Lecture-2
Biomolecules

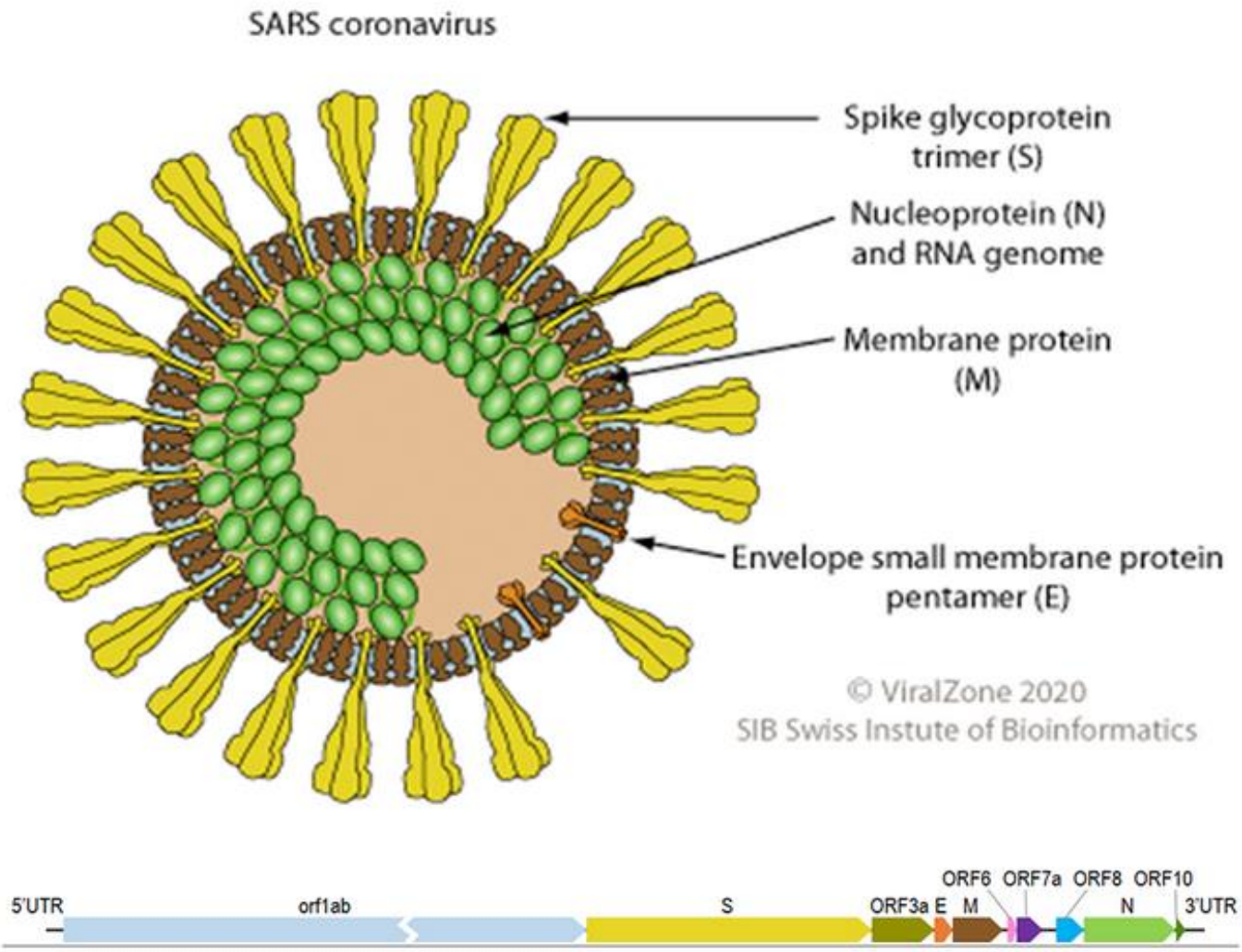
Goal

Goal of molecular cell biology - to understand the physiology of living cells in terms of the information that is encoded in the genome of the cell

How computer science can help in achieving this goal?

⇒ **To identify where are the genes in the genome, which gene is expressed when, where and how much, what factors affect its expression, what's its function, what happens in the disease state, what are the genetic variations and how to identify them, etc.**

What kind of biological data analysis helped in combating COVID-19 disease?



What kind of analysis can we carry out to know about the virus causing COVID-19?

- How to identify if a person is infected with SAR-COV-2?
- Is it the only known human coronavirus?
- Compare its genome with other viral genomes – to identify its closest relative
- What proteins aid in its transmission and infection?
- Identify drug targets and develop vaccines
- What organs/tissues are affected by its infection?
- Its rate of propagation
- Is it mutating and becoming more virulent, or milder with time, etc.

Cells

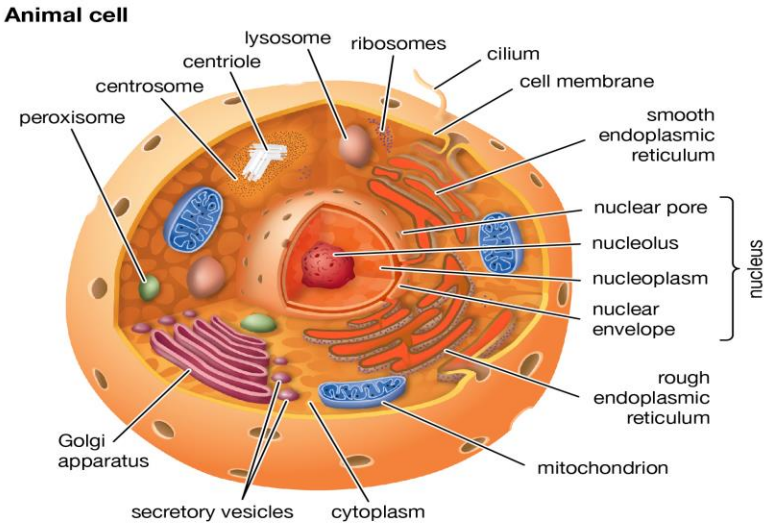
All living things are made of cells: small, membrane-enclosed units - have the ability to create copies of themselves by growing and dividing in two - replication

E. B. Wilson: "the key to every biological problem must be sought in the cell; for every living organism is, or at some time has been, a cell."

~ 10^{13} cells that form a human body, the whole organism has been generated by cell divisions from a single cell

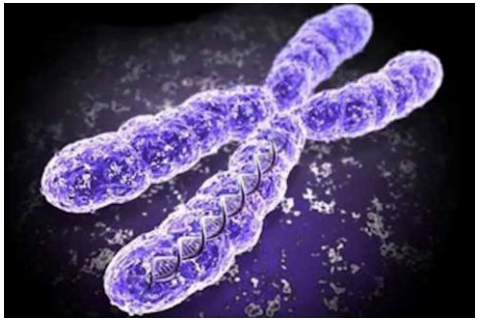
Cells are fundamental units of life
- the vehicle for all the hereditary information that defines each species.

Study of the structure, function, and behavior of cells is called Cell Biology



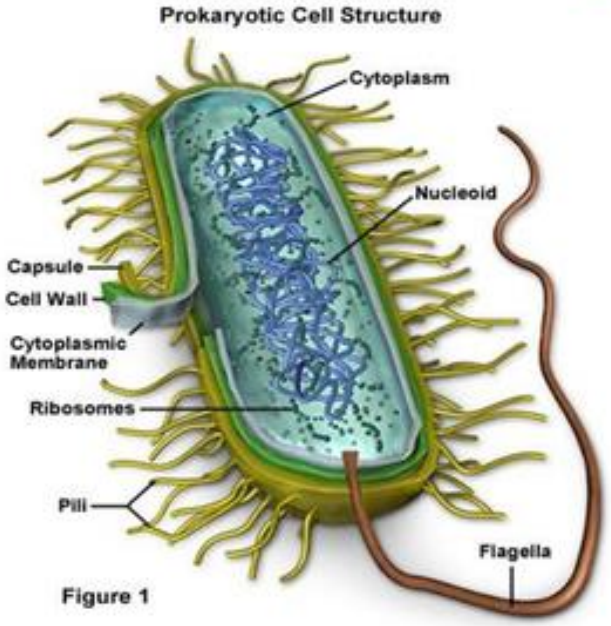
Cells and Chromosomes

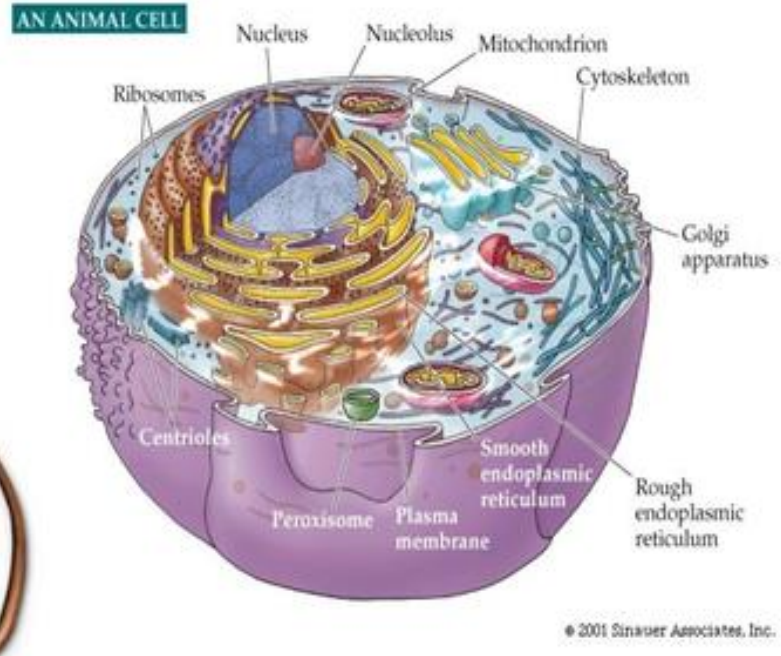
- **All cells store their hereditary information in the same linear chemical code: DNA (Deoxyribonucleic acid)**
  - **organized in coiled structures called chromosomes.**
- **Chromosomes are physically separate molecules that range in length from 50 - 250M base pairs.**
- **In most prokaryotes, each cell has a single chromosome.**
- **In eukaryotes, all cells contain same number of chromosomes, 8 in fruit flies, 46 in humans and bats, 84 in rhinoceros.**
- **In multi-cellular organisms, similar cells join together to form tissues.**
- **Complete DNA content of an organism is called the genome.**



Living organism divides into two major groups:

- **Prokaryotes - cells with no nucleus, e.g., bacteria and archaea**
- **Eukaryotes – cells with a nucleus, e.g., plants, animals and protozoas. These maybe unicellular (e.g., Yeasts) or multi-cellular (e.g., humans).**





Viruses

Viruses do not fall in either of the two divisions.

These are acellular entities with many of the properties of other life forms but are genetically and structurally too dissimilar to fit into the taxonomy scheme.

Viruses cannot be classified as living or non-living. They can replicate & carry out their functions only in a host – called obligate parasites.

May contain DNA or RNA as their nuclear material.

Viruses are acellular. So, if they do not have a cell, how does their genetic material remain intact?

DNA

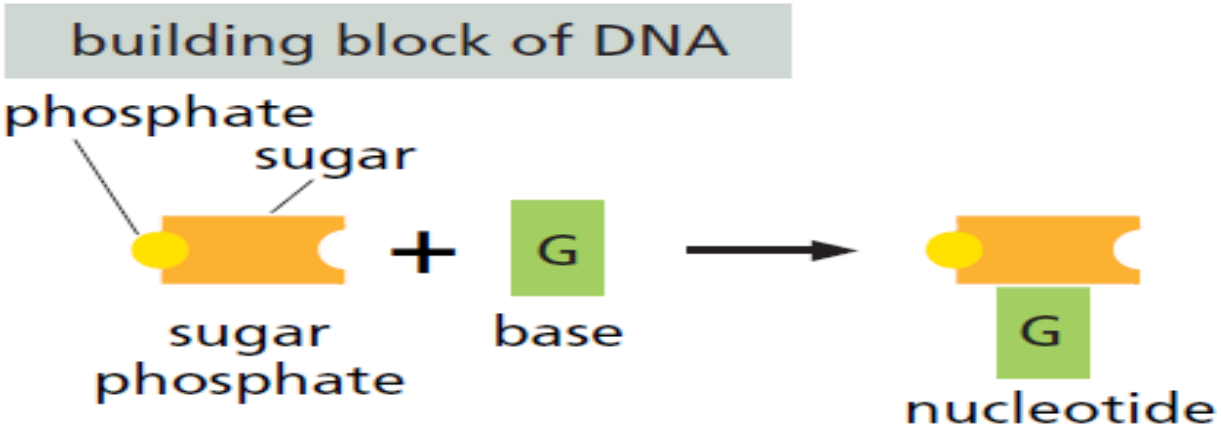
DNA (Deoxyribonucleic acid):

Composed of four basic units - called nucleotides

Each nucleotide contains - a sugar, a phosphate and one of the four bases:

Adenine (A), Thymine (T),

Guanine (G), Cytosine (C).

