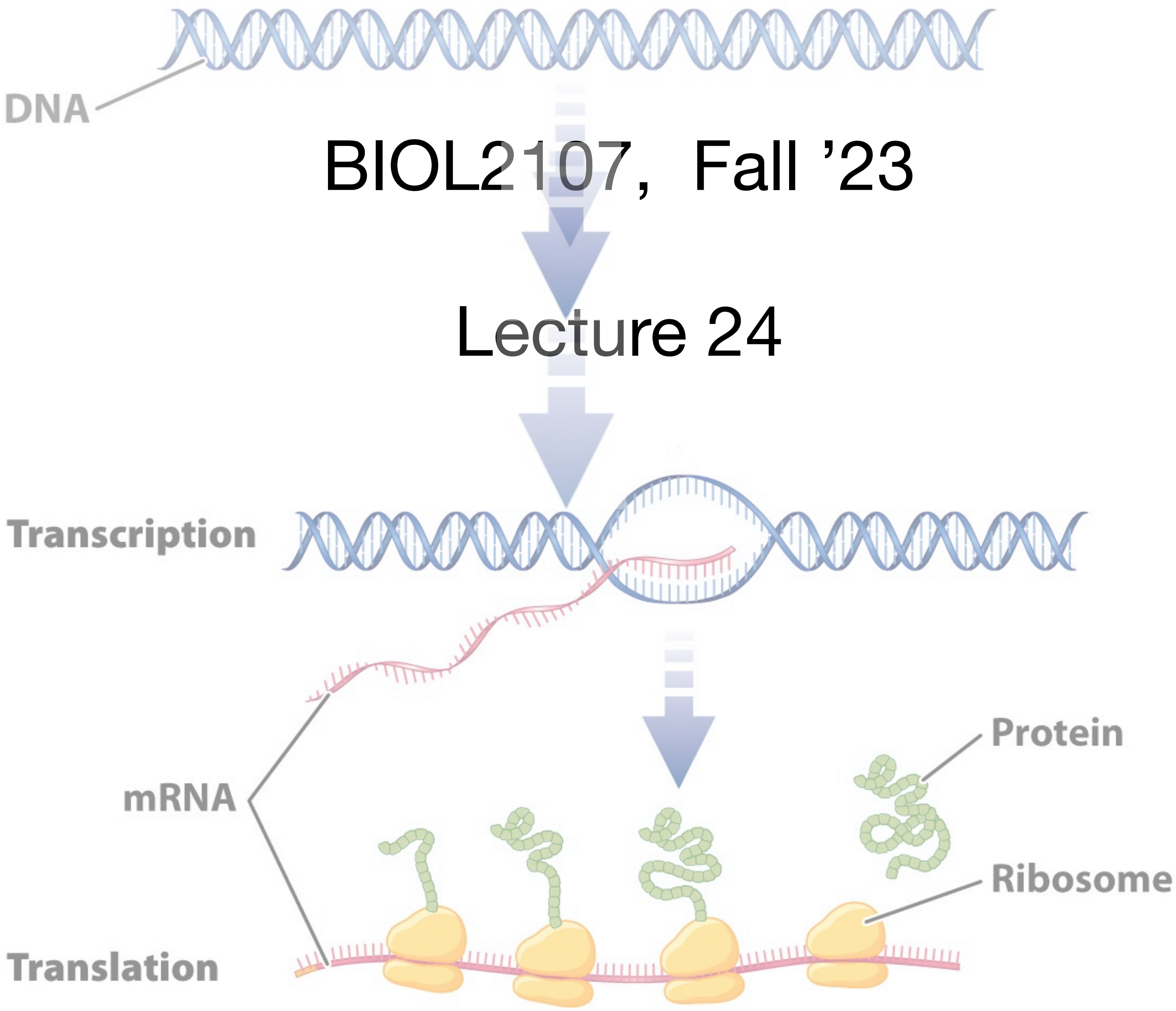
BIOL2107, Fall ’23

Lecture 24

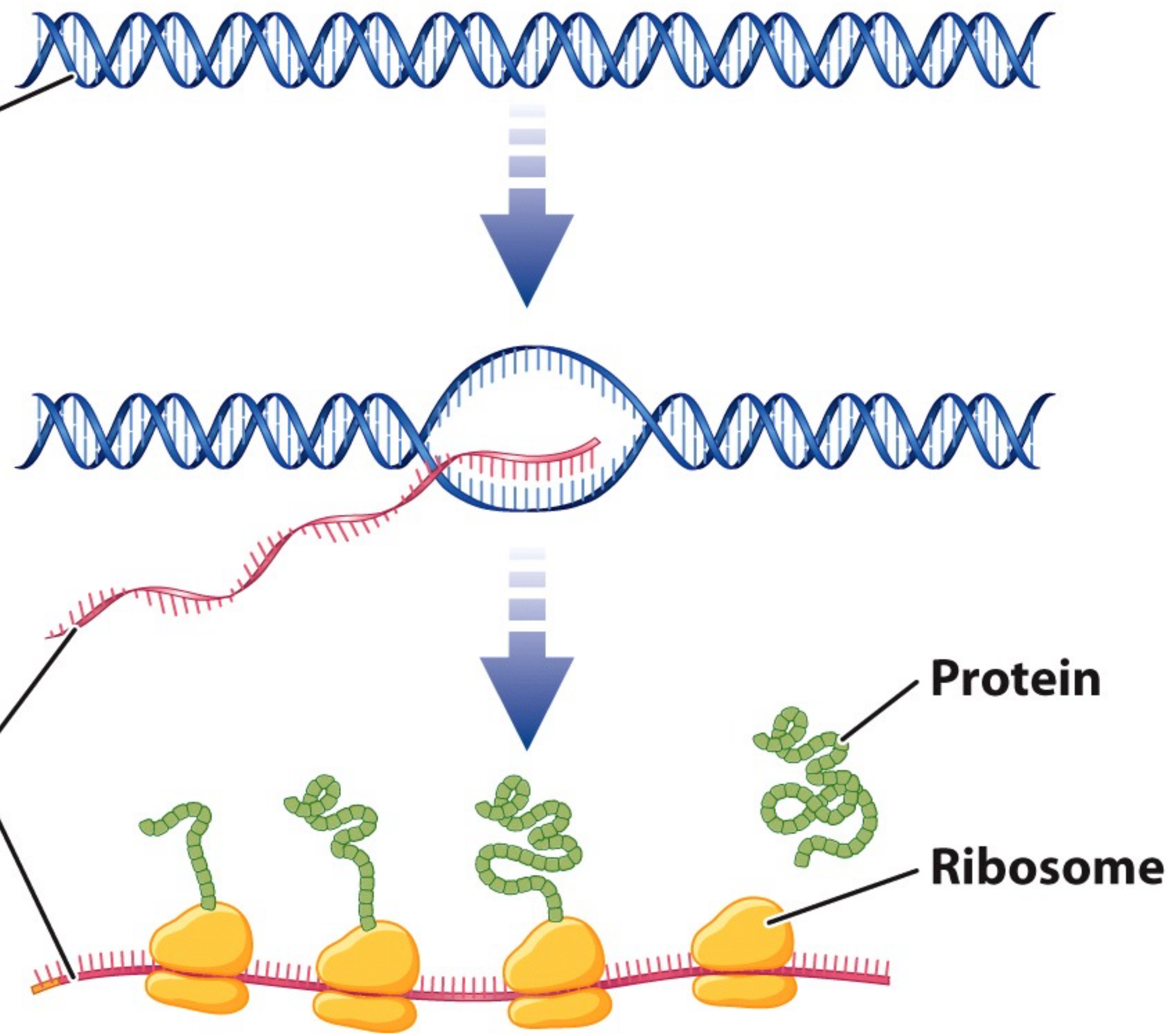


Central Dogma: Replication, Transcription and The Genetic code

Central Dogma

BIOLOGY HOW LIFE WORKS

biologyhowlifeworks.com



mRNA

rRNA

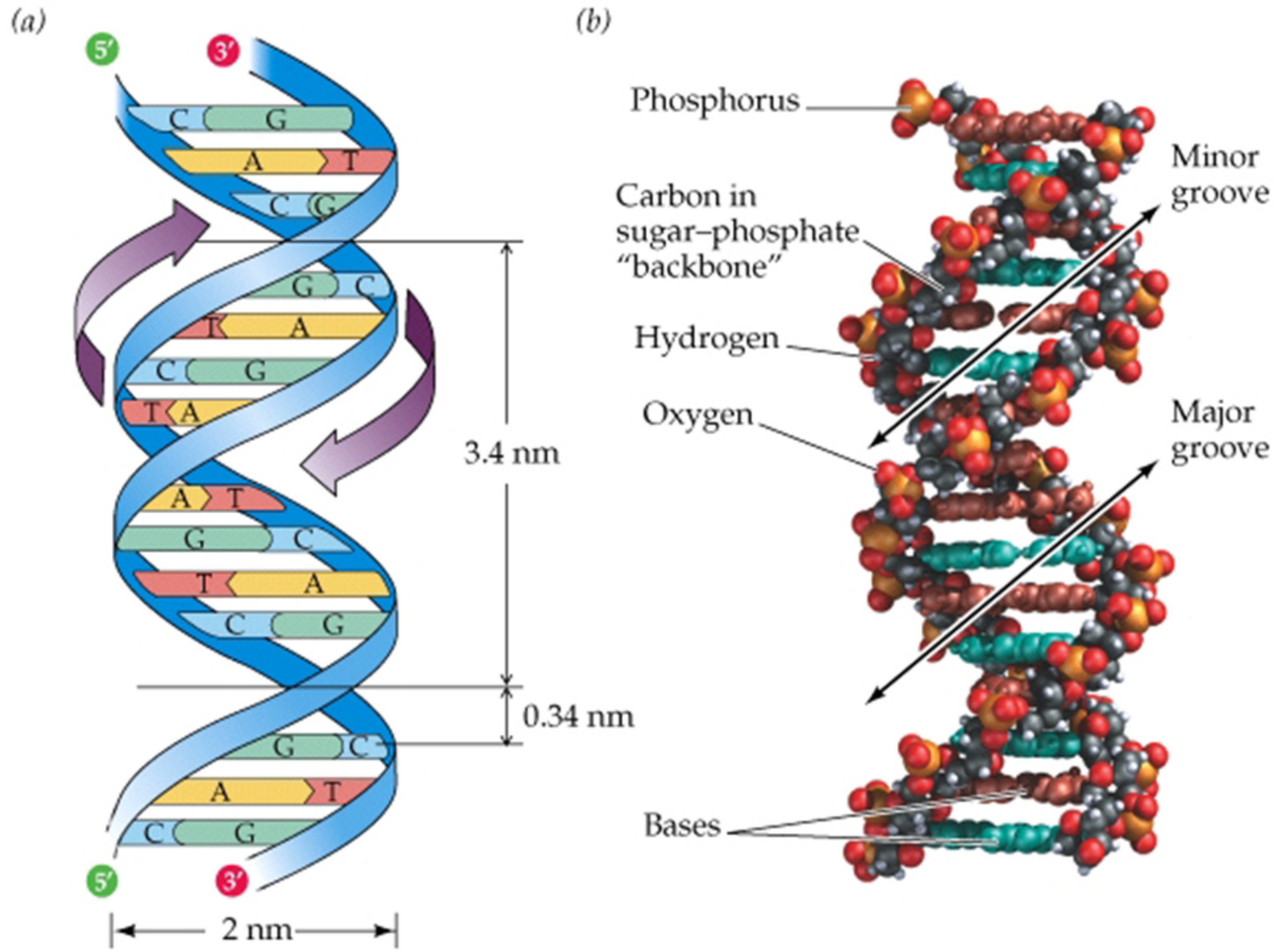
tRNA

microRNA

Catalytic

Structural

Regulatory

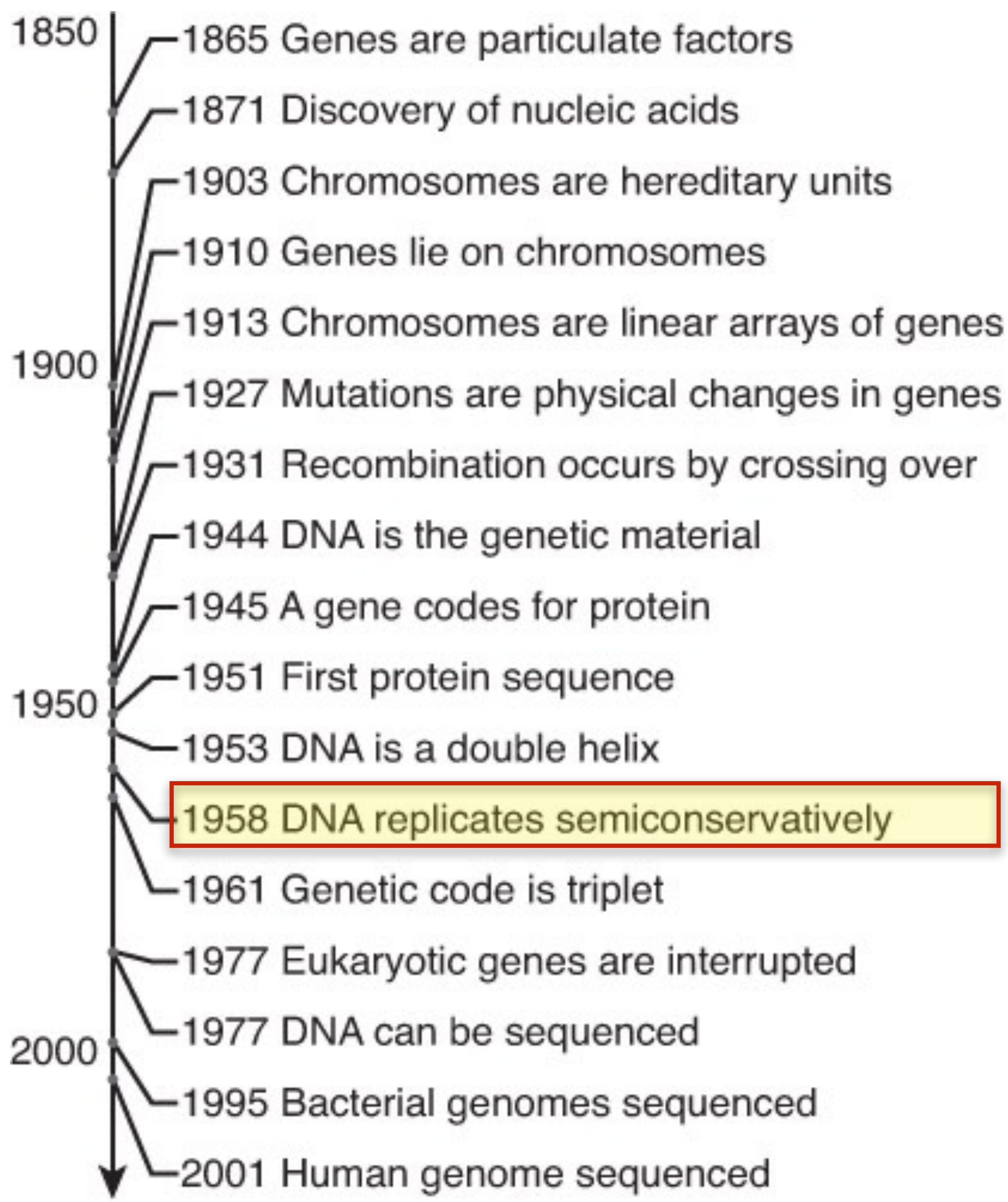


As the genetic material of the cell, DNA must perform four important functions:

It must be able to store all of an organism's genetic information.

