Bacteria (Prokaryotes) General

Bacteria → all are prokaryotes

prokaryote = "before nucleus"

smallest, simplest, oldest cells on earth
1-5µm (vs eucaryotes 10-100µ long)

if human hair were enlarged to size of tree trunk
→ bacterial cell would be size of cockroach

simple structure; not much internal structure
→ no organelles – much less efficient design

yet extremely successful group:
→ 1st cells – survived for 2 Billion Years as only kinds of cells on earth
  even after much more efficient cells appeared (eucaryotes) they remained successful and abundant

→ bacteria are the most common organism on the earth
  dominate the biosphere in terms of numbers (outnumber all eucaryotes combined)

eg. more bacterial cells in a handful of dirt than all people who have every lived
eg. 1 tsp rich soil contains 1 Billion bacterial cells; 40,000 species
eg. one species of bacteria (=Prochlorococcus sp.) outnumbers ALL other organisms in the open oceans
eg. as much as 70% of bacteria alive on earth live on and below the ocean floor
eg. the average office desk harbors 20,961 ‘germs’/sq in
→ ~400x more than the average toilet seat

→ In ‘number of cells’ bacteria dominate the cells found in many of their hosts:
  eg. cows: rumen contains over 25 gallons with 10B bacteria/tsp
  eg. humans: our bodies contain ~10x’s more bacterial cells than human cells
  → ~3-6lbs of bacteria/ person

only about 10,000 ‘species’ formally named;
most don’t grow on artificial media; cant study them

a new way of analyzing species (=metagenomics) allows us to better estimate the number of species present

current estimates are that we have described just 1% of bacterial species

Bacterial Structure

Microbial Communities

bacteria rarely occur in isolated colonies of a single species

while individual bacterial cells are too small to see without a microscope, bacteria are often found in microbial communities that are visible to the naked eye

→ large multicellular aggregations when nutrients are plentiful – then are easily visible

many species of microorganisms (bacteria, fungi, protozoa, algae)

tend to be embedded in matrix of water and organic molecules (glycoproteins and polysaccharides)

in some ways these microbial communities take on characteristics of multicellular organisms:

→ establish new lines of communication to coordinate their actions

they can control activities of the group; they can “talk” to each other by secreting certain chemicals
behavior of the group is different than of any individual species within group

eg. slime bacteria "hunt in packs"

swim together in huge swarms

lots of interactions and symbioses

Advantages to individual species in Microbial Communities:

1. provide more stable environment
2. protect cells from UV and heat
3. minimize effects of rapid changes in environment
   eg. dental plaque
4. may offer protection from predators
5. highly effective in trapping nutrients

most environments are nutrient scarce

eg. "swarms" of myxobacteria in soil

communal feeding

can only kill and digest other bacteria if in swarms, otherwise can't produce enough digestive enzymes

6. source of new genes that can be traded as needed

Kinds of microbial communities

some examples of different kinds of microbial communities:

- Colonies
- Bacterial Blooms
- Biofilms & Microbial Mats
- Stromatolites

1. Colonies

colonies of a single species of bacteria are almost never found in nature

but are common when grown on lab cultures

each colony may produce distinctive features such as color, smell, shape, etc. that can be used to help identify the species

a 'colony' on agar plate is assumed to be a massive growth of a single species of bacterium

only a few (<0.1%) bacterial species can be grown on artificial media:

selective media

prevents the growth of certain bacteria while allowing others to grow

enrichment media

has special nutrients that enhance the growth of the desired bacteria

differential media

contains a specific nutrient and an indicator the show whether the species is able to use that nutrient

2. Bacterial Blooms

rapid reproduction of bacteria produces vast quantities of cells, primarily of a single species

occur when conditions are favorable and food is plentiful

often visible on ponds and lakes in spring

eg. blue-green bacterial blooms often occur in ponds, lakes or reservoirs in spring or summer

rapid growth and decomposition often removes oxygen from water resulting in massive fish kills

eg. cloudy or smoky white blooms are a common problem in new or unbalanced aquaria

3. Biofilms (or microbial mats)

multilayered sheets of bacteria growing on rocks, streambeds, soil crumbs etc

biofilms are also important in medicine

eg. plaque on teeth causes tooth decay

eg. infections that should respond well to antibiotics don't once biofilm is established

the more interconnected the bacteria are, the more resistant to treatment they become

eg. 65-80% of chronic infections in industrialized nations linger because of biofilm formation:

cystic fibrosis

gum disease

chronic inner ear, urinary tract and bone infections

eg. MRSA (methicillin-resistant Staphylococcus aureus)

kills 90,000/yr in US

even more difficult to eradicate once a biofilm is established

4. Stromatolites

some of the oldest fossils of life on earth are bacterial communities called stromatolites

large rocky columns that take 1000's of years to grow

today bacteria still produce stromatolites that closely resemble the fossil ones

produced mainly by blue-green bacteria
Microscopic Structure of Bacteria

Most individual bacterial cells are way too small to be seen without a microscope.

There are, however, a handful of species that are 100 of times larger than most bacteria.

One species is even visible to the naked eye.

All bacteria are prokaryotes:
- No nucleus

Small cells, simple structure
- Usually no organelles
  - Much less efficient design

1. Cell Wall

Almost all bacteria have a rigid cell wall surrounding the cell membrane.

Bacterial cell walls have a unique structure and chemistry unlike the cell walls in any other kingdom.

The chemistry of cell wall varies from species to species.

In most bacteria, the cell wall is made of bacterial starch (= peptidoglycan).

The cell wall protects the bacteria.

- Allows them to live in "extreme" environments.

The rigid cell wall produces the three basic shapes of bacterial cells:
- cocci (spheres)
- rods (bacilli)
- spirals (includes curves and corkscrew shapes)

2. Capsule

Some bacteria produce a capsule.

- A gelatinous, sticky layer that allows bacteria to
  - Attach to substrates
  - Glues "colonies" together
  - Also increases pathogenic bacteria’s resistance to host’s defenses

3. Pili

Some bacteria have pili used for attachment.

And for bacterial conjugation in which genes are exchanged between two different bacterial cells.

(a type of primitive sexual reproduction)

Some bacteria can also use their pili as legs for walking on solid surfaces.

Pili can also conduct electricity allowing communication within the community.

4. Bacterial Flagellum

About half of all bacterial species are motile.

