<td></td>
<td>Substances exist in a gradient and move from areas of higher concentration toward areas of lower concentration in the gradient.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Facilitated diffusion</td>
<td></td>
<td>Molecule binds to a receptor in membrane and is carried across to other side</td>
<td>Molecule specific; transports both ways</td>
</tr>
<tr>
<td>Active</td>
<td>Energy expenditure is required.</td>
<td>Carrier-mediated active transport</td>
<td>Atoms or molecules are pumped into or out of the cell by specialized receptors. Driven by ATP or the proton motive force (Na⁺, K⁺)</td>
<td>Transports simple sugars, amino acids, inorganic ions</td>
</tr>
<tr>
<td></td>
<td>Molecules need not exist in a gradient.</td>
<td>Group translocation</td>
<td>Molecule is moved across membrane and simultaneously converted to a metabolically useful substance.</td>
<td>Alternate system for transporting nutrients (sugars, amino acids)</td>
</tr>
<tr>
<td></td>
<td>Rate of transport is increased.</td>
<td>Bulk transport</td>
<td>Mass transport of large particles, cells, and liquids by engulfment and vesicle formation</td>
<td>Includes endocytosis, phagocytosis, pinocytosis</td>
</tr>
</tbody>
</table>

Table 7.4 Summary of transport processes in cells