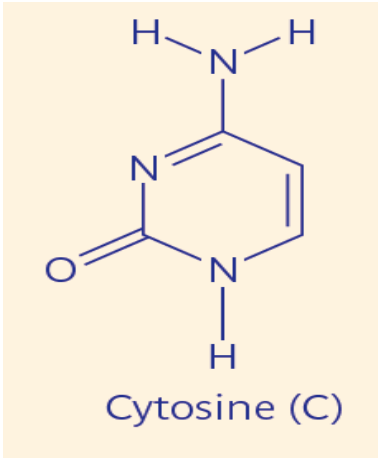


DNA

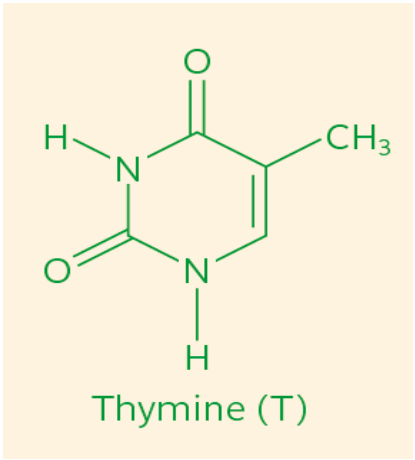
Bases: are **ring-shaped** and come in four types which fit together in pairs - this **pairing forms the basis of information carrying capacity of DNA.**

These are categorized as:

Pyrimidines

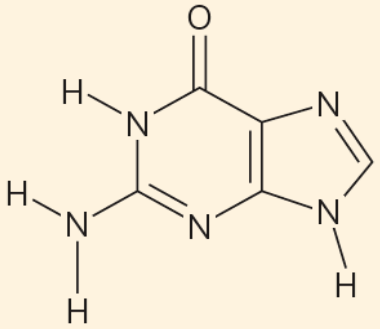


Cytosine (C)

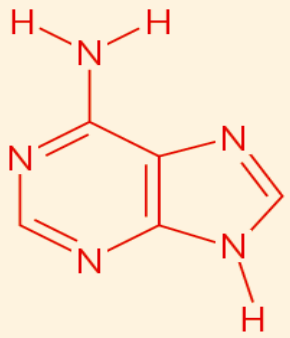


Thymine (T)

Purines



Guanine (G)



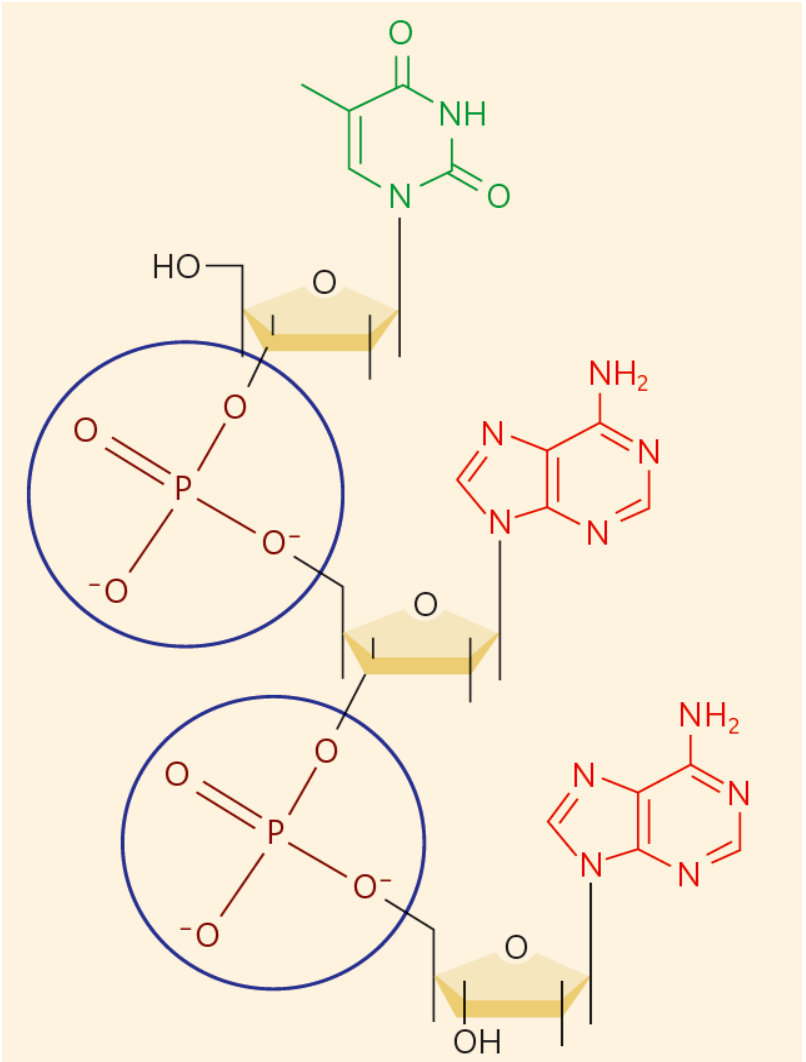
Adenine (A)

Base Pairing: C ⇔ G, A ⇔ T

DNA

Backbone of a polynucleotide strand is made of linked sugar-phosphate-sugar-phosphate, with one base joined to each sugar molecule.

- built by creating a phosphodiester bond that links 3′ carbon on the sugar of growing chain with the phosphate attached to 5′ carbon of an incoming nucleotide.



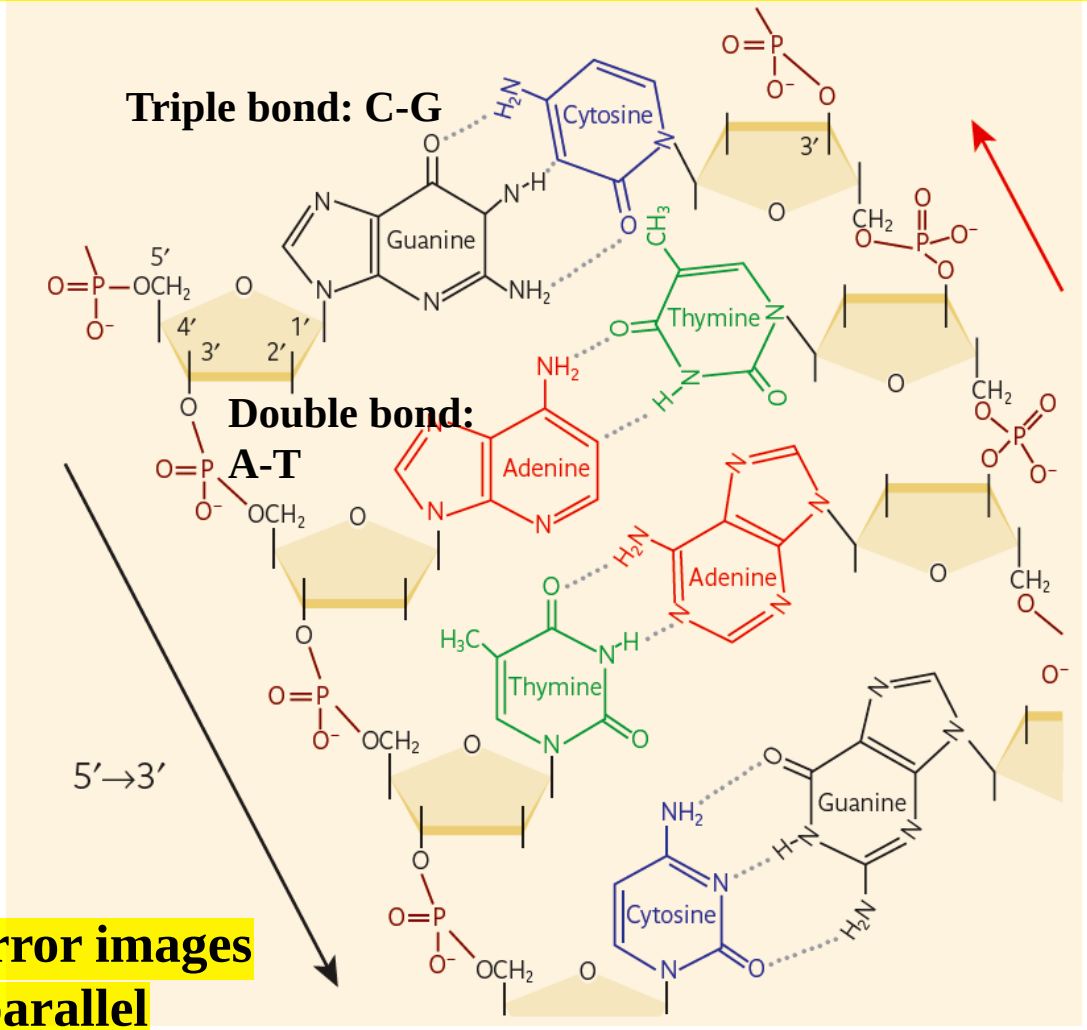
DNA Strand

DNA

Base Pairing: If two polynucleotide strands face each other, sugar-phosphate backbone runs down each side, and complementary pairs of bases in the middle spontaneously form hydrogen bonds:

Left Strand: 5' to 3': phosphate connected to 5' of sugar which is connected at 3' to the next phosphate

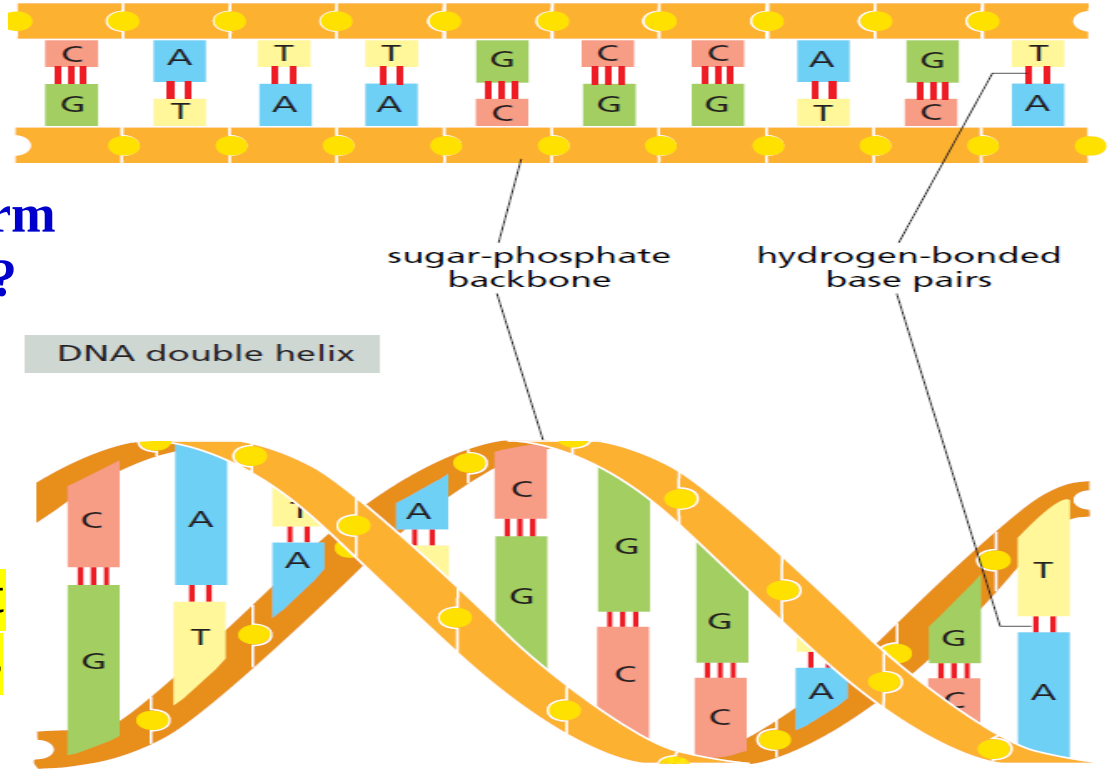
What is the sequence on both the strands?



Note: two strands are not mirror images of each other - they run antiparallel

DNA

Double-Stranded DNA: Nucleotides within each strand are linked by strong (covalent) chemical bonds; complementary nucleotides on opposite strands are held together by weak hydrogen bonds:



Why does DNA form a helical structure?

To minimize the destabilizing effect of water molecules

Double-Stranded DNA: **If the sequence in the forward strand in 5′ to 3′ direction is:**

5′ CATTGCCAGT 3′

Then what would be the sequence on the reverse strand when read in 5′ to 3′ orientation?

DNA

If the sequence in the forward strand in 5′ to 3′ direction is:

5′ CATTGCCAGT 3′

Then what is the sequence on the reverse strand when read in 5′ to 3′ orientation?

