



THE MOLECULAR HISTORY OF LIFE

FALL 2023




A SHORT RECAP (SESSION 1)

- EARTH IS 4.5 BILLION YEARS (GA) OLD
- ABOUT 4.4 GA, THE MOON-FORMING IMPACT TURNED THE EARTH INTO A BALL OF BOILING LAVA
- TEMPERATURES OVER 2,000°K FORCED ALL WATER FROM EARLY ACCRETION INTO THE GAS PHASE AND CONVERTED ALL EARLY ACCRETED CARBON TO ATMOSPHERIC CARBON DIOXIDE (CO₂)
- BY 4.2 TO 4.3 GA, THE EARTH HAD COOLED SUFFICIENTLY ENOUGH THAT THERE WAS LIQUID WATER
- FIRST OCEANS WERE ABOUT TWICE AS DEEP AS TODAY'S
- THE FIRST SIGNS OF LIFE APPEAR AS CARBON ISOTOPE SIGNATURES IN ROCKS 3.95 BILLION YEARS OF AGE
- THUS, SOMEWHERE ON THE OCEAN-COVERED EARLY EARTH AND IN A NARROW WINDOW OF TIME OF ONLY ABOUT 200 MILLION YEARS, THE FIRST CELLS CAME INTO EXISTENCE



A SHORT RECAP (SESSION 2 AND 3)


- PREBIOTIC SYNTHESIS OF ORGANIC COMPOUNDS
 - THE MAKINGS OF THE “RNA WORLD”
 - RNA INSIDE LIPID VESICLES
 - EVOLUTION OF THESE VESICLES INTO “PROTOCELLS”
 - BRINGING IN PROTEINS
 - THE PROTORIBOSOME
 - EMERGENCE OF THE UNIVERSAL GENETIC CODE
 - THE MOVE TOWARDS MORE STABLE DNA-BASED GENOMES
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WHERE ON EARTH IS ALL THIS HAPPENING?

- PREBIOTIC SYNTHESIS OF THE CONSTITUENTS OF PROTEINS, NUCLEIC ACIDS AND MEMBRANES
- POLYMERIZATION OF NUCLEIC ACIDS AND FORMATION OF FATTY ACID VESICLES ARE DRIVEN BY WET-DRY CYCLES IN ENVIRONMENTS OF LOW SALINITY
- WARM LITTLE PONDS: HOT SPRINGS AND FLUCTUATING FRESHWATER POOLS ARE PLAUSIBLE CANDIDATES FOR PREBIOTIC SITES SUPPORTING THE ASSEMBLY OF PROTOCELLS
- ALSO, MEMBRANE ASSEMBLY OCCURS MOST READILY IN SOLUTIONS WITH MINIMAL CONTENT OF SALT, WHICH SUGGESTS THAT CELLULAR LIFE BEGAN IN FRESH WATER POOLS ASSOCIATED WITH VOLCANIC ISLANDS RATHER THAN SUBMARINE HYDROTHERMAL VENTS.
- AND THIS HAPPENS IN NUMEROUS POOLS ALL OVER THE PLANET AND OVER MANY MILLIONS OF YEARS




THE ADVANTAGES OF BEING SMALL

- POOLS ON LAND HAVE ACCESS TO MULTIPLE POTENTIAL SOURCES OF BIOLOGICALLY RELEVANT ORGANIC COMPOUNDS: METEORITES, PREBIOTIC SYNTHESIS
 - WHATEVER THE SOURCE, IF THE ORGANIC COMPOUNDS FALL AND ARE DISPERSED INTO THE OCEANS, THEY WOULD FORM A VERY DILUTE SOLUTION
 - IN CONTRAST, THOSE SAME COMPOUNDS FALLING ON OR SYNTHESIZED AT VOLCANIC LAND MASSES EXPOSED TO THE ATMOSPHERE WOULD BECOME CONCENTRATED ON THE MINERAL SURFACES AND THEN WOULD BE FLUSHED INTO POOLS
 - CARBON DIOXIDE AND SULFUR DIOXIDE ARE MAJOR COMPONENTS OF VOLCANIC GASES AND ARE WEAK ACIDS WHEN DISSOLVED IN WATER. THEREFORE, THE CIRCULATING WATER IN HYDROTHERMAL FIELDS IS MODERATELY ACIDIC
 - MOST PHOSPHORUS ON EARTH IS IN THE FORM OF VERY STABLE AND HARD CALCIUM PHOSPHATE (APATITE, THINK TEETH). BUT PHOSPHATES CAN LEACH OUT OF APATITE IN ACIDIC CONDITIONS
 - THIS WOULD HAVE MADE PHOSPHATE AVAILABLE FOR SYNTHESIS OF NUCLEOTIDES
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SPREADING (GO WEST, YOUNG PROTOCELL)