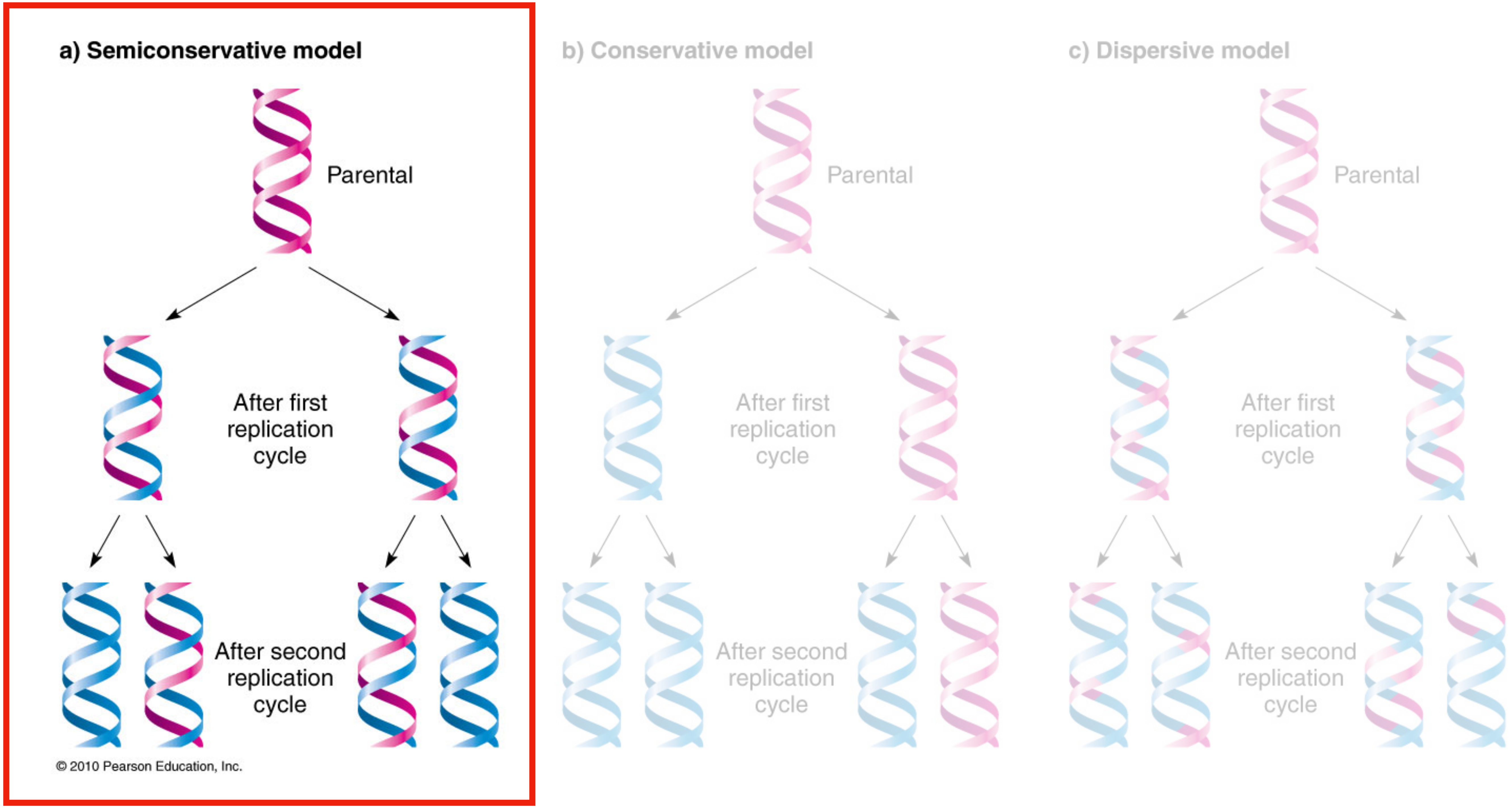
It must be susceptible to mutation.

It must be precisely replicated in the cell division cycle.



A brief history of genetics.

3 potential outcomes of Heavy Nitrogen (15N) experiments.



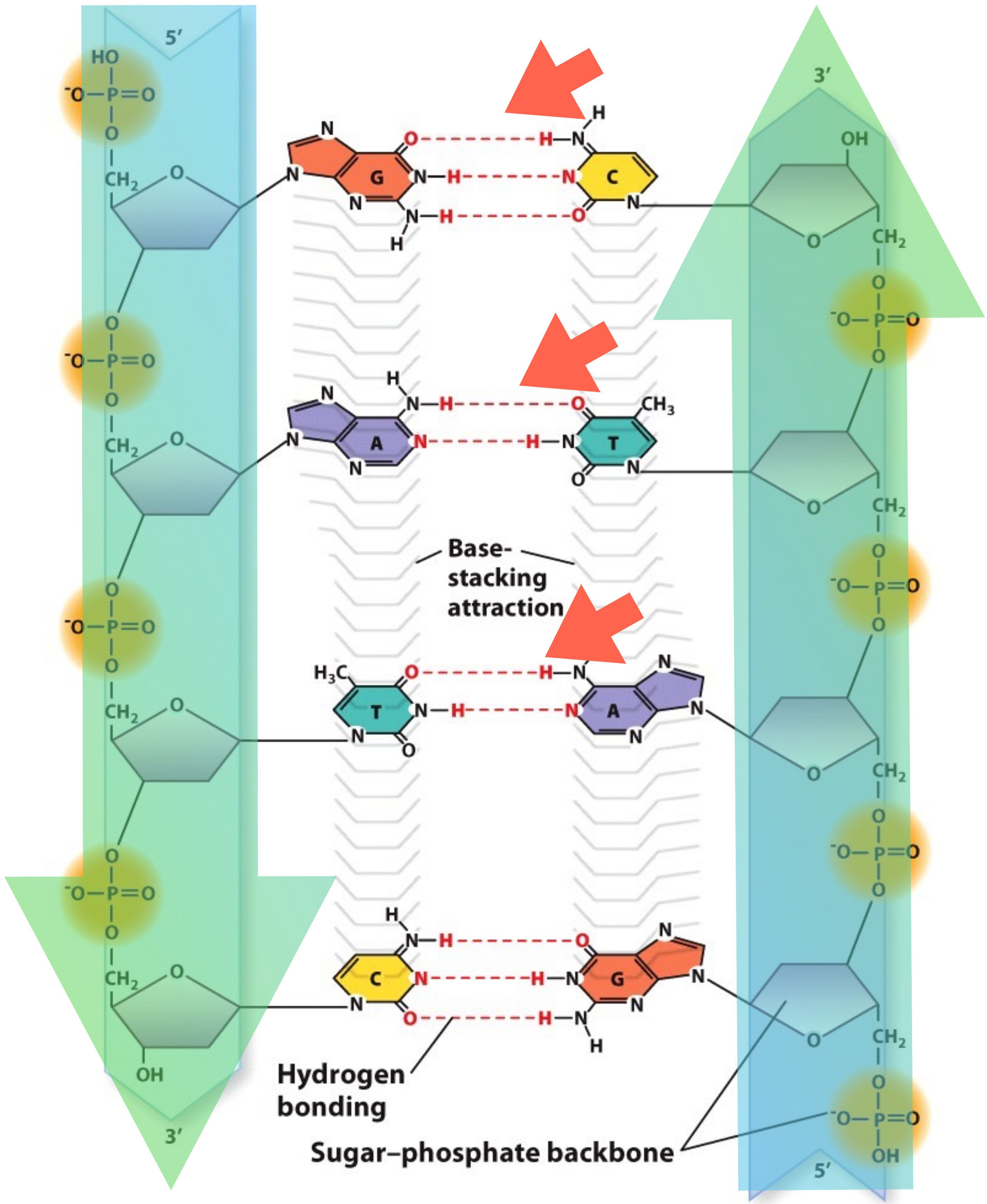
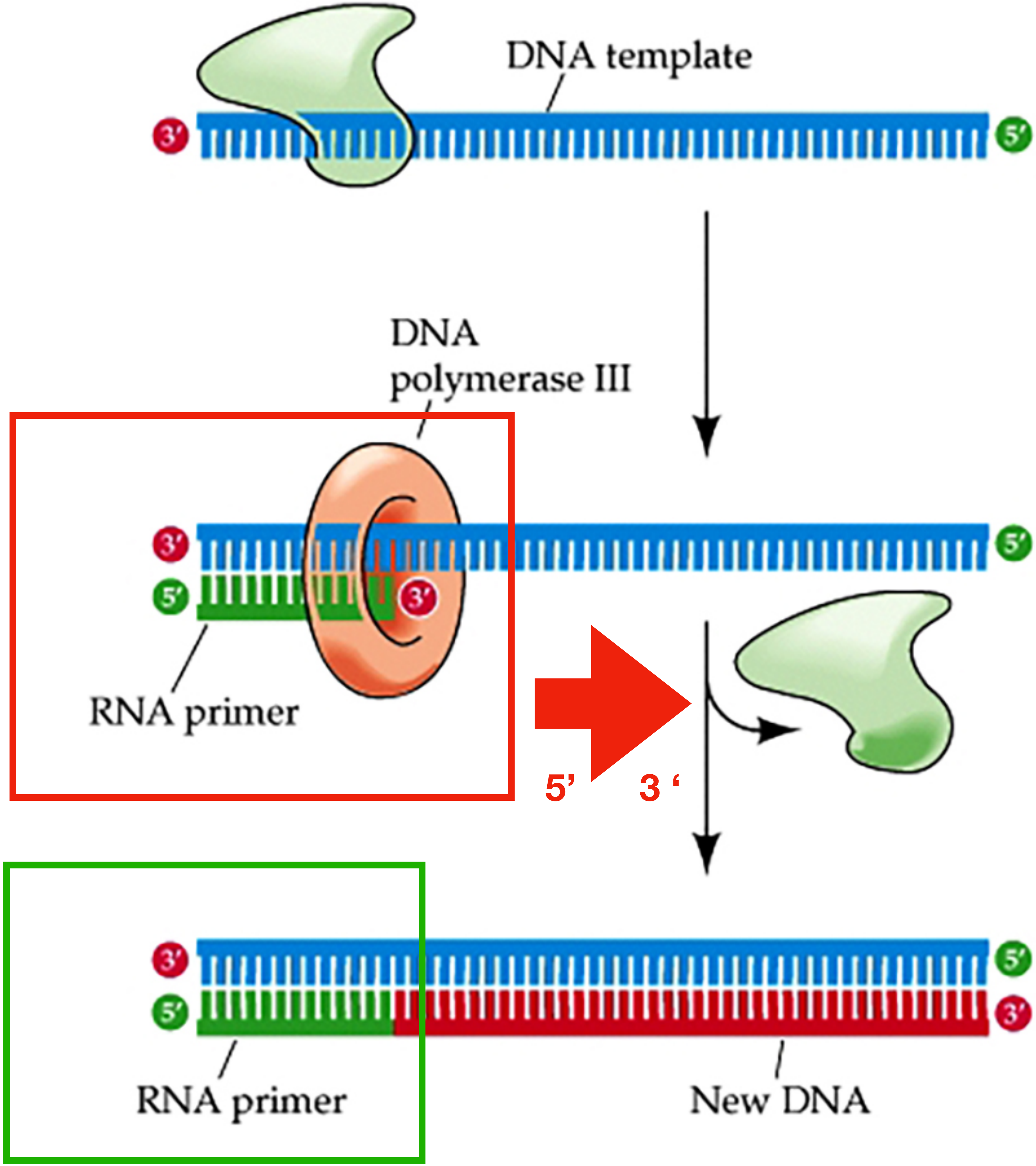
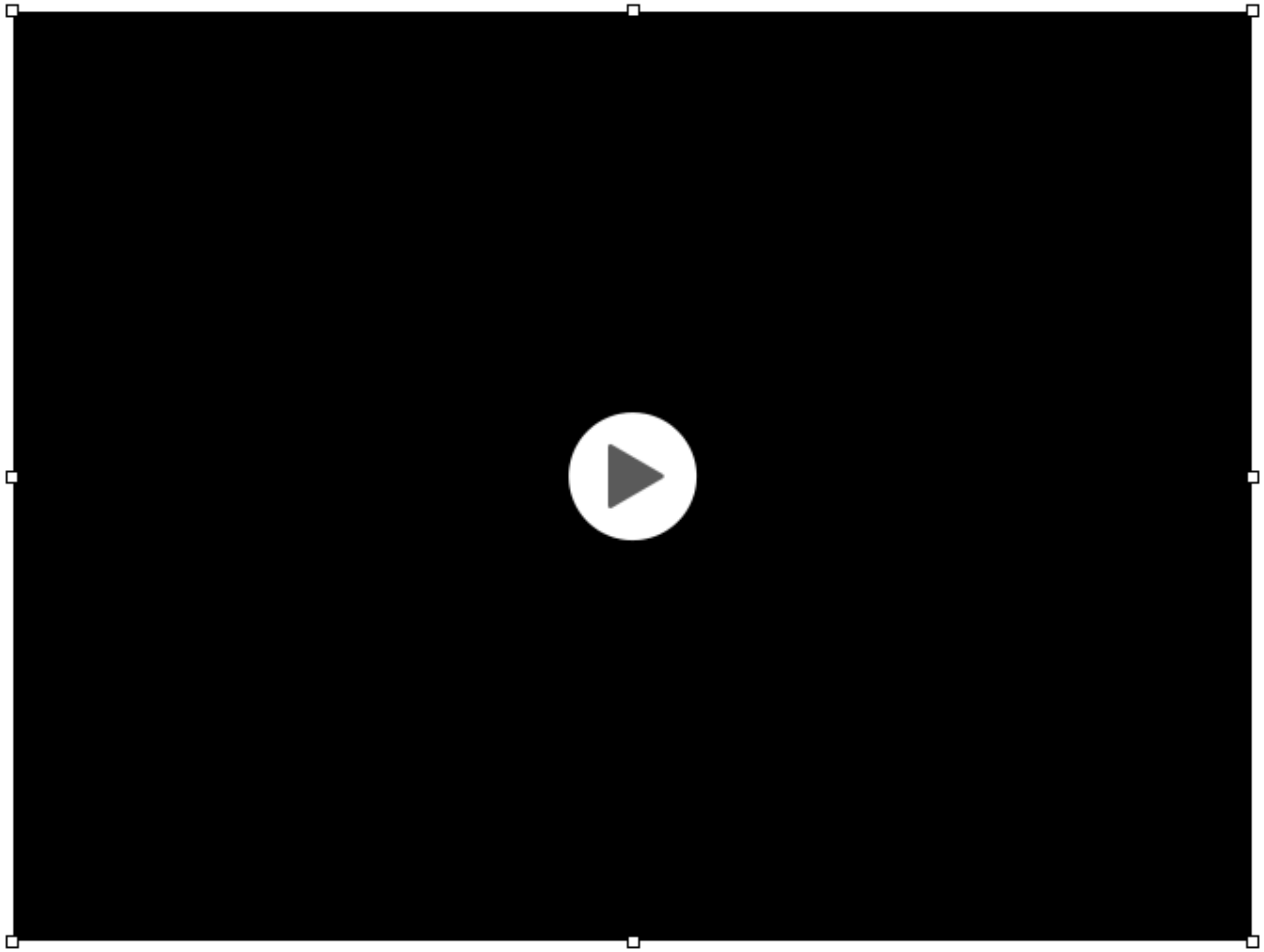


Figure 3.10

Biology: How Life Works


DNA template
3′
5′
DNA
polymerase III
3′
5′
5′
3′
RNA primer
5’
3 ‘
3′
5′
5′
3′
RNA primer
New DNA



DNA Replication

DNA replication begins with separation of the two paired strands of double-stranded DNA by proteins that unwind the double helix, creating a replication fork.