First write its complement:

5′ CATTGCCAGT 3′

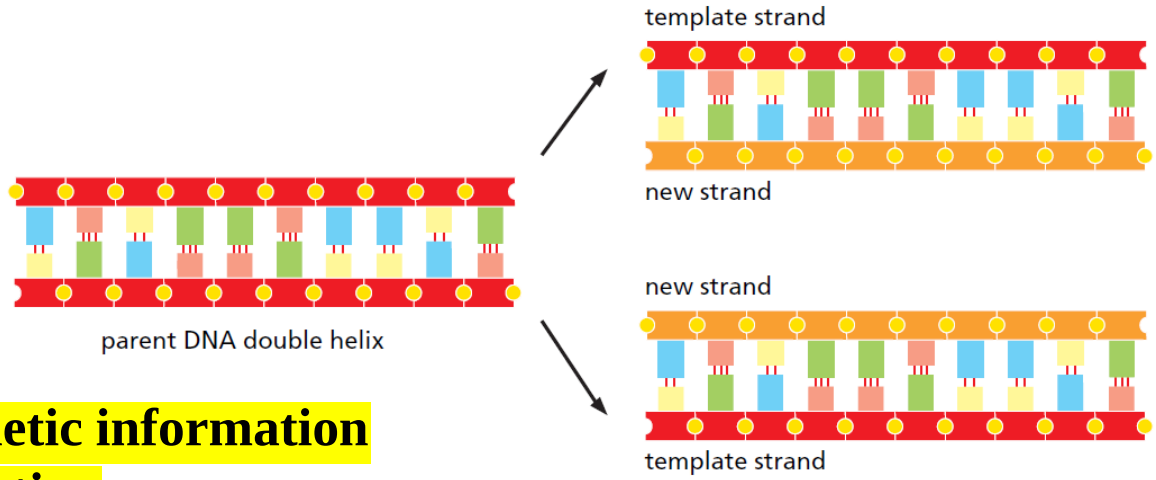
3′ GTAACGGTCA 5′

When read in 5′ to 3′ orientation, the sequence on the reverse strand is:

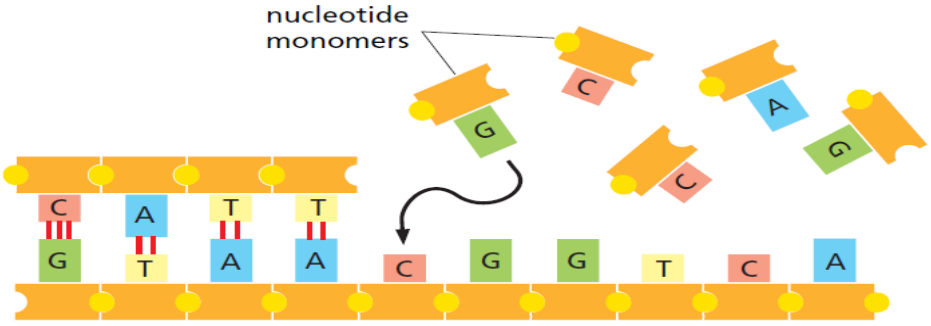
5′ ACTGGCAATG 3′

DNA Replication

In living cells DNA is not synthesized as a free strand in isolation, but on a template formed by a pre-existing DNA strand.



Copying of genetic information by DNA replication



templated polymerization

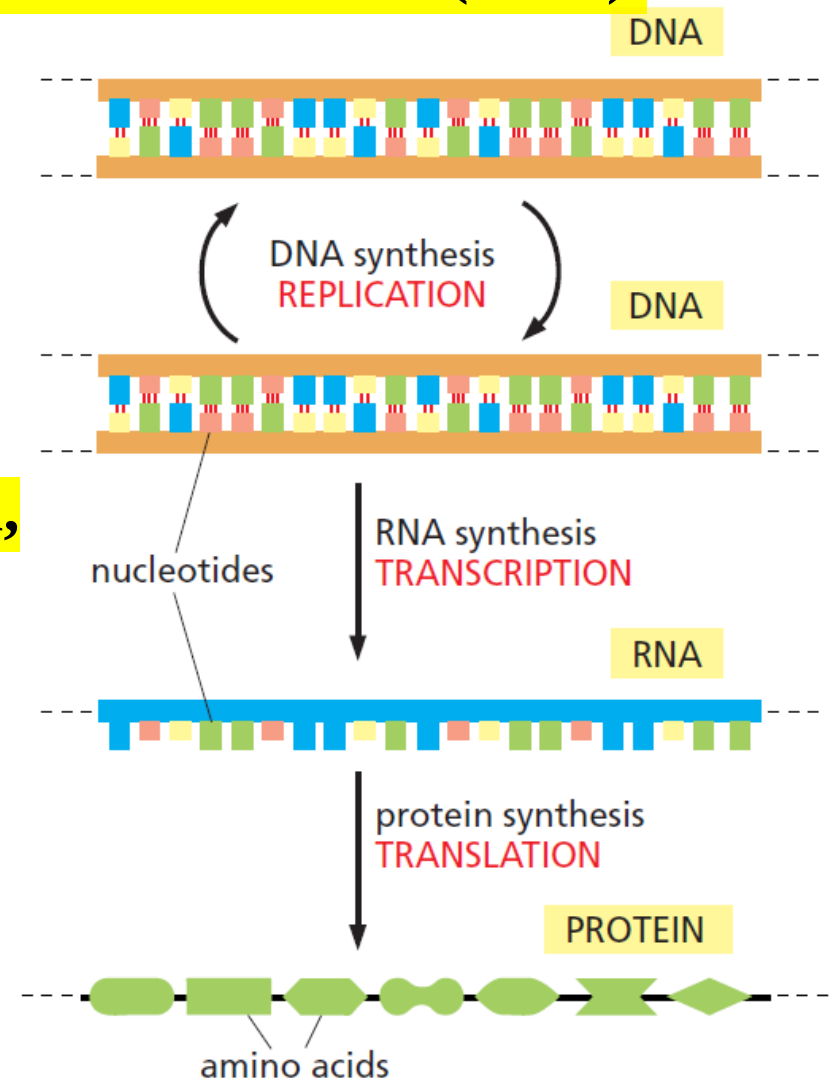
Central Dogma of Molecular Biology

All cells transcribe portions of their hereditary information into the same intermediary form: Ribonucleic acid (RNA).

DNA expresses its information, by letting the information guide the synthesis of other molecules in the cell: RNAs and Proteins

Process begins with a templated polymerization called transcription, for the synthesis of RNA.

In the more complex process of translation, these RNA molecules direct the synthesis of proteins



Ribonucleic Acid (RNA):

It is single-stranded molecule

Composed of four basic units - called nucleotides:

Each nucleotide contains - a sugar (ribose), a phosphate and one of the four bases: Adenine (A), Uracil (U), Guanine (G), Cytosine (C)

RNA polynucleotide strand is built by creating a phosphodiester bond between nucleotides.

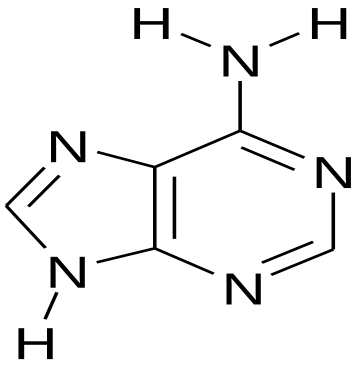
Intra-strand base pairing is a characteristic feature of RNA

Base Pairing – formed by weak H-bonds and follows the following complementarity rule:

G ⟷ C, A ⟷ U, and G ⟷ U

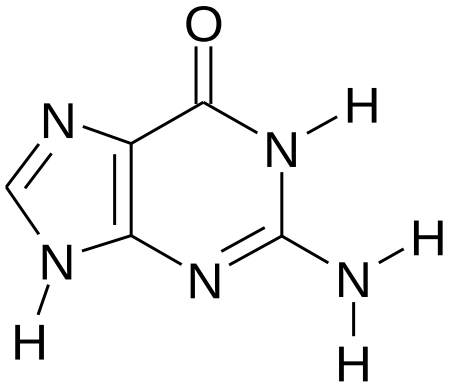
Ring Structure of Nucleic Acid bases

Adenine (A)

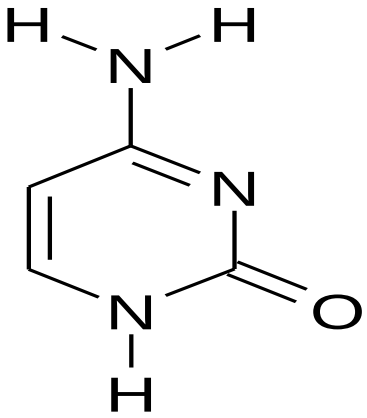


Purines

Guanine (G)

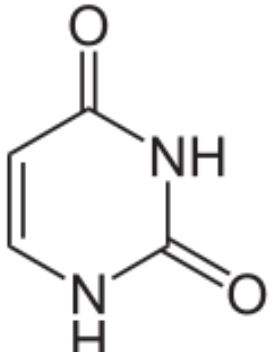


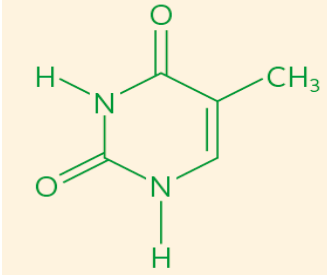
Cytosine (C)



Pyridimines

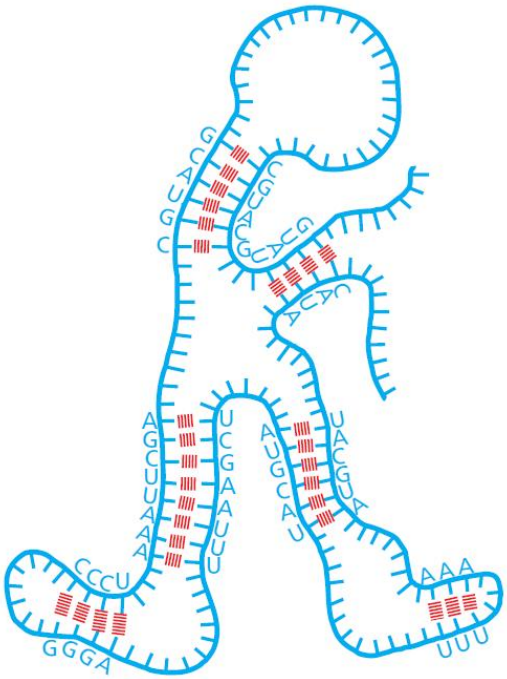
Uracil (U)

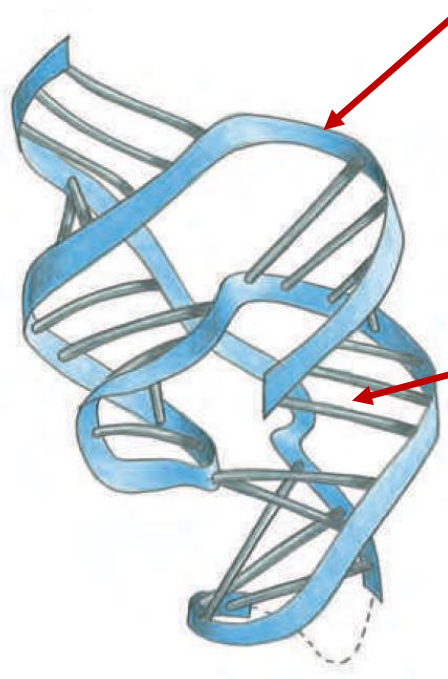




RNA

Nucleotide pairing between different regions of the RNA polymer chain causes the molecule to adopt a distinctive shape.

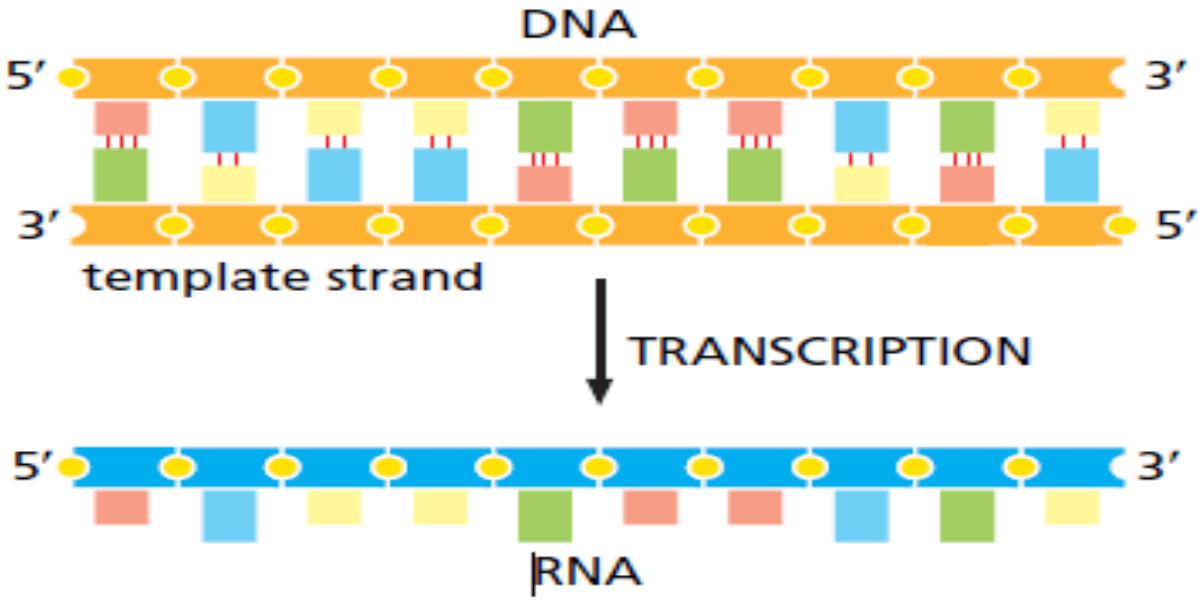




Distinct shapes of RNA molecules resulting from such internal associations enable it to recognize other molecules by binding to them selectively, or, in certain cases, catalyze chemical changes in the molecules that are bound.

