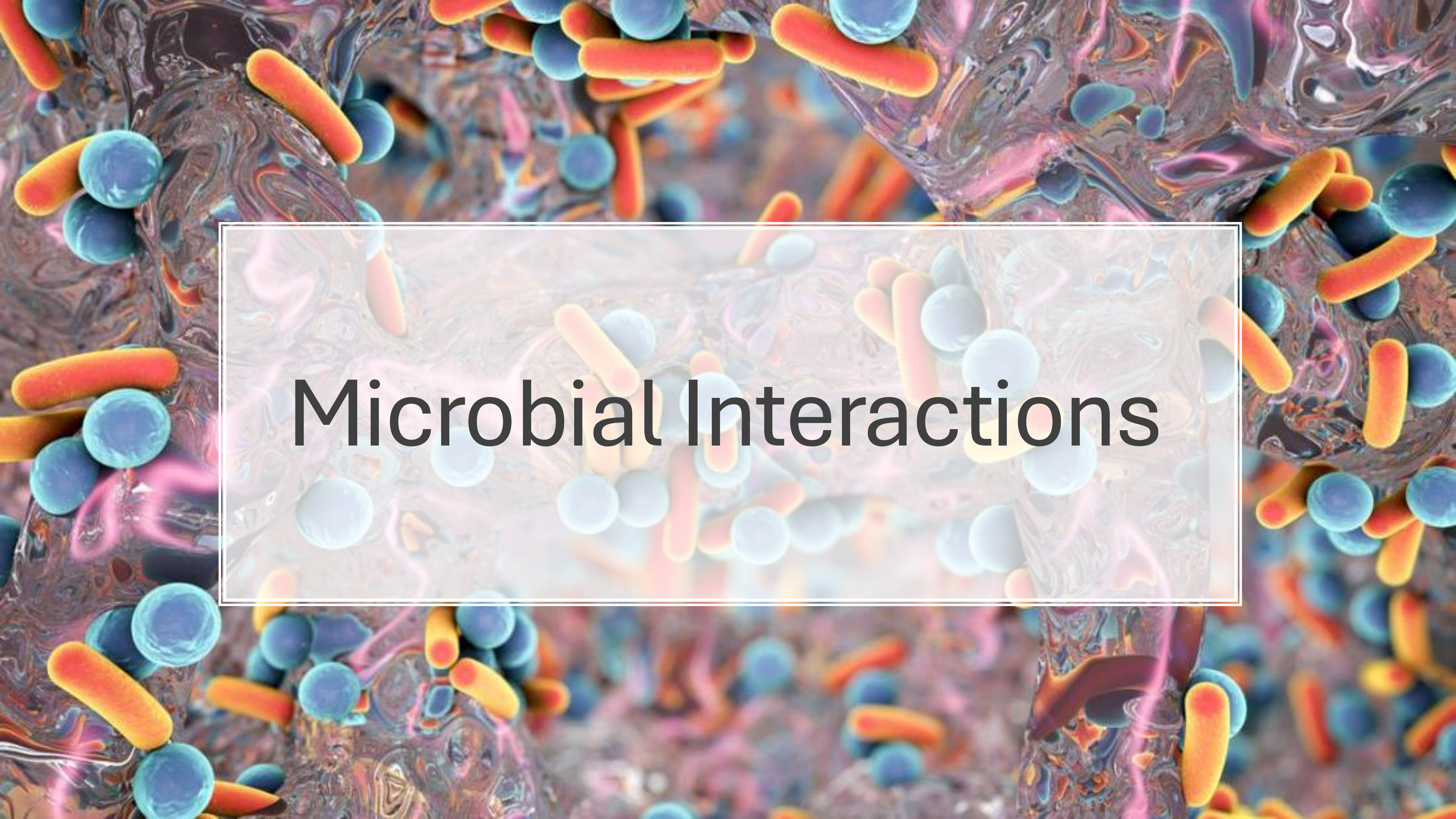
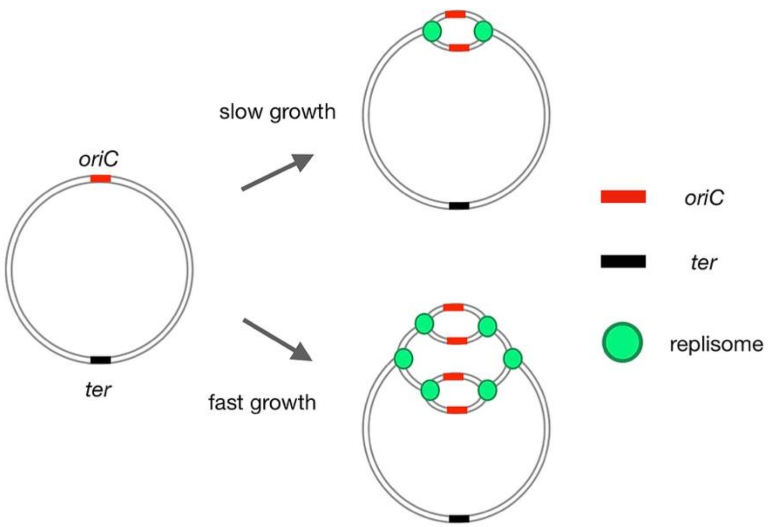


# Microbial Interactions

# Microbial Growth

- **Growth:** increase in the number of cells
- **Generation (doubling) time:** time required for microbial cells to double in number
  - Varies across for microbial species
  - Varies depending on conditions
  - Total number of cells = $2^{\text{number of generations}}$
  - E.g.: **Escherichia coli** = 20 minutes




| Numbers of Cells | Numbers Expressed as a Power of 2 | Visual Representation of Numbers |
|---|---|---|
| 1 | $2^0$ | • |
| 2 | $2^1$ | •• |
| 4 | $2^2$ | •••• |
| 8 | $2^3$ | •••••••• |
| 16 | $2^4$ | •••••••••••••••• |
| 32 | $2^5$ | •••••••••••••••••••••••••••••••• |

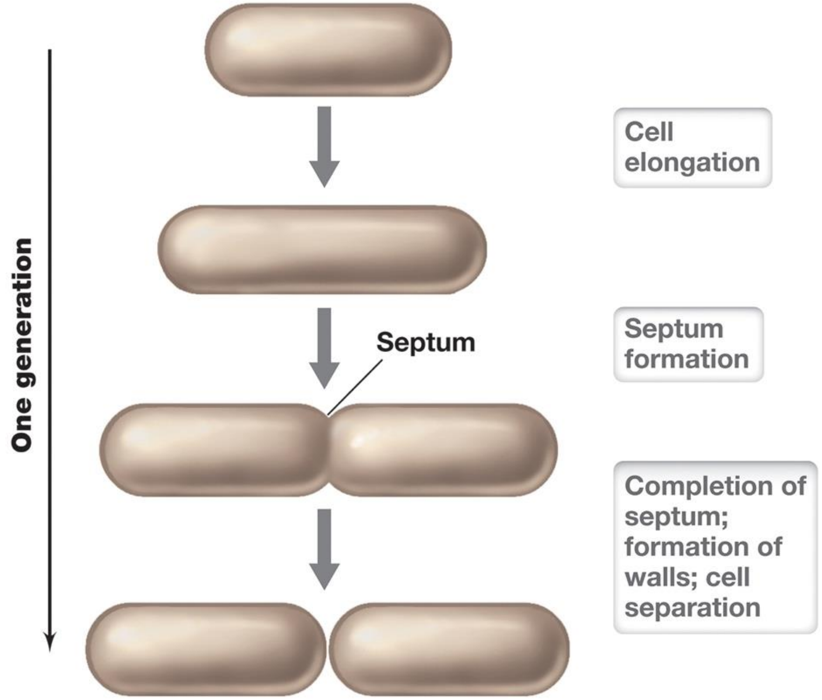
**(a)** Visual representation of increase in bacterial number over five generations. The number of bacteria doubles in each generation. The superscript indicates the generation; that is, $2^5$ = 5 generations.

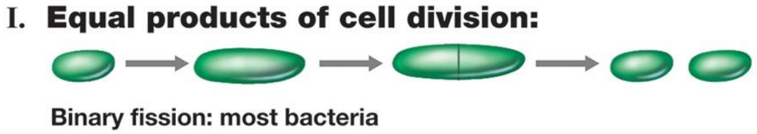
| Generation Number | Number of Cells | Log$_{10}$ of Number of Cells |
|---|---|---|
| 0 | $2^0$ = 1 | 0 |
| 5 | $2^5$ = 32 | 1.51 |
| 10 | $2^{10}$ = 1,024 | 3.01 |
| 15 | $2^{15}$ = 32,768 | 4.52 |
| 16 | $2^{16}$ = 65,536 | 4.82 |
| 17 | $2^{17}$ = 131,072 | 5.12 |
| 18 | $2^{18}$ = 262,144 | 5.42 |
| 19 | $2^{19}$ = 524,288 | 5.72 |
| 20 | $2^{20}$ = 1,048,576 | 6.02 |

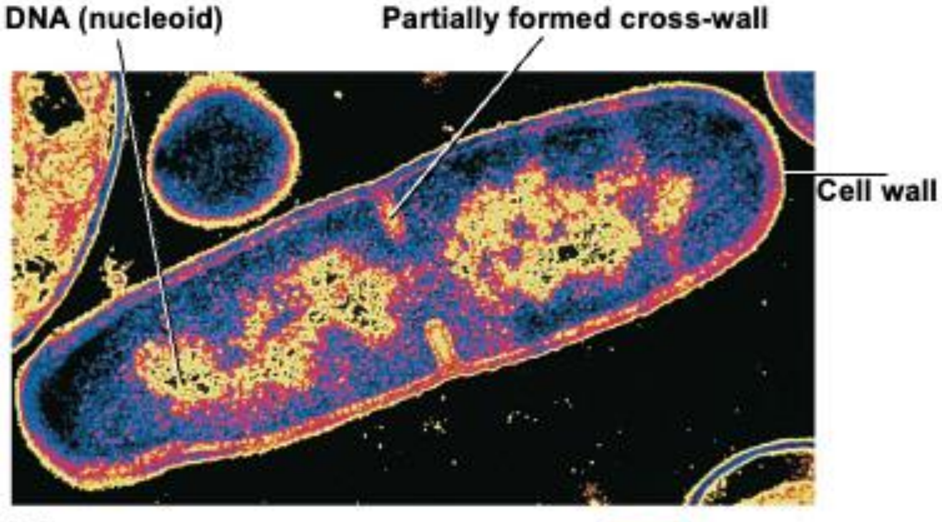
**(b)** Conversion of the number of cells in a population into the logarithmic expression of this number. To arrive at the numbers in the center column, use the $y^x$ key on your calculator. Enter 2 on the calculator; press $y^x$; enter 5; then press the = sign. The calculator will show the number 32. Thus, the fifth-generation population of bacteria will total 32 cells. To arrive at the numbers in the right-hand column, use the log key on your calculator. Enter the number 32; then press the log key. The calculator will show, rounded off, that the $\log_{10}$ of 32 is 1.51.

# Microbial Growth

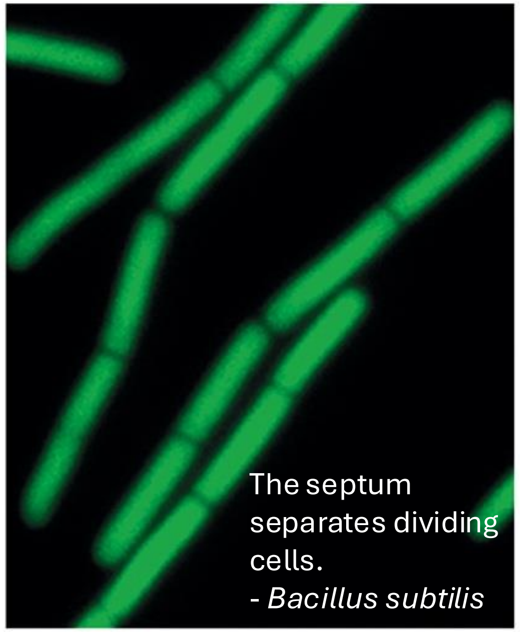
- **Binary fission**: cell division following enlargement of a cell to twice original size
- **Septum**: partition between dividing cells, pinches off between two daughter cells
- Balanced growth - a result of binary fission, producing nearly identical cells



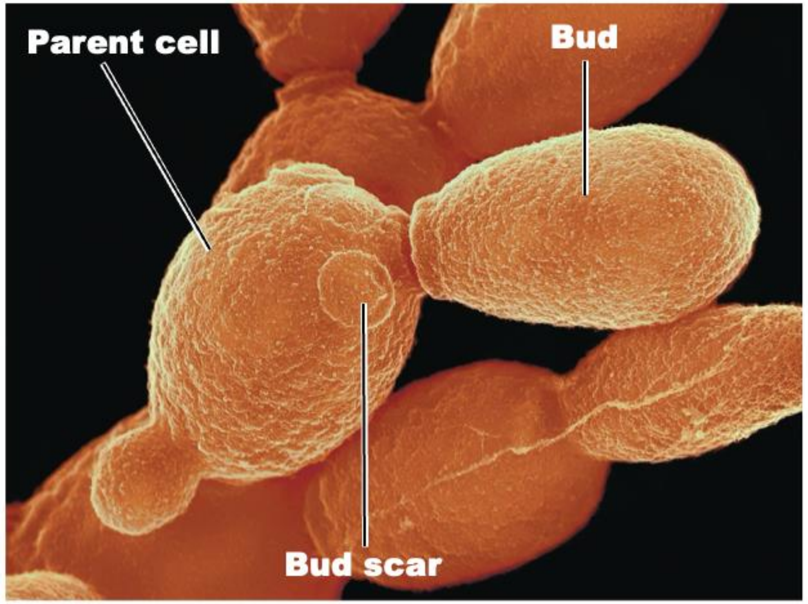



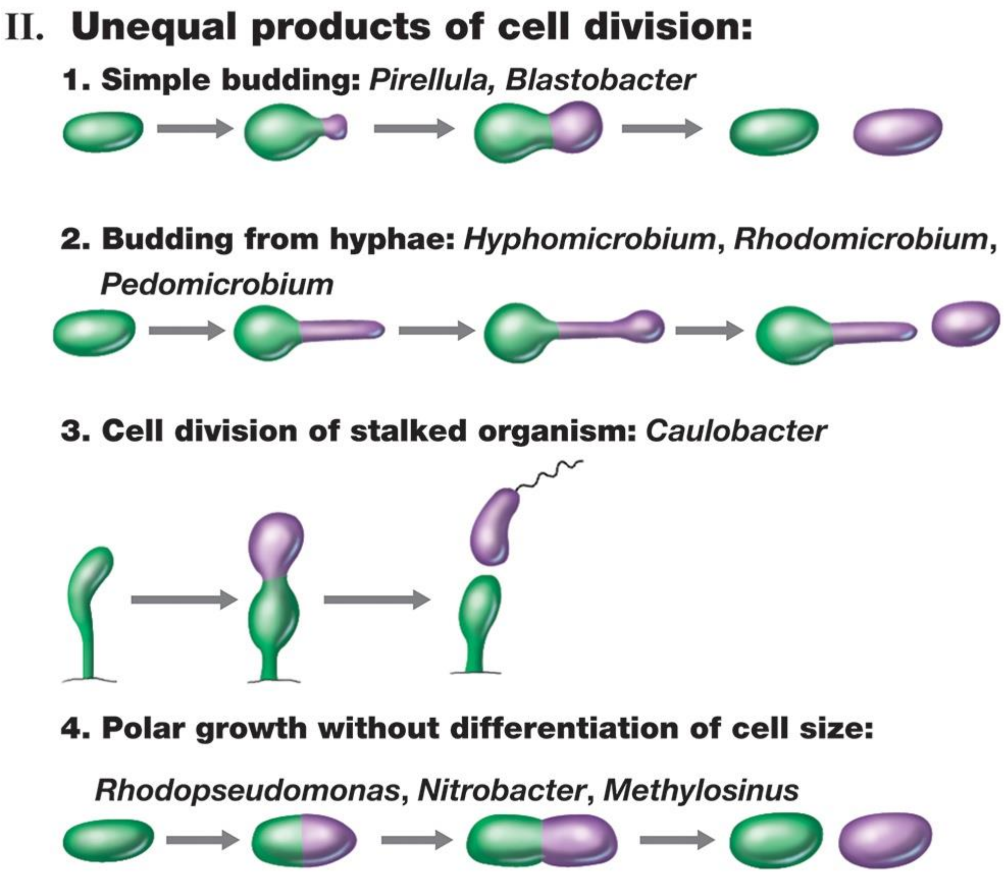

**(b)** A thin section of a cell of *Bacillus licheniformis* starting to divide



# Microbial Growth

- **Budding** cell division
  - Unequal cell growth forming different daughter cells.
  - Some budding bacteria form cytoplasmic extensions
  - Typical of yeasts (unicellular fungi)