- INTERCONNECTED HOT SPRING POOLS ON MOUNTAINOUS VOLCANIC LANDSCAPES HAVE THE OBVIOUS ADVANTAGE THAT THERE IS A CONTINUOUS DOWNHILL FLOW FROM POOL TO POOL DRIVEN BY GRAVITY, SO THAT PROTOCELL POPULATIONS CAN SPREAD TO OTHER POOLS WITH DISTINCT CHARACTERISTICS
 - DEHYDRATED FILMS CAN ALSO UNDERGO WINDBORNE DISTRIBUTION, A MECHANISM STILL USED TODAY BY MICROBIAL AND ALGAL MAT COMMUNITIES
 - DROPLETS CAN ALSO BECOME AIRBORNE
 - INNOVATIONS DEVELOPED IN ONE POOL CAN BE SHARED WITH POPULATIONS OCCUPYING ANOTHER
 - DIFFERENT ENVIRONMENTS PUT DIFFERENT SETS OF SELECTIVE PRESSURE TO DRIVE EVOLUTION OF SPECIFIC TRAITS
 - COLONIZATION BECOMES WIDESPREAD
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THE PROTOCELL LIFESTYLE

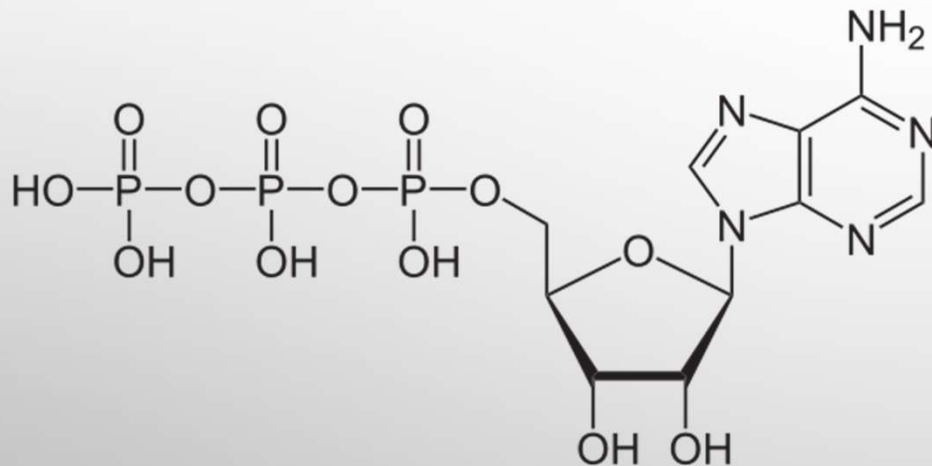
- PROTOCELLS WERE FLUID STRUCTURES
- FORMING, FALLING APART, REFORMING, FUSING WITH ONE ANOTHER
- NO HARD BOUNDARIES WITH THE ENVIRONMENT: MEMBRANES WERE POROUS, FRAGILE
- RIBOSOMES WERE PRESENT BUT NOT FULLY DEVELOPED → PROTEIN-MAKING WAS SLOPPY
- GENETIC MATERIAL WAS EVOLVING INTO “USEFUL” CODING
- EVENTUALLY SOLIDIFYING IN THE UNIVERSAL GENETIC CODE