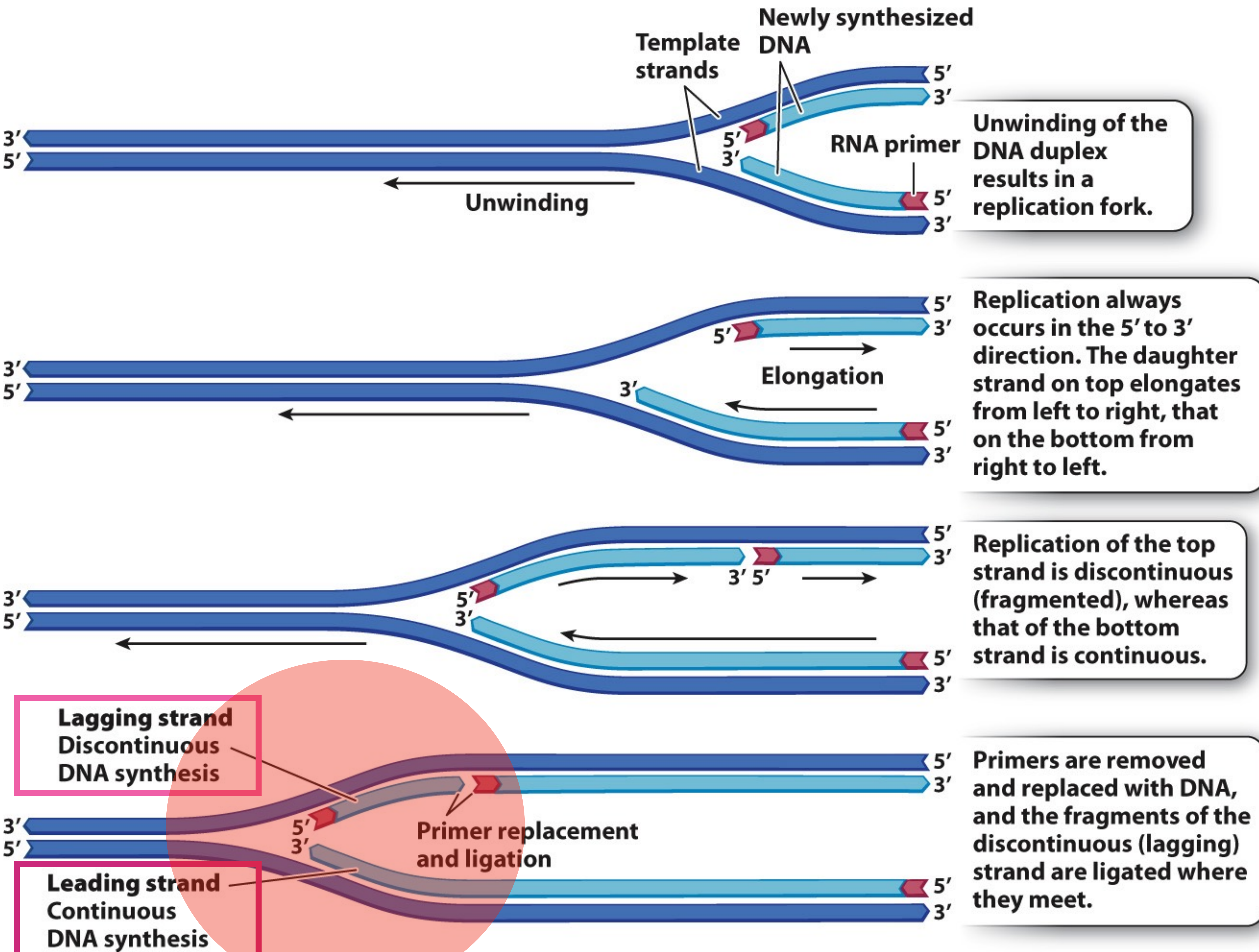


Figure 12.5

Biology: How Life Works, Second Edition

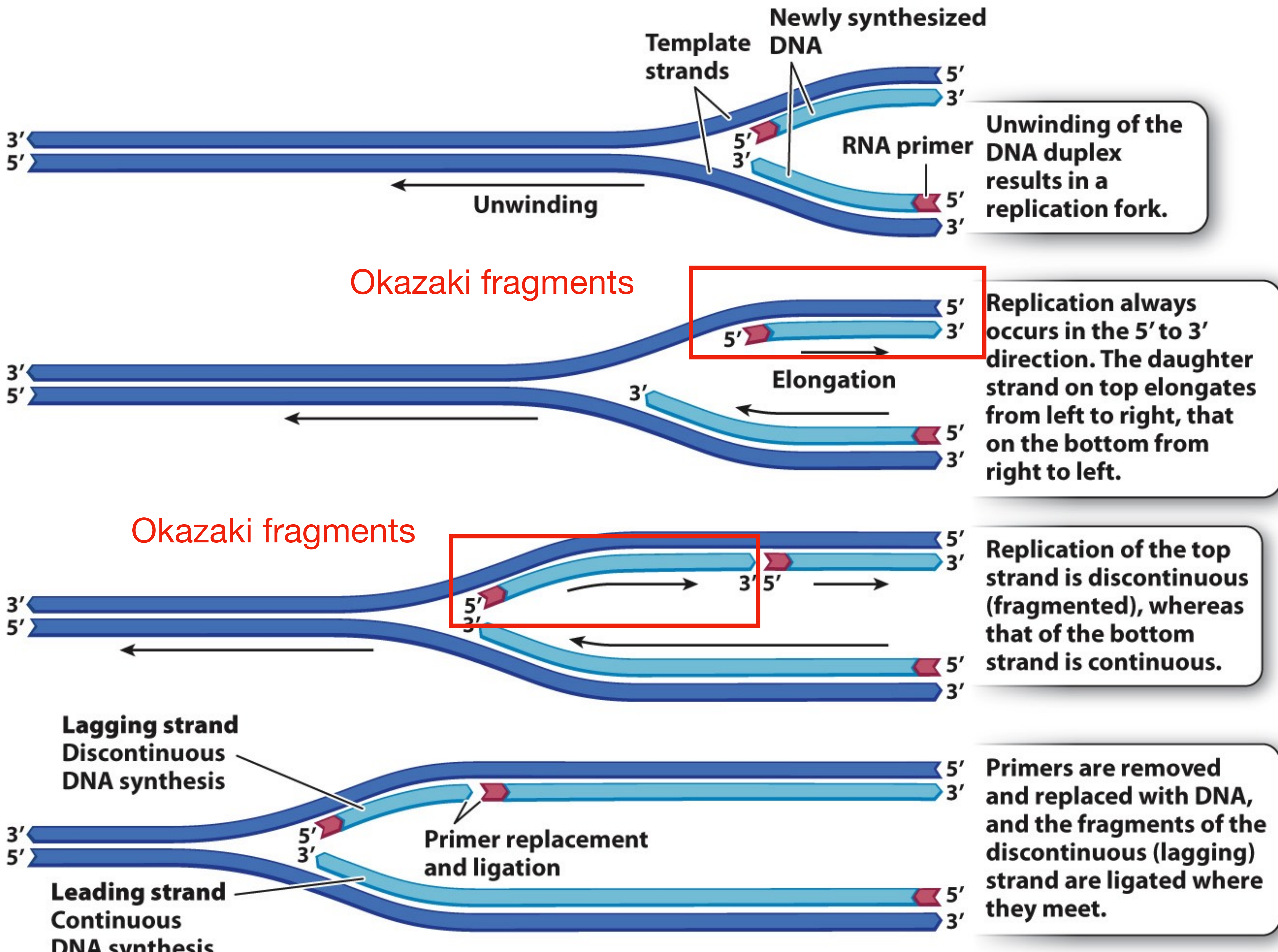


Figure 12.5
Biology: How Life Works, Second Edition

Okazaki fragments 2,000 bp (prokaryotes)
200 bp (eukaryotes)