# Microbial Growth

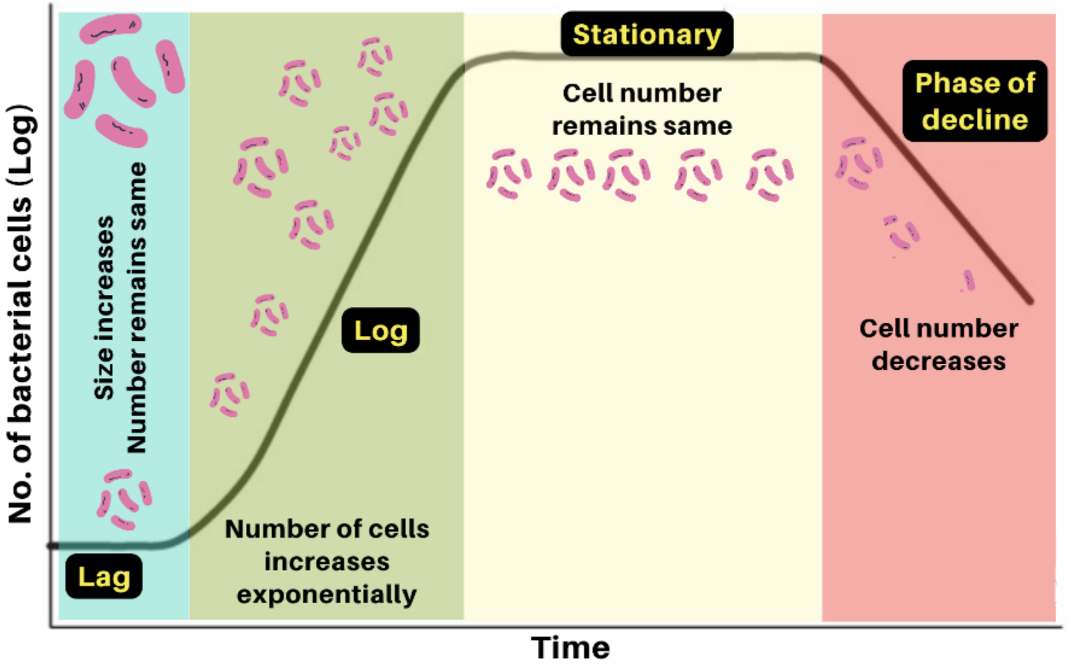
- Hyphal Growth
  - **Hyphae:** long, thin filaments of actinomycetes (gram-positive filamentous bacteria, **e.g.**, **Streptomyces**)
  - Hyphal growth occurs only at filament tip
  - Cell growth is not linked directly to division (no septa)

Streptomyces

# Microbial Growth Cycle

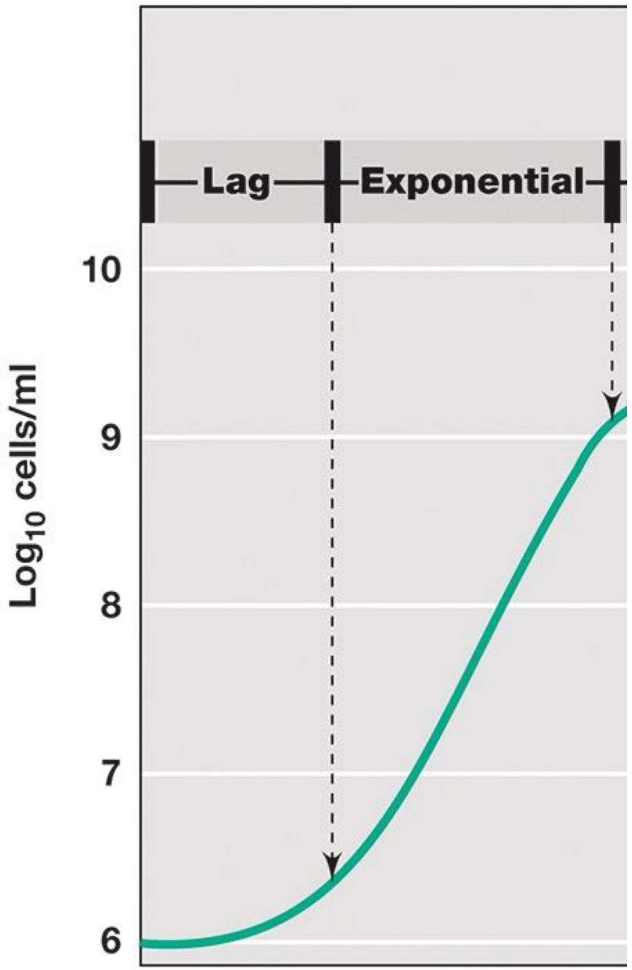
- **Batch culture:** a closed-system microbial culture of fixed volume

- Typical **growth curve** for population of cells grown in a closed system is characterized by four phases.
  - **lag phase**
  - **exponential phase**
  - **stationary phase**
  - **death phase**



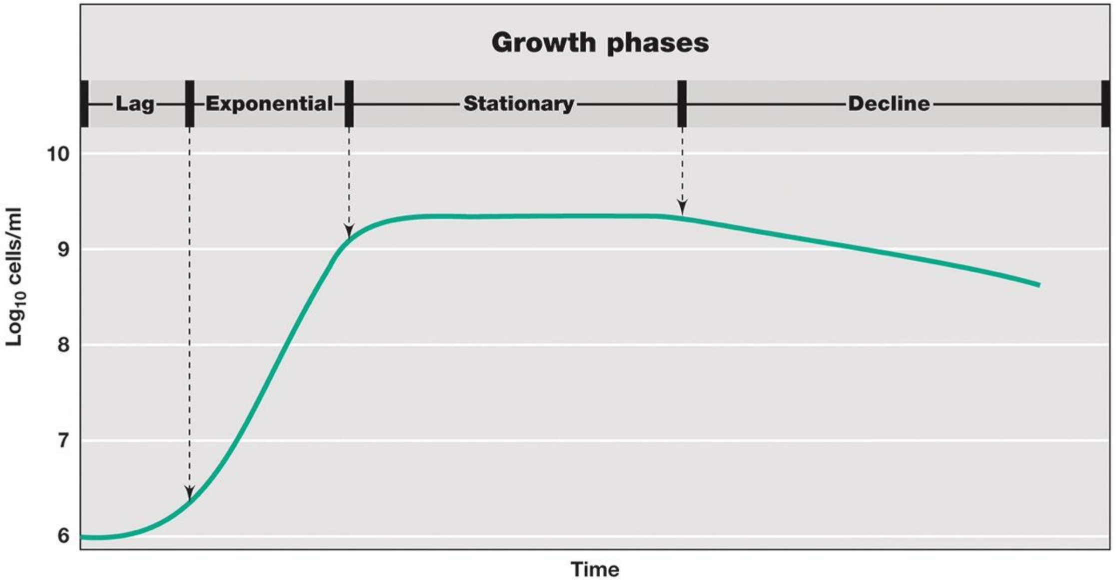
# Microbial Growth Cycle

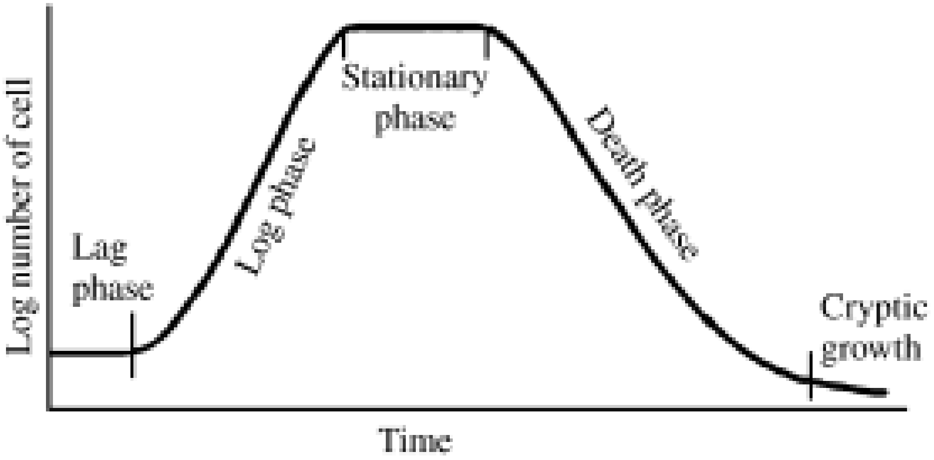
- Lag and Exponential Phases
  - **Lag phase:** interval between inoculation of a culture and beginning of growth
    - new conditions require altering metabolic state
    - time needed for biosynthesis of new enzymes and to produce required metabolites before growth can begin
  - **Exponential phase:** doubling at regular intervals
    - Balanced growth- cells are metabolically identical
    - rates vary greatly
    - influenced by media, conditions, organism itself
    - continues until conditions can no longer sustain growth



# Microbial Growth Cycle

- Stationary and Death Phases
  - Growth limited by nutrient depletion or waste accumulation
  - **Stationary phase:** growth rate of population is zero
  - Metabolism continues at greatly reduced rate
  - **Decline phase:** total number decreases due to cell death
  - **Cryptic growth:** subpopulations adapt



# Realistic growth rates in the environment

Growth rates of soil bacteria in nature are <1% of the maximum rate measured in the laboratory


# Niche space

- The growth of microorganisms in nature depends on the **growth conditions** and the available **resources** (nutrients)

- Differences in physicochemical conditions (temperature, pH, water, light, oxygen) and in the **type** and **amount** of different resources of an environment
  - This defines the niche for a particular microorganism

- Countless niches exist on Earth, which are responsible for the great metabolic diversity of today's microorganisms

# Niche space

*Deep mountain lakes*

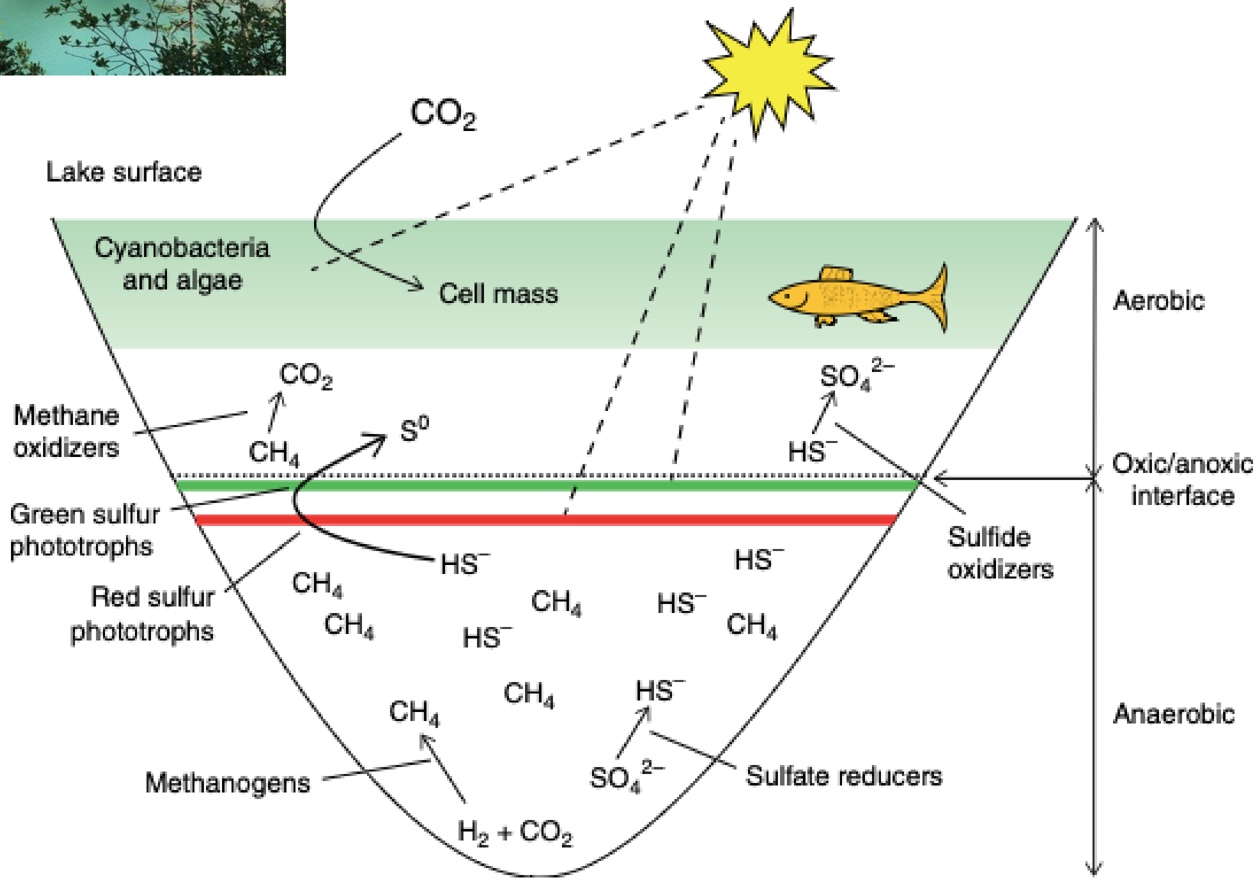



**Figure 4.9** A deep lake showing the stratified microbial processes. Cyanobacteria grow on the surface while anaerobic phototrophic bacteria are found in the sulfide rich environment. The position of the red and green photosynthetic bacteria indicates light penetration and the type of baceteriochlorophyll of the phototrophs. Hydrogen sulfide is produced in the anaerobic zone while methane and sulfide oxidation occurs at the oxic/anoxic interface.

**Figure 4.11** Structure of the chlorophyll *a* molecule. Different side groups are added at the encircled regions to produce different bacteriochlorophylls.

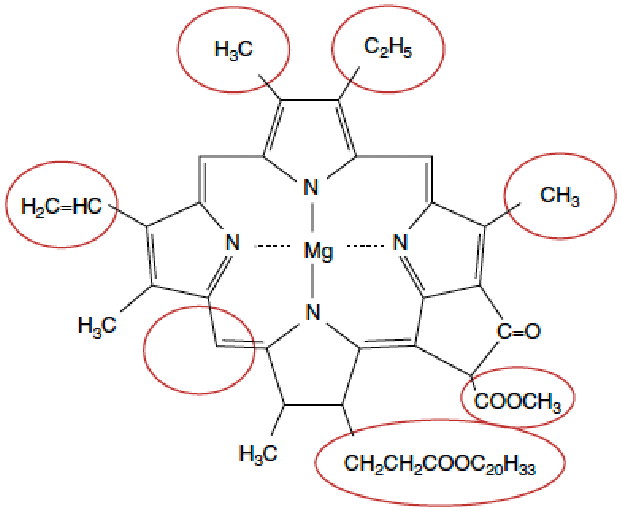



**Table 4.8** Selected photosynthetic bacteria and their

| Phylum | Genus | Wavelength of adsorption for purified chlorophyll (nm) |
|---|---|---|
| *Cyanobacteria* | *Anabaena* | 680, 700 |
| *Chloroflexi* | *Chloroflexus* (green non-sulfur)[c] | 800–810 |
| *Chlorobi* | *Chlorobium* (green sulfur) | 800–810 |
| *Betaprotobacteria* | *Rhodospirillum* (purple non-sulfur) | 800–810 |
| *Alphaproteobacteria* | *Blastochloris* | 835–850 |
| *Betaproteobacteria* | *Chromatium* (purple sulfur) | 800–810<br>835–950 |
| *Firmicutes* | *Heliobacterium* | 670, 788 |

# Niche space

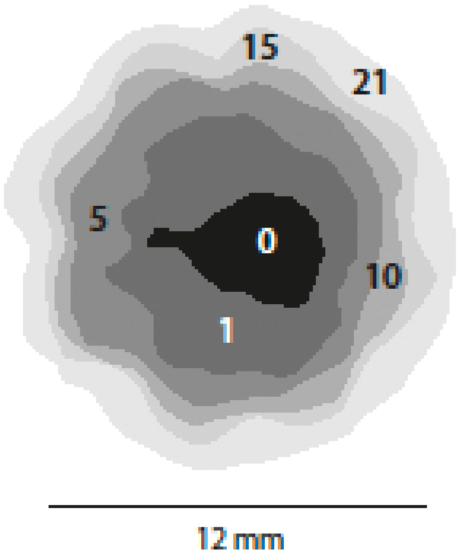
- **Physical** and **chemical gradients** can exist within a few millimetres in habitats

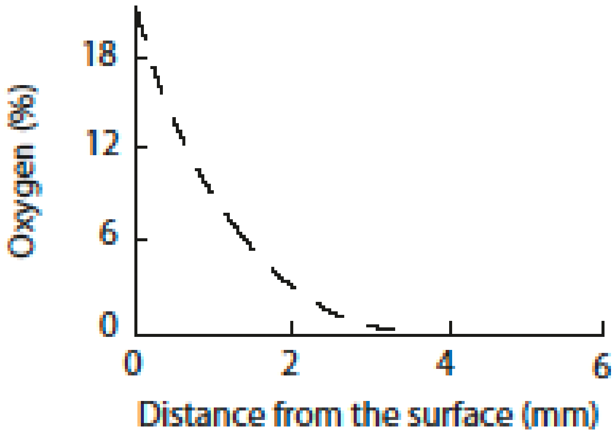
- Microenvironment
  - The immediate environmental surroundings of a microbial cell or group of cells
  - microenvironments are heterogeneous and can change very rapidly