- THESE PROTOCELLS, IN ORDER TO MAINTAIN STRUCTURE, HAD TO DEVELOP WAYS TO HARNESS ENERGY (REMEMBER, METABOLISM TO COUNTERACT ENTROPY)

HARNESSING ENERGY

- IN THIS EARLY ENVIRONMENT, POSSIBLE SOURCES OF ENERGY:
- THERMAL ENERGY → ALTHOUGH THEORETICALLY IT IS POSSIBLE TO USE THERMAL ENERGY TO LINK PHOSPHATE GROUPS INTO MORE ENERGETICALLY DENSE COMPOUNDS, SO FAR THIS HAS NOT BEEN ASCERTAINED AS PLAUSIBLE IN EARLY EARTH SCENARIOS
- SUN → REQUIRES THE EVOLUTION OF PIGMENTS ABLE TO CAPTURE PHOTONS LEADING TO AN EXCITED STATE; WHEN THIS ENERGY IS RELEASED, IT IS USED TO FORM CHEMICAL BONDS
- CHEMICAL ENERGY IN INORGANIC COMPOUNDS → SULFUR COMPOUNDS, IRON
- CHEMICAL ENERGY IN ORGANIC SUBSTRATES → ESPECIALLY SUGARS (SYNTHESIZED IN ABIOTIC CONDITIONS OR RELEASED FROM PROTOCELLS)
- **WHEN IT COMES TO HARNESSING ENERGY, LIFE IS DIVERSIFYING BY LEAPS AND BOUNDS!**


ATP: THE ENERGY CURRENCY OF LIFE



- WHATEVER THE SOURCE OF ENERGY (AS IN THE PREVIOUS SLIDE), IT IS USED TO SYNTHESIZE ATP
- EVERY REACTION THAT REQUIRES ENERGY IN A LIVING SYSTEM USES ATP AS ITS PRIMARY ENERGY SOURCE
- FUN FACT: THE HUMAN BODY USES ABOUT ITS WEIGHT IN ATP DAILY (WE DON'T EAT IT, WE TURN IT OVER → SYNTHESIS AND UTILIZATION). IT'S NOT AN ENERGY BANK DEPOSIT; IT'S ENERGY CASH




MEMBRANES ARE EVOLVING

- THE SIMPLE LIPID VESICLES DID NOT ALLOW THE MOVEMENT OF CHARGED AND/OR LARGE MOLECULES
 - PORES ALLOW NUTRIENT SOLUTES TO DIFFUSE INTO THE INTRACELLULAR VOLUME
 - FIRST SIMPLE PROTEINS (EVEN A 15-AMINO ACID POLYPEPTIDE) COULD ACT AS A PORE
 - THESE PROVIDE THE SITE FOR INSERTION OF ADDED DOMAINS TO ADD SUBSTRATE SPECIFICITY ETC. (AGAIN, THE KLUDGE FACTOR)
 - PORES CAN MOVE MORE THAN ONE COMPOUND
 - THESE CHANNELS COUPLED WITH ATPASES TO ALLOW ACTIVE (I.E. ENERGY-DEPENDENT) MOVEMENT ACROSS THE MEMBRANE
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BIOCHEMICAL CAPABILITIES ARE EVOLVING

- METABOLIC PATHWAYS FOR THE SYNTHESIS OF NUCLEOTIDES, AMINO ACIDS, MEMBRANE COMPONENTS, ETC.
 - RIBOSOMES ARE ACCRUING DOMAINS RESULTING IN MORE ACCURATE PROTEIN SYNTHESIS
 - RNA TRANSCRIPTION AND TRANSCRIPTION INITIATION GET MORE ACCURATE
 - DNA GENOMES ARE STABILIZED AND GETTING BIGGER
 - PROTEINS ARE EVOLVING TO PACKAGE THE LARGER DNA GENOMES TO FIT INTO THE PROTOCELL
 - MECHANISMS FOR DNA REPLICATION AND PROPER SEGREGATION INTO DAUGHTER CELLS EVOLVE
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IS THIS AN OMNIPOTENT ANCESTOR???