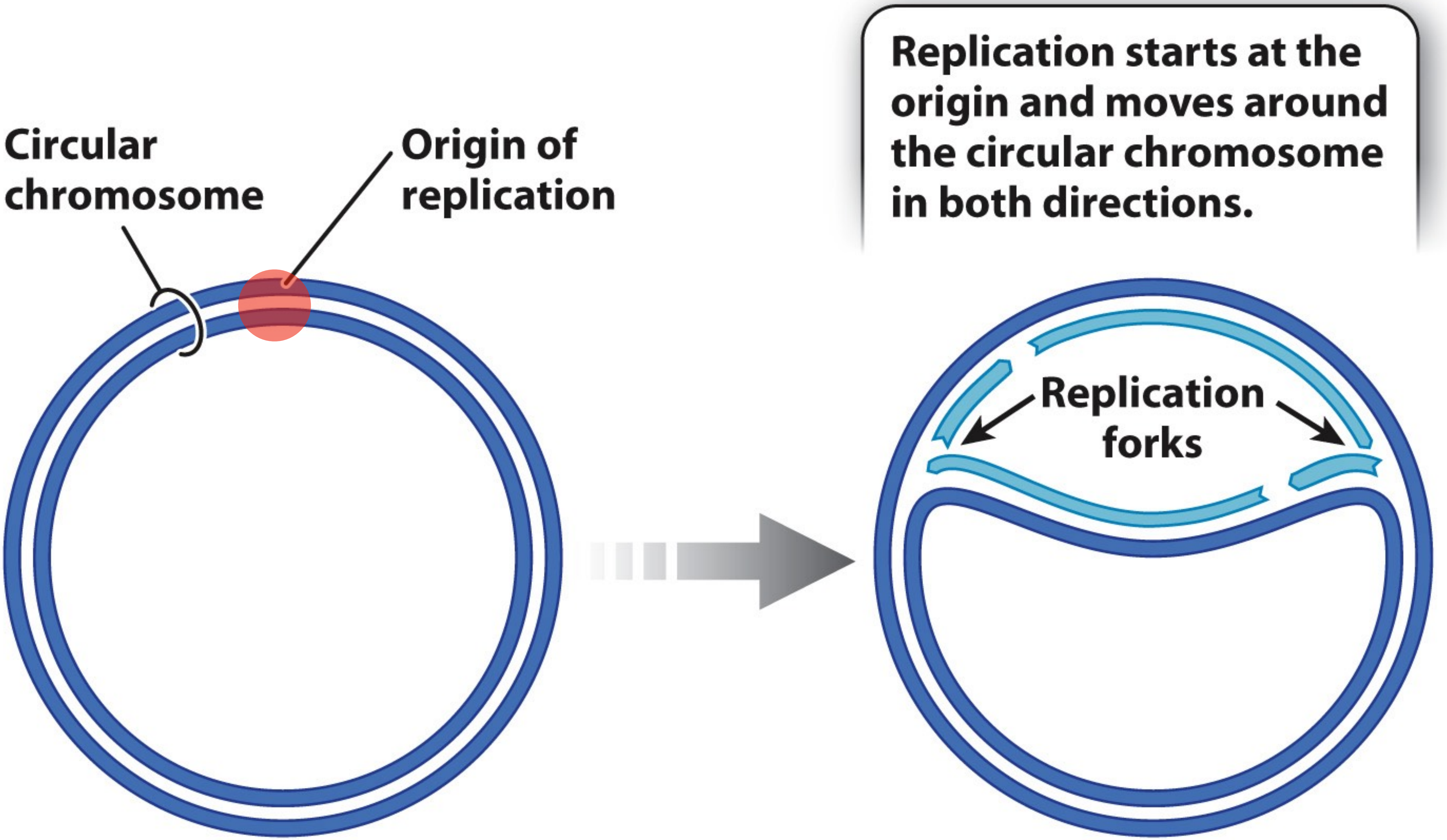


Figure 12.10
Biology: How Life Works, Second Edition

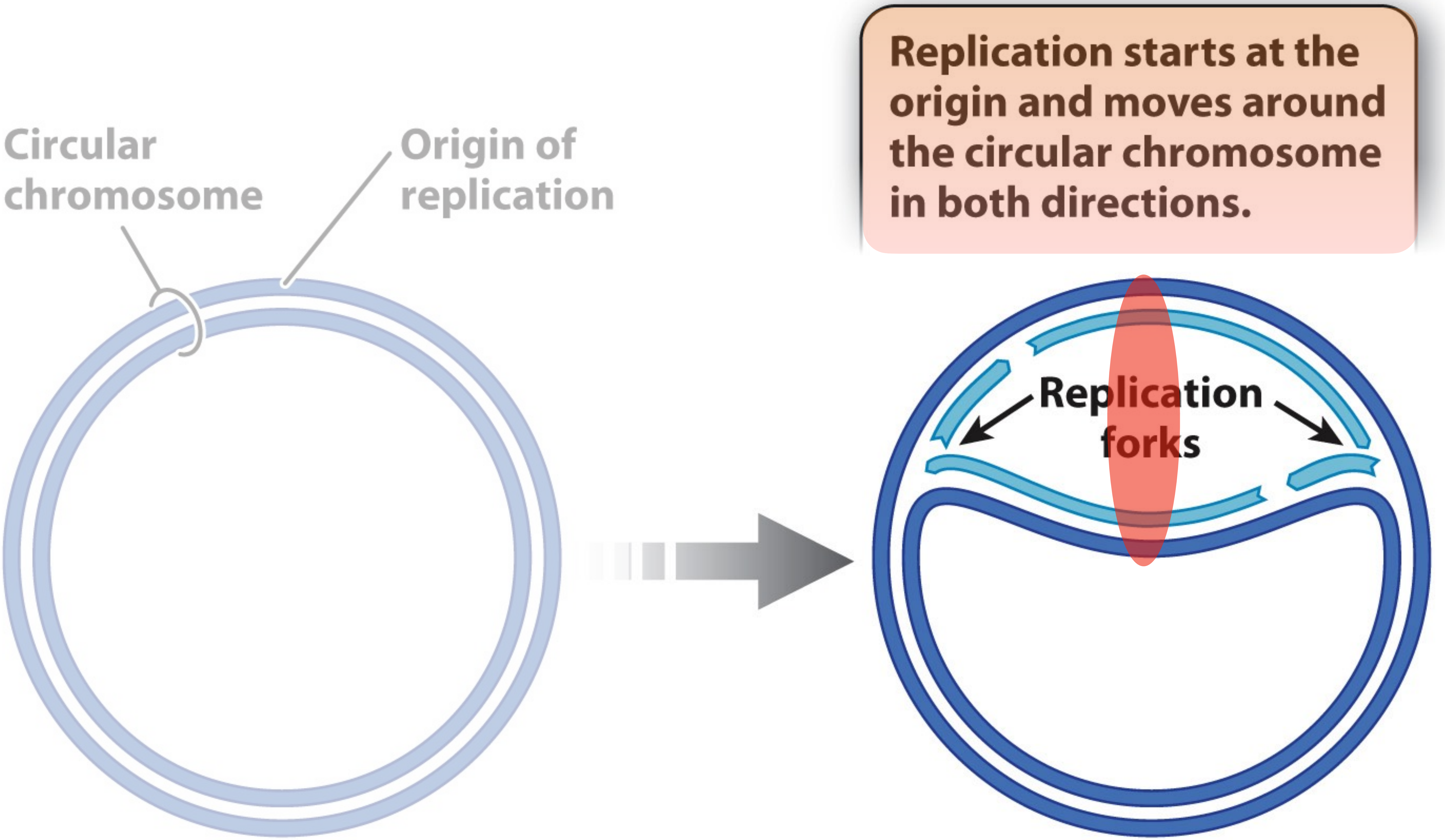


Figure 12.10
Biology: How Life Works, Second Edition

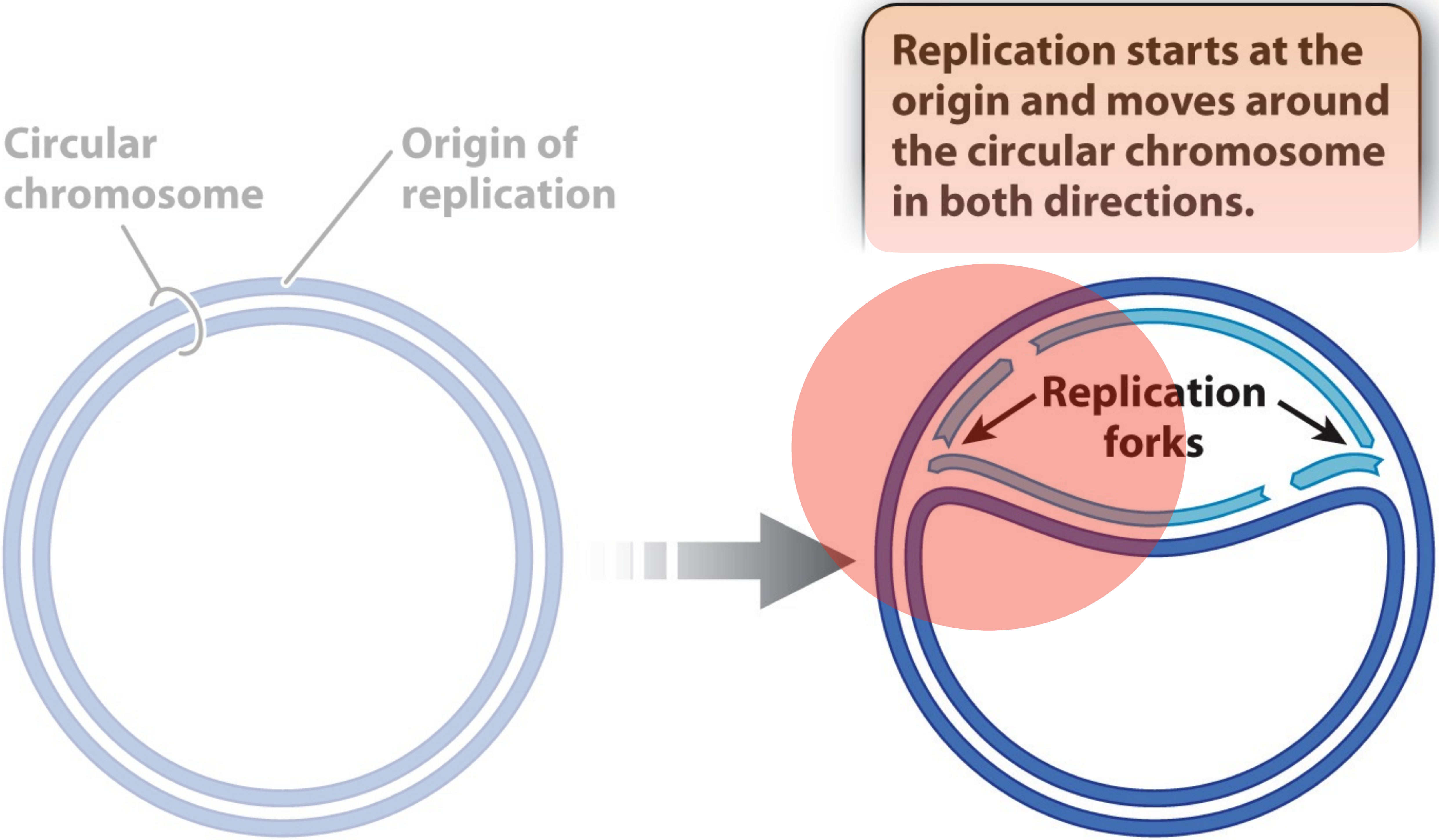


Figure 12.10
Biology: How Life Works, Second Edition

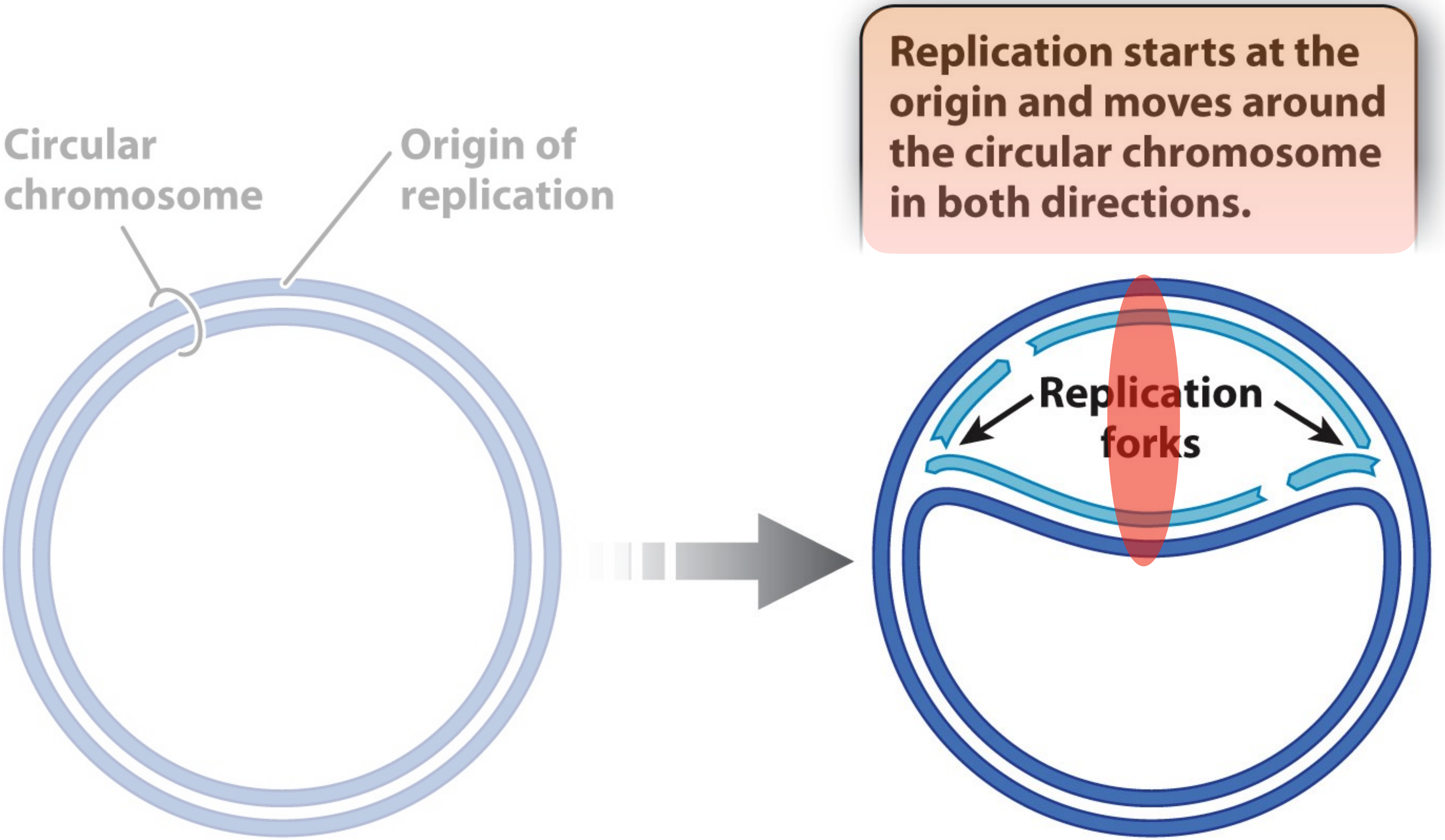


Figure 12.10
Biology: How Life Works, Second Edition