Can move up to 50µm/sec (~100x’s body length/sec)

Can move by:
- Flagella
- Slime trail
- Helical filaments (spirochaetes)

Most use one or more flagella.

Flagellum is whip-like rod that rotates like propeller to move bacteria along.

Bacterial flagellum is the only rotary motor known in the living world.

Can spin at 6,000 rpm.

Allows bacteria to move ~10x’s their length/second.

Many species interacting
- Like a miniature ecosystem of microorganisms

Produced most of the O₂ in the earth’s early atmosphere.

5. Multicellular "Behavior" in Bacteria

Some bacteria can come together to form "fruiting bodies" that produce spores for reproduction.

Sometimes simple mounds of cells.

Sometimes highly branching structures.

In some cases there is a division of labor as in fungi, animals and plants.

Microbiology & Disease: Bacteria General; Ziser, Lecture Notes, 2015.
ability to move and orient produces simple behaviors = "taxes"

→ movements toward or away from stimuli
e.g. such as light, food, oxygen, gravity, etc.
e.g. + & - chemotaxes
have specific receptor molecules on cell surface to detect chemicals

5. Magnetic Particles
some bacteria contain rows of magnetic particles that acts as a single, long magnet
allows them to orient toward the earth’s magnetic field
allows them to travel in straight lines to find "surface" of water, specific light level, food, etc
reduces the effects of Brownian motion

7. Endospores (bacterial spores)
some bacteria can form endospores to survive adverse conditions
very resistant to destruction

8. Cytoskeleton
like eukaryote cells the cytoskeleton is a series of interconnected protein fibers within the cell
in bacteria it anchors structures such as flagella, and magnetic particles and in some, helps to maintain shape

9. Vacuoles
a few bacteria have internal sacs that contain enzymes for specific jobs or that store various chemicals

10. Chromosomes & Genes
all living cells contain chromosomes
genome = all the genetic material that a cell contains
bacterial genome contains about 3000 genes
(humans contain ~21,000 genes)
bacterial genes are contained on two kinds of DNA:
a. chromosome
b. plasmids

Bacterial Physiology

Bacterial Growth
new bacterial cells can only grow slightly in size
when we say bacteria “grow” we usually mean they are reproducing, i.e. increasing in numbers
bacterial growth = bacterial reproduction
one of the reasons bacteria are so successful is that most reproduce very rapidly
most bacterial reproduction is by asexual fission
asexual reproduction is much faster than sexual reproduction

the Life Cycle of bacteria is measured as the time between when the cell is first formed and when it divides by fission
time between divisions = generation time

generation time is typically about 20 ± 30 minutes

Staph aureus 30 min
M. tuberculosis 18 hrs
T. pallidium 33 hrs
E. coli 20 min
e.g. E. coli: one cell at 8:00 am, no limiting factors:
→ 36 hrs later → 1 foot over surface of earth
some newly discovered bacteria found in the deepest, most barren parts of the ocean have the longest bacterial life cycles known: 100's of 1000's of years before each division slowest metabolism of any known life form

**Bacterial Metabolism**

Prokaryotes have a very simple structure but show an almost unlimited variety of metabolic pathways. Bacteria show more metabolic diversity than all other kingdoms combined:

- every kind of food eaten by any other form of life can be eaten by some species of bacteria
- some nutrients can only be used by bacteria and not by any other form of life
- bacteria can do photosynthesis dozens of different ways versus plants or algae which have only one type of photosynthesis
- bacteria can produce energy (respiration) in 100's of different ways versus only 1 way for plants and animals

**Bacterial Nutrition**

All life requires food for survival, in most organisms food must provide 2 main resources:

A. building blocks (nutrients)

  - simple elements & molecules to construct larger organic molecules & cell parts

B. an energy source

  - energy powers all metabolism and everything the cell "does"

**A. Building Blocks**

As does all life bacteria require sources of Carbon, Hydrogen, Oxygen and Nitrogen, Phosphorus, etc as well as several other elements:

- as a rule bacteria require fewer and often simpler essential nutrients than higher life forms
  - eg. humans require about a dozen essential organic molecules; vitamins, some amino acids and some fatty acids
  - many bacteria can make ALL the organic molecules they need from simple atoms and inorganic molecules; they require NO essential organic molecules

- also, bacteria, as a group, rely on an extremely diverse group of nutrients compared to us.

Bacteria can use 1000’s of different kinds of nutrients:

- virtually every natural and human made chemical can be eaten by at least some bacterial species
  - including minerals in rock, acids, hydrogen sulfide, sulphur, etc
  - some bacteria can even break down pesticides, herbicides, petroleum, asphalt, DDT, concrete, computer chips, paints, even plastic and glass

- eg. the plastic we throw in the oceans harbors 1000’s of species of bacteria forming a uniquely identifiable plastisphere

**eg. Carbon**

- of the essential nutrients carbon is often the most critical
- carbon is needed for building any kind of organic molecule
  - eg. humans get carbon atoms from eating organic molecules
  - eg. plants get all the C they need from CO₂
- but bacteria can get carbon from a wide variety of sources:
  - eg. organic carbon: methane, alcohols, sugars, starches, proteins, fats, petroleum, plastics, etc
  - eg inorganic carbon: CO₂, calcium carbonate, bicarbonate, etc

**eg. Nitrogen**

Nitrogen is essential for making proteins and nucleic acids:

- most living organisms are fairly limited in the sources of nitrogen that they can use:
  - eg. animals get all their N from eating proteins
  - eg. plants need no organic foods, they get N from small inorganic nitrogen chemicals in the soil such as ammonia

- bacteria can eat many forms of nitrogen both organic and inorganic:
  - eg. a few bacteria can fix nitrogen gas from the air
  - bacteria are the only organisms that can do this

- N₂ gas makes up 80% of atm but is completely unusable by all other life forms

**eg. Phosphorus**

- eg. organic carbon: methanes, alcohol, sugars, starches, proteins, fats, petroleum, plastics, etc
- eg inorganic carbon: CO₂, calcium carbonate, bicarbonate, etc
most organisms including us get most of our phosphorus from organic molecules such as nucleic acids and lipids, and a few inorganic phosphates

plants get all their phosphorus from inorganic phosphates in the soil

again, bacteria can extract phosphorus from virtually any phosphorus containing compound, organic or inorganic

because bacteria can “eat” almost anything, they are very effective decomposers and recyclers

→ bacteria are of major importance in the world’s biogeochemical cycles
  
  eg. nitrogen cycle, carbon cycle, etc

bacteria can even decompose (= eat) “nonbiodegradable” compounds

eg. rough estimates for time to degrade:

- leather: 2,000 yrs
- plastic: 1,000’s of yrs
- humus: 35,000 yrs
- glass: 1,000,000’s of yrs
- lignite: 1 million yrs
- amber: 25 million yrs
- chitin: 500 million yrs

→ but each is eventually broken down

most bacteria are heterotrophs

they can eat a wide variety organic molecules to break down for energy

eg. plants and animals generally break down sugars for respiration

eg. bacteria can break down sugars as well as almost any other organic molecules such as proteins, fats, oils, starches, etc.