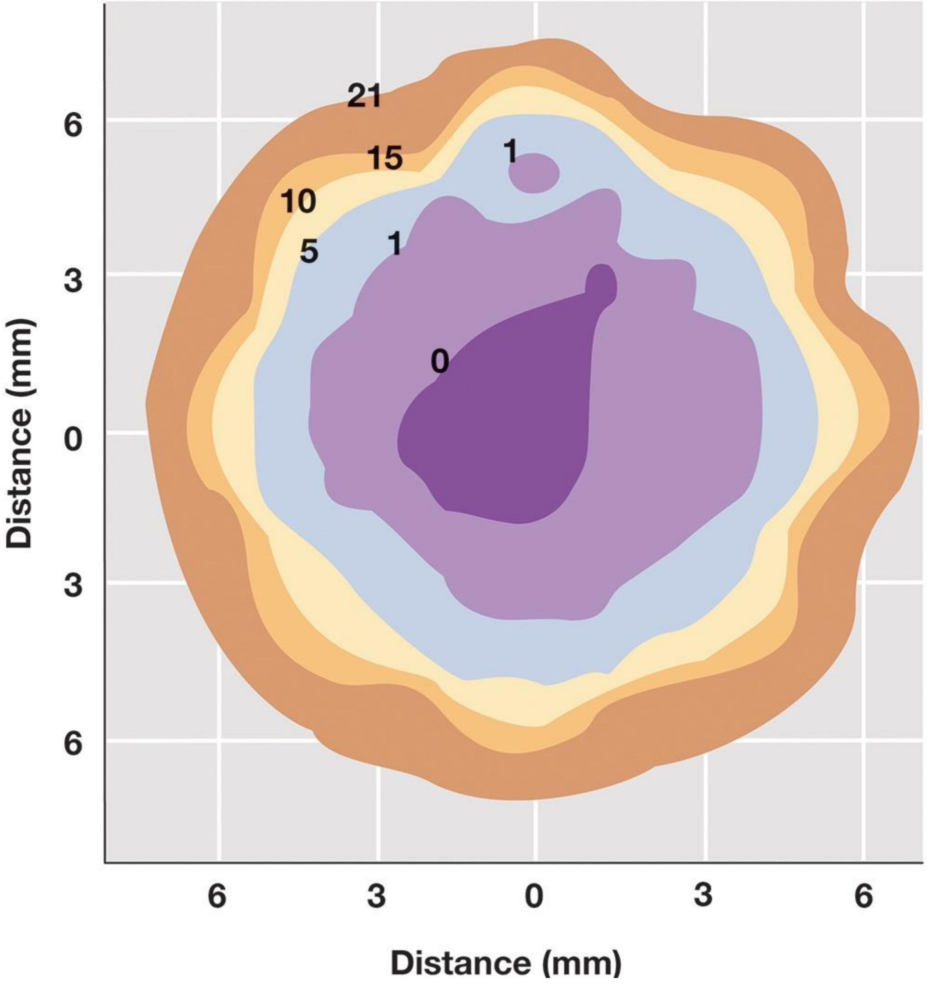
# Niche space

Example: Soil particles contain many microenvironments

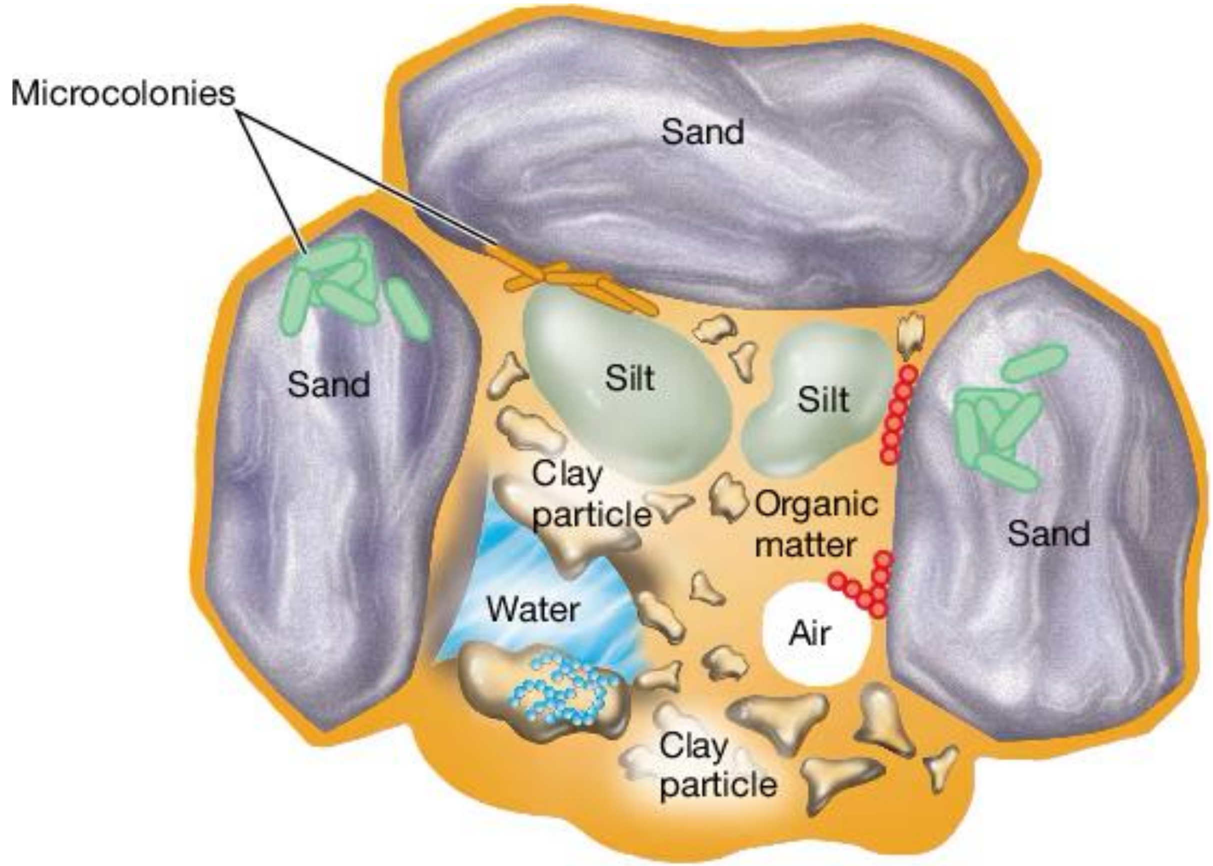
- Oxygen Microenvironments

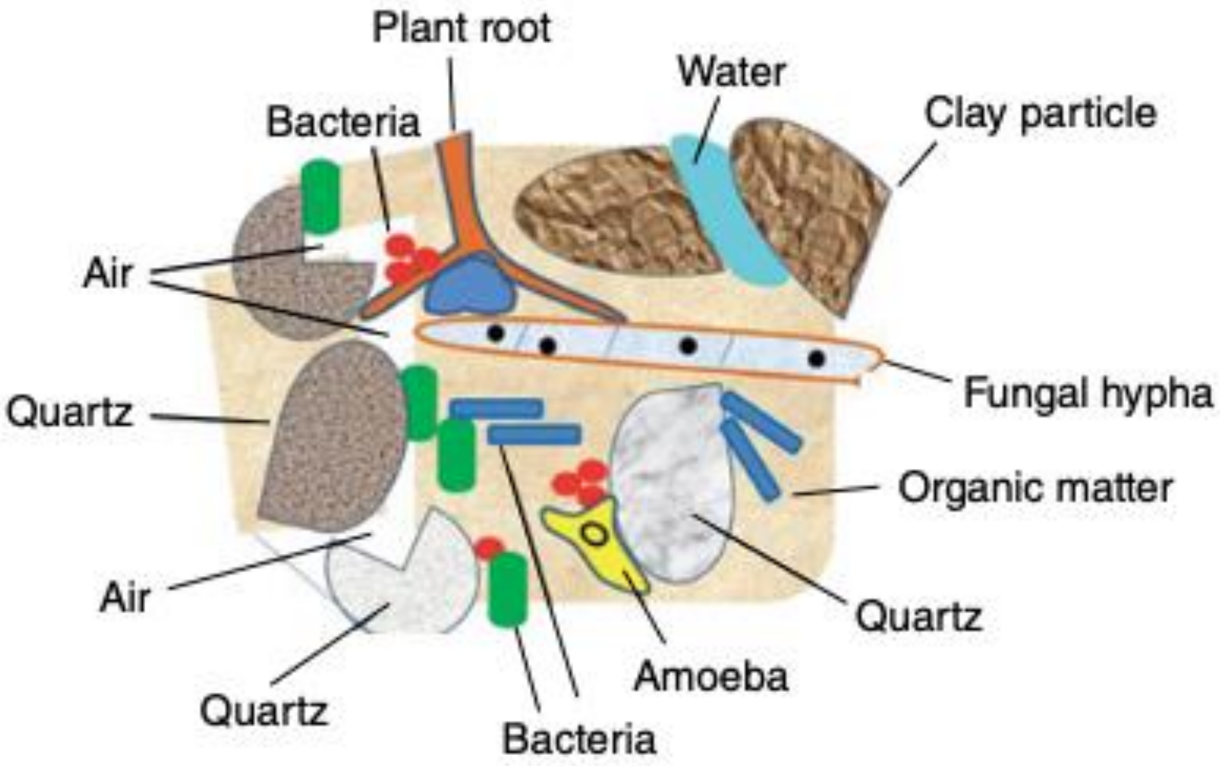


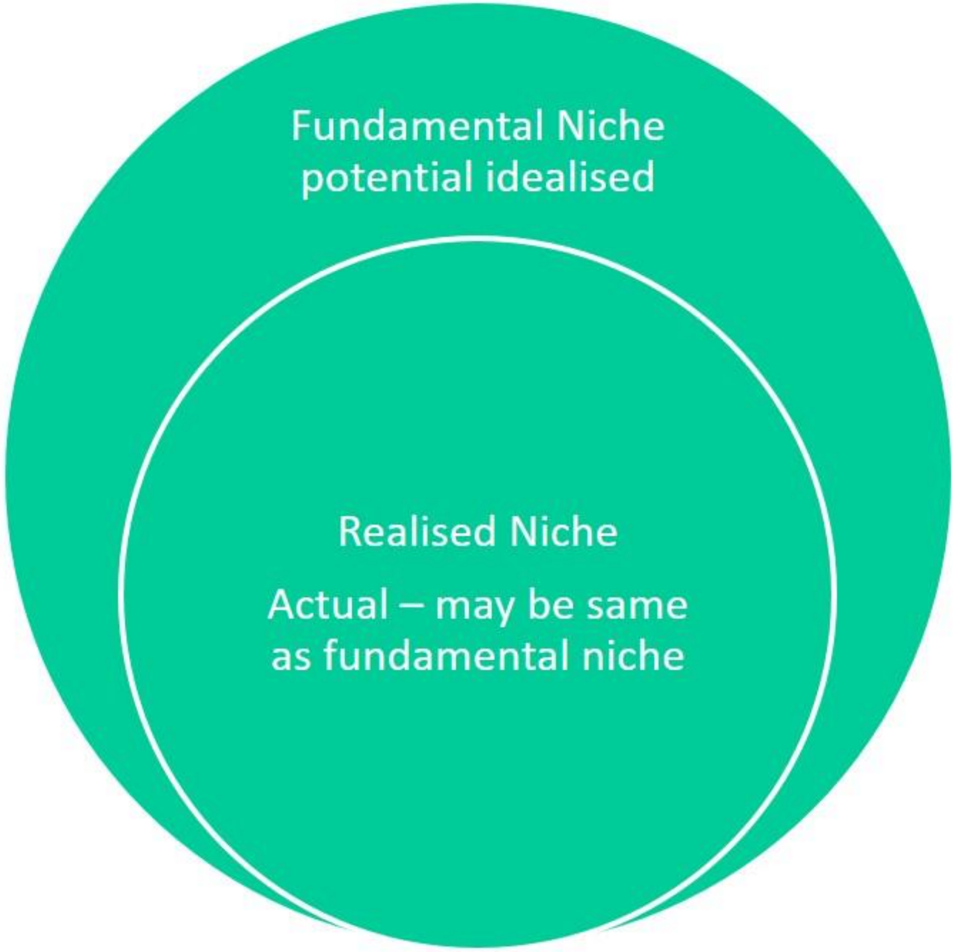
# Niche space


Microcolonies
Sand
Sand
Silt
Silt
Sand
Clay
particle
Organic
matter
Water
Air
Clay
particle


Plant root
Water
Bacteria
Clay particle
Air
Fungal hypha
Quartz
Organic matter
Air
Quartz
Quartz
Amoeba
Bacteria

# Niche space

- Microbes have both a **realized niche** and a **fundamental niche**
  - The fundamental niche indicates where an organism could live,
  - while the realized niche is where an organism does live, given resource limitations and competition



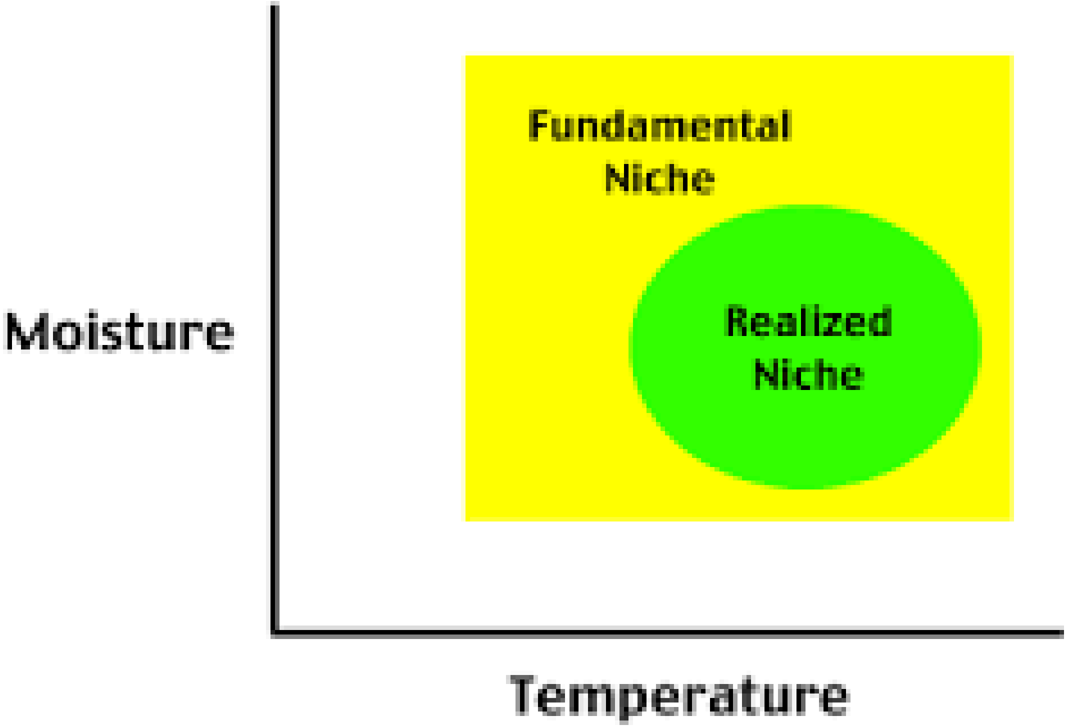
# Niche space

The **fundamental environmental niche**

- the set of environmental conditions in which a species can theoretically (i.e., physiologically) live and reproduce in

The **realised environmental niche**

- the restricted set of conditions a species actually occupies *in situ* when accounting for biological interactions (e.g., competition, predation)