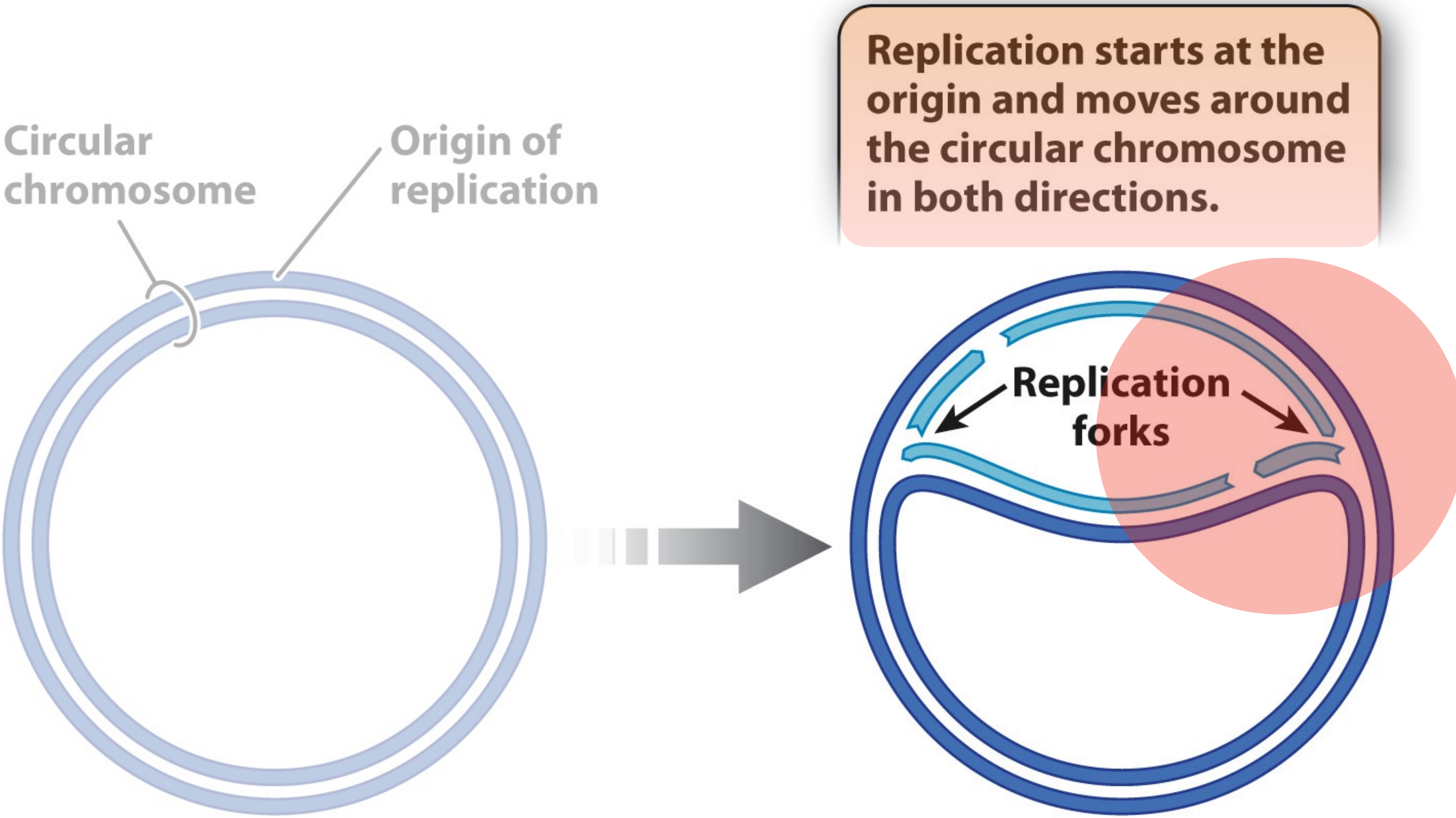


Figure 12.10
Biology: How Life Works, Second Edition

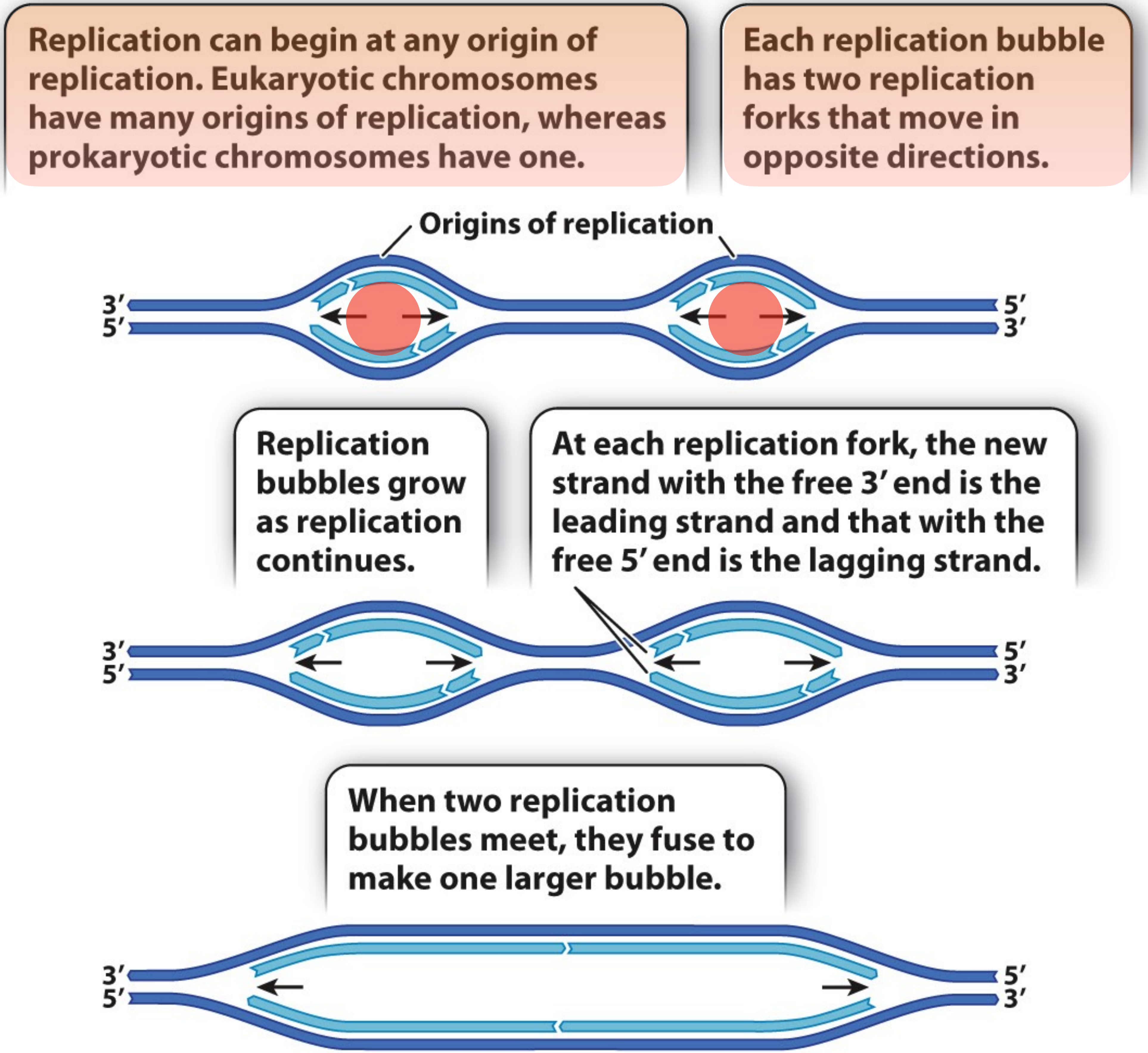


Figure 12.9
Biology: How Life Works, Second Edition

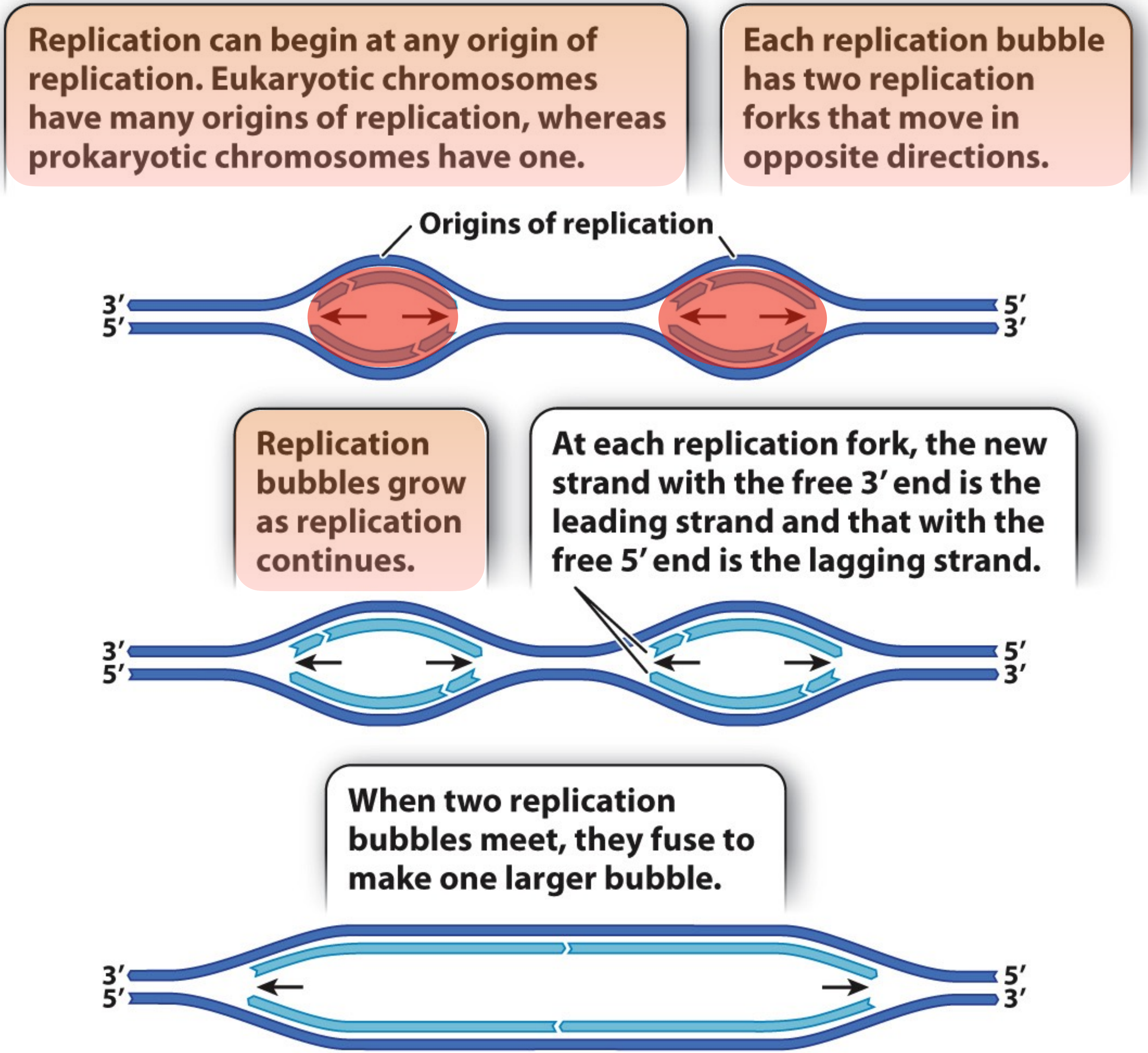


Figure 12.9
Biology: How Life Works, Second Edition

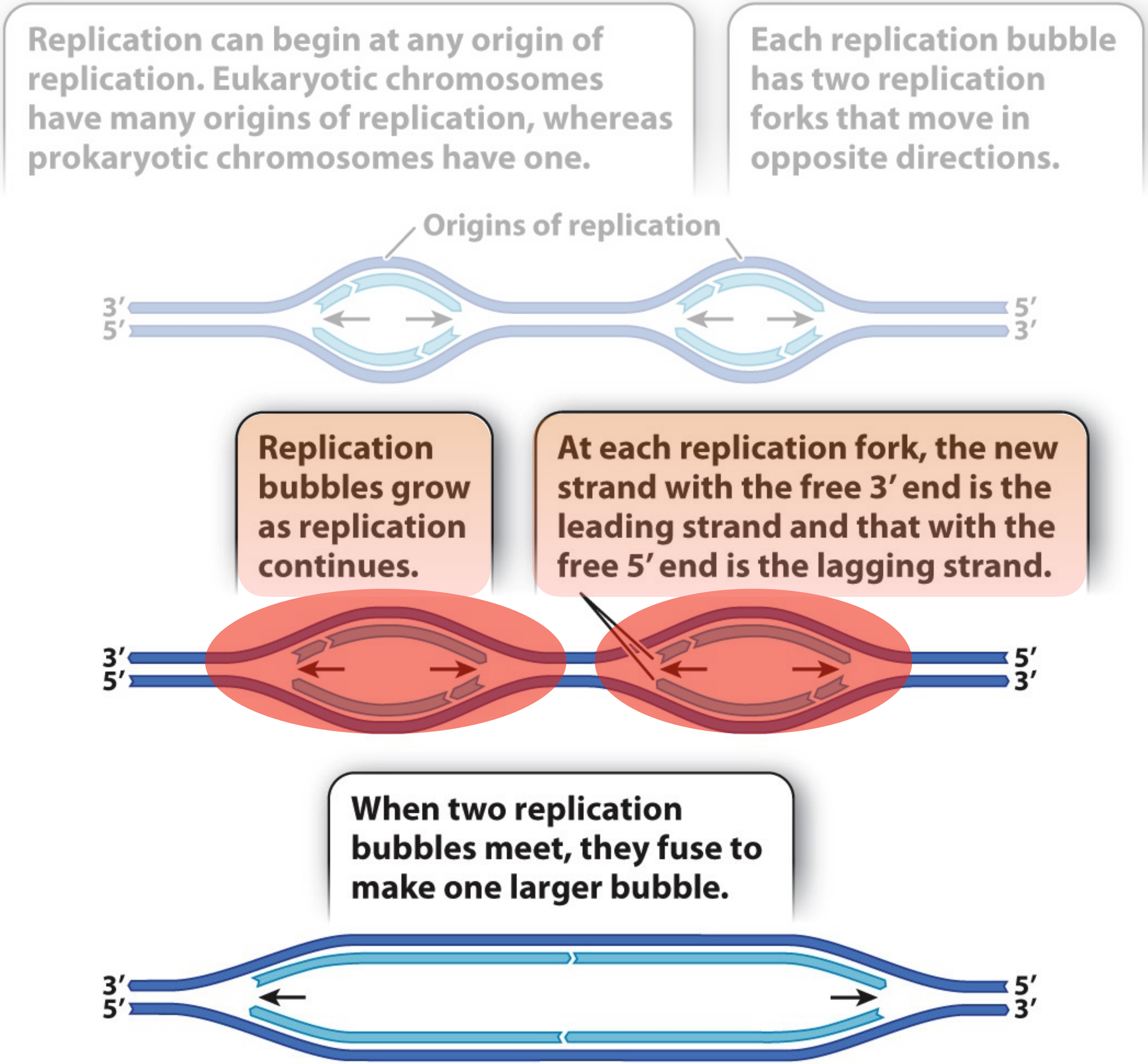


Figure 12.9
Biology: How Life Works, Second Edition