→ some organisms (algae, plants, blue-green bacteria) can make their own sugars and organic molecules from small inorganic molecules using some other outside energy source

= Autotrophs

eg. plants need only simple inorganic nutrients

they then use energy from sunlight to convert these into organic sugars and other large molecules

they can then break these sugars down to release energy for all their needs

some bacteria are autotrophs and use some other source of energy to build their own organic molecules for respiration

Bacterial Energy Sources

all life uses energy in the form of chemical bonds

chemical bonds in all molecules are “stored energy”

when you break those bonds → energy is released

eg. chemical bonds in gasoline are broken down to provide energy for movement

ALL life gets its energy from breaking the chemical bonds in sugars and other organic molecules

producing energy this way = respiration

these sugars and other energy storing molecules can come from two sources:

→ most organisms (eg. animals and fungi) must eat organic molecules (eg. sugars, starches, proteins, etc) and then break them down to extract energy

= Heterotrophs

eg. animals (including humans) eat mainly large complex organic molecules

then break them down to extract nutrients and to produce energy

eg. energy from sunlight

like plants and algae do

eg. blue green bacteria

eg. energy from inorganic compounds

no plant or animal can extract energy from small inorganic compounds

certain bacteria can oxidizes inorganic compounds for energy

eg. H₂S; NH₃; Fe²⁺, S₂, H₂, H₂SO₄, etc

eg. some deep ocean autotrophs (thermal vents) extract energy from the oxidation of hydrogen sulfide to sulfate

Bacterial Respiration

ALL life gets its energy from breaking the chemical bonds in sugars and other organic molecules

= respiration

most life, including plants & animals, break down sugars using oxygen gas

→ aerobic respiration

completely breaks sugars down to CO₂ & H₂O

much more efficient

much more complicated set of reactions
but many bacteria can partially break down sugars into smaller organic compounds without using oxygen gas

→ **anaerobic respiration**

much simpler process
only partially breaks down the sugars, etc
much less efficient

one example of anaerobic respiration is **fermentation**

many bacteria are **fermenters**

→ extract energy from sugars by converting them to other organic compounds

- carbon dioxide
- acetone
- alcohols
- vitamins
- lactic acid
- acetic acid
- citric acid

eg. sugars

many of these fermentation products have become commercially important products

**Growth Rate**

in nature, bacteria rarely grow as richly as in lab cultures

bacteria are **opportunistic**

→ when conditions or nutrients are right they reproduce quickly
→ when conditions are unfavorable or food runs out metabolism slows or ceases

the rate of bacterial growth is often affected mostly by the essential nutrients in shortest supply

when essential nutrients are abundant get rapid reproduction (growth)

→ often form **blooms**

as essential nutrients are depleted growth slows or stops altogether

living bacteria have been found living in 8.7 Million year old sediment below the floor of the ocean

nutrients are so scarce that they grow extremely slowly

they grow so slowly that they rarely even divide for probably 100,000’ of years

**Environmental Factors**

because bacteria are relatively simple and very adaptable they can survive, and even thrive, under many conditions that we would consider quite harsh

eg. ideal conditions for humans: nice balmy temperatures not too hot, not too dry, plenty of food and drink, not overcrowded, etc.

bacteria, as a group, have the **widest tolerances** for temp, pH, salt, etc than any other kingdom of organisms

their rates of growth and reproduction are greatly affected by various environmental factors:

- **temperature preferences**
- **pH tolerance**
- **salt concentrations**
- **oxygen requirements**
- **light** (for photosynthetic bacteria)

each species has its own preferences and **tolerance limits** for these factors

**Extremophiles**

organisms that prefer the “extremes” of these conditions needed for life are called **extremophiles**

eg. (our “normal” = 98º F) microbes that thrive in temperatures 122ºF (>50ºC) = **thermophiles**

hot springs, ocean thermal vents

eg. (our normal pH~7) microbes that thrive in pH <5 = **acidophiles**

acid lakes and bogs, mine tailing drainage

eg. (our normal ~0-3%) microbes that thrive in salt concentrations ~10-20% = **halophiles** (sea=3% salt)

great salt lake, dead sea, desalination ponds

**Oxygen Requirements**

bacteria have various requirements for **oxygen** gas depending on their kind of respiration

**obligate aerobes** (strict aerobes)

→ die without oxygen gas

**obligate anaerobes** (strict anaerobes)

→ die in the presence of oxygen gas

**facultative anaerobes**

→ can use oxygen when available, and do anaerobic metabolism when its not

**Bioluminescence**

some deep water marine bacteria are bioluminescent
glowing "food" attracts bacterial feeders as a means of dispersal for the bacteria

**Exposure to Radiation**

Deemed “the world’s toughest bacterium”

Deinococcus radiodurans was discovered in 1956 in a can of meat that had spoiled despite being sterilized by radiation.

found that it can withstand and actually grow during exposure to 3 million rads of radiation (=1000’s x’s lethal human exposure)

exposure to such strong radiation breaks its genome into pieces but the bacterium is able to quickly repair itself.

it can also withstand extreme heat, cold and high acidity.

we still have no idea of its natural habitat.

**Bacterial Dormancy & Spores**

scientists have found living bacteria inside 30,000 year old salt crystals from Death Valley.

they fed on algae entombed in a tiny droplet of hypersaline water within the crystal.

bacteria trapped in ice crystals for over 500,000 years, over a mile below the surface are able to survive & metabolize in a film of liquid water that allows diffusion of nutrients but no reproduction, just waiting for the ice to melt.

even when nutrients are in short supply bacteria don’t necessarily die.