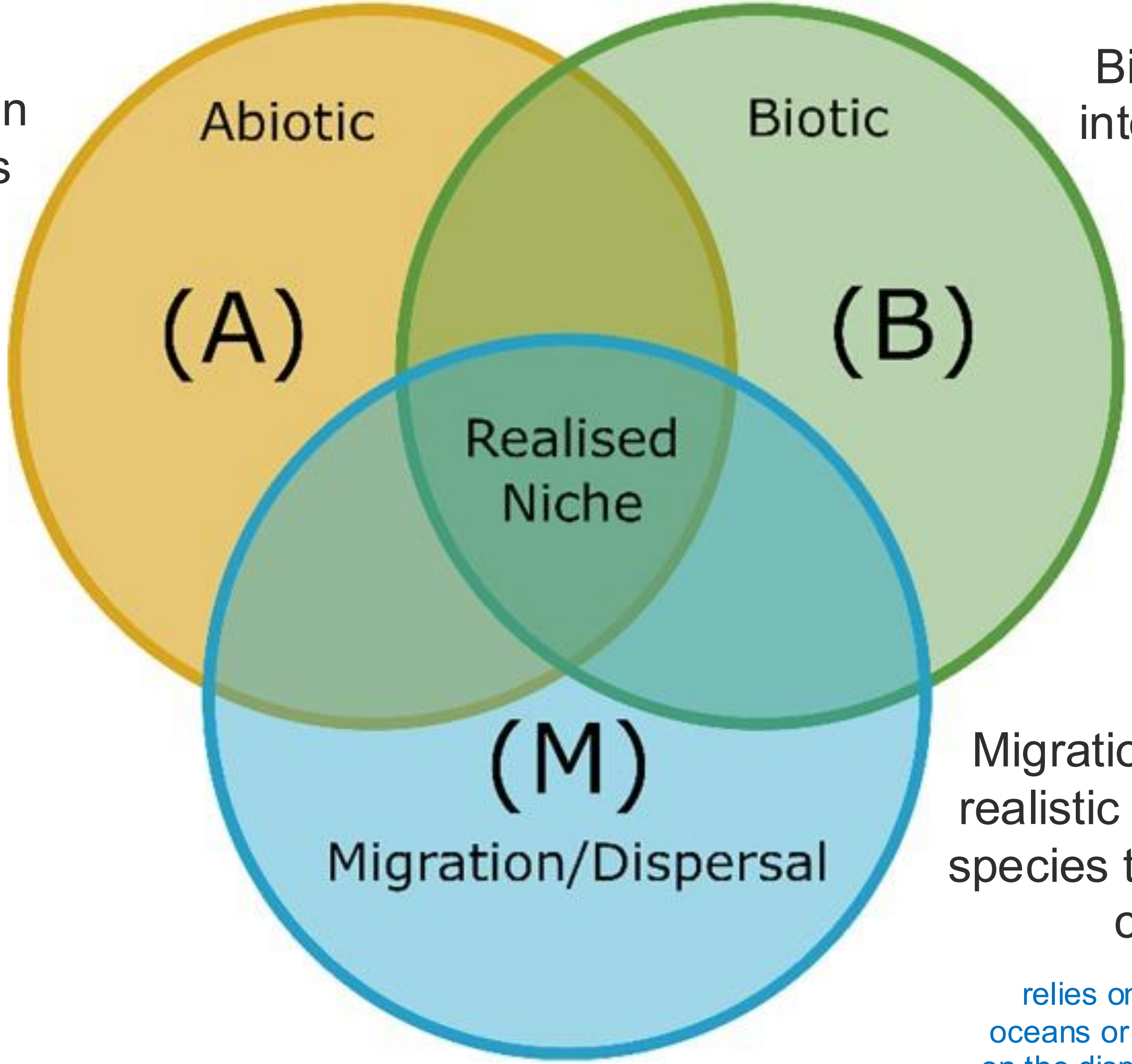



Realised niche is a subset of the fundamental niche

# Biotic–Abiotic–Migration (BAM) framework

Abiotic factors impose the physiological limits on the ability of the species to persist in an area.

physicochemical properties of the environment – temperature, O2 availability, N/P availability… etc




Biotic factors include a set of interactions with other species

interactions can be either positive (such as mutualism) or negative (such as competition or predation)

Migration/Dispersal is the realistic accessibility of the species to environments for colonisation

relies on land configuration (e.g., oceans or mountains as barriers) and on the dispersal abilities of the species

Malard and Guissan, 2023

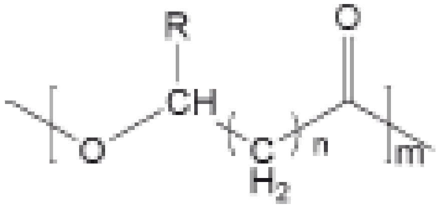
# Environments fluctuate

- Physiochemical conditions in an environment are subject to rapid change, both spatially and temporally
  - Nutrients often enter an ecosystem in varying amounts. A large accumulation of nutrients may be followed by a period of severe nutrient deficiency.
- Resources in natural environments are highly variable, and many microbes in nature face a “feast-or-famine” existence
- Growth rates of microbes in nature are usually well below maximum growth rates defined in the laboratory
  - In nature,  extended periods of exponential growth of microorganisms are rare

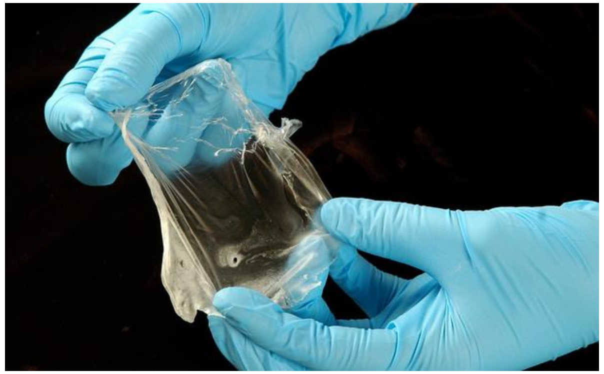
# Sidenote

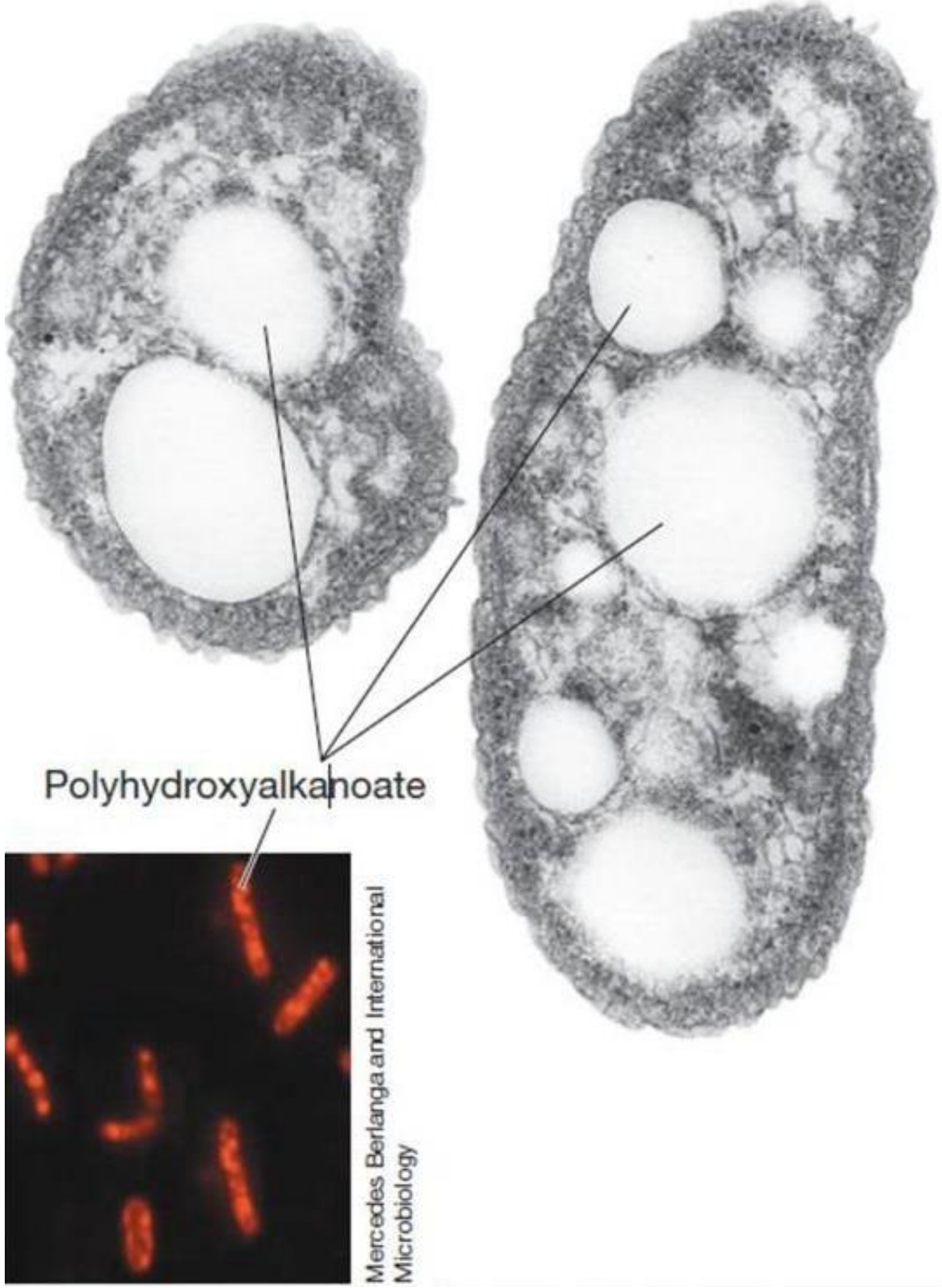
Many microorganisms have evolved biochemical systems that produce storage polymers as reserve materials to store excess nutrients available under favourable growing conditions for use during periods of nutrient scarcity.

Bioplastics




PHA

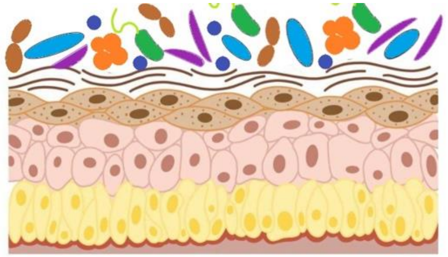




Competition and cooperation occur between microbes in natural systems

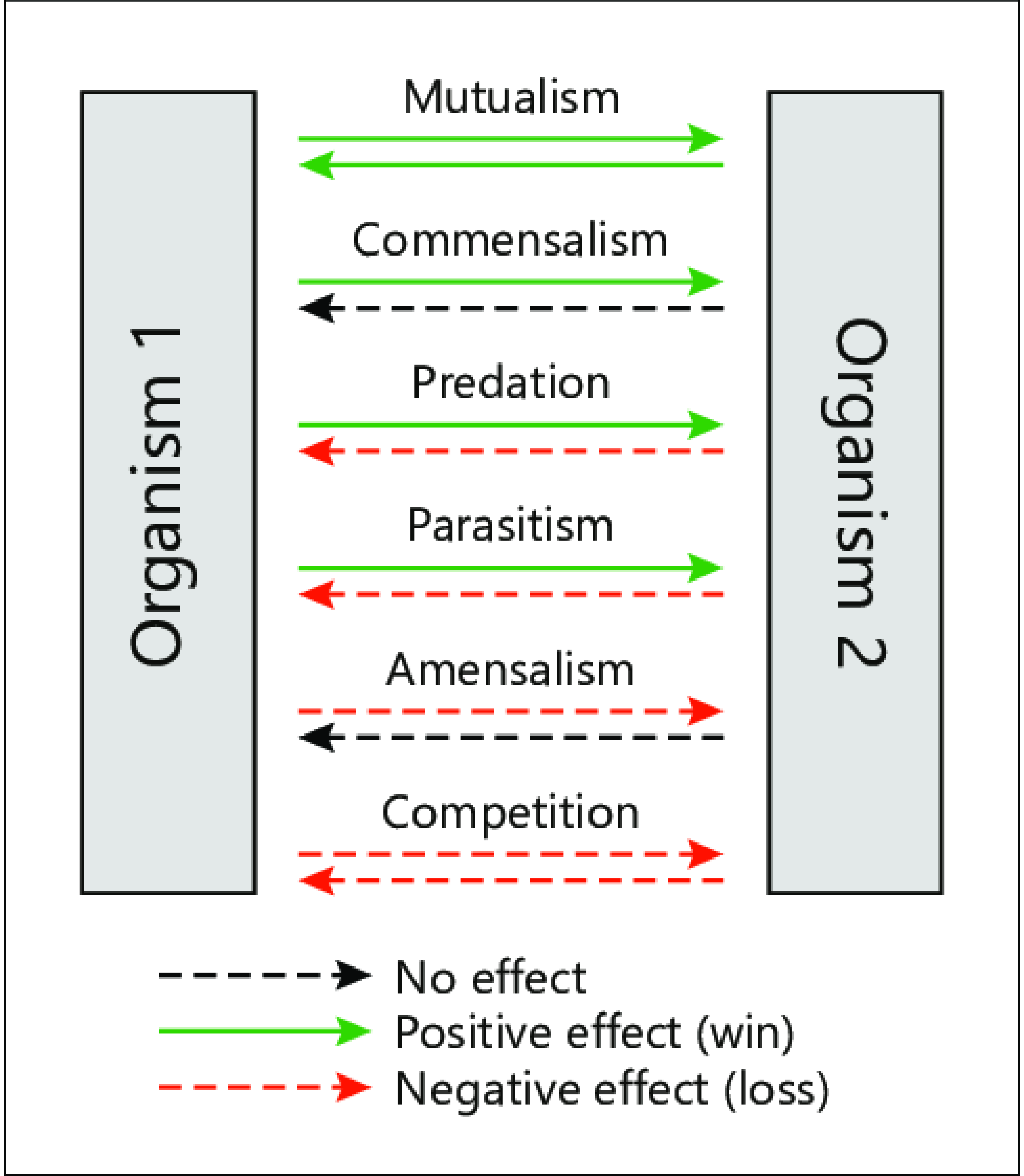
# Microbial Interactions

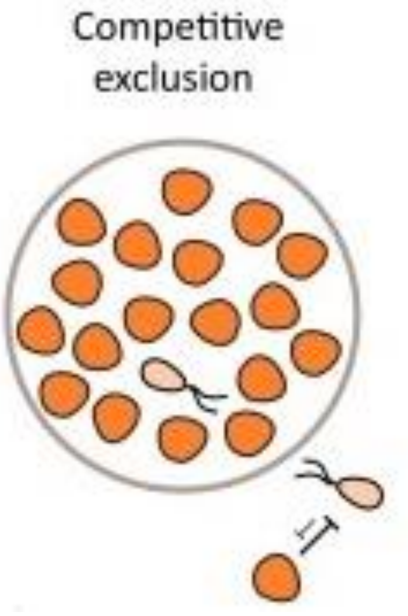
- Neutralism: partners can coexist without interacting with each other
  - No exchanges of metabolites, no competition, no alteration of the environment
  - Usually when densities is low (marine habitats or oligotrophic lake habitats)



- Competition
  - At higher densities (e.g. competition for food or light)
  - Outcome of competition depends on availability of nutrients and microbial growth rates

- Antagonism
  - One microorganism has a direct negative impact on another (inhibition, killing
  - Antibiotic production, predation
- Cooperation
  - Mutualism – both microbial species benefit from interaction
  - Commensalism – one microorganism benefits from another
  - Symbiosis – mandatory interaction between organism
  - Syntrophy – two microorganisms complement each other in substrate utilization


Organism 1
Mutualism
Commensalism
Predation
Parasitism
Amensalism
Competition
Organism 2
No effect
Positive effect (win)
Negative effect (loss)




# Microbial Competition

- Energy and nutrient sources are often present in limiting conditions
- Competition for nutrients is one of the major types of interactions among microbial species
- Outcomes depend on growth rates of the species
- Fast-growing organism can generally outcompete slow-growing ones
  - Competitive exclusion

# Microbial Competition

- The outcome of a competition between different microorganisms depends nutrient uptake rates, inherent metabolic rates and ultimately growth rates.