- SOUNDS TOO MUCH LIKE A MIRACLE FOR COMFORT
 - ALL THESE INVENTIONS HAPPEN IN PARALLEL
 - IT'S A TIME OF RAMPANT INNOVATION
 - THESE INNOVATIONS ARE SHARED
 - THE “OMNIPOTENT ANCESTOR” IS ACTUALLY A **COMMUNITY** OF CELLS FREELY EXCHANGING INFORMATION
 - THIS IS A WEB OF CELLS, PERVADING THE BIOSPHERE, SHARING THE SUCCESS STORIES!
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WHAT MAKES THIS SHARING POSSIBLE

- UNIVERSAL GENETIC CODE
 - NON-ISOLATING, 'PERMEABLE' CELL BOUNDARIES
 - FUSION OF PROTOCELLS
 - PICKING UP EXOGENOUS DNA FROM THE ENVIRONMENT

 - THE TANGLED ROOTS OF HORIZONTAL SHARING THROUGH COMMUNAL PROTOCELLS CAN NOW SUPPORT THE GROWTH OF MULTIPLE INTERWOVEN BRANCHES AS THE TREE OF LIFE BEGINS TO FORM
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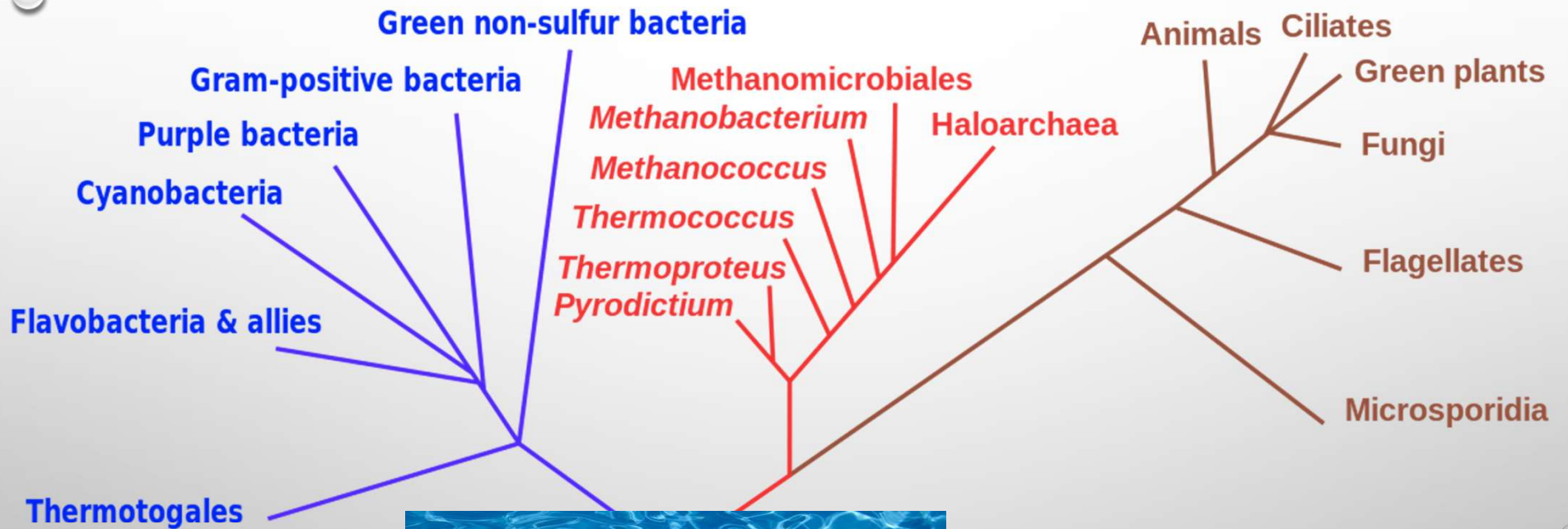
CROSSING THE DARWINIAN THRESHOLD (OR PICKING FROM THE POOL)