→ they can enter a *dormant state* in which metabolism ceases for up to 1000’s of years, until favorable conditions return.

→ some can form resistant bacterial *spores*.

Spores are extremely resistant to destruction.

eg. *B. anthracis* → 50-70 yrs.

eg. from deep ocean sediments → 5800 yrs.

eg. spores extracted from salt crystals in 250 M year old deposits.

→ Bacterial Cells can be essentially immortal.

**Bacterial Mutations & Evolution**

Evolution is based on variations caused by **sexual reproduction and mutations**

→ nature then selects the cells with the most useful combination of traits.

How did bacteria, which reproduce primarily asexually evolve and diversify so quickly?

→ but have many ways to alter their genetic makeup.

1. due to rapid life cycles, **natural mutations** are another main source of genetic variations.

   one of the main sources of genetic variations over generations is random natural mutations.

   all life mutates and passes some of these mutations on to the next generation.

   we (humans) accumulate about 60 mutations per generation (20 yrs) that we pass on to our children.

   bacteria mutate 100 x’s faster than humans and reproduce every 15 or 20 minutes.

   → populations of *E. coli* can accumulate about 10 million mutations per day.

2. bacteria do perform a simple kind of "sexual reproduction" called **conjugation**.

   2 different strains use *pili* to exchange some genes (not all).

3. viruses that infect bacteria sometimes add new genes to the bacteria but don’t kill the bacteria.

4. bacteria can **trade genes** easily with other species of bacteria, even with eukaryotes.

   their DNA is loose inside cells → easy access to genes.

   they often have spare strands of DNA (extra genes).

5. bacteria can even absorb DNA from the environment.

   when bacterial cells die the DNA is released some of it can be taken up by surrounding cells.

   this environmental DNA can even be ancient DNA from now extinct species.

**Bacterial ‘Species’**

a **species** is defined as a group (population) of organisms that naturally interbreed with each other.

the typical distinction between different **species** does.
bacteria “create a huge planetary gene pool that gives rise to temporarily classifiable bacterial 'types' or 'strains' which radically and quickly change, keeping up with the environmental conditions” –Margulis and Sagan, 1995

we are now also beginning to find bacterial genes in plants and animals, being passed on to offspring and contributing to evolution of species

So, Why are Bacteria So Successful?

even though:
bacteria are the smallest, most primitive cells on earth
simple structure; not much internal structure →no organelles
much less efficient at metabolism

yet:
bacteria dominate the biosphere in terms of numbers;
play vital role in the recycling of nutrients
virtually all other forms of life are dependent on bacteria directly or indirectly for their survival
→ bacteria are generally not dependent on any other life form for their survival

Why?

1. bacteria have a relatively simple, relatively uncomplicated structure
→ much less efficient but very adaptable

2. bacteria have tremendous physiological diversity

→ bacteria can metabolize 1000’s of different kinds of nutrients
→ can use many food and energy sources as available; and change as needed

3. bacteria, as a group, have the widest tolerances for temp, pH, salt, etc than any other kingdom of organisms
   → many species can survive, and even thrive, under many conditions that we would consider quite harsh

4. they have a rapid reproductive rate to quickly take advantage of optimal conditions when they occur
   → asexual reproduction is much faster than sexual reproduction

5. when nutrients are in short supply or conditions are unfavorable they don’t necessarily die
   → they can enter a dormant state
   → some can form bacterial spores
   they can remain dormant or 1000’s even millions of years
always there and ready to take advantage of favorable conditions

6. can freely and rapidly mutate, absorb genes from their surroundings and exchange genes with viruses and other bacteria to adapt to new foods, conditions or become more resistant to harsh conditions
Ecological Roles of Bacteria

1. Biogeochemical Cycles

Bacteria are essential for cycling nutrients virtually ANY naturally occurring organic chemical and many synthetic organic chemicals can be broken down (“eaten”) by at least some bacteria including: paper, paints, leather, textiles, computer chips, metals, petroleum, concrete, plastics, DDT, etc.

If they weren’t here, we wouldn’t be either the world would fill up with dead animals and plants we would run out of nutrients

2. Primary Producers

Bacteria are base of food chain in some ecosystems

eg. Prochlorococcus (the world’s most abundant marine organism) and other marine phytoplankton carry out about half of the world’s photosynthesis

eg. blue green bacteria in aquatic ecosystems

eg. hydrothermal vents

3. Oxygen Production

BG bacteria were the only autotrophs for billions of years and created our oxygen containing atmosphere and even today make most of the O₂ in our atmosphere

4. Numerous Symbioses

Symbiotic bacteria are common in all kingdoms of life, including bacteria symbiotic with other bacteria almost all animals have bacterial symbionts

a. Cellulose Digesting Bacteria

Some species of bacteria, some protists, and most fungi are able to produce the proper enzymes to digest cellulose in plants virtually no animal species can produce cellulose digesting enzymes

animals that are strict herbivores rely on cellulose digesting microorganisms to extract nutrients from plant materials

eg. termites

100’s of species of cellulose digesting bacteria a diet restricted to wood only (not softer green parts of plants) is very low in nitrogen and termites also have nitrogen fixing bacteria that convert N₂ into useable nutrients for the termites

eg. Ruminant mammals (such as cows)

A portion of their stomachs are modified into fermentation chambers they have several 100 species of cellulose digesting bacteria, 40-50 species of cellulose digesting protists, and some fungal species (billions of cells/ml; 1/5th tsp) that ferment the plant material to release nutrients for the cow to absorb

b. Root Nodules; a symbiosis between bacteria and plants

Nitrogen is an important nutrient for all forms of life and one of the most hard to get essential nutrients for plants even though the air contains 80% N₂, no higher organisms can use it therefore nitrogen is usually in short supply for most organisms

eg. Rhizobium: N₂ → NH₃

eg. methane seeps

Some plant roots have a symbiotic relationship with these nitrogen fixing bacteria mainly legumes (beans, peas, bluebonnets) also some bryophytes, water fern, some cycads

Plants secrete chemicals into soil to attract bacteria

Rhizobium or some cyanobacteria (mainly Anabaena or Nostoc) responds by secreting chemicals that trigger plant to enclose the bacterial cells

Nitrogen can only be “fixed” in low O₂ conditions so the plant creates a “growth chamber”: a swelling on root called root nodules