- In nature microorganism grow with mixtures of substrates

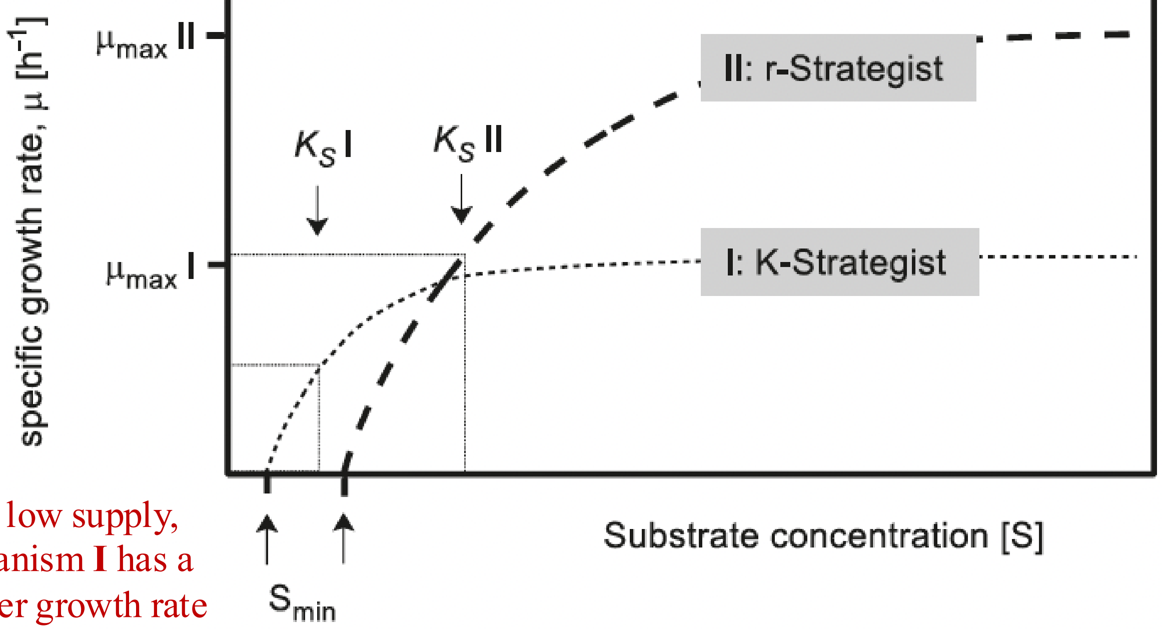
# Microbial Competition

Microbial adaptation strategies to substrate concentration

At a high substrate supply, organism **II** will grow much faster than organism

**Organism II** has a high *Ks* and a high *μ*max

**Organism I** has a high substrate affinity (a low *Ks*) value and a low maximum specific growth rate




Easily lost

Persist

At low supply, organism **I** has a higher growth rate than organism **II** and will outcompete it

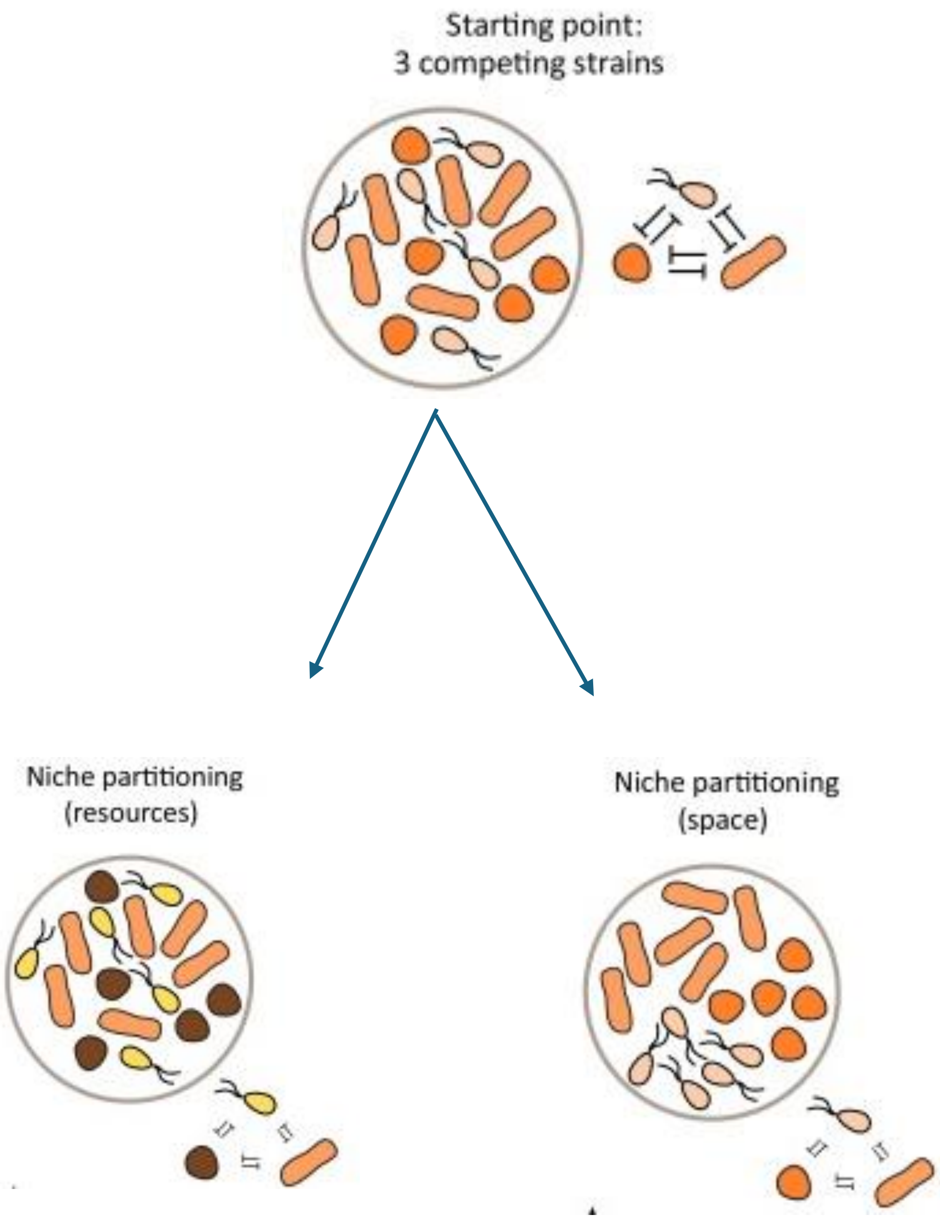
Maximum specific growth rate: *μ*max

Substrate affinity: $K_s$

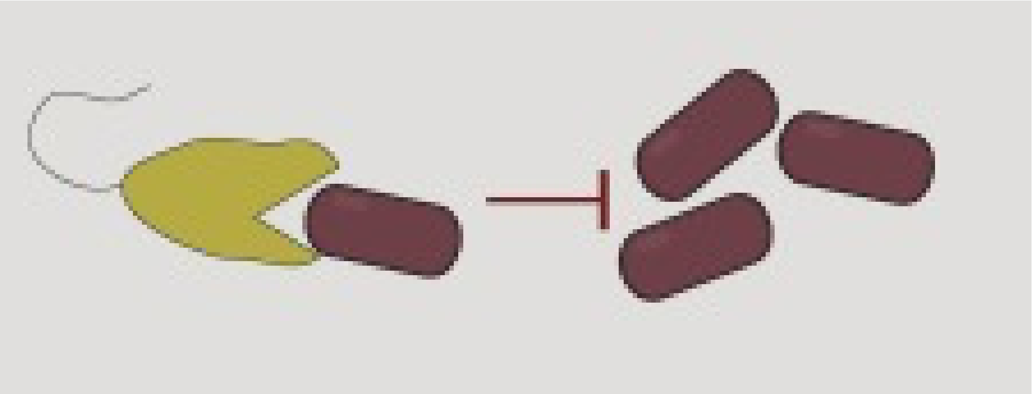
$K_s$ represents the concentration of substrate at which the specific growth rate of microorganisms is half of the maximum rate.

# Microbial Competition

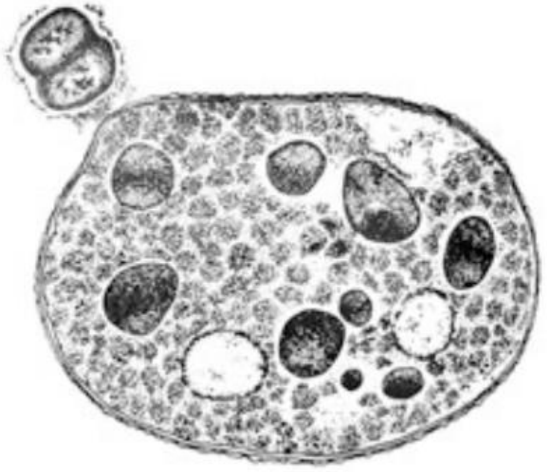
- In an ecosystem, fast and slow growing species can live side by side.



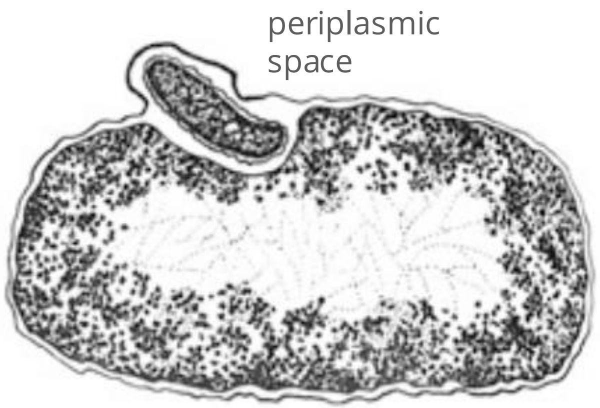
# Microbial Antagonism



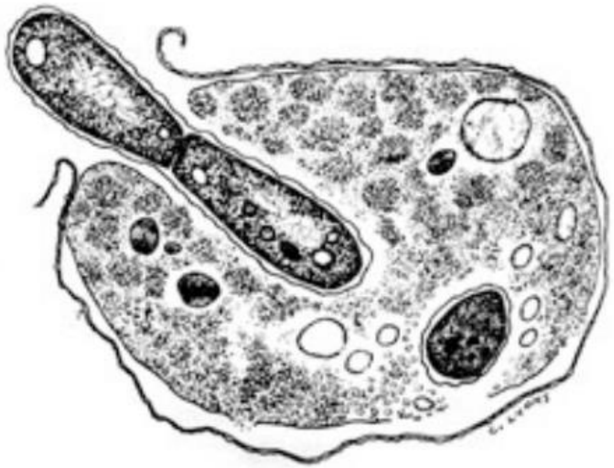
- Predation



Vampirococcus

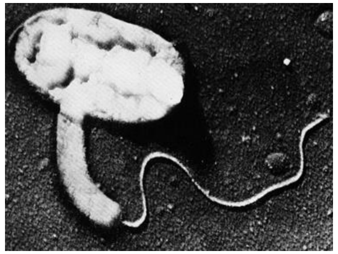



Bdellovibrio



Daptobacter

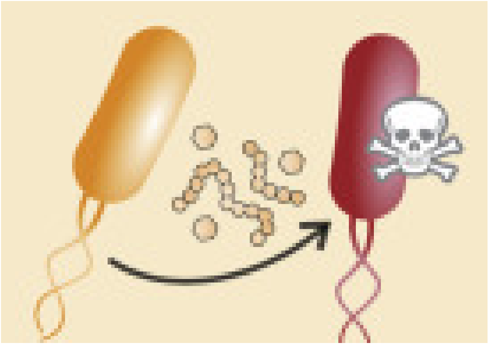

Epibiont: "living on top of"

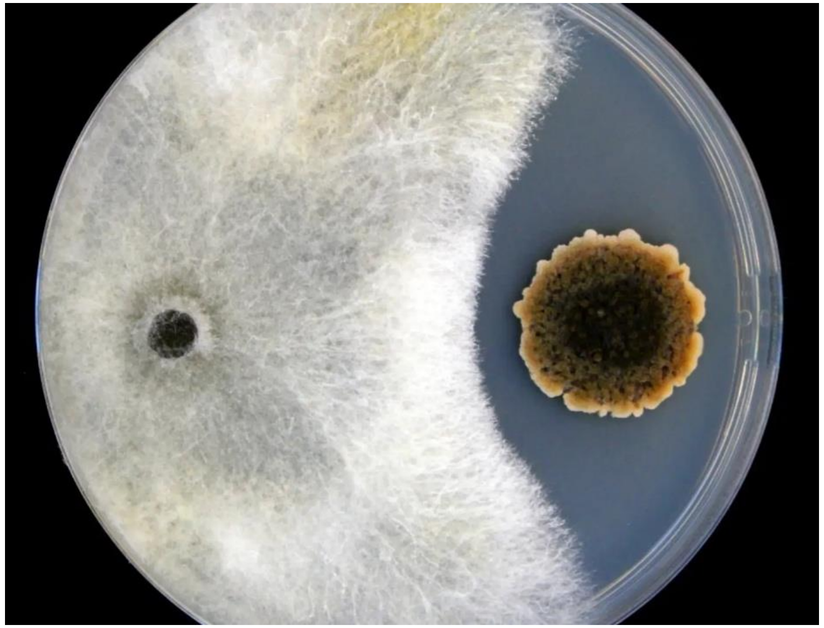


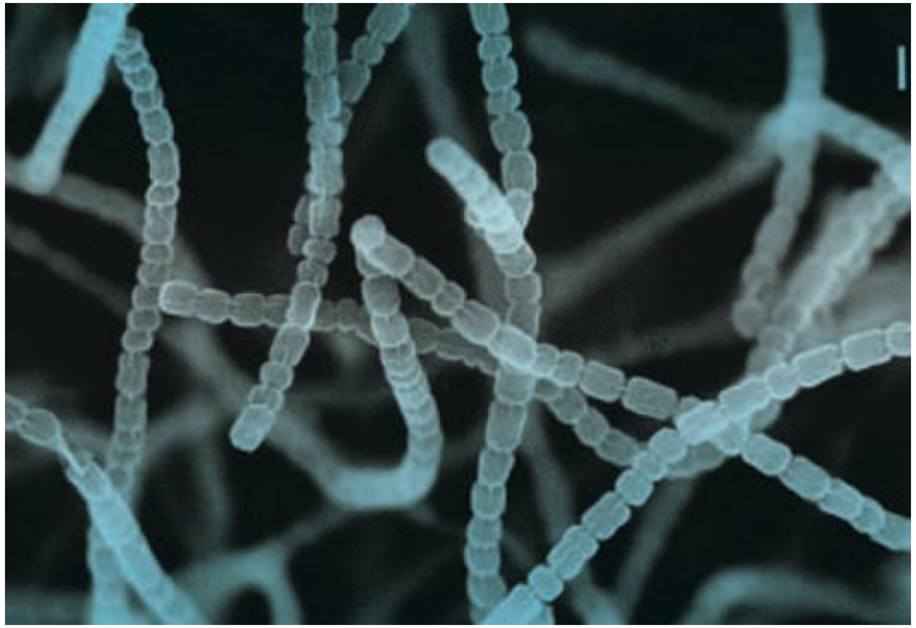
Ectoparasitic

# Microbial Antagonism

- Production of antifungals and antibiotics





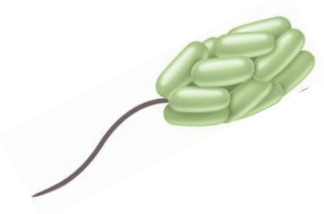


80% of antibiotics are sourced from the genus *Streptomyces*

soil-dwelling Gram-positive bacteria

# Mutualism

- Interaction is beneficial to both organism, but not mandatory



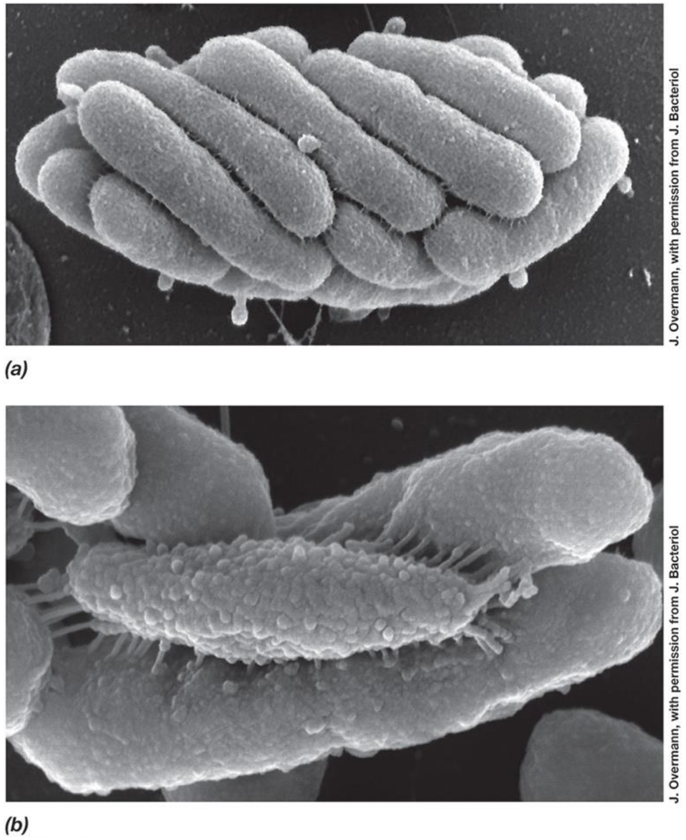
*Chlorochromatium Aggregatum*

# Mutualism

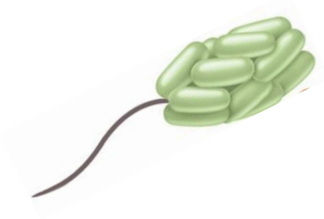
In freshwater there are microbial mutualisms called **consortia**

- nonmotile green sulfur bacteria (epibiont)
    - obligately anaerobic phototrophs
    - *Chlorobium*

- motile, non-phototrophic bacteria
    - flagellated rod-shaped bacterium



# Mutualism



Motile consortial

*"Chlorochromatium Aggregatum"*

These consortia are found in stratified sulfidic lakes

- Light penetrates to layers with $H_2S$
- Constantly changing gradients of light, oxygen, and $H_2S$ throughout the day.