RNA Synthesis:

RNA is also read in the 5′ to 3′ orientation.



RNA molecules that are copied from the genes (which ultimately direct the synthesis of proteins) are called messenger RNA (mRNA) molecules.

RNA Synthesis

1. For the following DNA sequence in the forward strand:

5′ CATTGCCAGT 3′

What will be the sequence of the RNA strand synthesized?

2. If the following DNA sequence is used as template for RNA synthesis:

5′ CATTGCCAGT 3′

Give the sequence of the RNA strand read in 5′ to 3′ orientation.

RNA Synthesis

1. If the DNA sequence in the forward strand is given as:

5′ CATTGCCAGT 3′

Template sequence used for RNA synthesis is its complement:

5′ CATTGCCAGT 3′

3′ GTAACGGTCA 5′ template

The synthesized RNA sequence is the reverse complement of the template:

3′ GTAACGGTCA 5′ template

5′ CAUUGCCAGU 3′ RNA

- i.e., synthesized RNA sequence is basically the DNA sequence in the forward strand with T replaced by U

RNA Synthesis

If the template DNA sequence for RNA synthesis is given:

5′ CATTGCCAGT 3′

First write its complement:

5′ CATTGCCAGT 3′

3′ GUAACGGUCA 5′ complement

Then the synthesized RNA sequence in 5′ to 3′ orientation is:

5′ ACUGGCAAUG 3′ RNA

- i.e., synthesized RNA sequence is basically the complement of the template DNA sequence with T replaced by U, when read in the 5′ to 3′ orientation

RNA Synthesis:

There are other RNA molecules also obtained from genes. The final product in such cases is RNA.

These RNAs are known as noncoding RNAs because they do not code for protein.

e.g., in yeast *Saccharomyces cerevisiae*, over 1200 genes (~15%) produce RNA as their final product; Humans may produce on the order of 10,000 noncoding RNAs.

These RNAs, like proteins, serve as enzymatic, structural, and regulatory components for a wide variety of processes in the cell.

TABLE 6–1 Principal Types of RNAs Produced in Cells	
Type of RNA	Function
mRNAs	Messenger RNAs, code for proteins
rRNAs	Ribosomal RNAs, form the basic structure of the ribosome and catalyze protein synthesis
tRNAs	Transfer RNAs, central to protein synthesis as adaptors between mRNA and amino acids
snRNAs	Small nuclear RNAs, function in a variety of nuclear processes, including the splicing of pre-mRNA
snoRNAs	Small nucleolar RNAs, help to process and chemically modify rRNAs
miRNAs	MicroRNAs, regulate gene expression by blocking translation of specific mRNAs and cause their degradation
siRNAs	Small interfering RNAs, turn off gene expression by directing the degradation of selective mRNAs and the establishment of compact chromatin structures
piRNAs	Piwi-interacting RNAs, bind to piwi proteins and protect the germ line from transposable elements
lncRNAs	Long noncoding RNAs, many of which serve as scaffolds; they regulate diverse cell processes, including X-chromosome inactivation

Note: rRNA, tRNA and snRNA play an important role in protein synthesis

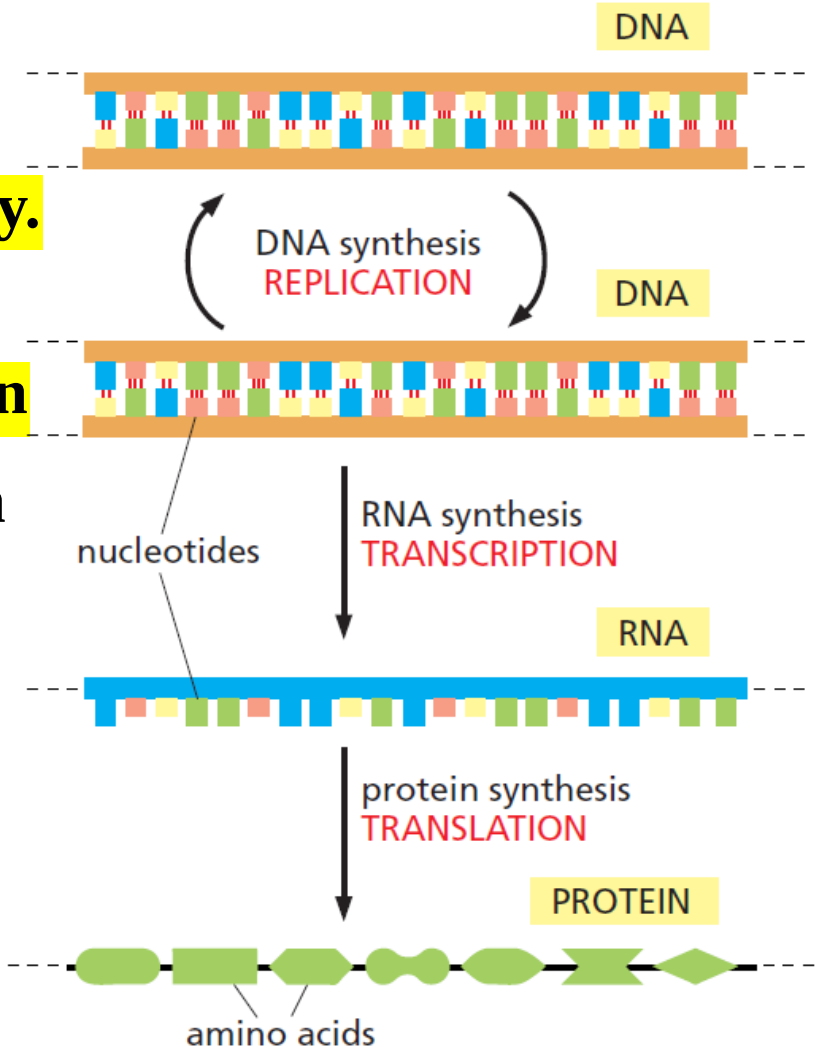
Protein Synthesis

Proteins are synthesized from DNA in a two-step process:

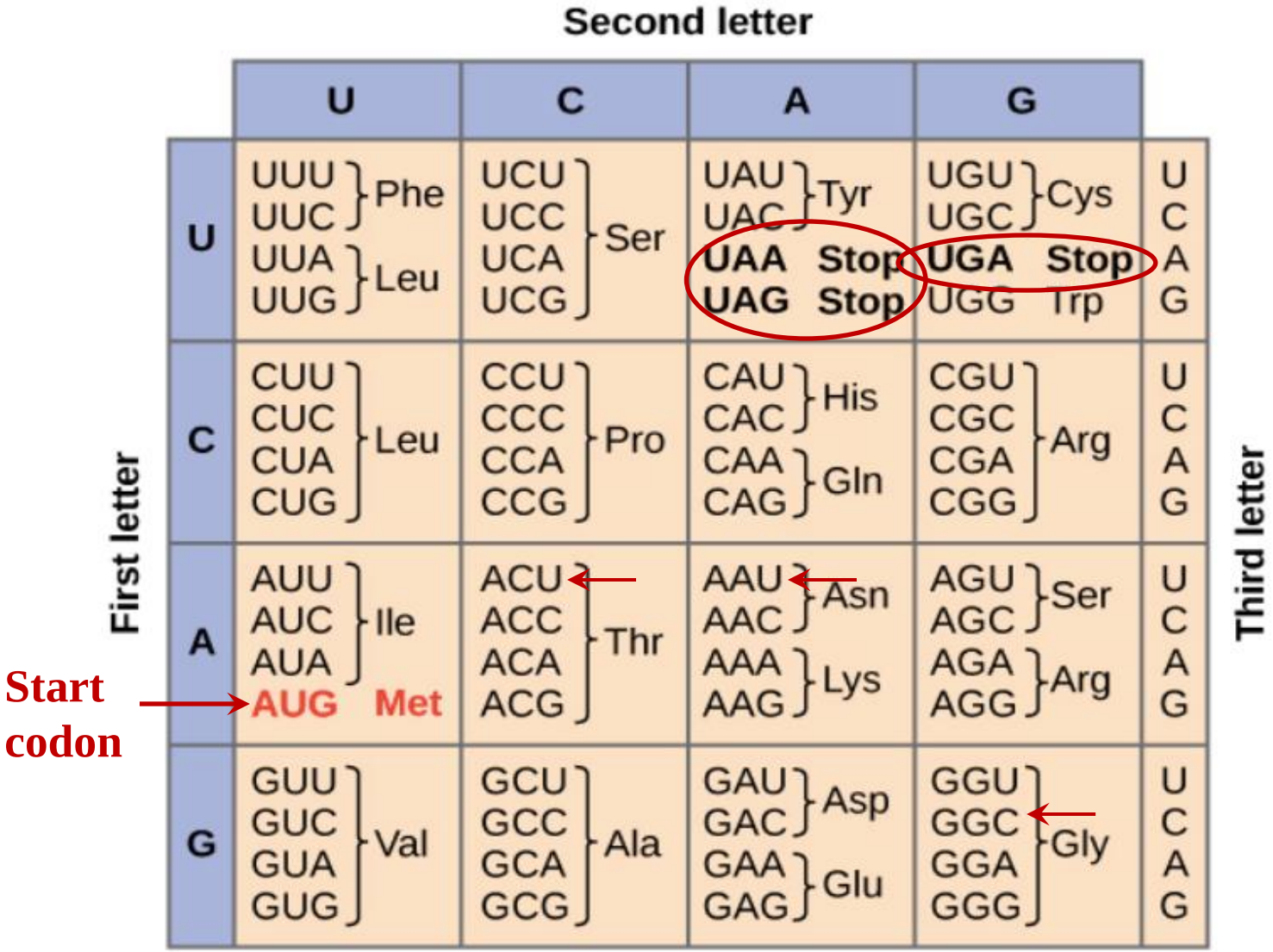
Each chromosome has several genes that code for various traits in the body.

RNA molecules direct synthesis of proteins in a process called translation

- **information in mRNA is read out in groups of three nucleotides, called codons.**



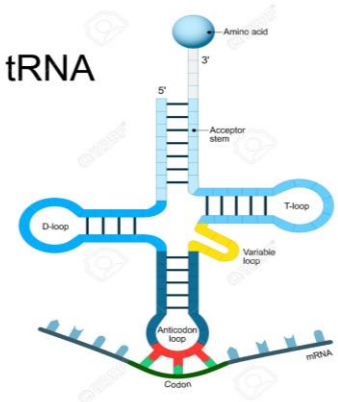
The Genetic Code



The genetic code is degenerate

Protein Synthesis

Using the genetic code, obtain the amino acid sequence synthesized from the following mRNA sequence:

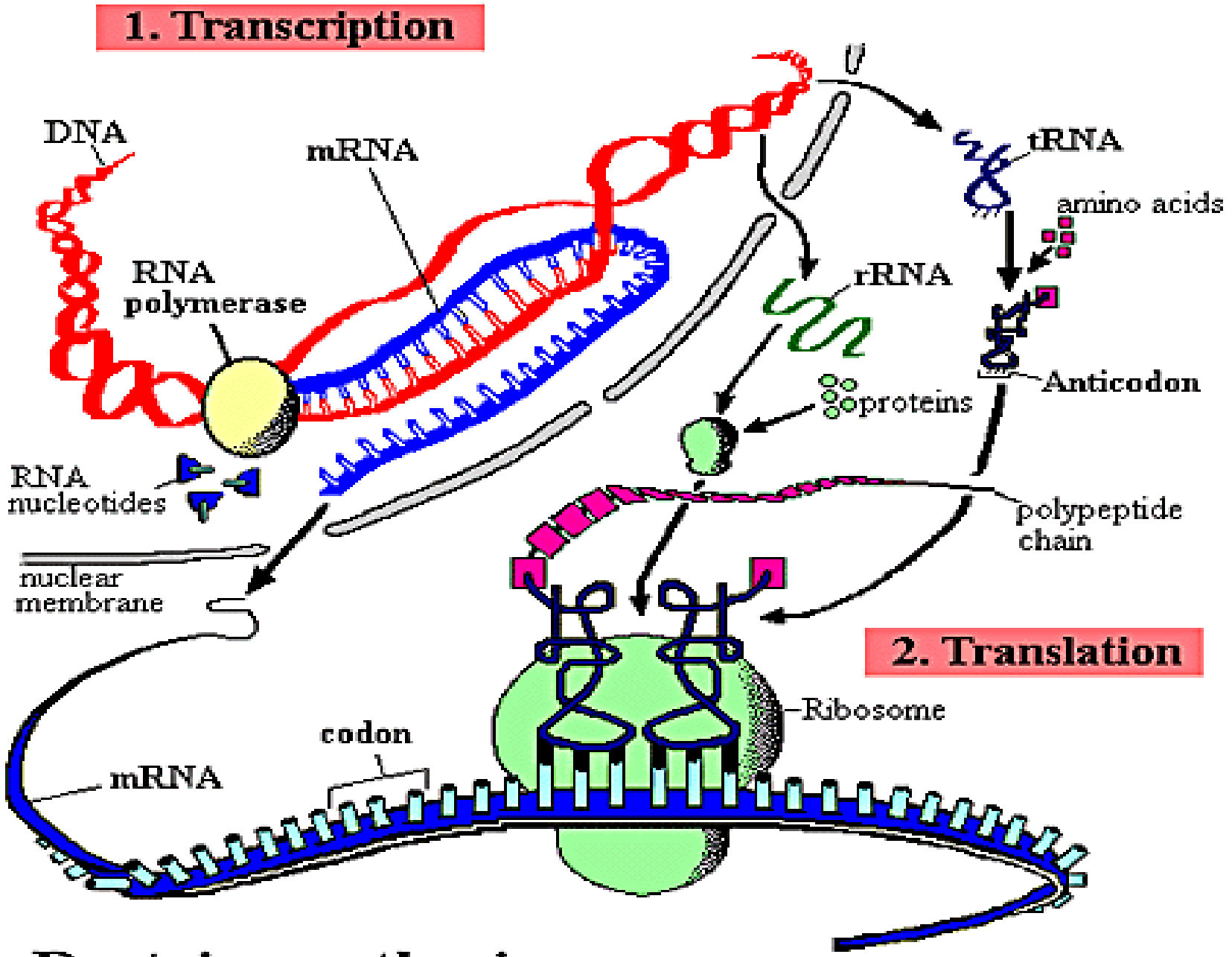


5′ ACU GGC AAU 3′

Thr Gly Asn

This genetic code is read out by a class of small RNA molecules, called transfer RNAs (tRNAs).

- **each type of tRNA attaches at one end a specific amino acid and at its other end has a specific sequence of 3 nucleotides - an anticodon that enables it to recognize, through base-pairing, a particular codon in the mRNA sequence.**
- **This process occurs on ribosome, a large multi-molecular machine composed of both proteins and ribosomal RNA.**



Protein synthesis

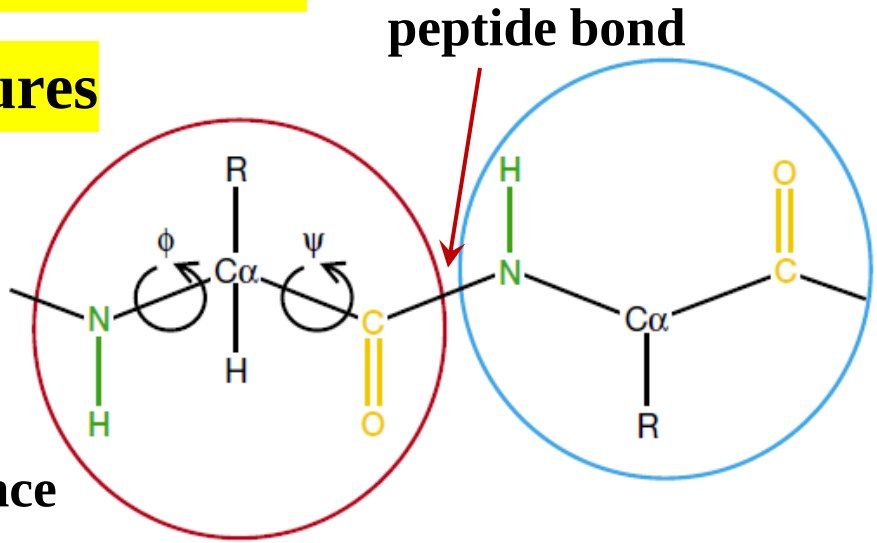
Proteins

Like DNA and RNA, Proteins carry information in linear sequence on a 20-letter alphabet, called amino acids:

ATRVGTCWPRA

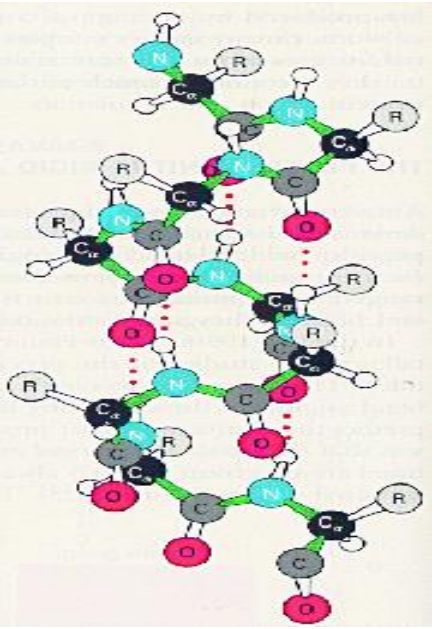
Protein structure is divided in 4 hierarchical levels:

- **Primary structure - represented by AA sequences**
- **Secondary structure - α-helices & β-sheets**
- **Tertiary and Quaternary structures - represented by 3D structures**



Backbone - N-C_α-C sequence

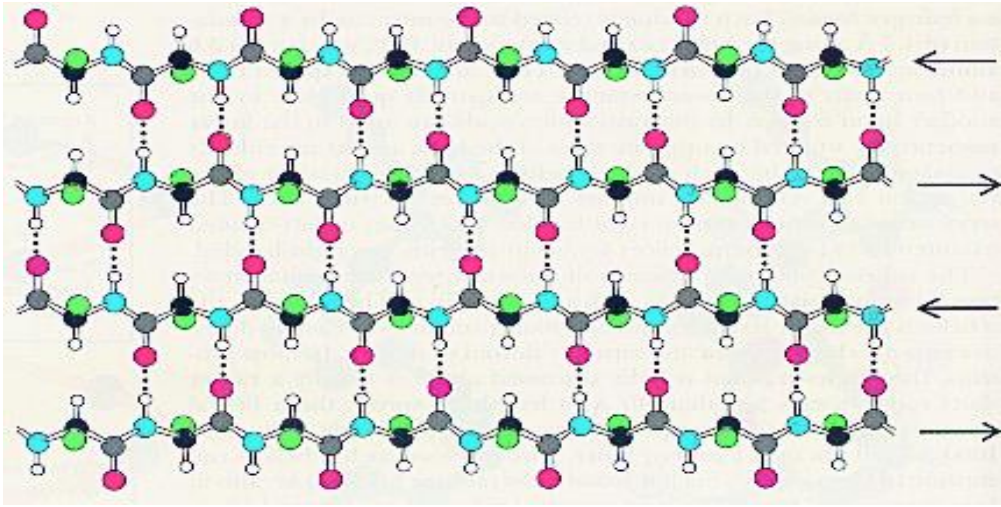
Primary Structure: ATRVGTCWPRA



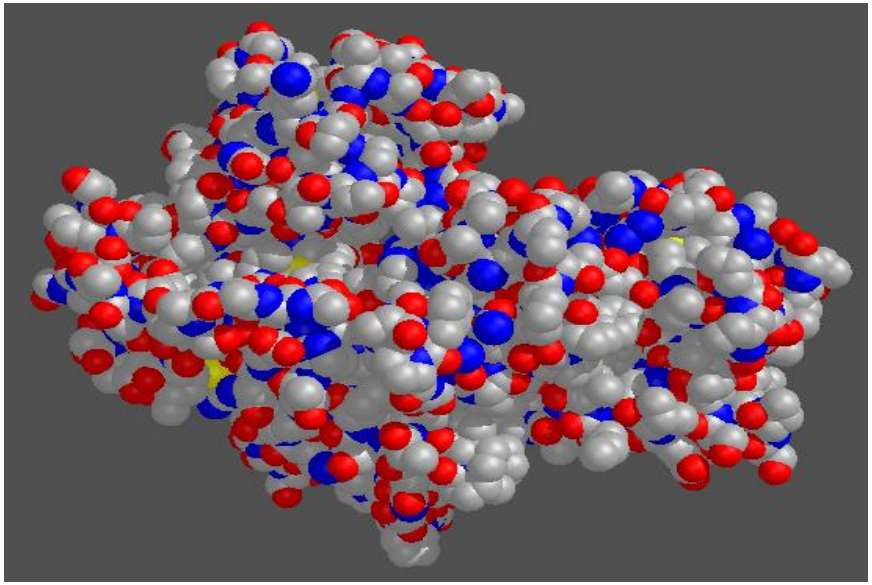
α-helix

Secondary Structures

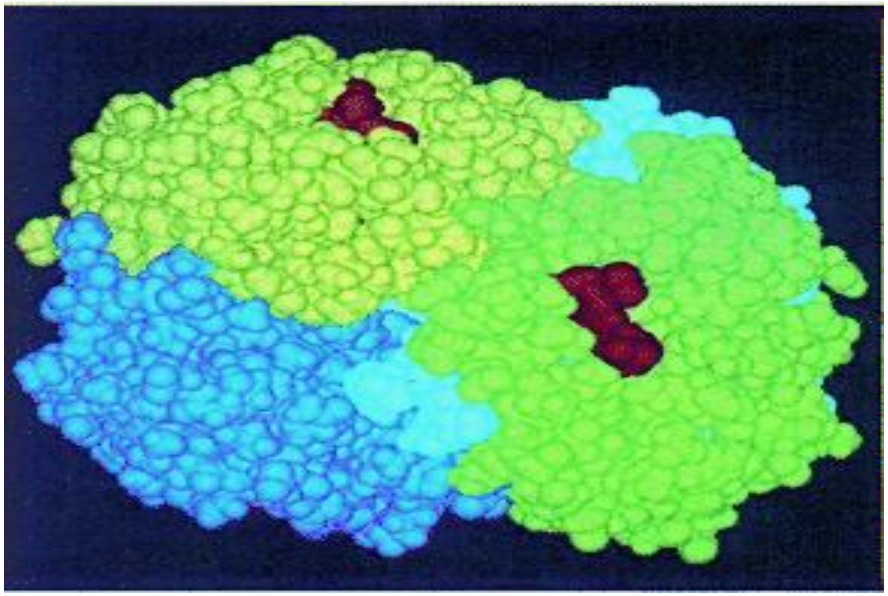
β-sheets



Tertiary Structure



Quaternary Structure



Function of Proteins

- **Proteins make up much of the cellular structure – hair, skin, fingernails, etc.**
- **Enzymes – catalyze chemical reactions within the cell**
- **Transcription factors – regulate the manner in which genes direct production of other proteins**
- **Receptors – proteins on the surface of cells act as receptors for hormones and other signaling molecules**
- **Recognize and bind to Nucleic acids (DNA, RNA) and other Proteins – to carry out their functions in the cell**

Genes

Special sequences in the DNA code for genes:

- **Protein-coding genes, for which the final product is a protein.**
  - **Same gene may give rise to more than one protein (~ 6 per gene in humans).**
- **Non-coding RNA genes - for which the final product is RNA**