Each nodule contains millions of bacteria

Bacteria convert nitrogen gas (N₂) into useable nitrogen ‘fertilizer’ for the plant

eg. Rhizobium: N₂ → NH₃
up to 30% of the plants sugars made by photosynthesis are given to the bacterial symbionts in exchange for the NH$_3$ they produce

bacteria get nice place to live and free carbs

plant gets hard to get nitrogen fertilizer in the form of ammonia

**other symbioses with N-fixing bacteria:**
- diatoms
- fungi of certain lichens
- shipworms
- termites

c. Petroleum Fly Larvae

the adult fly lives around petroleum seeps (eg. La Brea tar pits) feeding on insects that get stuck in the goo

its larvae actually live in the oil and survive by eating the bacteria that thrive in the oil and are symbiotic in their guts.

d. Human bacterial symbionts; the “normal flora” or “microbiome”

"you are born 100% human, but die 90% microbial"

-even this adage has been recently disproven:

- make essential vitamins
- protect us from pathogens
- provide additional nutrients from food eaten
- remove plant toxins and some carcinogens
- remove chemicals like H$_2$ gas that are toxic to “good” gut bacteria
- activate our immune systems to better resist infections

gut bacteria change and adapt as foods change

- those better able to metabolize dominant food tend to increase

- eg. baby:milk $\rightarrow$ solid food $\rightarrow$ vegetables

we are beginning to see that our symbiotic microorganisms play an essential role in our survival, adaptation and evolution

our microbiome is also strongly correlated with our genetic makeup

- may be as distinctive as our fingerprints; mostly correlated with genes that control our immune system

a new (2011) study shows that the abundance of certain bacteria in your feces correlates with your age, gender, body mass index, and nationality

bacteria colonize our gut in the womb where they begin to shape our immune system and susceptibility to diseases

3 lbs of bacteria (10x’s the number of human cells; 400 microbial genes for each human gene)

- mainly in gut

- eg. dental plaque on human teeth contains 100 or more bacterial species; many of which are found no where else in nature

- eg. some places on the skin contain up to 300 different species

- the “richest” areas: belly button, buttocks & gluteal crease

- only a few species were found: greasy spot behind ear, side of nose, toe webs and sternum

which species you have on your skin determine whether you get acne or not

some are **mutualistic** (both benefit)

- eg. skin bacteria play a vital role in preventing unchecked inflammation triggered by injury and bacterial pathogens

- widespread use of antibacterial hand gels may exacerbate such skin inflammation

- eg. gut bacteria

- $\rightarrow$ help break down hard to digest fibers and starches

obesity, diabetes, Crohn’s disease, colitis, autism may be the result of an imbalanced microbial ecosystem in our guts

some forms of severe malnutrition have been linked to a particulary group of intestinal bacteria

intestinal bacteria have also been linked to celiac disease & inflammatory bowel syndrome

some are **commensals** (don’t benefit or harm us)

- but many of these are **opportunists**

- $\rightarrow$ can sometimes cause problems

d. some bacteria (bdellovibrions) are parasitic inside other bacteria

e. some algae & protozoa have a mutualistic relationship with bacteria

- eg. bacteria inside protist inside termite

f. some fungi have a symbiosis with blue green bacteria

- eg. one form of lichens

5. Unique Bacterial Ecosystems:
A. Deep Ocean Hydrothermal Vents

discovered in 70’s at deep ocean ridges
hot mineral rich waters flowing out of cracks in the crust,
especially rich in $\text{H}_2\text{S}$ (hydrogen sulfide)
whole community of organisms, many are unique species;
include large worms and clams, crabs, shrimp, fish, and dense clouds of bacteria
bacteria live inside the tissues of some of these animals;
the animals absorb $\text{H}_2\text{S}$ from the hot waters,
use **hemoglobin** to carry this $\text{H}_2\text{S}$ to the bacteria deep in their tissues
the bacteria use the energy in $\text{H}_2\text{S}$ to make sugars which the animals absorb
therefore it’s an entire ecosystem that is not based on solar energy for autotrophic production

B. Hydrocarbon Seeps

methane (natural gas) leaks from sediment in Gulf of Mexico
creates methane pools on seafloor
mussels at hydrocarbon (methane) seeps have symbiotic bacteria in their gills
these bacteria oxidize methane to get energy and food
bacteria live in vacuoles of gill cells
clam gets organic molecules made from the methane and secreted by the bacteria

**Direct Human Impacts of Bacteria**

1. Crop Production

one of the most limiting nutrients especially for plants is **nitrogen**
but there is lots of nitrogen in the air $\rightarrow 80\% \text{ N}_2$
some bacteria can **fix** this nitrogen gas $\rightarrow$ only organisms that can do this
some of these bacteria form symbiotic **root**

2. Food Products

fermenting bacteria are used to make a wide variety of **foods**:
- bread, bakery products, yogurt, cheeses, etc, etc, etc,
many of the smells and flavors of these food products is due to the bacterial used
most of these products use a culture of 6 - 8 different bacterial species; often with several fungal species as well

A. Cheeses

Often produced by the actions of groups of microorganisms including bacteria and fungi
the characteristic textures and flavors of different cheeses result from; the kind of milk used (cow, goat, sheep, etc); whether the cheese is ripened (cured) or unripened and what mixture of microorganisms are used

The first step in making most cheeses is to prepare a **curd** by adding lactic acid bacteria and rennin or bacterial enzymes to milk.
The bacteria sour the milk and enzymes coagulate the milk protein, casein, to produce a **soft ‘curd’** to make cheese and a **liquid ‘whey’** which is a waste product.
The amount of whey removed determines the hardness of the cheese. eg. soft cheeses the whey is simply drained away. Harder cheeses are heated and pressurized to remove additional whey from the mixture.

After this separation, most cheeses are ripened with inoculations of various species of bacteria and/or fungi.

B. Other milk based products

**eg. Yogurt**
The lactose in the milk is fermented by microorganisms to produce lactic acid. The flavor is a result of the sugar and the 2-3% lactic acid generated by this fermentation.

**eg. Butter**
Butter is produced by inoculating cream or milk with microorganisms and allowing it to. The characteristic aroma and taste of butter result from the fermentation process.