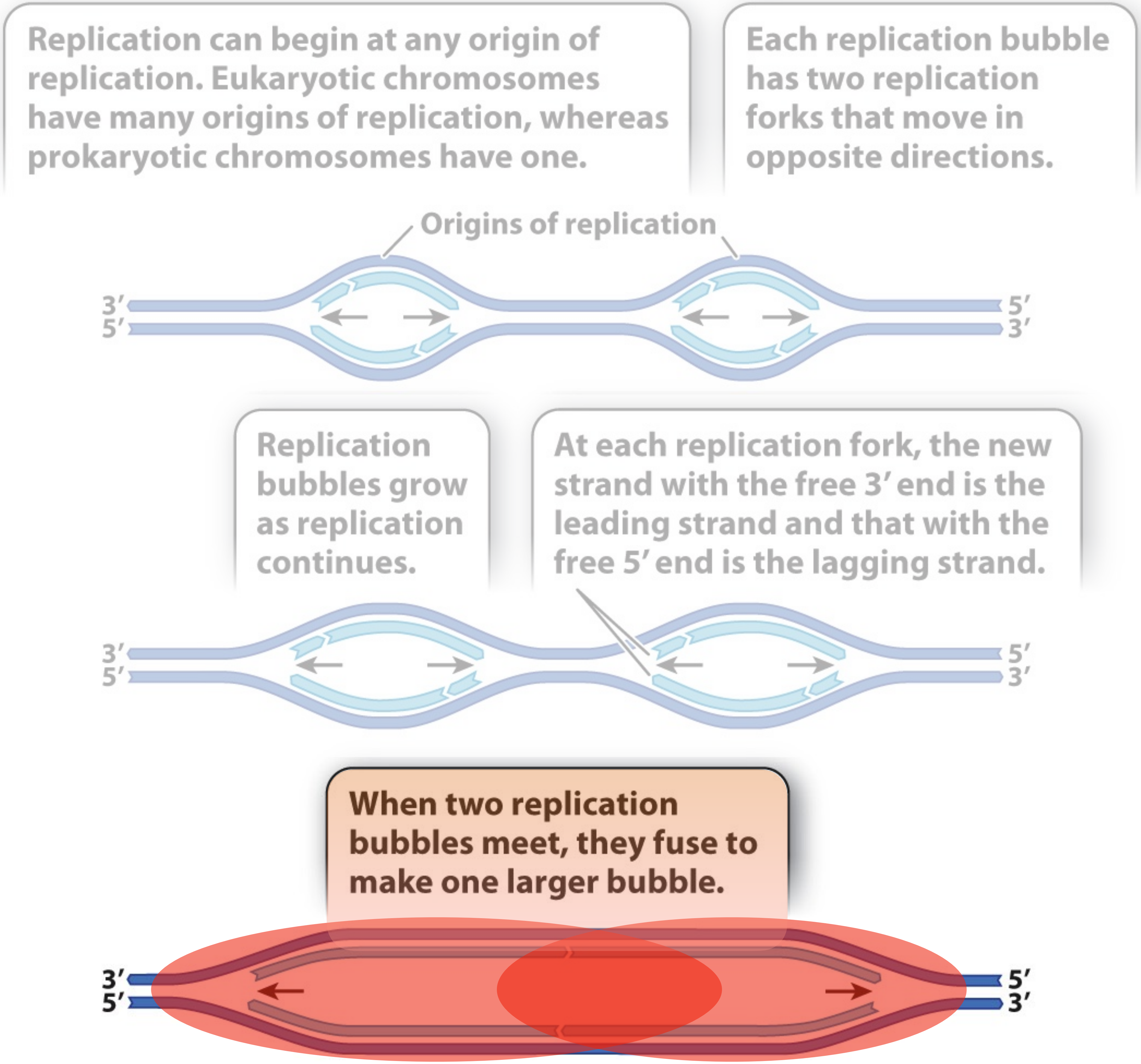
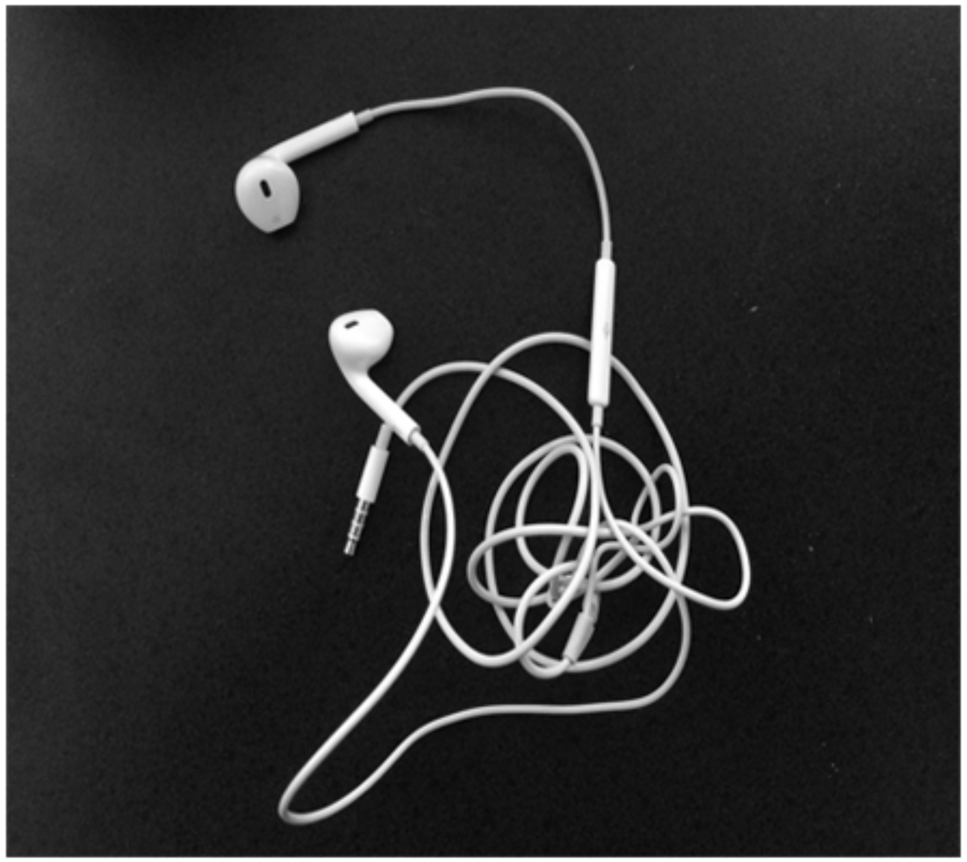
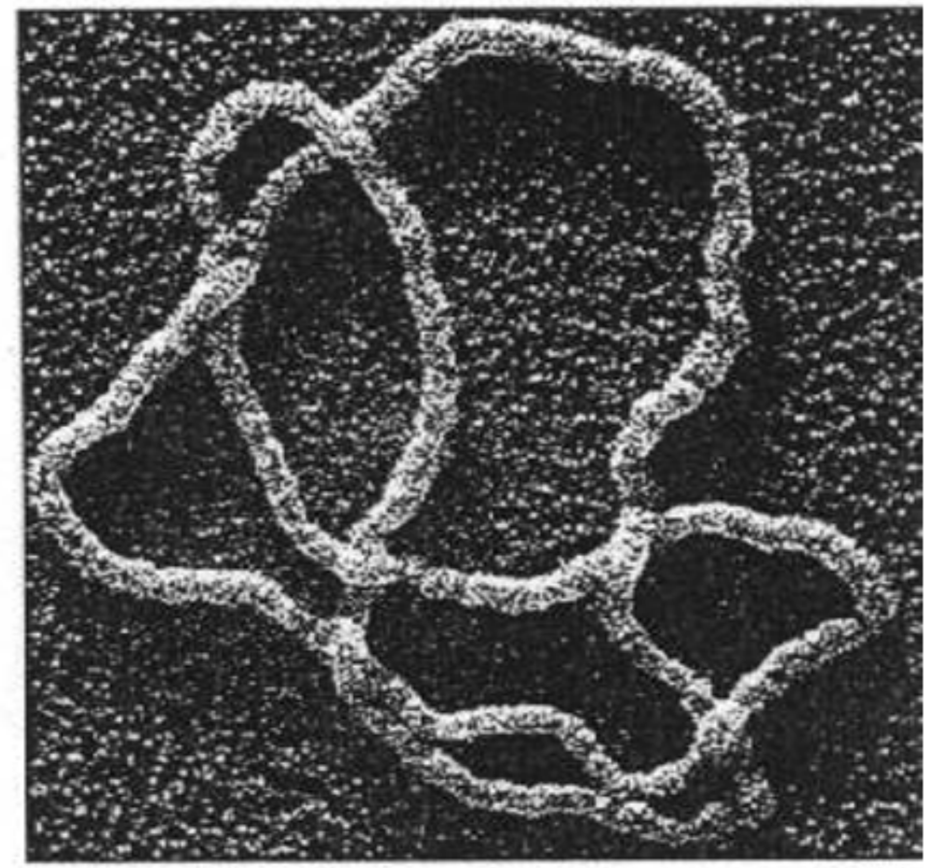


Figure 12.9

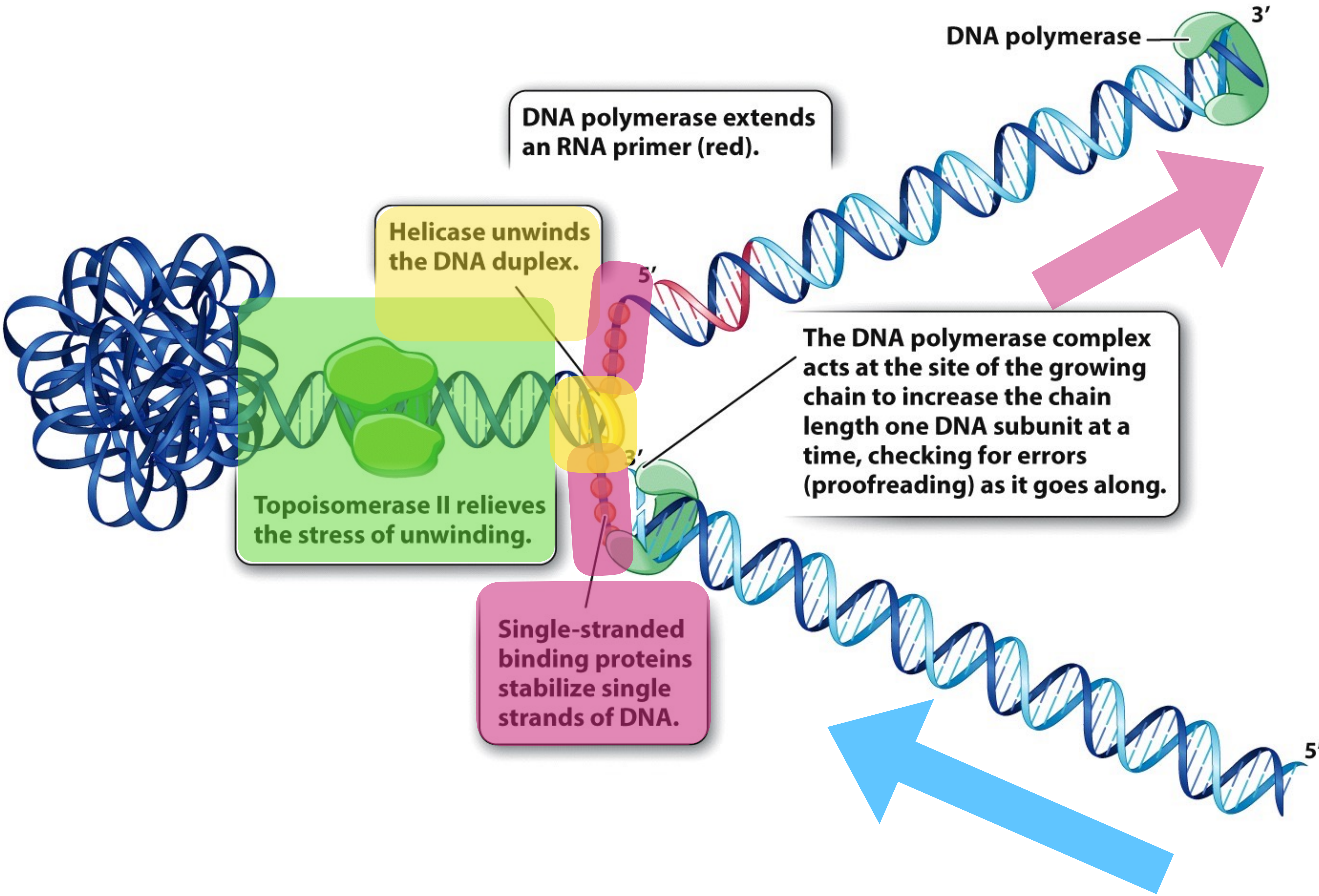
Biology: How Life Works, Second Edition



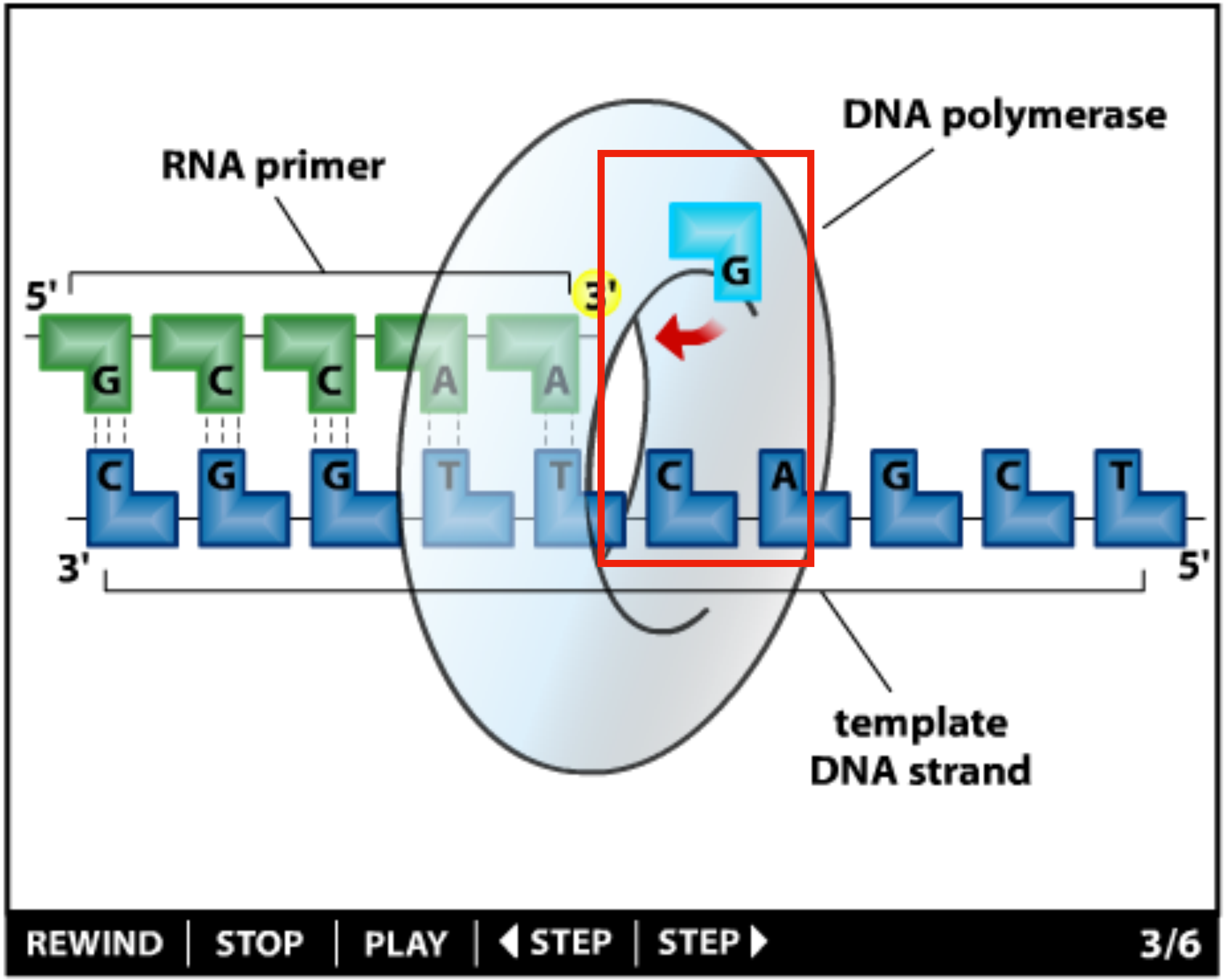
Houghton B. 2016 Typical state of iphone headphones



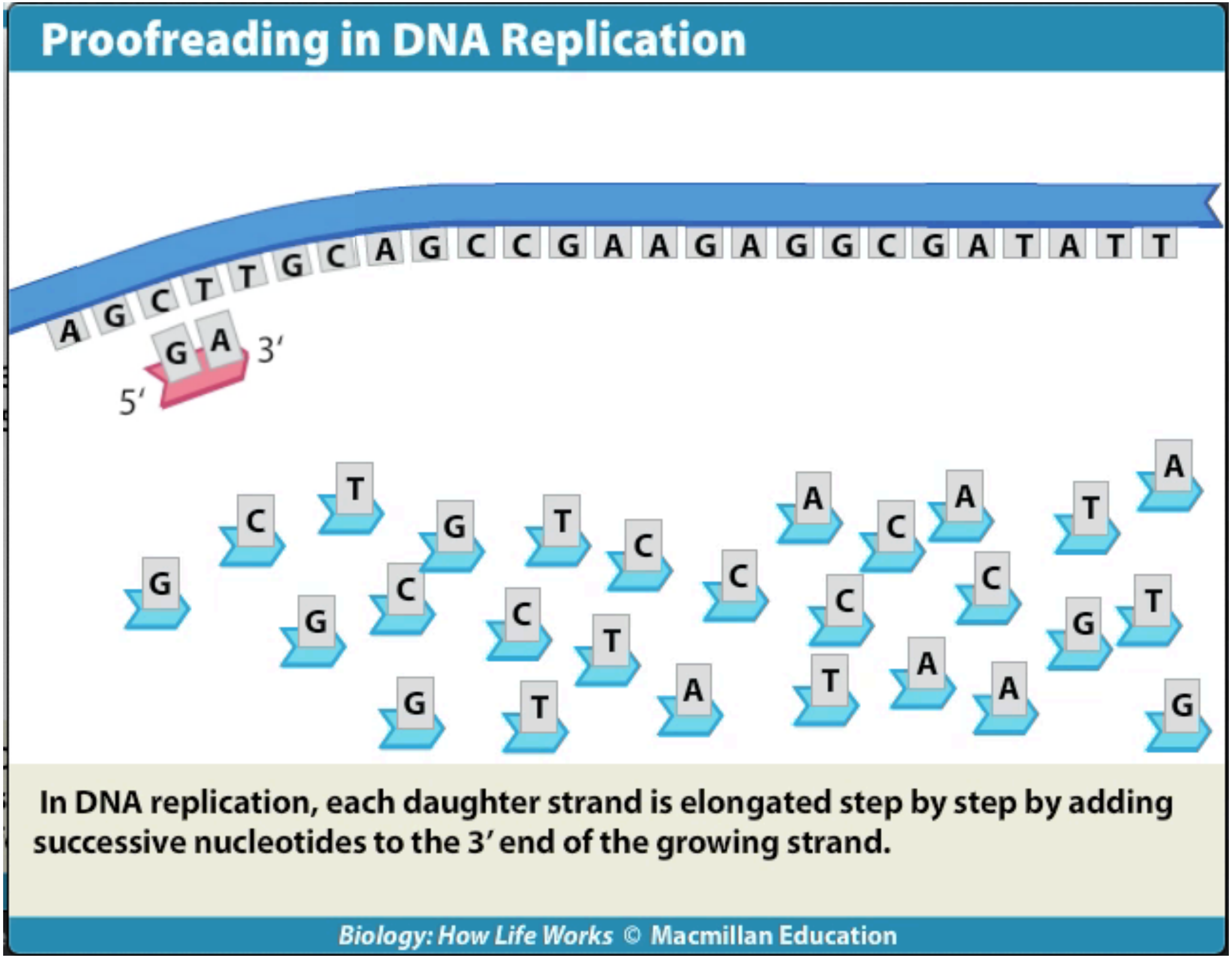
Sumners, D. 1995. Notices of the AMS 42:528-537.