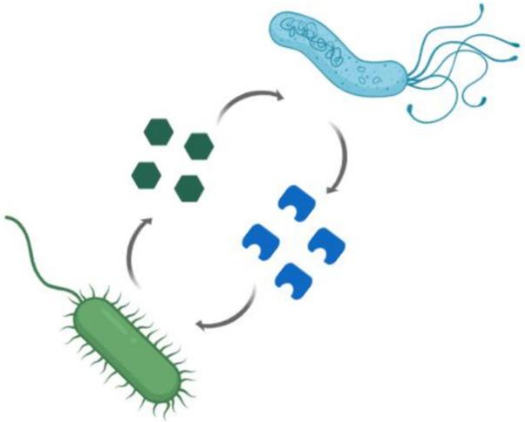
Oxygenic photosynthesis

$12H_2O + 6CO_2 + \text{photons} \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2$

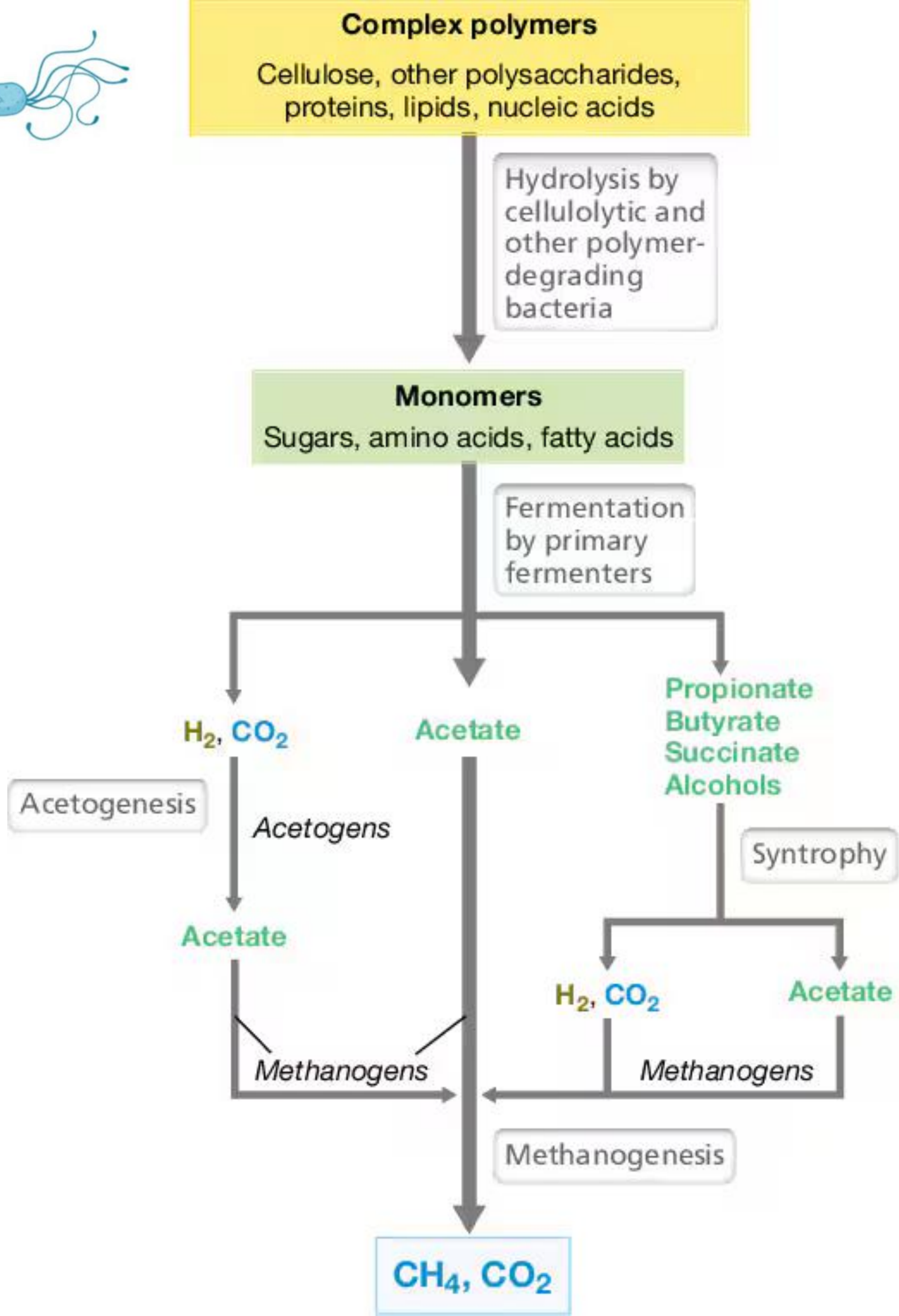
Anoxygenic photosynthesis

$2H_2S + CO_2 + \text{photon} \rightarrow CH_2O + H_2O + 2S^0$

# Syntrophy




- Microbes work together to carry out transformations that neither can accomplish alone
- Most syntrophic reactions are secondary fermentations in which organisms ferment the fermentation products of other anaerobes
- Metabolic cooperation can also be seen in organisms that carry out complementary metabolisms

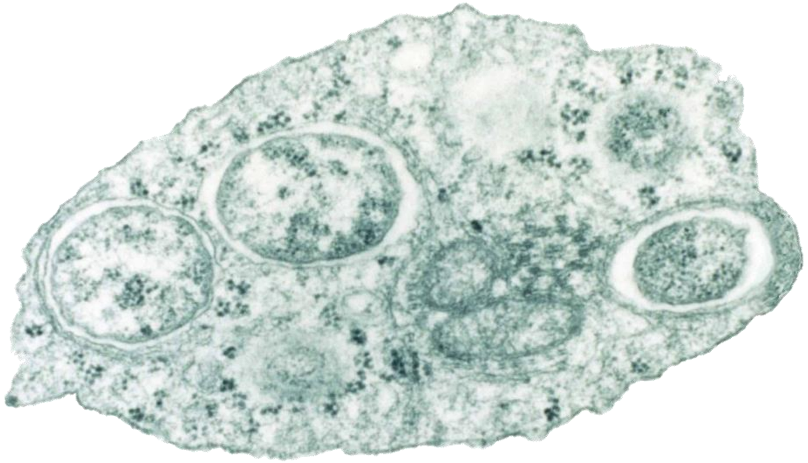


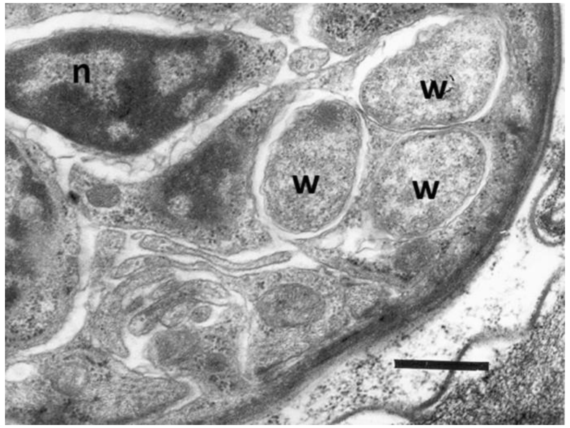
# Symbiosis

Obligate interactions between the two organisms

- If one partner lives outside the cells of the other partner, it is called **ectosymbiosis**

- The intracellular settlement of the partner is called **endosymbiosis**



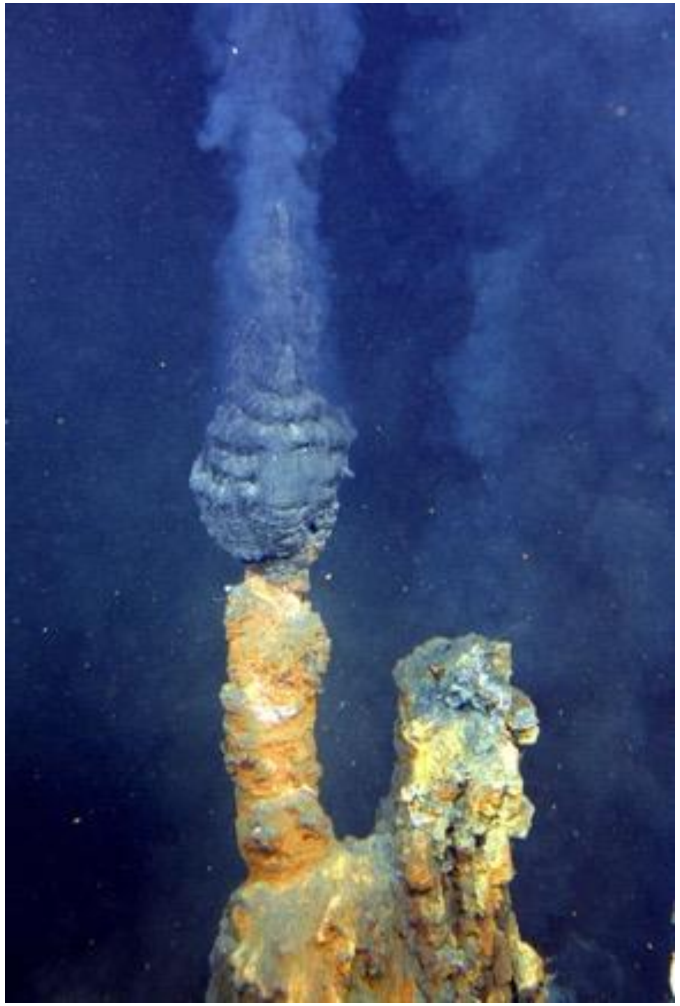


# Symbiosis

Methanotrophic consortia

- couple the activities of two anaerobic microbes effectively oxidizing methane to $CO_2$ in anoxic marine sediments

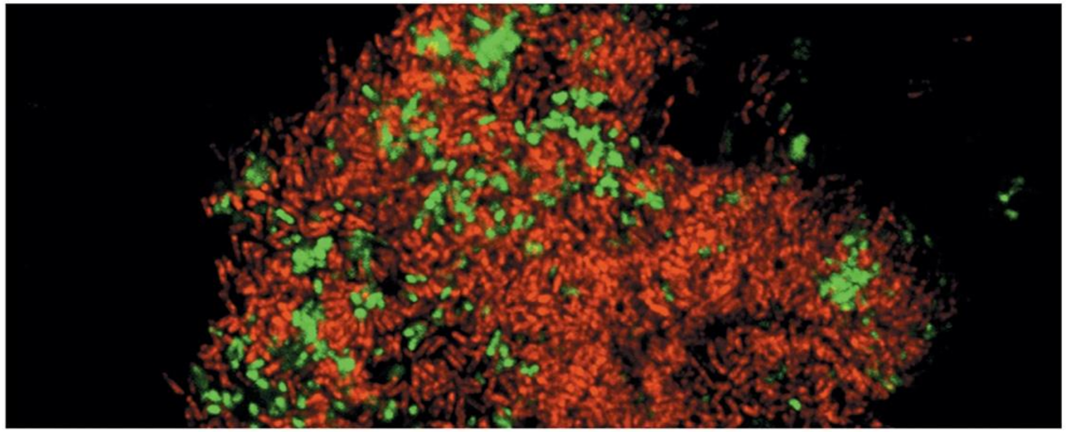
- specific methane-oxidizing (methanotrophic) Archaea form intimate associations with sulfate-reducing bacteria



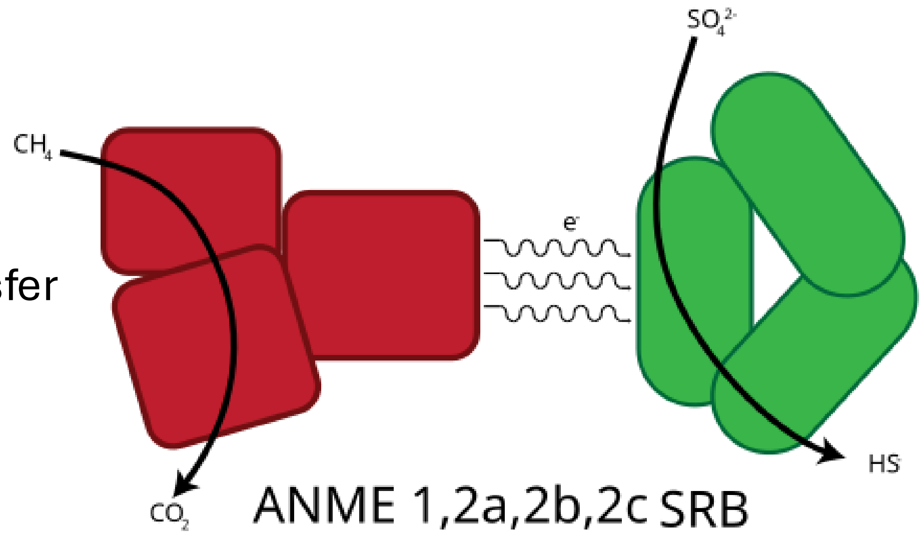
# Symbiosis

- Anaerobic Methane-Oxidizing Consortia

- A methanotrophic consortia enriched from geothermally heated sediments
- ANME methanotroph (red fluorescence) and its sulfate-reducing bacterial partner (green fluorescence)



Direct Interspecies Electron Transfer




$$CH_4 + SO_4^{2-} + H^+ \rightarrow CO_2 + HS^- + 2\,H_2O \quad \Delta G^{0'} = -18\ \text{kJ}$$

# Symbiosis

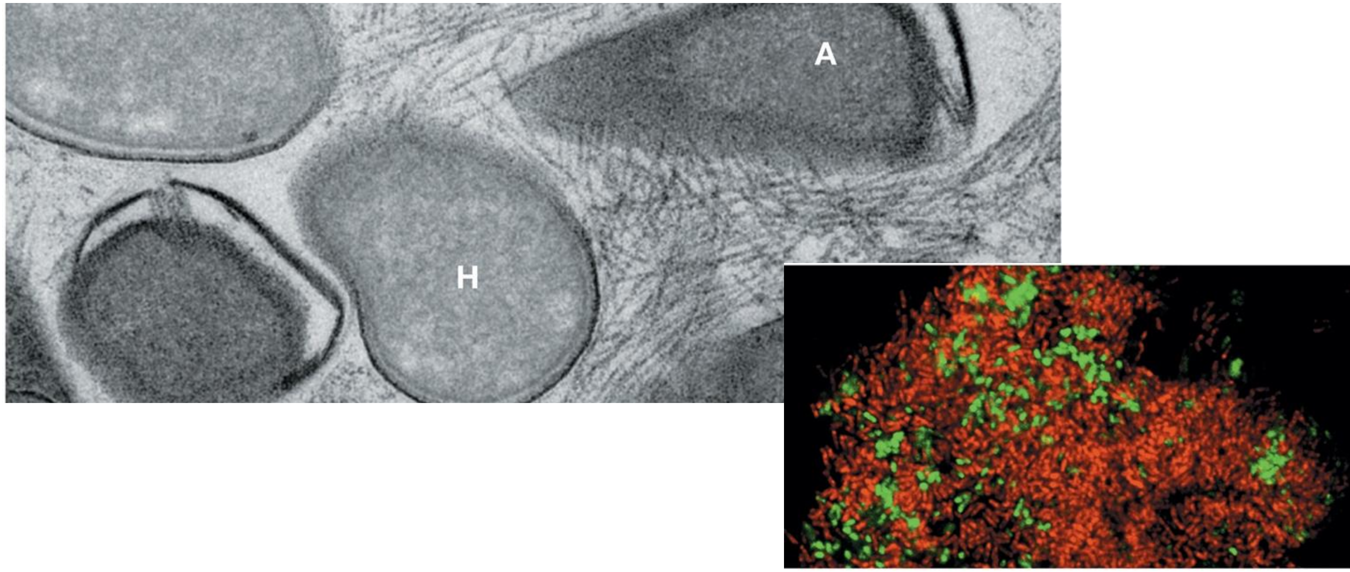
- A methanotrophic consortia enriched from geothermally heated sediments

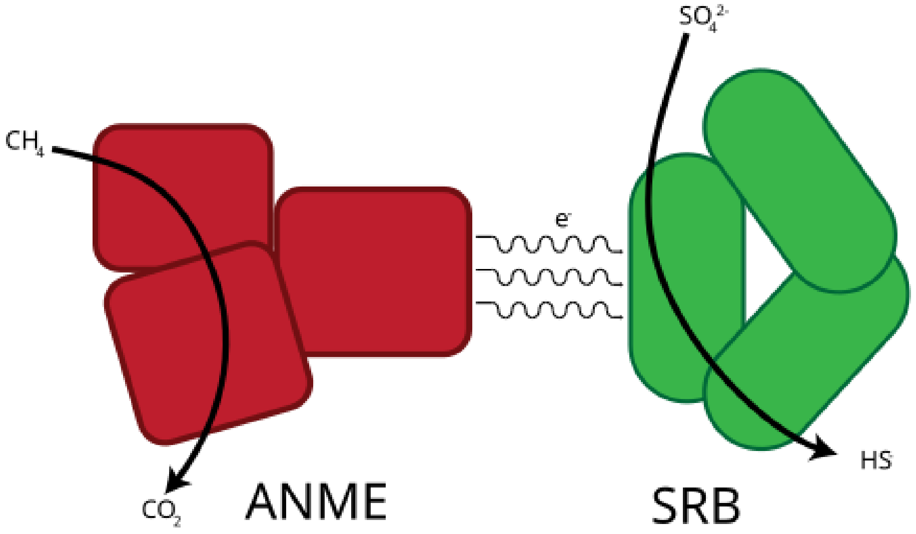
- ANME methanotroph (red) and its sulfate-reducing bacterial partner (green)