**eg. Buttermilk**

**eg. Sour Cream**

C. Sourdough Bread

Wheat flour is fermented using *S. exiguus* and *Lactobacillus sanfrancisco* to produce the tart, acidy flavor
D. Oriental Sauces

e. Soy Sauce, Memmi
Soy sauce is produced by the fermentation of roasted soy beans and wheat using a mixture of various bacteria and fungal species including:

E. Vinegar

Vinegar is a fermented food traditionally made by the spontaneous souring of wine. Industrial Vinegar production begins by inoculating the fruit juice with yeasts which ferment it to an alcohol content of 10-20%. Then the juice in inoculated with the bacterium, Acetobacter aceti, which convert the alcohol to acetic acid.

F. Cured vegetables

e. Sauerkraut
Sauerkraut is produced by the natural fermentation of layers of shredded cabbage alternating with layers of salt. The salt inhibits undesirable bacteria and draws out the juices of the cabbage. In two to three months fermentation by microorganisms produce acids and esters with the desired aromas and flavor.

e. Pickles
Pickles are made by fermenting cucumbers in a mixture of bacteria normally found growing on them.

e. Green Olives

e. Kimchi
Made from shredded cabbage fermented with lactic acid bacteria

G. Cured Meats

e. Cured (Fermented) Beef or Pork Sausages
eg. Pepperoni, Salami, Thuringer, Polsa
These are generally produced by adding seasoning agents to the ground meats, stuffing the meat into casings and incubating them with a bacterial culture at warm temperatures. Mixed acids produced from the fermentation give the sausage its unique flavor and aroma.

3. Beverages

A. Acidophilus Milk
Lactobacillus acidophilus is added to milk to produce an acidity of 2-3% lactic acid.

B. Coffee
After coffee beans are picked they are soaked in water containing natural cultures to loosen the berry skins before roasting. Some fermentation occurs which is believed to produce some of the unique flavors of various varieties of coffee.

C. Cocoa
Microbial fermentation is used to help remove the cocoa beans from the pulp covering them in the pod. The products of this fermentation contribute to the flavor of the cocoa.

4. Bacteria as food

the only bacteria cultured today as a protein supplement is Spirulina, a bluegreen bacterium common in freshwater lakes and ponds as "pond scum"

some claim many unsubstantiated benefits
but no solid evidence for most claims

e. cure AIDS, Alzheimer’s, herpes, etc
also: energize body, enhance digestion, focus mind, keep pets healthy, etc

complaints about nausea and diarrhea are common

there is some interest in using bacteria directly as food product

bacteria are high in protein

Meat and fish contains ~20% protein
bacterial cells contain ~50% protein

and can be easily grown in large quantities to produce protein much quicker than cattle or other animals:

eg. estimated yield of protein produced per day by:

1000 lb steer → 1 lb
1000 lbs soybeans → 100 lbs
1000 lbs bacteria → 100 trillion lbs

and bacterial protein would also be >10x’s cheaper than cattle or fish protein

5. Industrial Microbiology:

a. current production:

uses large cultures of bacteria and other microorganisms to produce various industrial chemicals such as amino acids, citric acid, enzymes, pharmaceuticals, etc

e. amylase (Bacillus subtilis) → textiles, food and drink production

e. proteases (Bacillus) → clarify beer, tenderize meat, used in toothpaste to reduce plaque; some used in laundry detergents to help clean

e. rennet (several species) → prepares curd for cheese making

e. leather tanning

e. linen processing; uses Clostridium species

eg. millions of pounds of specific amino acids and vitamins are extracted from bacterial culture

b. future production:

eg. sticky slime secreted by bacteria contains a natural adhesive that may be less expensive but just as strong as a wood adhesive for making plywood and particleboard

e. genetically engineered bacteria are
increasing the variety of industrial products we can produce from bacteria

6. Pharmaceutical Products

a. many natural bacterial products are harvested for pharmaceutical purposes:

eg. antibiotics.  antibiotics were first discovered in fungi (eg. Penicillin); today many antibiotics are also extracted from “fungus-like” bacteria.

Amphotomycin from Streptomyces canus
Bacitracin from Bacillus subtilis
Erythromycin from Streptomyces erythreus
Nystatin from Streptomyces noursei

eg. botox. botulism toxin, one of the deadliest bacterial toxins is injected into muscles of face and head to eliminate wrinkles

also is used to treat migraines

new (2010) research has found that facial expressions trigger and intensify appropriate feelings

paralysis produced by botox injections may alter emotional reactions associated with proper facial expression and may even weaken brain circuits that coordinate some emotions

eg. streptokinase (Streptococcus) → dissolves clots, reduced heart attacks

b. Genetic Engineering

genes for human proteins have been inserted into bacteria and cultures of these bacteria now produce commercial quantities of:

human insulin
human growth hormone
human somatostatin
human interferon

7. Microbial damage to foods and other products

because bacteria are such good decomposers they cause billions of dollars in crop and materials losses each year

eg. $50 B/yr stored foods are lost due to bacteria

eg. paper, paints, textiles, leather, metal, etc are destroyed or weakened

8. Microbial Corrosion

metal corrosion causes $100’s of Billions of dollars in damage to pipelines, bridges, storage tanks etc in the US each year

almost all metal corrosion is caused at least partly by bacteria

many bacteria produce hydrogen sulfide and various acids that corrode metals and other products

eg. the “ruddles” on the sunken titanic are largely due to bacterial activity

long term exposfer may also cause bacterial corrosion on many other materials such as plastics, concrete

9. Mining of Minerals

some bacteria are associated with gold and other mineral deposits

can be used to extract and concentrate metals from low grade ores and slag

eg. gold

some bacteria can extract gold from solution and convert it into gold particles that can be extracted

researchers have now developed a genetically modified bacterium that emits light when gold is detected. Can use light meter to detect the signal

eg. Maganese Nodules

fist sized, deep sea mineral deposits formed by bacteria

1st discovered on Challenger expedition of 1874

contain high concentrations of Fe, Mn, Cu, Ni, Co

esp abundant on red clay sediments of NE Pacific

US Bureau of Mines estimates the richest deposits exceed 16 Billion metric tons (17.6 B tons)

→ 20x’s all known land reserves of some of these minerals

→ >2000 years worth at current usage

→estimate that 16 Million tons accumulate each year (“grow” ~ 1-10mm/million yrs)

small scale trials have collected some

→ still not economically feasible

eg. 2006 some bacteria are being used to recover palladium from spent catalytic converters