- AS PROTOCELLS BECOME MORE COMPLEX, “COMMUNAL LIVING” BECOMES LESS TENABLE
 - THE TANGLED WEB OF PROTOCELLS TEND TO COALESCE INTO DEFINED BRANCHES
 - EVENTUALLY, INDIVIDUAL CELLS WOULD BECOME SUFFICIENTLY ADVANCED TO SURVIVE AND REPRODUCE FREELY IN SOLUTION, DETACHED FROM THEIR ORIGINAL COMMUNAL COMPLEXES.
 - RAMPANT HORIZONTAL GENE TRANSFER IS RESTRICTED
 - VERTICAL INHERITANCE STARTS TO PREDOMINATE
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Bacteria

Archaea

Eukarya



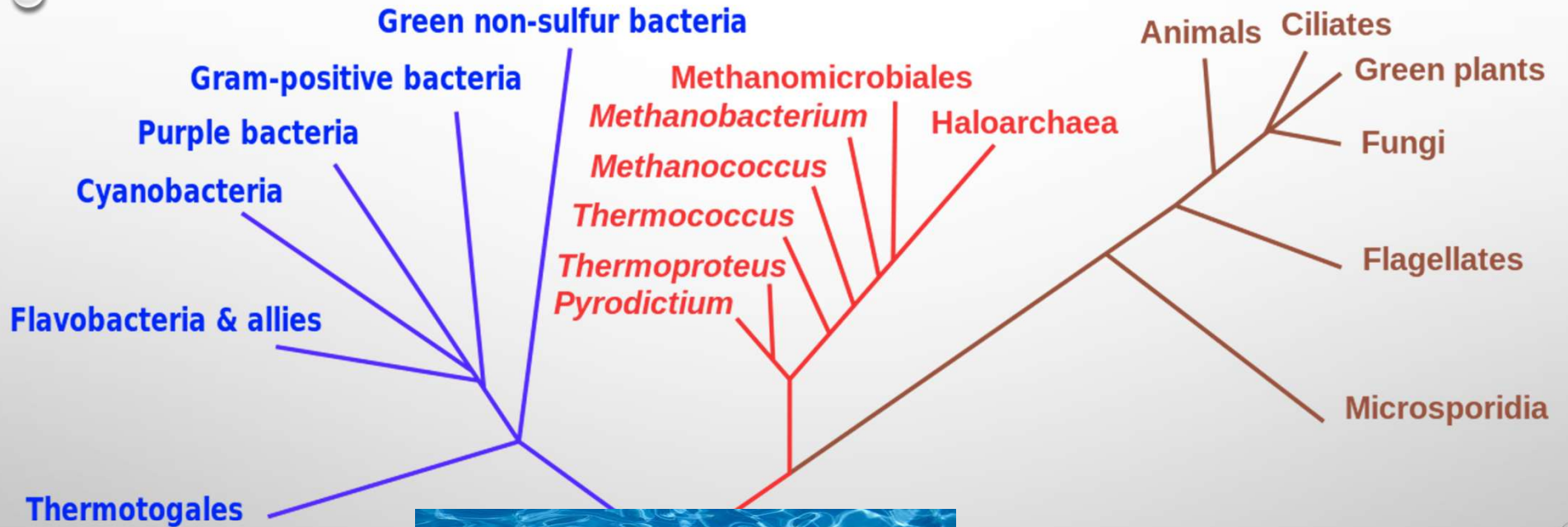
DARWINIAN THRESHOLD



Bacteria

Archaea

Eukarya



BECOMING A...