- Electron micrograph of a thin section through the consortia, showing the electrically conductive “nanowires” produced by the sulfate reducer (H), connecting it electrically to cytochrome-rich proteins on the surface of the ANME methanotroph (A)

$$CH_4 + SO_4^{2-} + H^+ \rightarrow CO_2 + HS^- + 2\,H_2O \quad \Delta G^{0'} = -18\ \text{kJ}$$

- Anaerobic Methane-Oxidizing Consortia

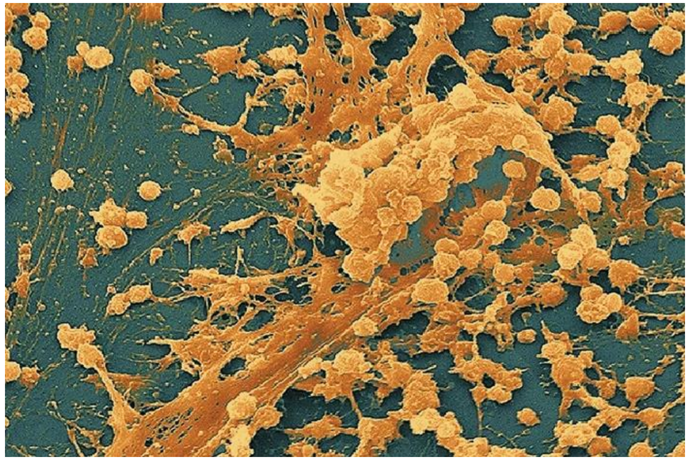



$CH_4 \rightarrow CO_2 + 8e^- + 8H^+$

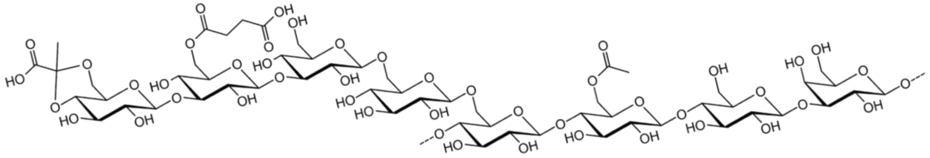
$SO_4^{2-} + 8e^- + 10H^+ \rightarrow HS^- + 4H_2O$

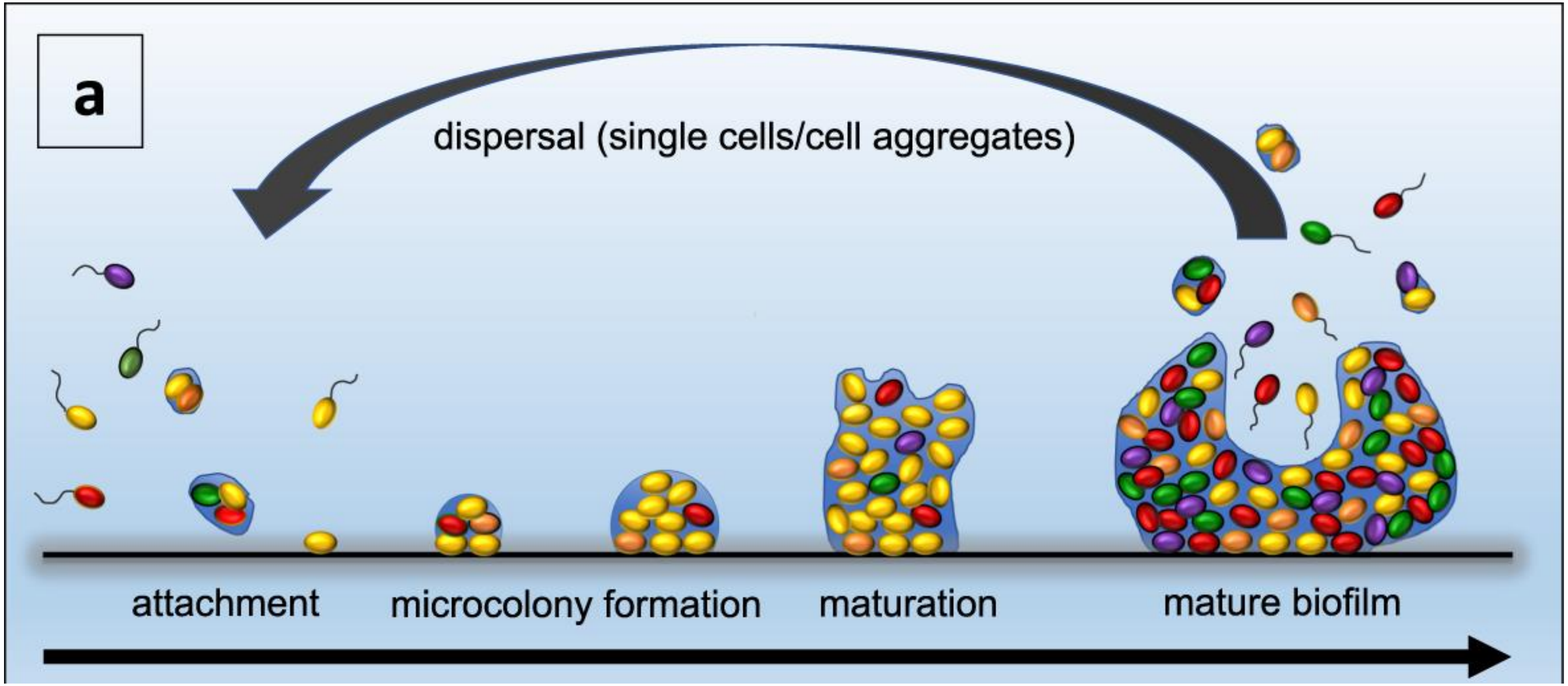
# Biofilms



Complex colonies of microorganisms
Offer protective coatings for microbes to shield them from unfavourable environments

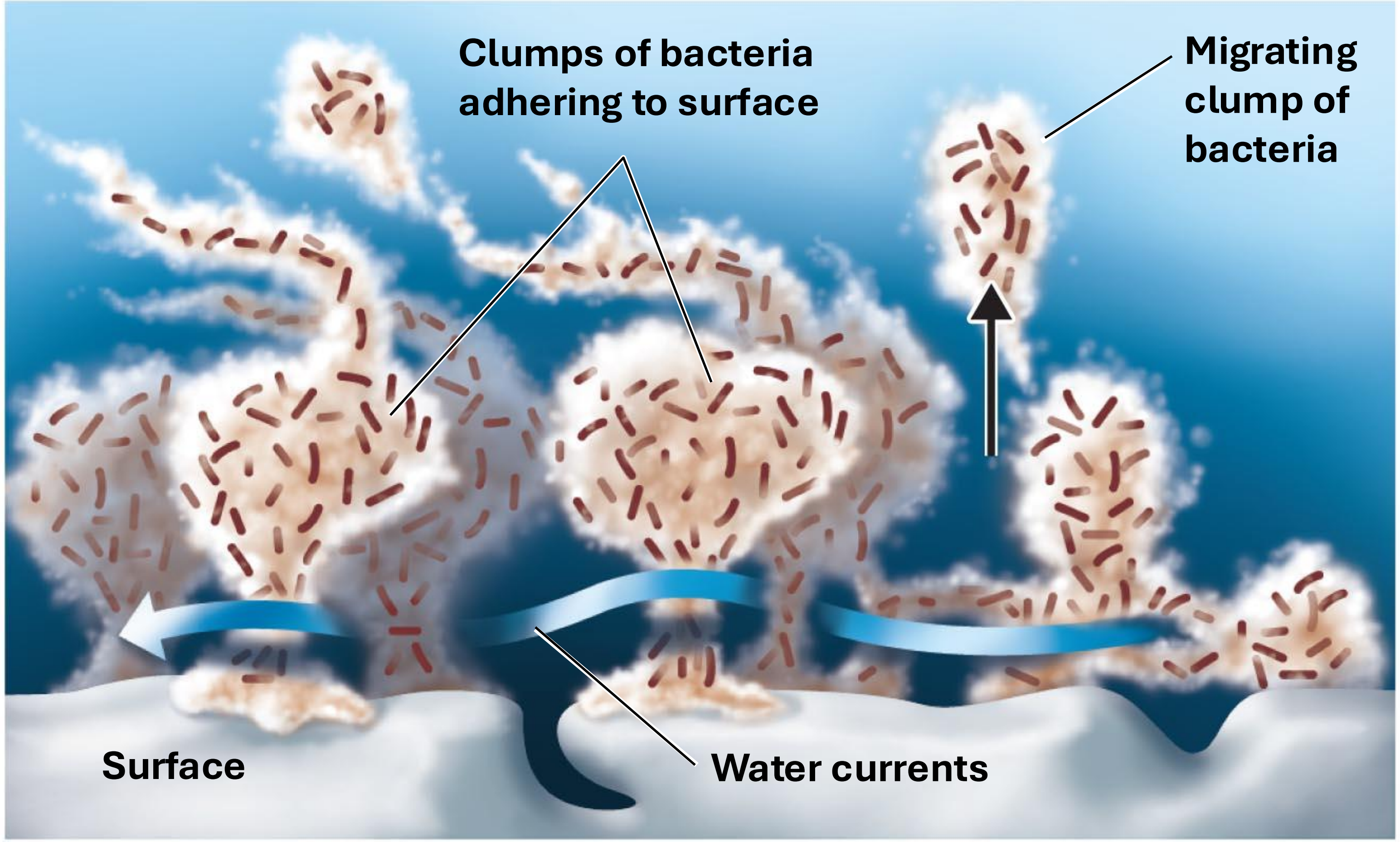
# Biofilms






substratum

- Extracellular polymeric substance (EPS) matrix is made by microorganism
- Cells entangled in a polysaccharide matrix attached to surface




Water currents move, as shown by the blue arrow, among pillars of slime formed by the growth of bacteria attached to solid surfaces. This allows efficient access to nutrients and removal of bacterial waste products. Individual slime-forming bacteria or bacteria in clumps of slime detach and move to new locations.

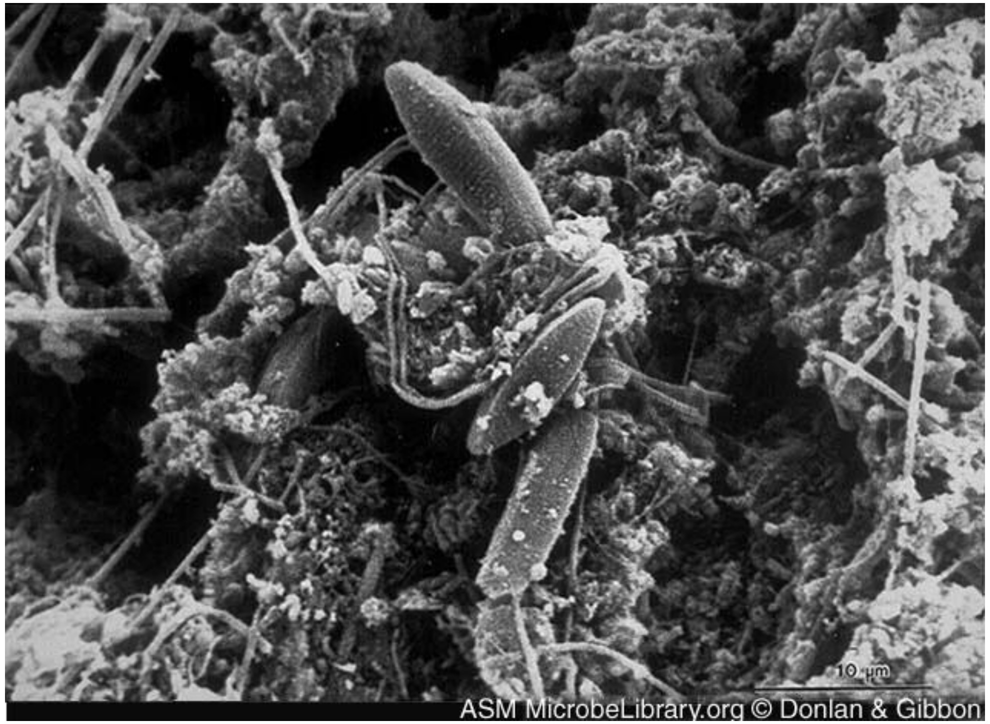
# Biofilms

- Multiple species or single species
  - Organised communities of microorganisms (e.g. bacteria, protozoa, algae, fungi)

- Predominant form of microbial life that is ubiquitous in natural ecosystems

- Exchange of nutrients
  - Syntrophic interactions

- Exchange of genetic material




Akin to multicellular organisms?

- division of labour among specialised cell types (same species)

- the division of labour via the interaction of different taxonomic groups (multiple species)

# Quorum Sensing

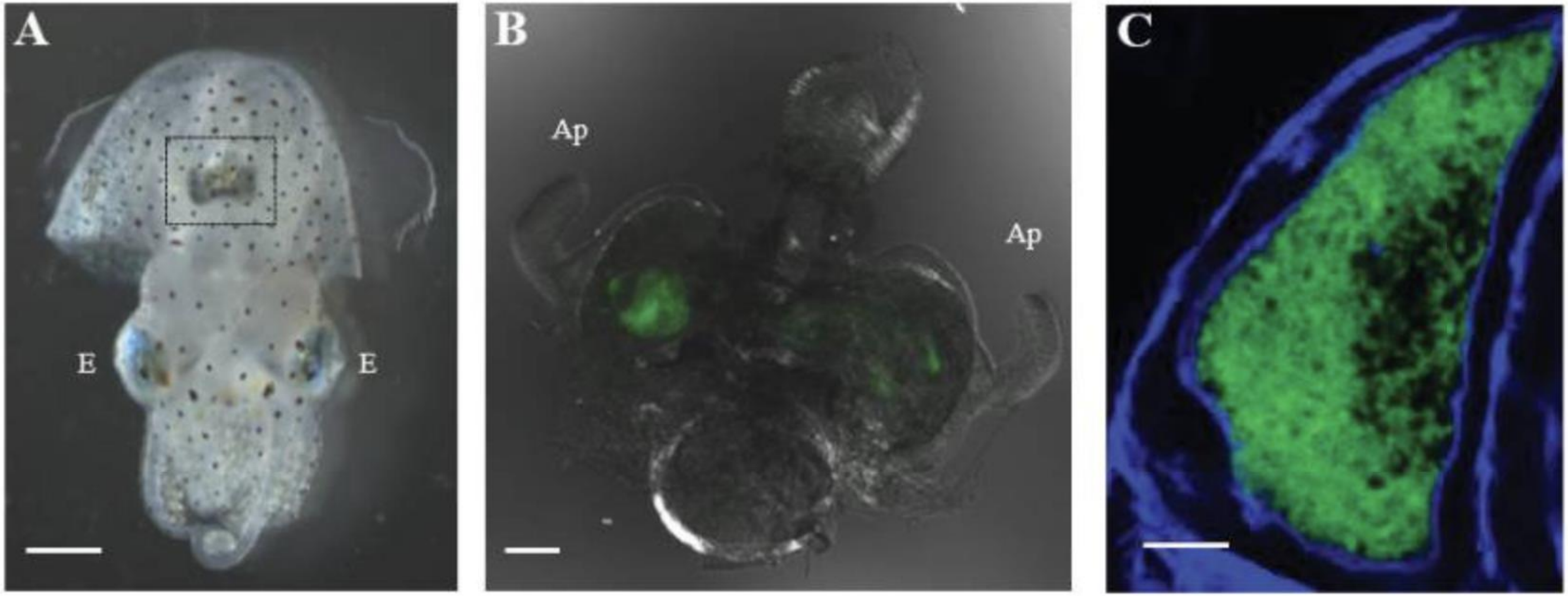
- The ability of bacteria to communicate with each other is called **quorum sensing**
  - Intercellular form of communication
  - Produce and secrete signalling molecules
  - Measurement of the cell density