10. Bioremediation

because of their ability to metabolize such a wide variety of chemicals bacteria are being tested and used to help decontaminate hazardous waste sites

soil bacteria can sometimes transform highly toxic chemicals into harmless compounds

eg. contaminated soil around munitions factories are laced
with species that can metabolize nitroglycerine and other explosives
e.g. soil bacteria that can transform benzene benzene into harmless chemicals
e.g. a community of bacteria that break down components of petroleum are sprinkled on oil spills to reduce the damage they might cause on beaches
eg. some bacteria can decompose creosote, trichloroethylene and 245-T (agent orange)
as our knowledge increases we will be able to drastically cut the costs of cleanup of contaminated sites

11. Renewable Energy Production

a. Methane Production
Some bacteria (archaea) are used for energy (methane) production
a typical dairy cow produces 200-600 l of methane/day; 50-150 kg/yr
if burnt, a cows annual methane emissions would yield about as much energy as 200 liters of gasoline
gut bacteria produce 2B tons of methane/yr affect global carbon cycle
methane collected from garbage and dung used as renewable energy source

eg. Staphylococcus aureus
When S. aureus is allowed to grow in foods, it can produce a toxin that causes illness.
Although cooking destroys the bacteria, the toxin produced is heat stable and may not be destroyed.
Staphylococcal food poisoning occurs most often in foods that require hand preparation, such as potato salad, ham salad and sandwich spreads.

e. Salmonella
The gastrointestinal tracts of animals and man are common sources of Salmonella.
High protein foods such as meat, poultry, fish and eggs are most commonly associated with Salmonella.
The major causes of salmonellosis are contamination of cooked foods and insufficient cooking.
contamination of cooked foods occurs from contact with surfaces or utensils that were not properly washed after use with raw products.

eg. Clostridium botulinum
Botulism accounts for fewer than one of every 400 cases of food poisoning in the U.S. It occurs mostly in home-canned foods.
Cl. botulinum can exist as a heat-resistant spore, and can grow and produce a neurotoxin in under processed, home-canned foods.
An affected food may show signs of spoilage such as a bulging can or an off-odor.

b. Biofuels
existing biofuels are produced from waste cooking fats or hydrocarbon producing plants
they cannot be processed by refineries
genetically engineered bacteria can now be made to convert waste sugar to feedstock for refineries
would dramatically reduces cost of alternative energy production
c. Fuel Cells
biologists have recently (2006) powered a small fuel cell by feeding bacteria chocolate factory wastes (diluted caramel and nougat wastes)
the bacteria broke down the waste sugars to produce hydrogen
the hydrogen was used to power a fuel cell could provide a waste for normally landfilled wastes
another microbe (Rhodoferax ferrireducens) is

12. Toxic Blooms
some cyanobacteria can cause toxic fish kills in fw ponds, lakes and reservoirs
especially in spring and fall

13. Bacterial Diseases

a. Food Poisoning
It is estimated that between 24 and 81 million cases of food borne diarrhea disease occur each year in the United States,
costing between $5 billion and $17 billion in medical care and lost productivity.
More than 90 percent of the cases of food poisoning each year are caused by Staphylococcus aureus, Salmonella, Clostridium perfringens, Campylobacter, Listeria monocytogenes, Vibrio parahaemolyticus, Bacillus cereus, and Entero-pathogenic Escherichia coli.
These bacteria are commonly found on many raw foods. Normally a large number of food-poisoning bacteria must be present to cause illness.
Poor personal hygiene, improper cleaning of storage and preparation areas and unclean utensils cause contamination of raw and cooked foods.
b. Bacterial Pathogens

[some examples of bacterial diseases]

**Tuberculosis** *(Mycobacterium tuberculosis)*  
**Gonorrhoea** *(Neisseria gonorrhoea)*  
**Syphilis** *(Treponema pallidum)*  
**Borellia** → relapsing fever, lyme disease  
**Leptospira** → leptospirosis from urine of dogs, cats, pigs  
**Legionella** → legionnaires disease  
**Bordetella** → whooping cough  
**Salmonella** → typhoid fever  
**Shigella** → bacillary dysentery  
**Yersinia** → plague  
**Vibrio** → cholera  
**Clostridium**: botulism, gas gangrene, tetanus  
**Staphylococcus aureus**  
**Streptococcus pneumonia**

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Some Examples of Bacterial Diseases:

eg. **Tuberculosis** *(Mycobacterium tuberculosis)*

is an ancient disease  
→ skeletons and mummies from 4500 BC show signs of the disease  
has been called the world’s most neglected epidemic  
→ kills more people worldwide than any other infectious disease  
about 1/3\(^{rd}\) of the world’s population is infected,  
with 8-10 million new cases each year  
about 2 million people die each year from the disease  
one of most easily combated diseases if caught early  
very difficult to get rid of in advanced cases  
slow growing pathogen – respiratory disease  
infection in lungs causes formation of ‘tubercles’  
90% of infected people remain infected for life but  
ever develop symptoms of the disease = **asymptomatic** (subclinical)

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Good example of a balanced host/parasite relationship  
→ hosts are usually not aware of pathogen and it is usually eliminated by the immune system  
if body’s defenses fail → disease results  
most commonly acquired by inhaling  
has long incubation period  
the infection causes formation of tubercles in lungs as bacteria multiply inside  
of body’s defenses are overwhelmed may produce symptoms:  
weight loss  
coughing bloody cough  
fatigue  
weakness  
anorexia  
low grade fever  
may become a chronic infection  
major concerns today:  
1. two new strains have appeared:  
   → a fast growing form  
grows 1000x’s faster  
much more easily spread → don’t need extended contact (just standing in line with infected can get it)  
   → a completely antibiotic resistant form  
2. increased poverty and urbanization  
   → rates in cities higher than in rural areas  
is a disease of the urban poor, homeless, AIDS victims  
3. increase in HIV patients  
   more susceptible to infection
**eg. Anthrax (Bacillus anthracis)**

- common soil organism
  - grows slowly in soil
- produces spores that can persist for years
  - up to 60 years
- is a zoonosis – animal disease that people can catch
  - a fatal disease of livestock; eg. sheep, cattle, goats, horses
  - people catch it from animals, not usually from other people
  - soil is a reservoir → spores can persist
  - in humans is mainly and occupational disease: farmers, vets, textile and fur workers, etc
- ID is very low: 1-3 spores
- enters through cuts and abrasions on skin or spores can be inhaled