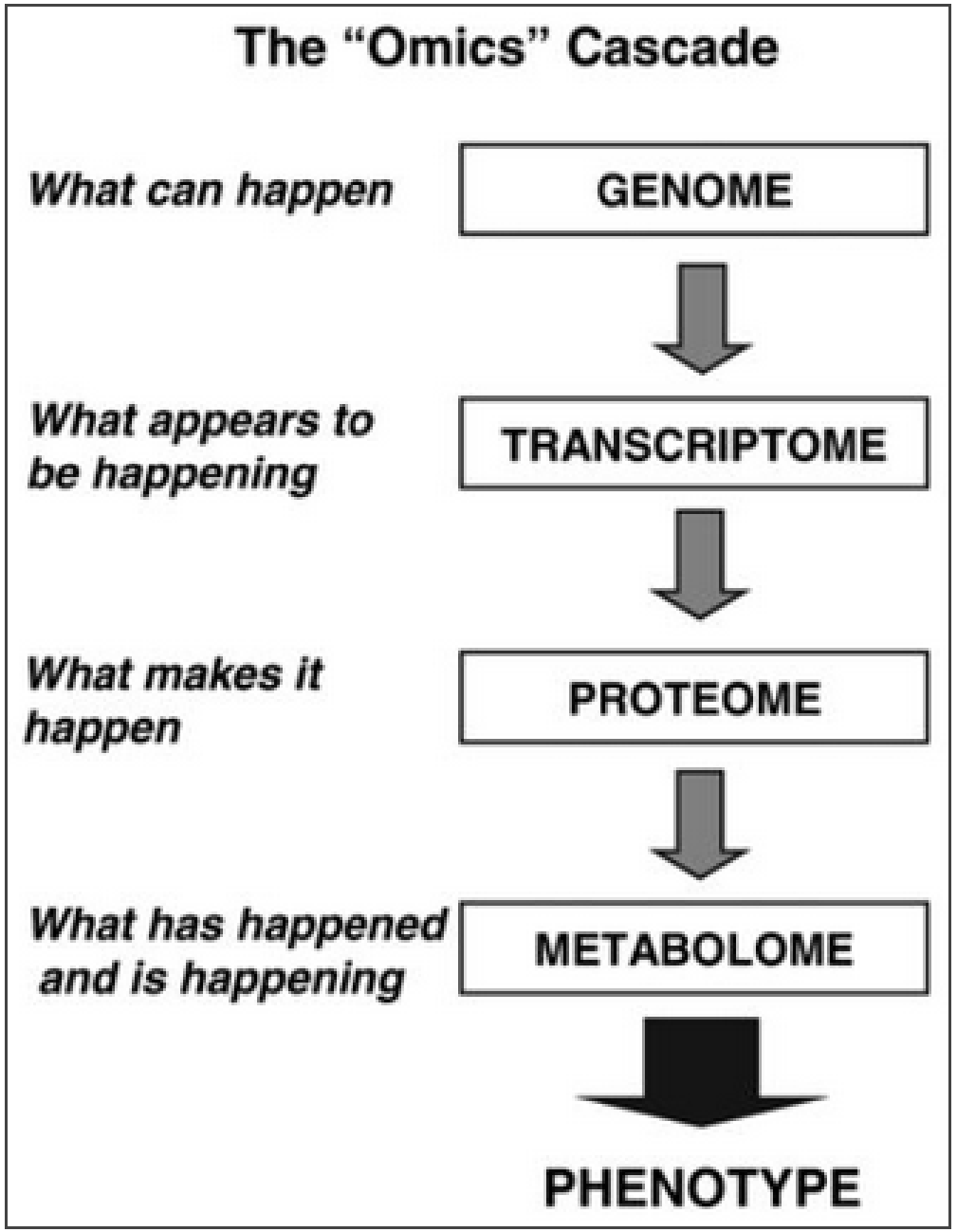
Genotype – An organism's genotype is the set of genes that it carries.

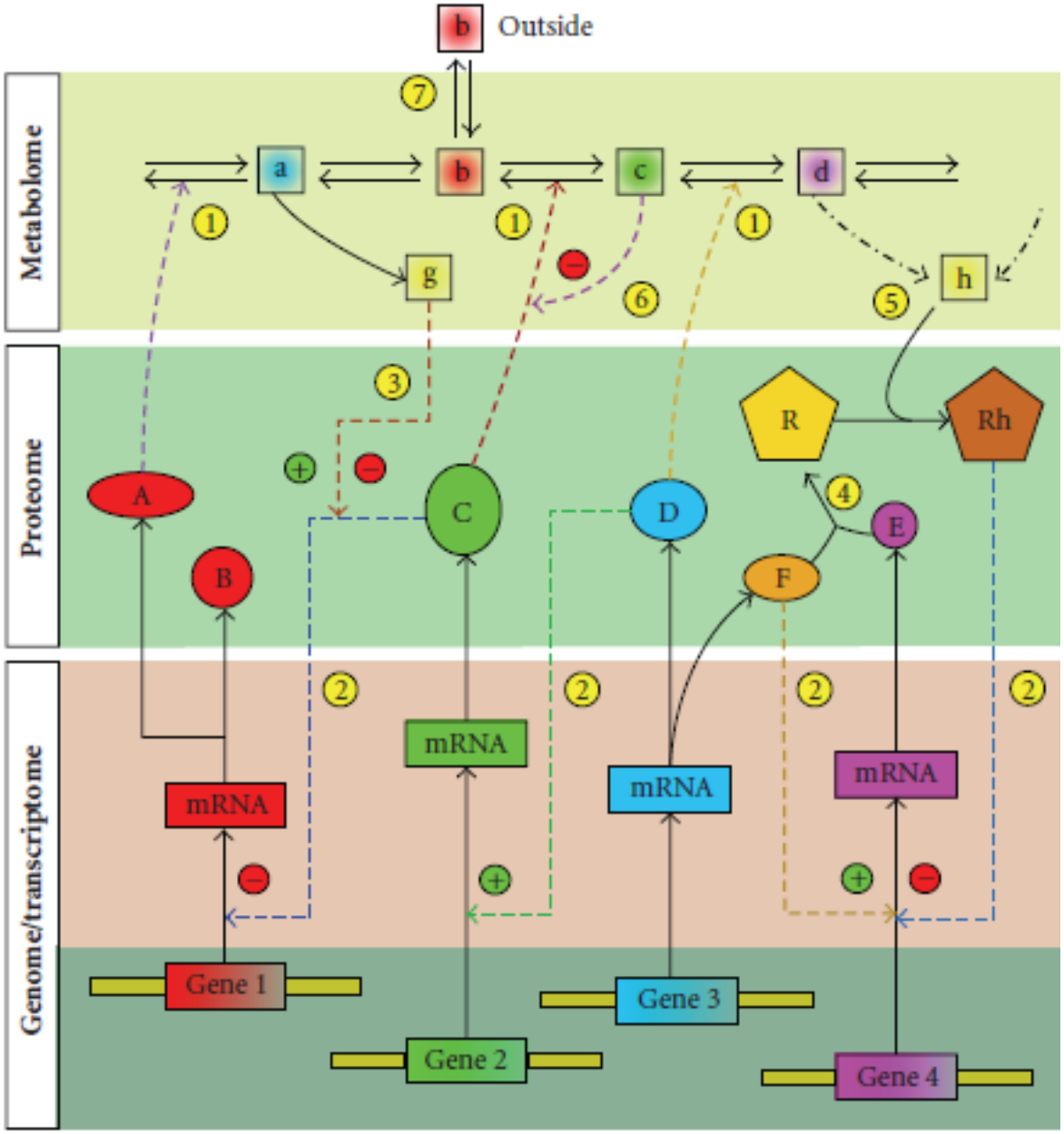
Phenotype – An organism's phenotype is all of its observable characteristics which are influenced both by its genotype and by the environment e.g., height, hair colour, levels of hormones, etc.

Differences in the genotypes can produce different phenotypes

Genes for ear form are different, causing one of the cats to have normal ears and the other to have curled ears

A change in environment also can affect the phenotype. Pinkness is <u>not</u> encoded in the genotype of flamingos – but the food they eat – brine shrimp and blue-green algae from which they obtain a natural pink dye, canthaxanthin.


The "Omics" Cascade
What can happen
GENOME
What appears to be happening
TRANSCRIPTOME
What makes it happen
PROTEOME
What has happened and is happening
METABOLOME
PHENOTYPE



Analyze Network of Networks

Types of interactions:

(1) enzyme catalysis,
(2) posttranscriptional control of gene expression by proteins
(3) effect of metabolite on gene transcription mediated by protein
(4) protein-protein interaction
(5) effect of a downstream metabolite on transcription through binding by protein
(6) Feedback inhibition/activation of an enzyme by a metabolite
(7) exchange of a metabolite with outside of the system (eg ,cell)

Complexity and interdependency of biochemical networks

Genes

The biological function of a gene is to preserve and express the genetic information encoded within it

Genes are normally very stable entities

Genetic stability is not absolute, however.

Genes may occasionally become altered; these changes called mutations create new alleles.

Mutant genes are also stable entities and are inherited in the same way as normal, wild-type genes.

Genes

Normal diploid cells of humans contain two sets of genes – one set inherited from each parent.

- corresponding genes derived from each parent are called alleles.

Together the two alleles govern the phenotype of an organism.

What is the percentage of genes in a genome?

Genes

Gene-fraction varies from ~70% in prokaryotes to ~2 - 3% in humans

- **does that imply prokaryotes have more gene content than eukaryotes?**

- **Size of a prokaryotic genome? Eukaryotic genome?**

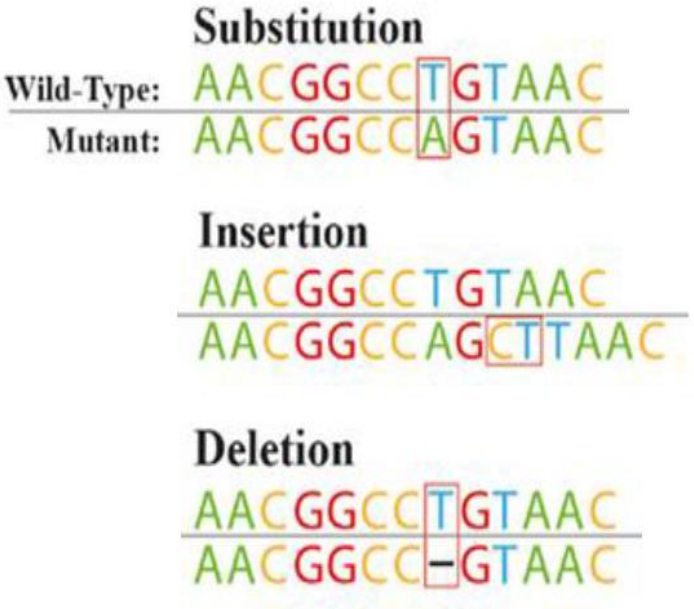
What is the function of the remaining ~97-98% of H. genome?

Major part of the genome is repetitive (~50%), and the remaining part consists of noncoding regions, whose functions may include providing chromosomal structural integrity and regulating where, when, and in what quantity proteins are made.

Mutations

Mutations - are local changes in the DNA content, caused by inexact replication and are of various kinds:

- **Substitution - a base is replaced by another - may or may not alter the protein sequence depending on the place it occurs.**
- **Insertion/Deletion – addition/removal of one or more bases – results in a frame-shift in coding regions.**
- **Rearrangement - a change in the order of complete segments along a chromosome – large scale variation**



Mutations

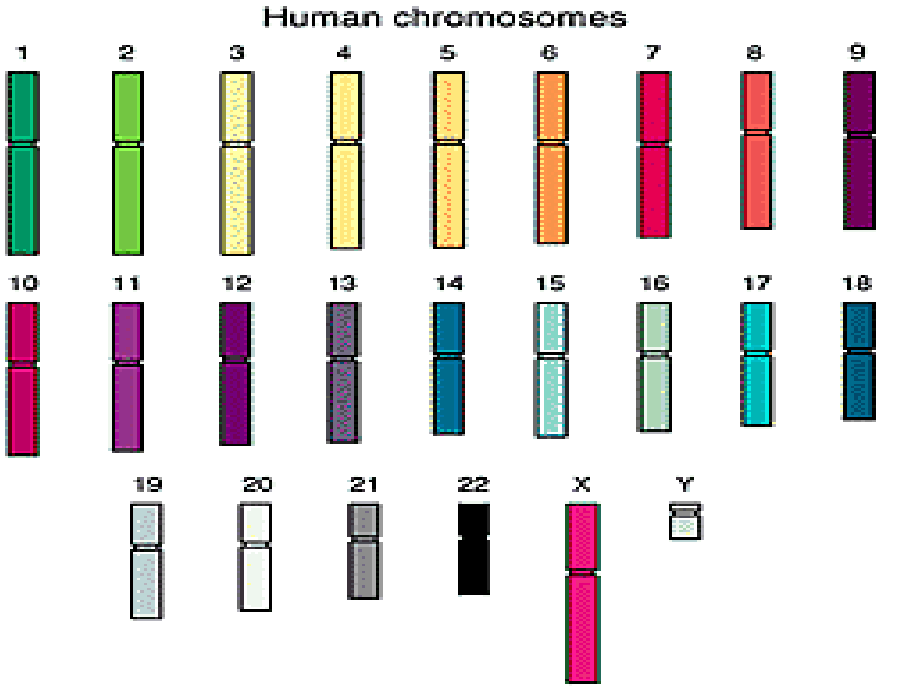
Role of Mutations:

- **Mutations are the source of phenotypic variation on which natural selection acts, creating species & changing them.**

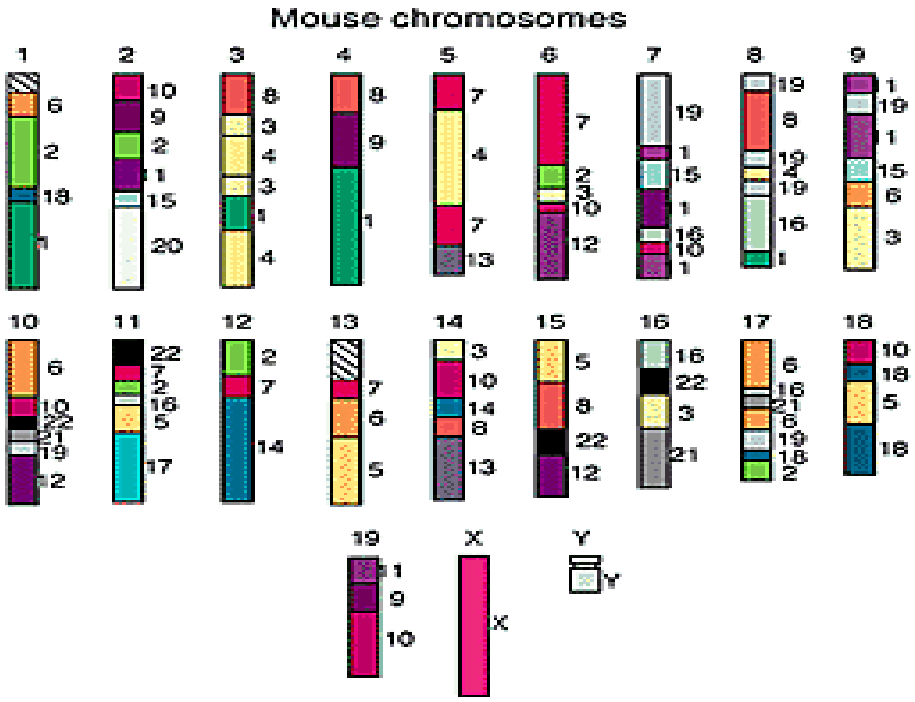
Without mutations there wouldn't be any evolution!