- **BACTERIUM**


- DEVELOPING A ROBUST CELL WALL
- DEFINING THE START POINTS OF RNA SYNTHESIS (I.E. GENES)
- DNA PACKAGING
- DEFINING THE BACTERIAL MEMBRANE

- **ARCHAEUM/EUKARYOTE**

- MULTIPLE SOLUTIONS TO THE CELL WALL
- COMPLETELY DIFFERENT TRANSCRIPTION START MACHINERY
- COMPLETELY DIFFERENT DNA PACKAGING
- COMPLETELY DIFFERENT MEMBRANE



CELL WALL

- A STRUCTURAL LAYER SURROUNDING CELLS
 - PROVIDES THE CELL WITH BOTH STRUCTURAL SUPPORT AND PROTECTION, AND ALSO ACTS AS A FILTERING MECHANISM
 - A MAJOR FUNCTION IS TO ACT AS PRESSURE VESSELS, PREVENTING OVER-EXPANSION OF THE CELL WHEN WATER ENTERS
 - IN BACTERIA IT IS COMPOSED OF A MESH OF SUGARS AND AMINO ACIDS
 - ABSENT IN MANY EUKARYOTES, INCLUDING ANIMALS
 - DIFFERENT STRUCTURES IN PLANTS AND FUNGI
 - FOUR DIFFERENT KINDS IN ARCHAEA
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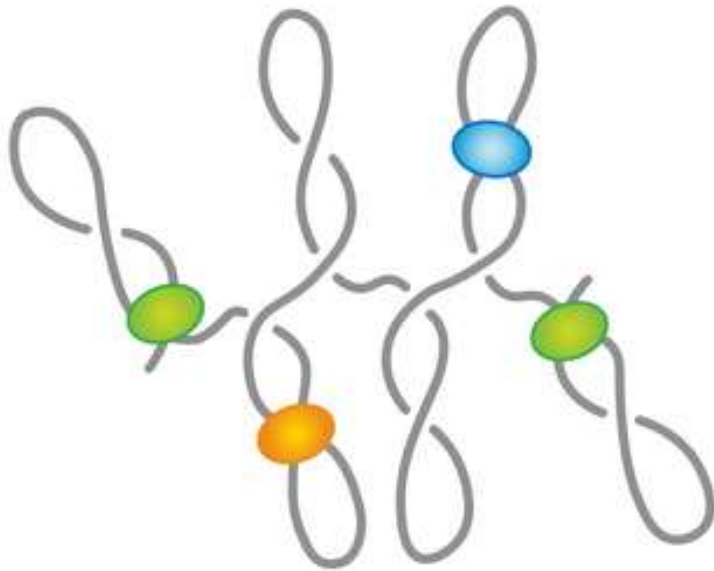


TRANSCRIPTION INITIATION

- PROMOTER STRUCTURE
 - PROMOTER RECOGNITION (SIGMA FACTOR VS TRANSCRIPTION FACTOR AND LATER RECRUITMENT OF POLYMERASE)
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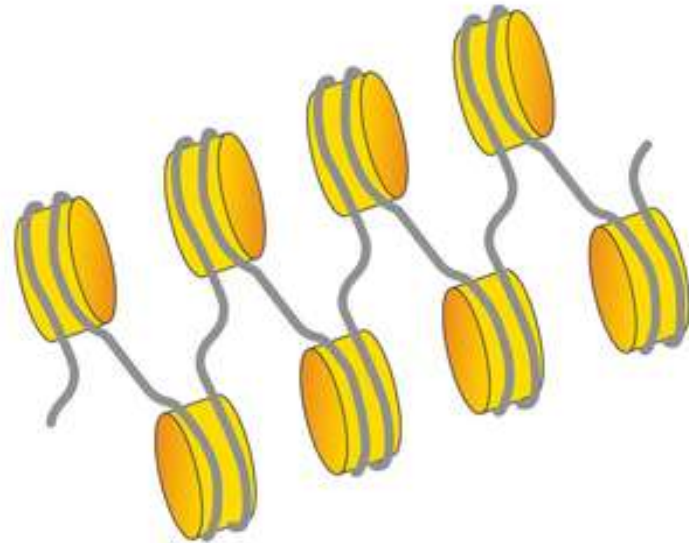
DNA PACKAGING

A. Bacteria



Negative plectonemic supercoils

B. Eukaryotes



Negative toroidal supercoils

CELL MEMBRANE