**cutaneous anthrax**

- if spores enter skin through abrasions or cuts:
  - begins as a skin infection of pustules

**pulmonary anthrax**

- is the most dangerous form; much higher mortality rate
  - → can be fatal within hours
- need pretty high exposure to spores to actually get the disease
- produces flu like symptoms
- gets into blood much more quickly → systemic toxemia

**eg. Syphilis (Treponema pallidum)**

- humans are only natural hosts
- STD → survives only a few minutes to hours in body secretions; up to 36 hrs in stored blood
- first recognized in 1500’s:
  - thought it may have been a disease picked up by Native Americans and spread to Europeans,
  - new evidence doubts this, it was in Europe before contact with Americas
- very common in US until 40’s and discovery of penicillin
- on increase again today
- esp among prostitutes and drug users
- disease is slow and progressive with long periods of latency
  - easily treated in early stages, difficult to treat in advanced stages
- progresses through three major stages:
  - 1st – (9-90d after infection)
  - after sexual contact, the bacteria enters through breaks in skin
  - produce open sores in genital area (cancre)
  - they persist for several weeks, then heal
  - 2nd – (3 wks – 6 mo after 1st stage heals)
    - several months later the bacteria have spread throughout the body,
    - secondary lesions appear on skin surface: trunk, arms, legs, genitalia, palms, soles
    - highly infectious at this stage
    - causes fever, headaches, sore throat, rash, etc.
    - symptoms disappear in a few weeks
  - 3rd – (3-30 yrs after primary infection)
    - latent period lasts up to 20 years, about 30% of patients untreated will show severe pathology
    - noncommunicable unless secondary lesions appear again
    - causes soft lesions in skin, bone, blood vessels, liver, CNS
    - wide range of symptoms depending on tissue showing lesions:
      - rupture of blood vessels
      - heart damage
      - blindness
      - derangement
      - convulsions
      - brain damage
eg. Gonorrhea (*Neisseria gonorrhoeae*)

highly infectious **sexually transmitted disease**

known from ancient times

- described in 3500 BC Egyptian papyrus
- 3rd century BC, Hippocrates described its mode of transmission:
  "excesses of the pleasure of venus"  ie. "venereal disease"

strictly human pathogen

several hundred thousand (600,000) cases reported in US each year

> 60% cases are 15 – 24 yrs old

→ but millions may be infected and not know

requires direct body contact

→ does not survive more than 1-2 hours outside body

**Infectious Dose:** ~100-1000 bacteria

in males

→ usually infects urethra = acute urethritis

→ causing yellowish discharge

if untreated may lead to arthritis, endocarditis or meningitis

but many are asymptomatic

in females

urinary and reproductive systems may both get infected

often mild or asymptomatic in early stages

→ most common cause of spread of the disease

produces bloody vaginal discharge in ~1/2 cases

if untreated, may ascend to cause pelvic inflammatory disease

scar tissue produced may cause sterility

infants born to infected moms may become infected

→ results in blindness

silver nitrate, or now antibiotics applied to child's eyes immediately after birth

14. Bacterial pathogens have also been implicated in contributing to some psychological diseases such as obsessive compulsive disorder (Streptococcus sp.)

15. Sewage Treatment

eg. activated sludge

16. Bacteria for Biological Control

eg. *Bacillus thuringiensis* → a pathogen of Lepidoptera only

as bacterial cells make spores it also makes a diamond shaped protein crystals

sprayed on leaves these crystals dissolves in caterpillar stomach juices

on dissolving it causes paralysis and death to caterpillar

eg. *Bacillus popilliae* → kills Japanese beetle larvae

17. Forensics

researchers have recently reported (2010) that the 1400 or so different kinds of bacteria on our fingers can leave a unique "microbeprint" on surfaces such as computer keyboards and mice

samples up to 2 weeks old could be linked to a specific user

18. Future Applications:

a. pharmaceuticals

bacteria living in extreme environments are being screened for useful chemicals

eg. The "Berkeley Pit" in Butte, Mont., is the nation's largest environmental-disaster site, with 40 billion gallons of highly toxic copper-mine waste. Researchers have found more than 160 types of "extremophiles" in the pit and have demonstrated that some are effective against lung and ovarian cancers.

the botulism toxin extracted from *Clostridium* species is the Botox used in "beauty" treatments

b. gut flora

our bacterial symbionts exist as a complex interacting community with specific characteristics

we're finding that each person has a unique set of microorganisms on their skin and in their guts

eg. The bacteria found on a keyboard can identify the user as well as fingerprints

→ intestinal flora seem to have a dramatic effect on several "autoimmune" diseases

promising research has shown fecal transplants have cured symptoms of Parkinsons, diabetes and obesity
gut bacteria affect our mood and behavior
the bacteria telegraph chemicals to the brain via vagus nerve that can have a direct effect on behavior
may be direct connection to gut flora and psychiatric disorders such as depression, autism and schizophrenia
use of antibiotics can cause dramatic and long term changes in our gut flora and increase risk of some chronic diseases such as IBS
with each use of antibiotics the gut flora usually return to previous numbers and diversity
but occasionally, changes remain permanent
in the future:
eg. might be able to test for changes in kinds and numbers of species as an early indication of certain diseases
eq. doctors may prescribe bacterial supplements to improve physical health
eq. fecal transplants: restores bowel flora to a healthy state
eq. 100% cure rate for C. difficile infections, a deadly disease common in patients on antibiotic therapy
c. using bacteria for data storage
scientists are looking for a more permanent way to store information
9 germ attacks in Tokyo
→ action was meant to kill millions but there were no known injuries or deaths
1991: Gulf War: Iraq had deployed but not used missiles carrying anthrax, botulism and aflatoxin
2001: Anthrax was mailed to several people and businesses in east coast → several deaths
1975 Biological weapons convention
produced 1st worldwide treaty; prohibited development, production and stockpiling and use of biological arms
Anthrax as a Biowarfare Agent
preferred biowarfare agent since it lasts long and can be relatively easily dispersed
50% of people who inhale 8000-10,000 spores will die
most research as biowarfare agent centers around making the spores lighter and more easily spread in air