- **They are responsible for inherited disorders and diseases, which involve alterations in gene.**
- **Large scale rearrangements are responsible for creating new species, e.g., the human and mouse genome are very similar – major difference being the internal order of DNA segments.**

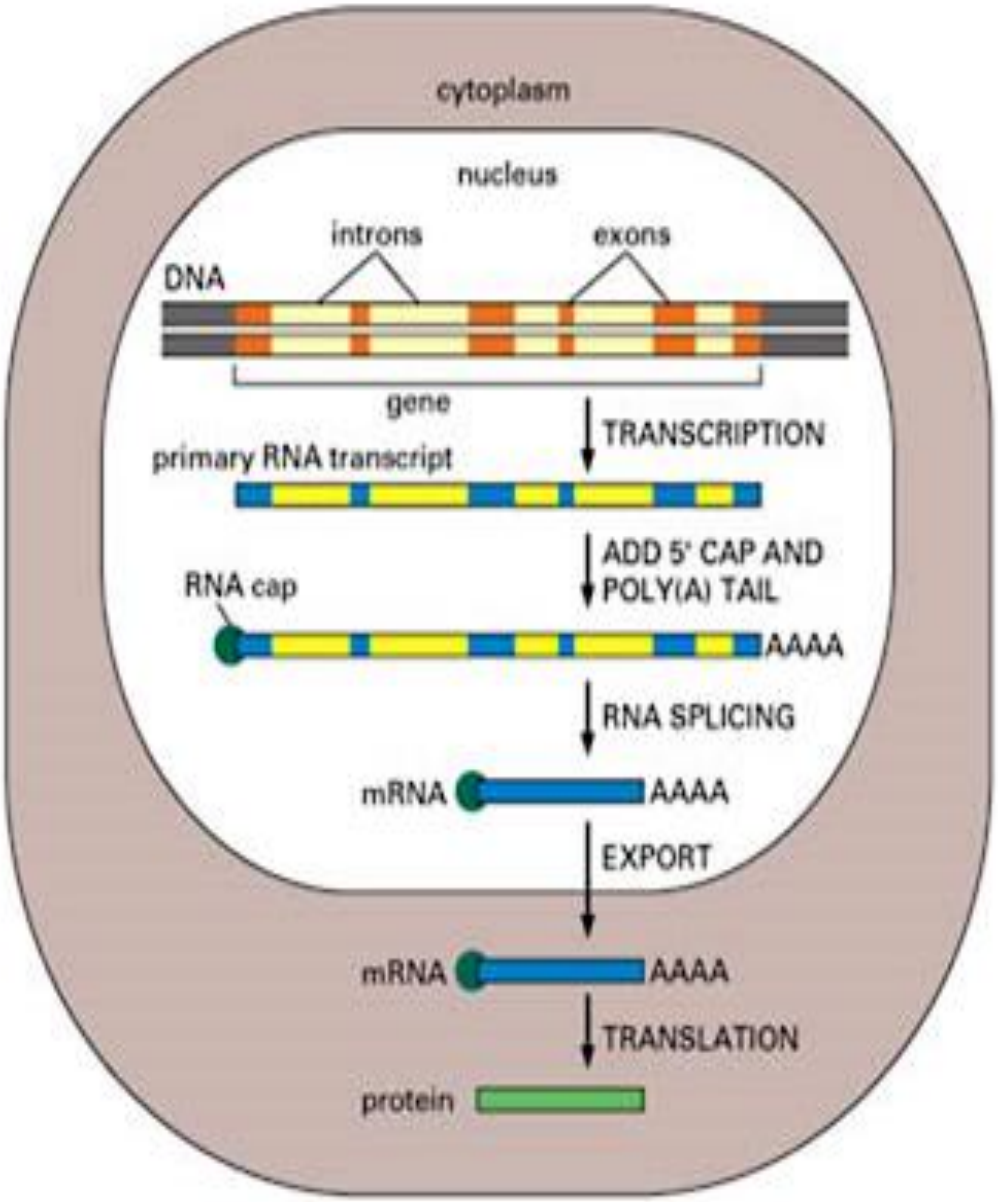
Chromosomal rearrangements occur both within and between chromosomes during evolution

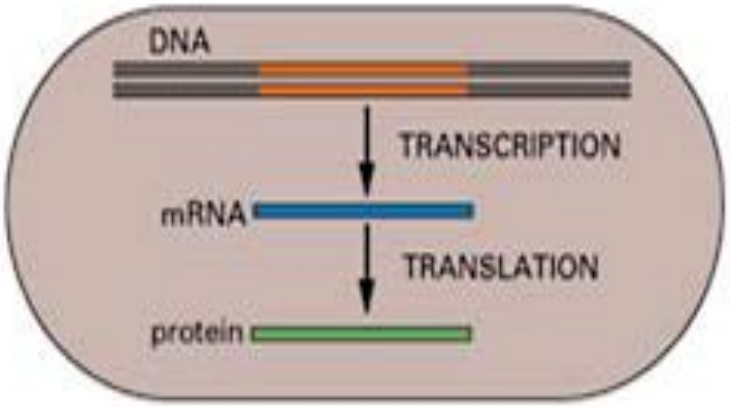


The colors on the mouse chromosomes and the numbers alongside indicate the human chromosomes containing homologous segments.