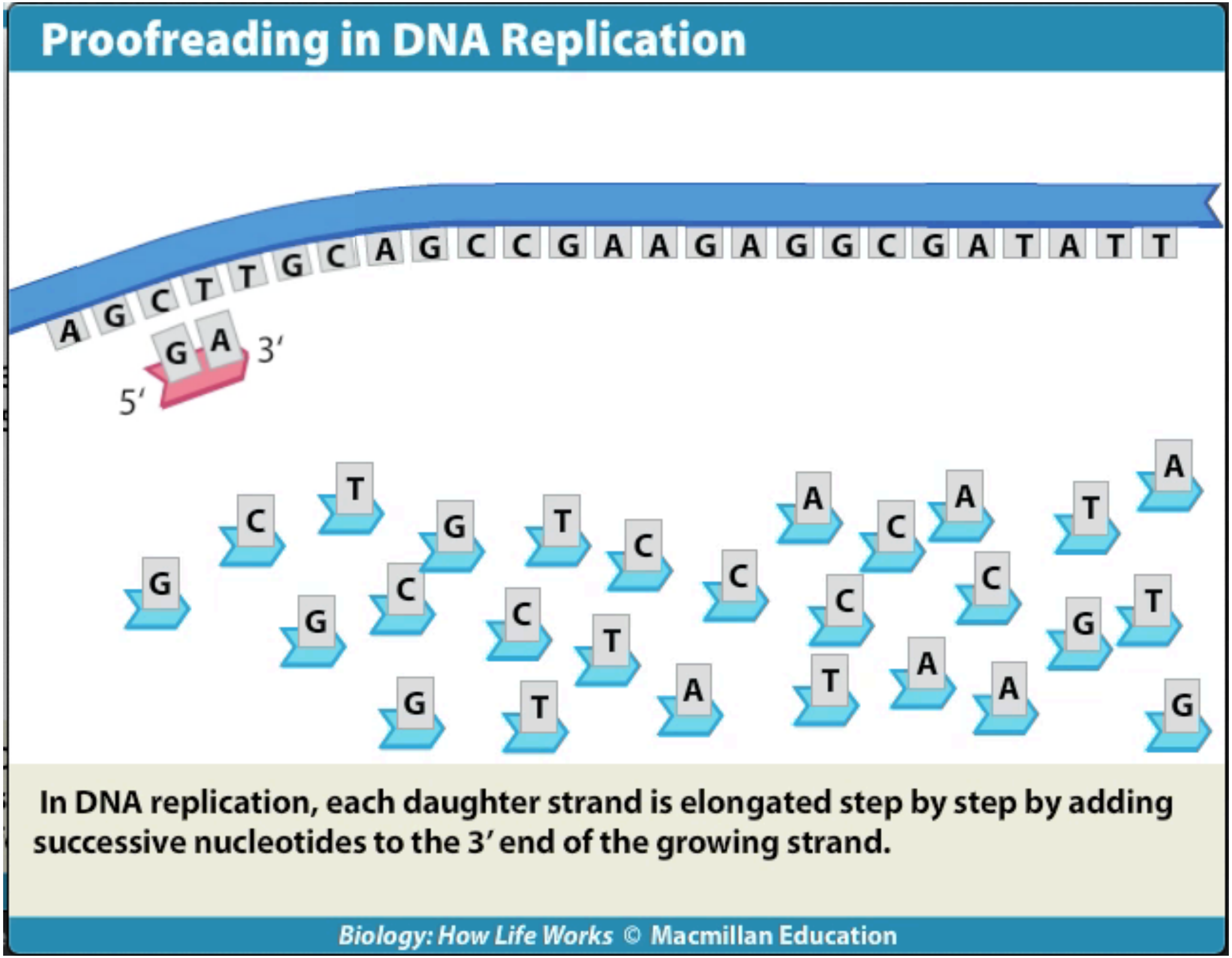
DNA polymerase
3′
DNA polymerase extends an RNA primer (red).
Helicase unwinds the DNA duplex.
5′
The DNA polymerase complex acts at the site of the growing chain to increase the chain length one DNA subunit at a time, checking for errors (proofreading) as it goes along.
3′
Topoisomerase II relieves the stress of unwinding.
Single-stranded binding proteins stabilize single strands of DNA.
5′



DNA polymerase
RNA primer
5'
3'
G
C
C
A
A
C
G
G
T
T
C
A
G
C
T
G
3'
5'
template
DNA strand
REWIND
STOP
PLAY
STEP
STEP
3/6

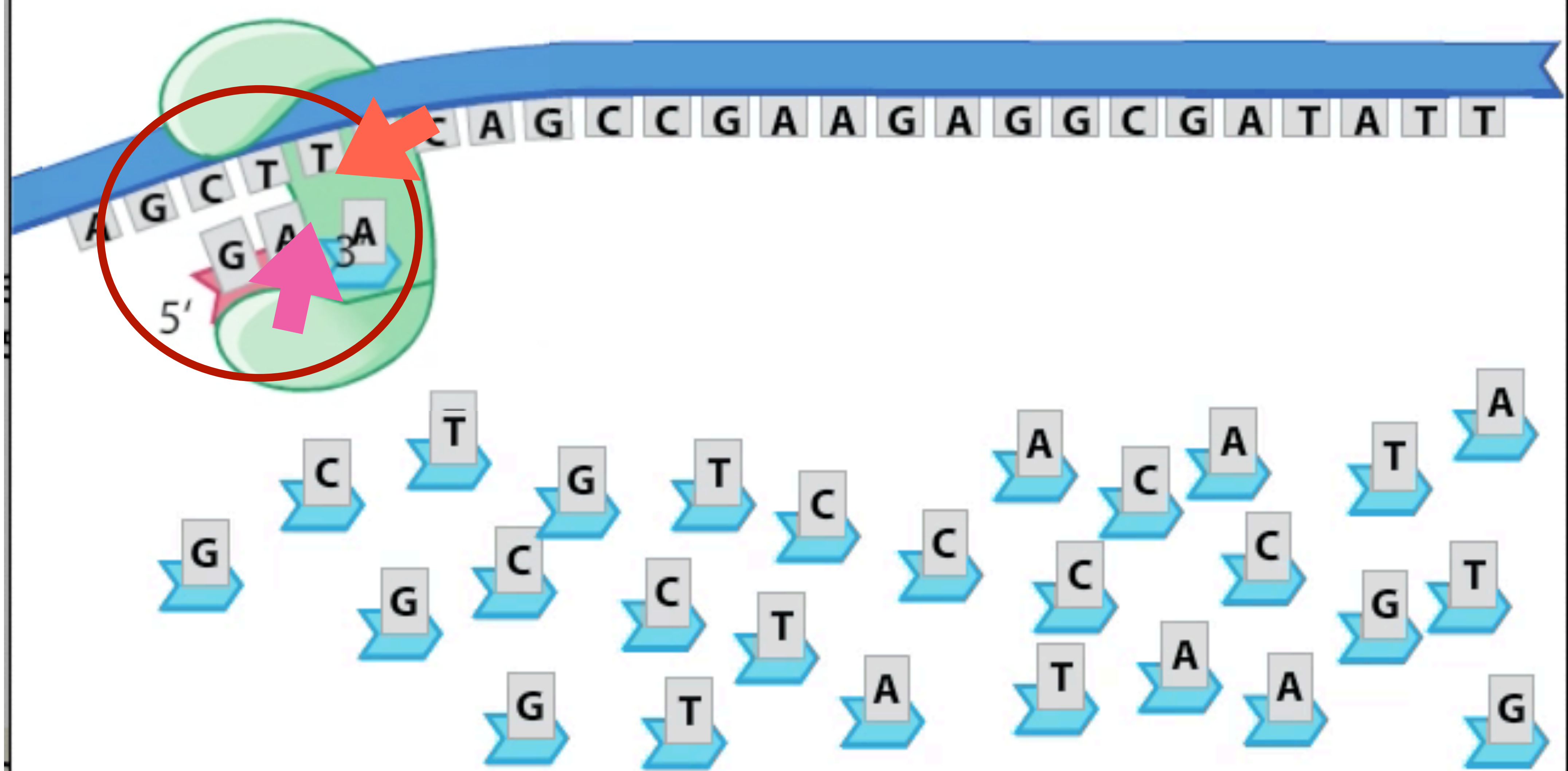


750 - 1,000 bases replicated per second



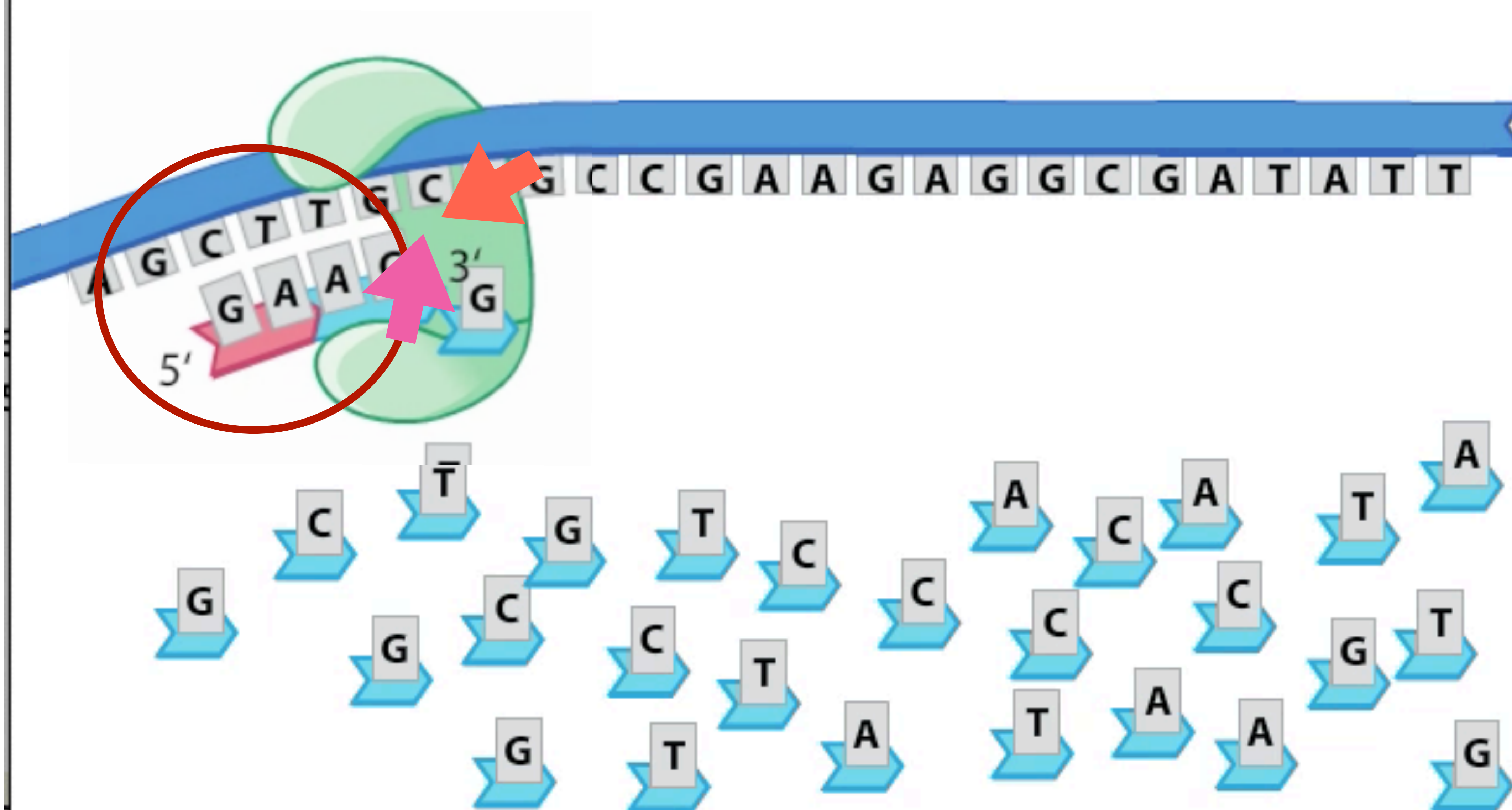
1 error in 1x 10⁹ (1 in 1,000,000,000) bases replicated