- Initiate coordinated group behaviour
  - Luminescence
  - Spore formation
  - Antibiotic production
  - Biofilm production

signalling molecules -> autoinducers

chemotactic gradient

# Quorum Sensing




*E. scolopes*

light organ
osaccharides -> chemoattractants

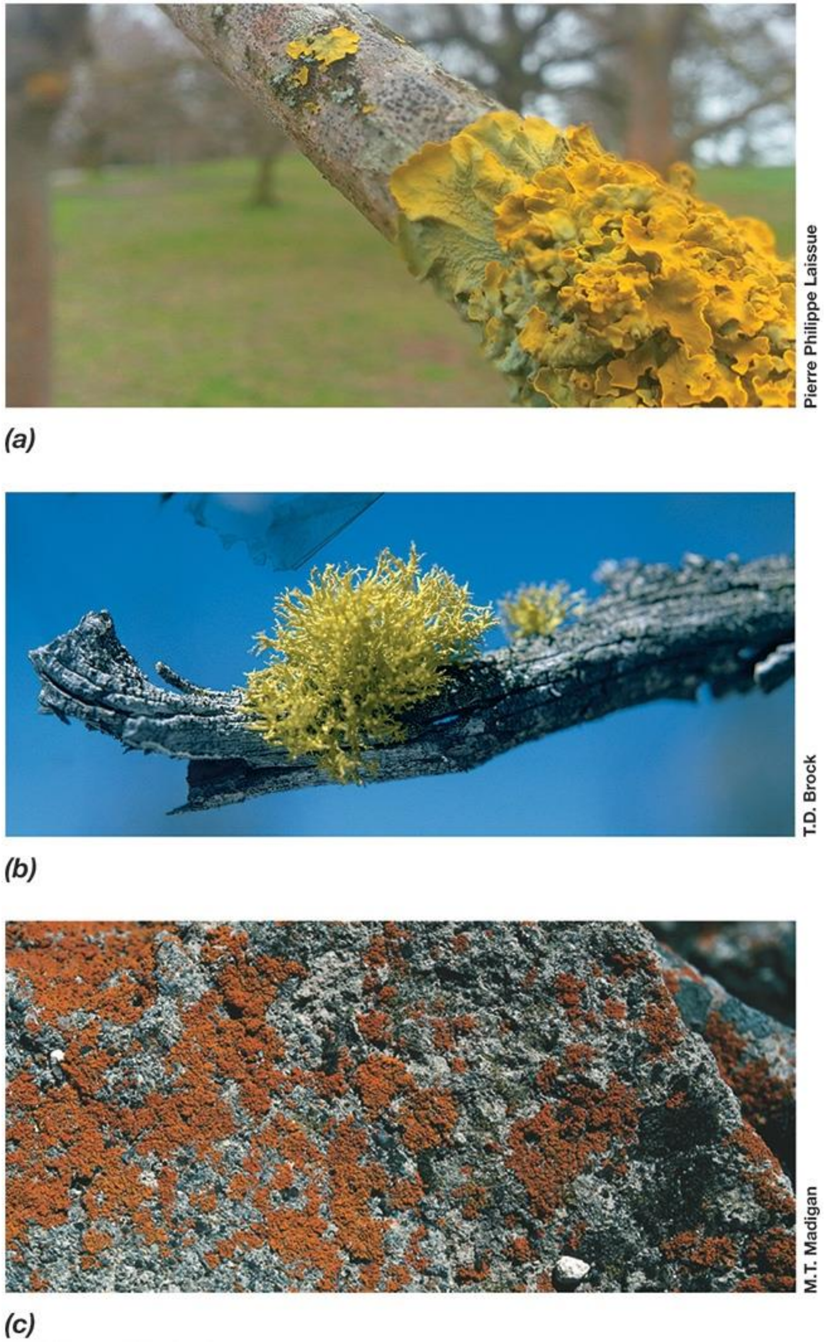
$10^5$ *V. fischeri* CFU/mL

seawater containing as little as 1000 *V. fischeri* CFU/mL

# Lichens

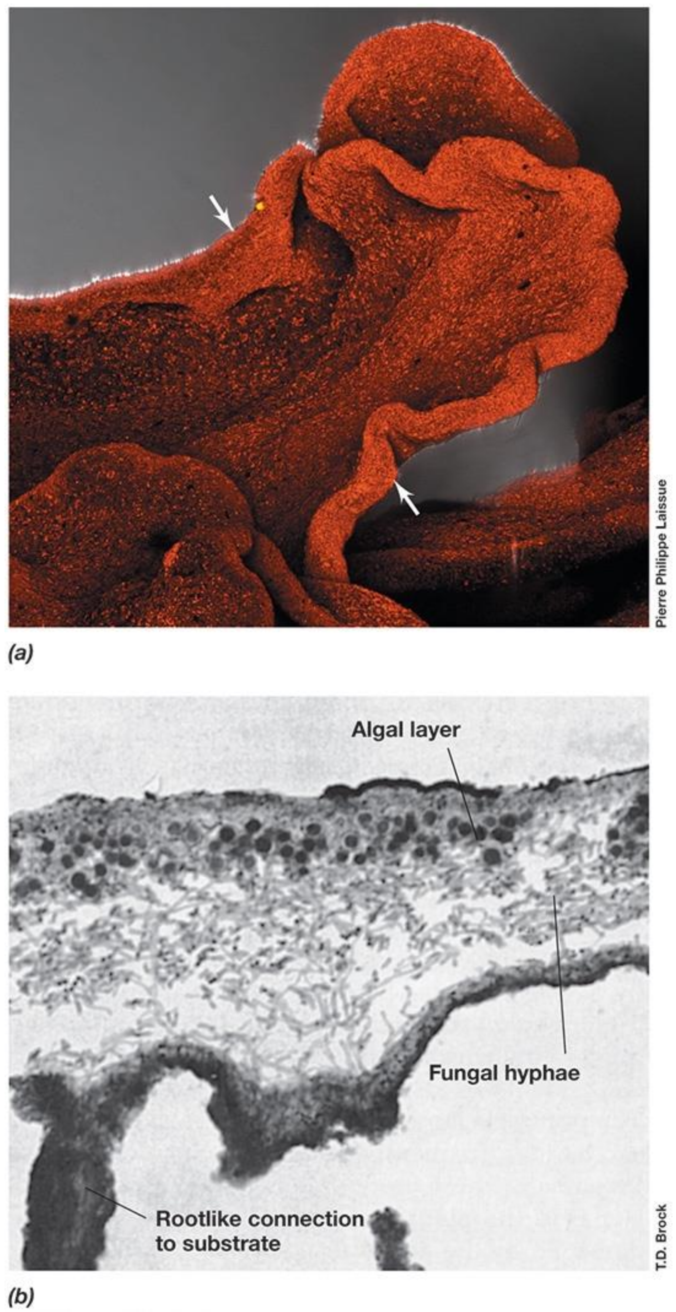
- Lichens are a mutualistic relationship between:
  - Mycobiont: fungus
  - Photobiont: alga or cyanobacterium

- Often found on rocks, tree bark, house roofs, and the surfaces of bare soils



# Lichens

- The photobiont is photosynthetic and produces organic matter and often nitrogen-fixing
- The fungus provides a structure within which the phototrophic partner can grow protected
- Lichens are more complex than previously considered as they contain bacterial and archaeal microbiota



# Extra slides

**Ethanol fermentation carried out by the syntroph:**

$$2\ CH_3CH_2OH + 2\ H_2O \rightarrow 4\ H_2 + 2\ CH_3COO^- + 2\ H^+$$

$$\Delta G^{0\prime} = +19.4 \text{ kJ/reaction}$$

**Methanogenesis carried out by the methanogen:**

$$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$$

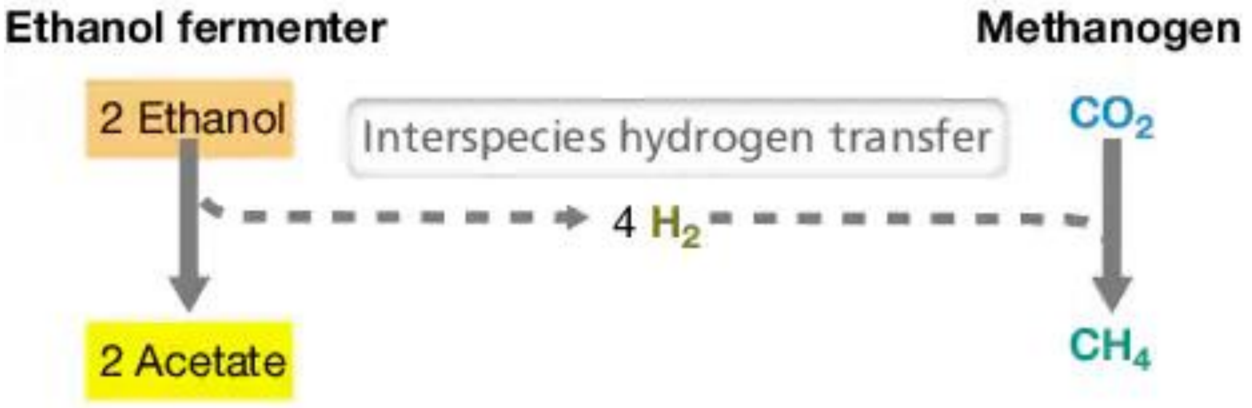
$$\Delta G^{0\prime} = -130.7 \text{ kJ/reaction}$$

**Coupled reaction in coculture of syntroph and methanogen:**

$$2\ CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2\ CH_3COO^- + 2\ H^+$$

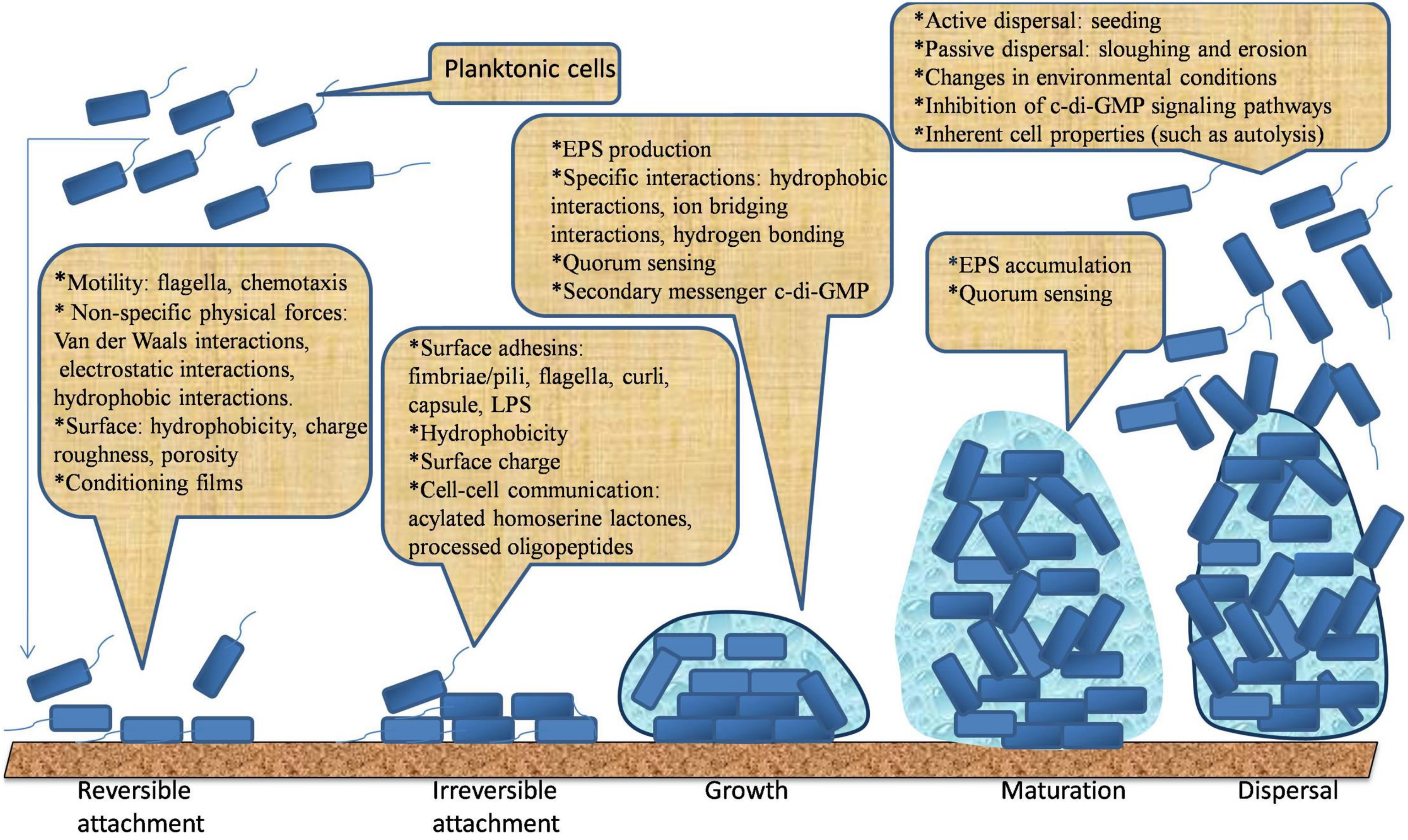
$$\Delta G^{0\prime} = -111.3 \text{ kJ/reaction}$$

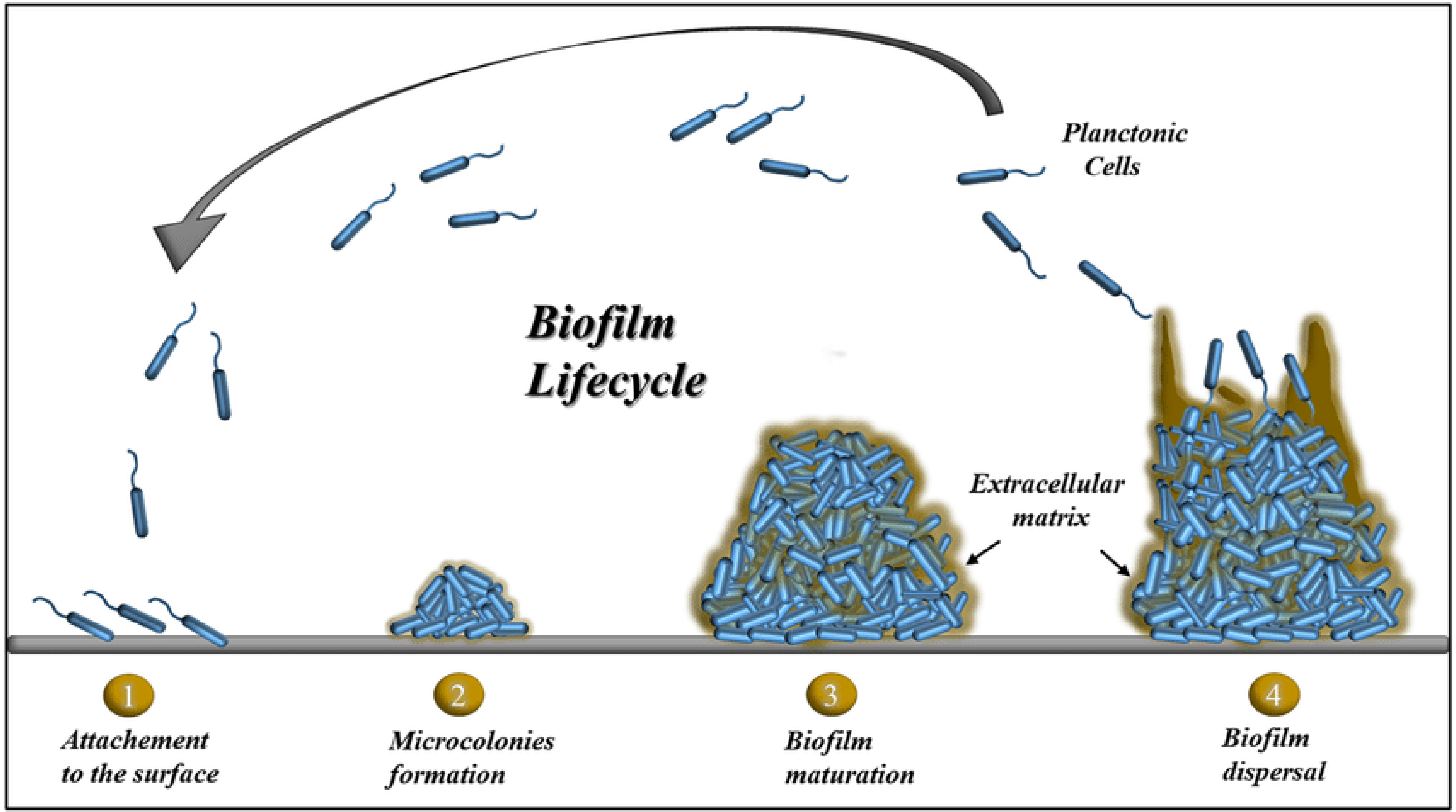
*(a)* **Reactions**




*(b)* **Overview of syntrophic transfer of $H_2$**

# The five main phases leading to the development and dispersal of biofilm





Biofilm
Lifecycle
Planctonic
Cells
Extracellular
matrix
1
Attachement
to the surface
2
Microcolonies
formation
3
Biofilm
maturation
4
Biofilm
dispersal

# Microbial Growth Cycle

- **Continuous culture:** an open system
- **Chemostat:** most common type of continuous culture device; known volume added while spent medium is removed at same rate
- **Steady state:** cell density and substrate concentration do not change over time