Steps Leading from Gene to Protein

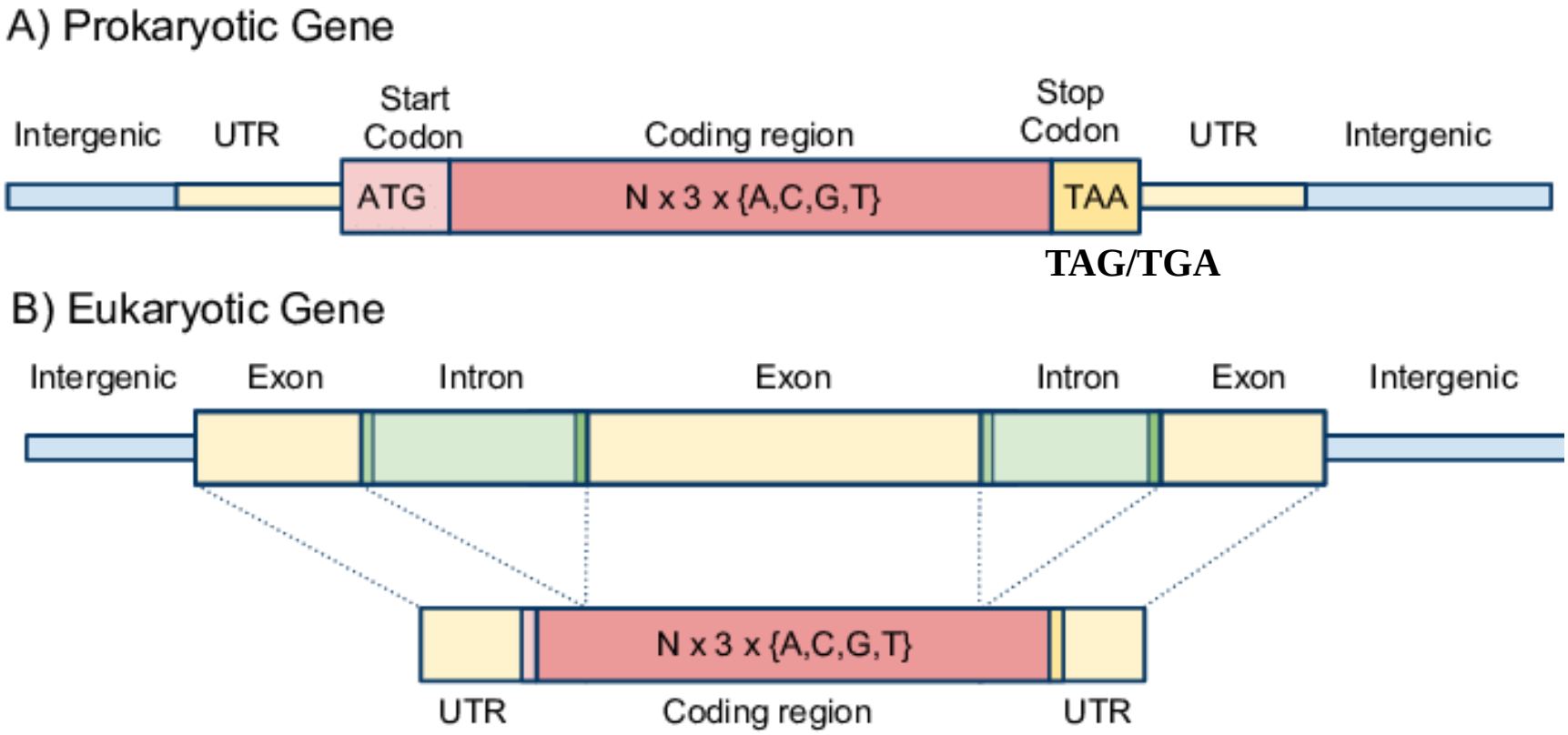




Prokaryotes

Eukaryotes

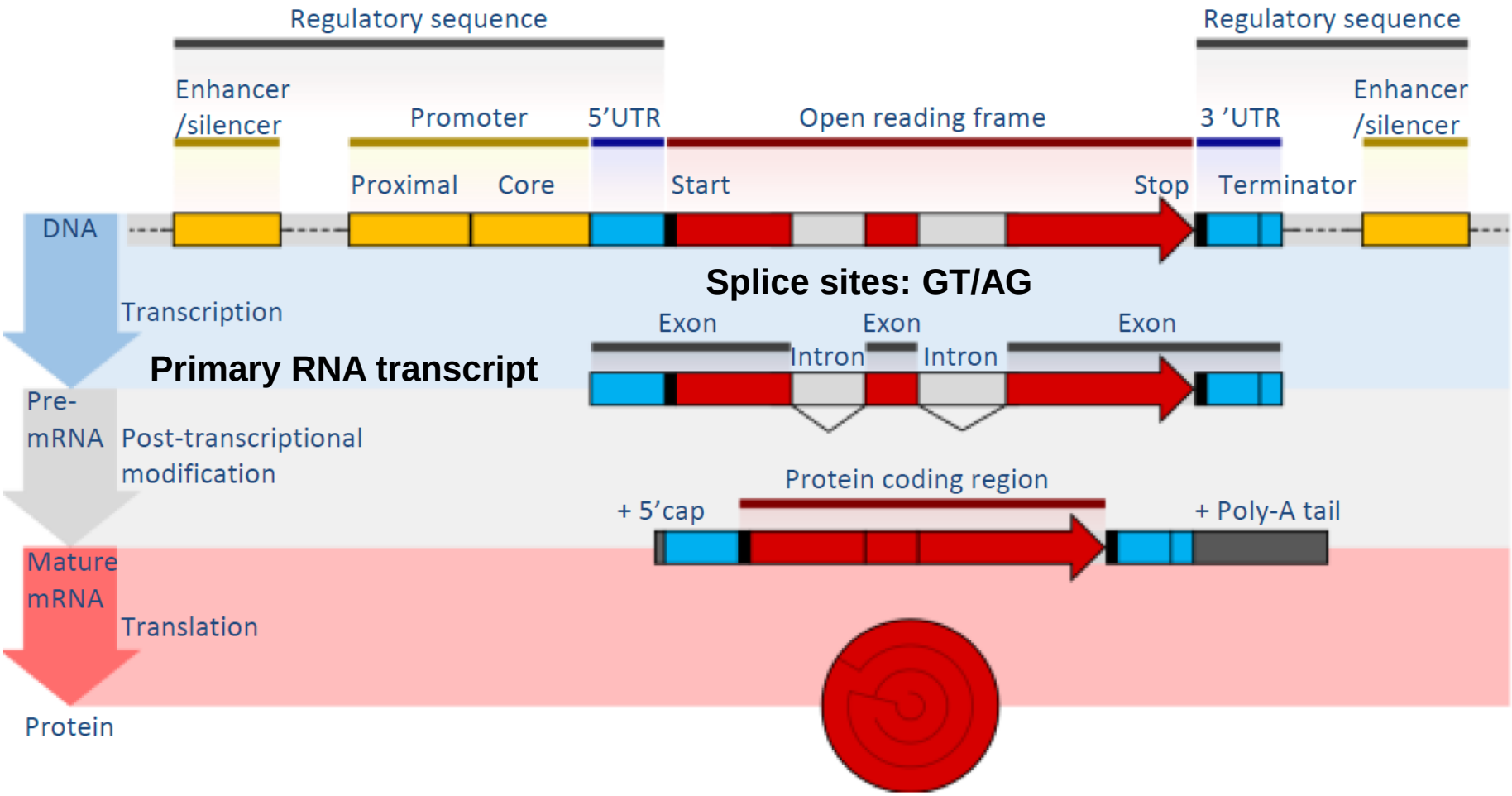
Gene Structure



UTR: Untranslated region

Eukaryote Gene Structure

Start codon: ATG **Stop Codon: TAA/TAG/TGA**



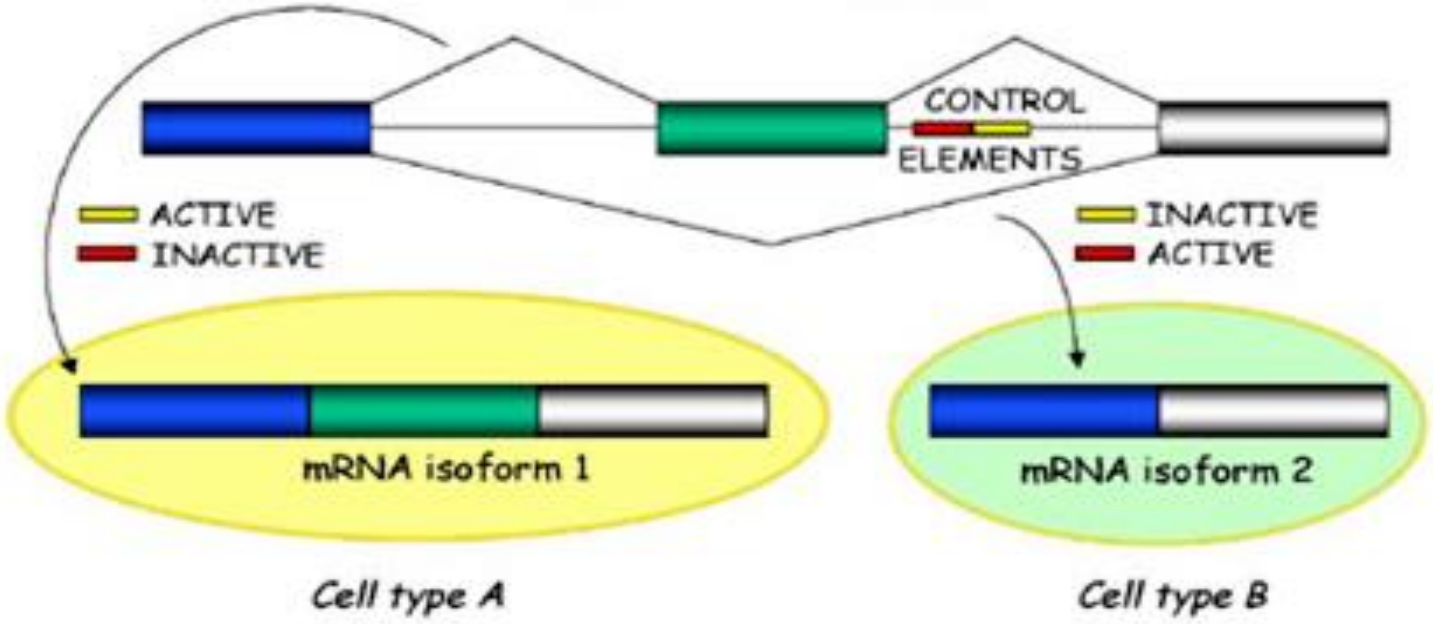
Transcription is initiated only at certain specific positions in the sequence, signaling the beginning of genes, called promoters.

Alternative Splicing

- **In many cases, the pattern of splicing can vary depending on the tissue in which the transcription occurs.**

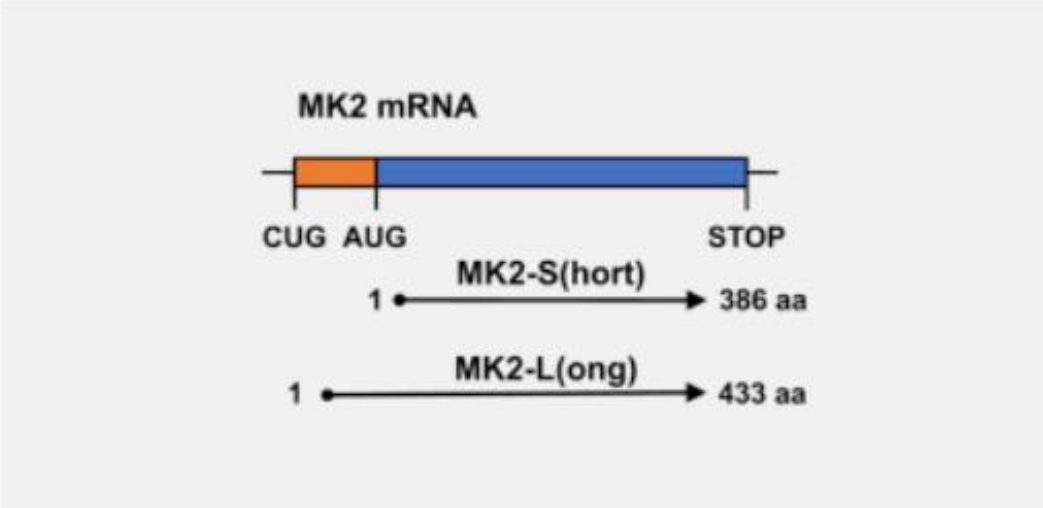
  e.g., an exon maybe spliced in the gene transcribed in liver, but retained when transcribed in the brain.

- **This variation called alternative splicing, contributes to the overall protein diversity in the organism**



Alternative Initiation

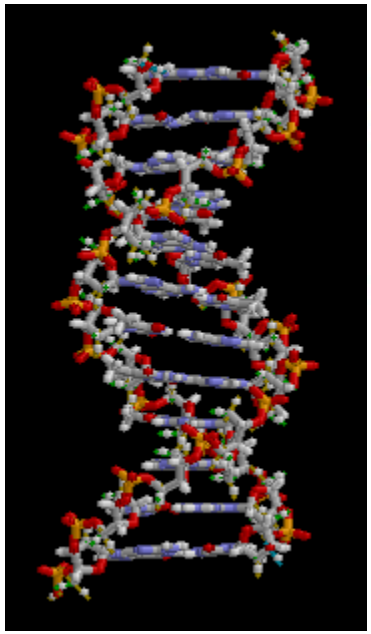
- **Another type of variation that contributes to protein diversity is alternative initiation**

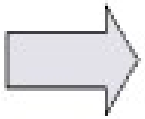


- **Alternative translation is an important mechanism of post-transcriptional gene regulation leading to the expression of different protein isoforms originating from the same mRNA**

Data Representation

DNA - a complex, dynamic, three-dimensional molecule represented as a string of alphabets





```
acgtcgtagttccagtc
```

- a perfect representation for computer analysis

Data Representation

For all computational purposes, a DNA sequence is considered to be a string on a 4-letter alphabet: A, T, G, C

ACGCTGAATAGC

Aim: to find grammar & syntax rules of DNA language based on this 4-letter alphabet

- similar to English Grammar to form meaningful sentences

Similarly, RNA sequence is represented as a string of 4 alphabets and protein sequence a string of 20 alphabets

Biological Sequence Analysis

Pattern Recognition:

Assumption in biological sequence analysis:

- strings carrying information will be different from random strings

If a hidden pattern can be identified in a string, it must be carrying some functional information

Biological Sequence Analysis

Order of occurrence of bases:

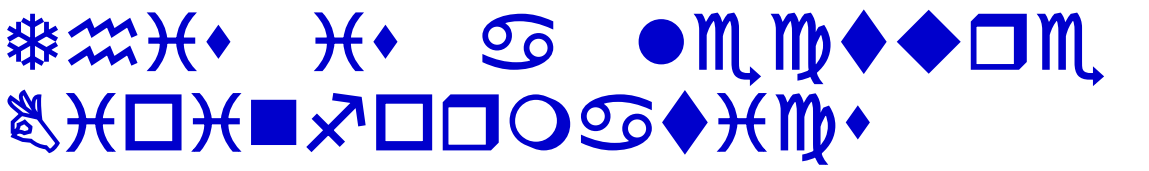
not completely random

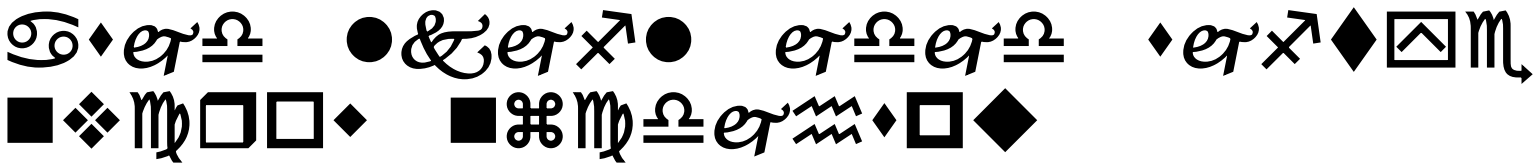
- Different regions of the genome exhibit different patterns of the four bases, A, T, G, C

e.g., protein coding regions, regulatory regions, intron/exon boundaries, repeat regions, etc.

Aim: Identify various patterns to infer their functional roles

Example





This is a lecture on bioinformatics

asjd lkjfl jdjd sjftye nvcrow nzcdjhspu

Frequency of letters

A.	7.3%	N.	7.8%
B.	0.9%	O.	7.4%
C.	3.0%	P.	2.7%
D.	4.4%	Q.	0.3%
E.	13.0%	R.	7.7%
F.	2.8%	S.	6.3%
G.	1.6%	T.	9.3%
H.	3.5%	U.	2.7%
I.	7.4%	V.	1.3%
J.	0.2%	W.	1.6%
K.	0.3%	X.	0.5%
L.	3.5%	Y.	1.9%
M.	2.5%	Z.	0.1%

Other statistics

Frequencies of the most common first letter of a word, last letter of a word, doublets, triplets, etc.

20 most used words in written English

- **the of to in and a for was is that on at he with by be it an as his**

20 most used words in spoken English

- **the and I to of a you that in it is yes was this but on well he have for**

Parallels in DNA language

ATGGTGGTCATGGCGCCCCGAACCCTCTTCCTGCTG
CTCTCGGGGGCCCTGACCCTGACCGAGACCTGGGCG
GGTGAGTGCGGGGTCAGGAGGGAAACAGCCCCTGC
GCGGAGGAGGGAGGGGCCGGCCCGGCGGG

GTCTCAACCCCTCCTCGCCCCCAGGCTCCCACTCCA
TGAGGTATTTCAGCGCCGCCGTGTCCCGGCCCGGCC
GCGGGGAGCCCCGCTTCATCGCCATGGGCTACGTGG
ACGACACGCAGTTCGTGCGGTTC

Parallels in DNA language

ATG GTG GTC ATG GCG CCC CGA ACC CTC TTC CTG CTG CTC TCG GGG GCC CTG ACC CTG ACC GAG ACC TGG GCG GGT GAG TGC GGG GTC AGG AGG GAA ACA GCC CCT GCG CGG AGG AGG GAG GGG CCG GCC CGG CGG…

GTC TCA ACC CCT CCT CGC CCC CAG GCT CCC ACT CCA TGA GGT ATT TCA GCG CCG CCG TGT CCC GGC CCG GCC GCG GGG AGC CCC GCT TCA TCG CCA TGG GCT ACG TGG ACG ACA CGC AGT TCG TGC GGT TC…

1st exon and 1st intron of Human HLA gene

This task needs to be automated because of the large genome sizes:

Smallest genome:

Mycoplasma genitalium 0.5×10^6 bp

Human genome: 3×10^9 bp – not the largest!

~ 10-100 times the Britannica Encyclopedia

Plant genomes are even larger.

DNA Sequence Analysis

- **Evolution has operated on every sequence that we see today - genes and sequences involved in gene regulation are conserved.**
- **these are transferred, like code modules, from one organism to another.**
- **Because of evolution, similar sequences have similar functions.**
- **Algorithms for comparing sequences and finding similar regions are at the heart of computational biology.**