Proofreading in DNA Replication



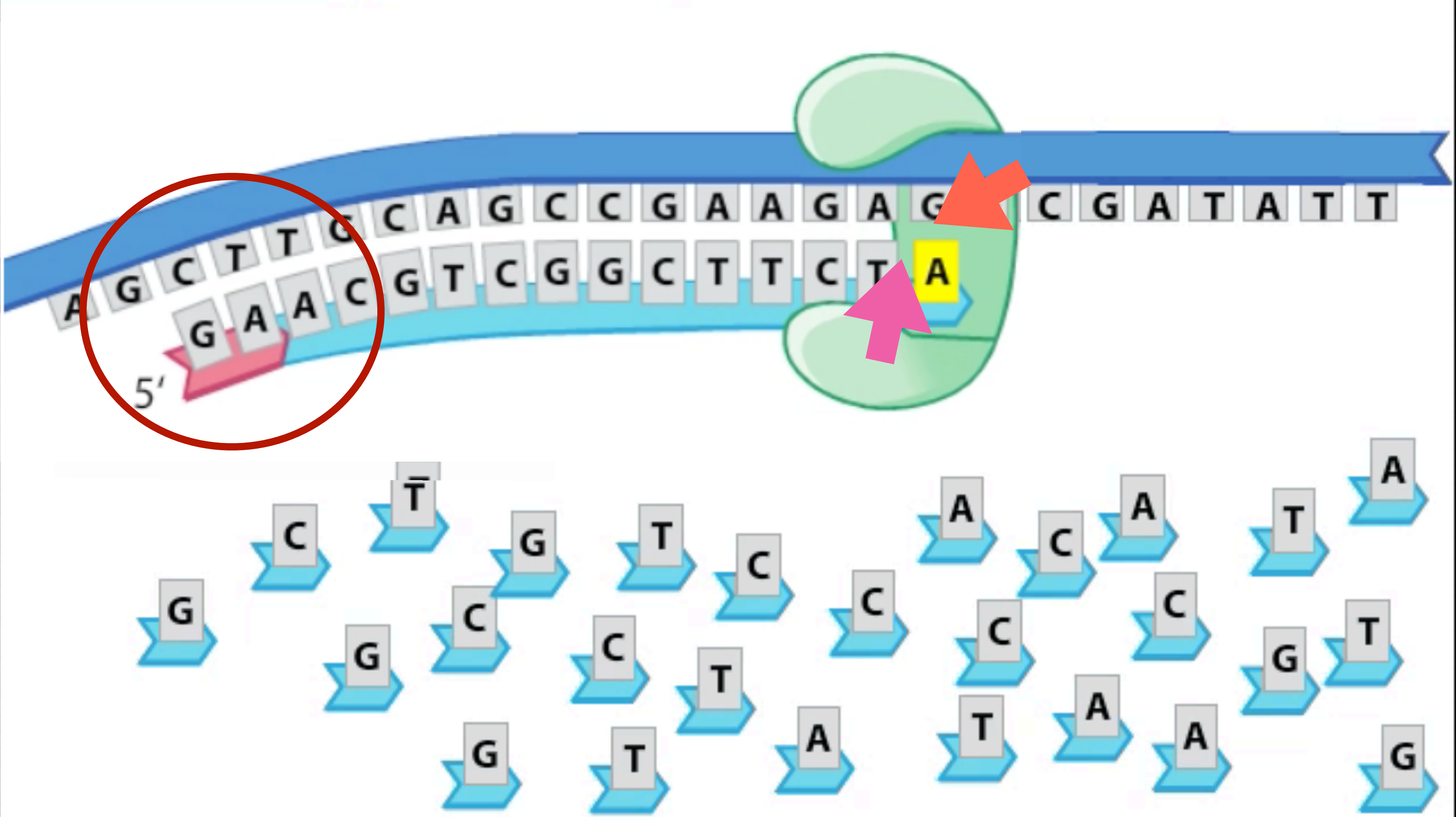
In DNA replication, each daughter strand is elongated step by step by adding successive nucleotides to the 3′ end of the growing strand.

Proofreading in DNA Replication



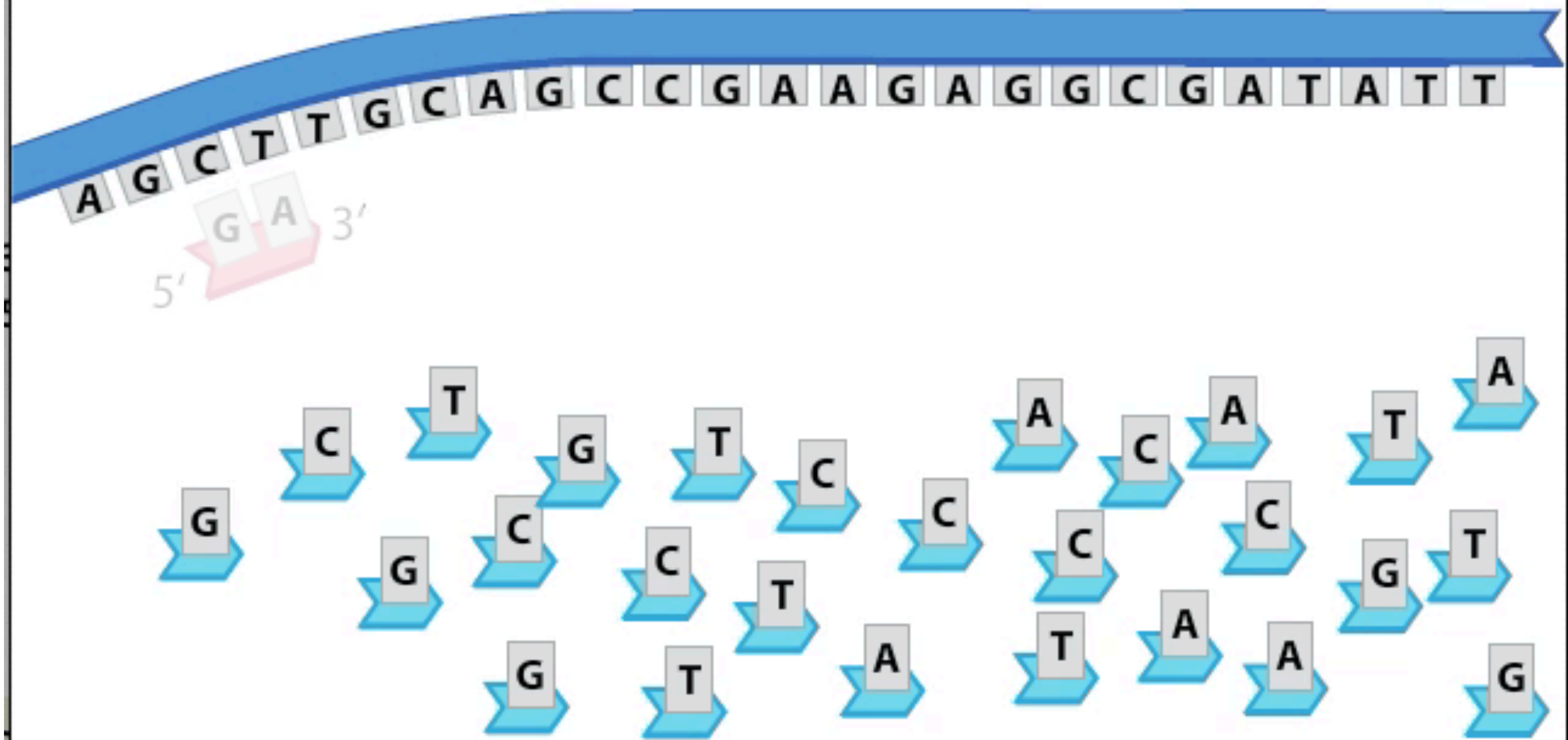
In DNA replication, each daughter strand is elongated step by step by adding successive nucleotides to the 3′ end of the growing strand.

Proofreading in DNA Replication



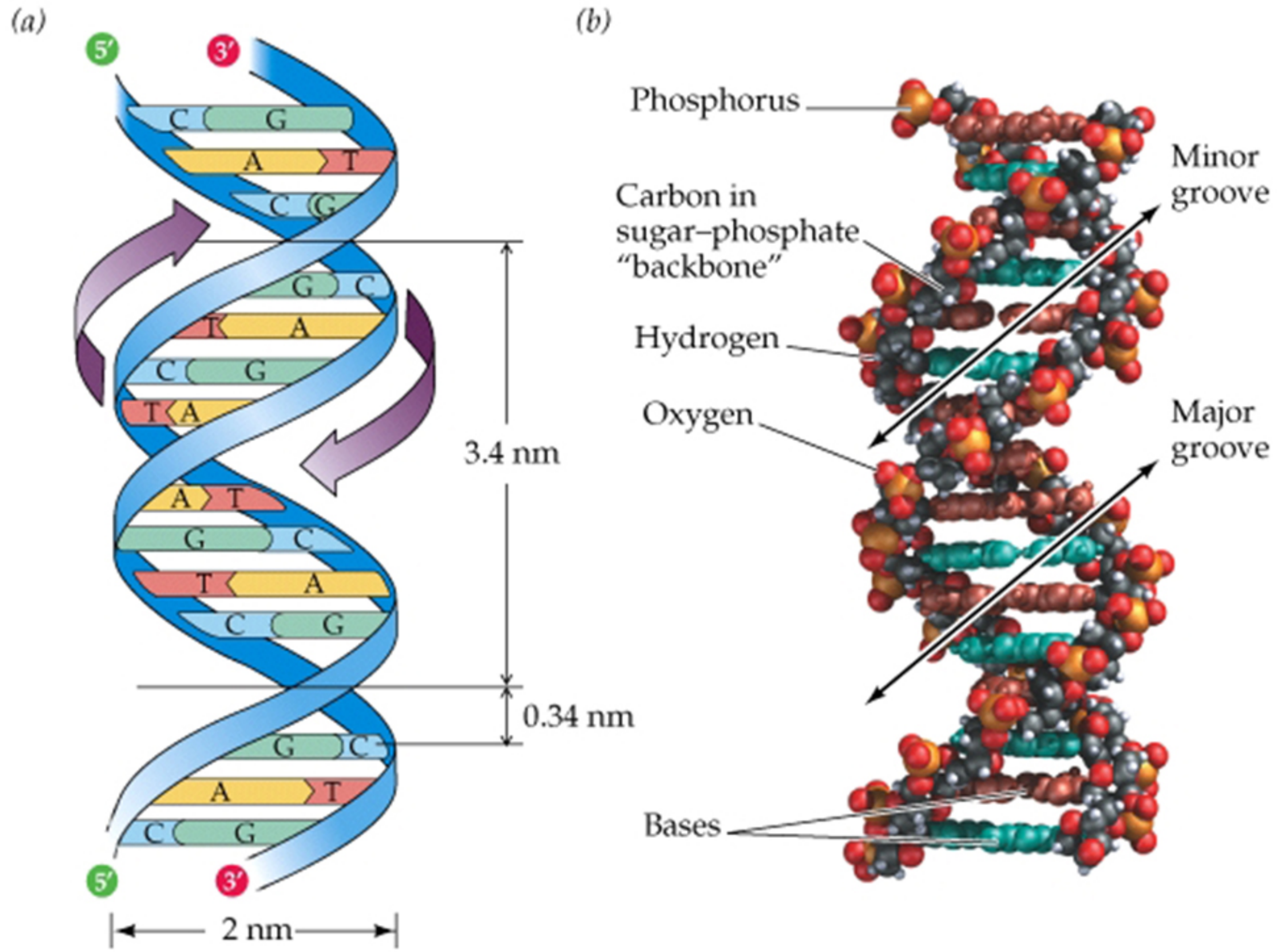
In DNA replication, each daughter strand is elongated step by step by adding successive nucleotides to the 3′ end of the growing strand.

Proofreading in DNA Replication



In DNA replication, each daughter strand is elongated step by step by adding successive nucleotides to the 3′ end of the growing strand.

1 error in 1x 10^9 (1 in 1,000,000,000) bases replicated



As the genetic material of the cell, DNA must perform four important functions:

It must be able to store all of an organism's genetic information.

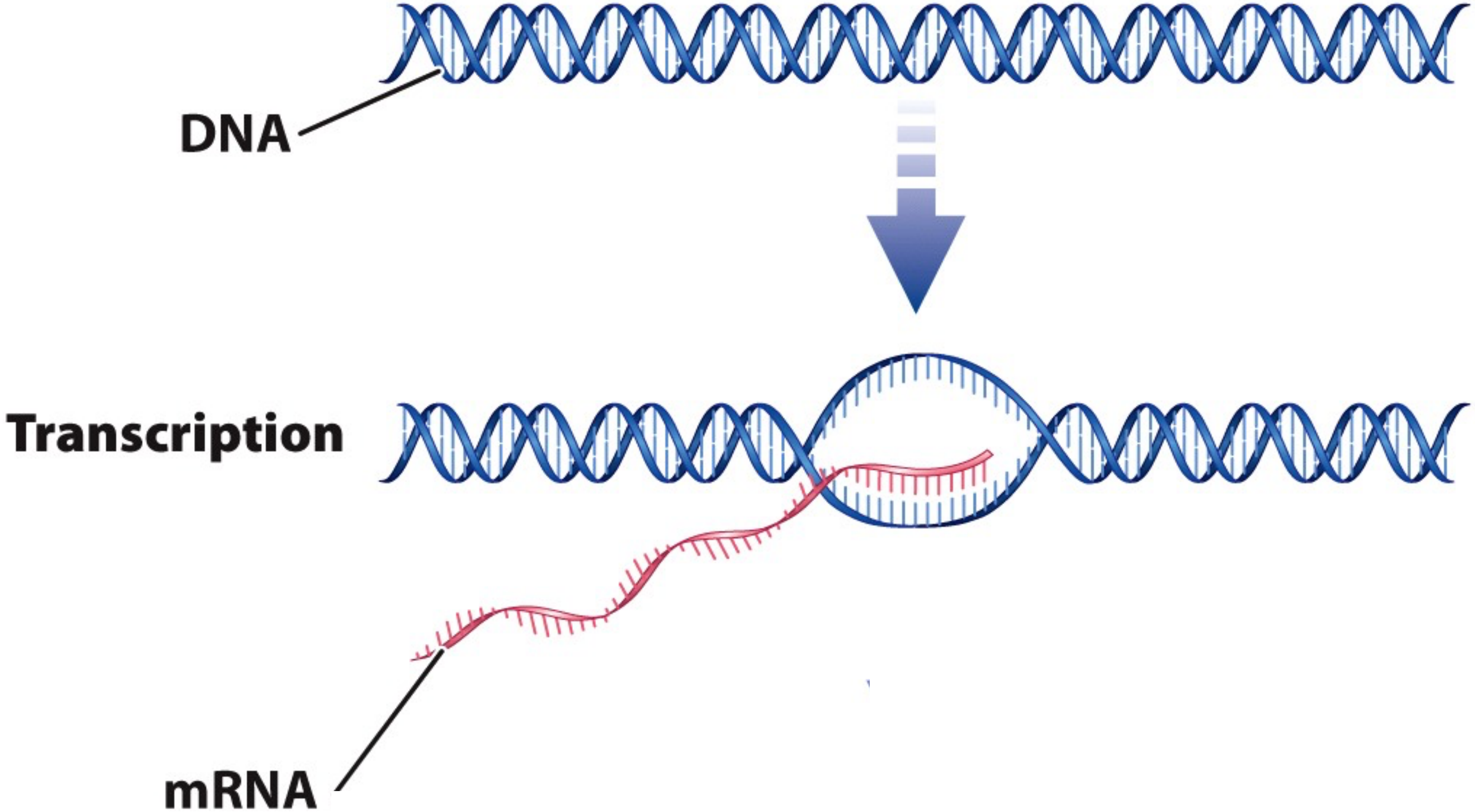
It must be susceptible to mutation.

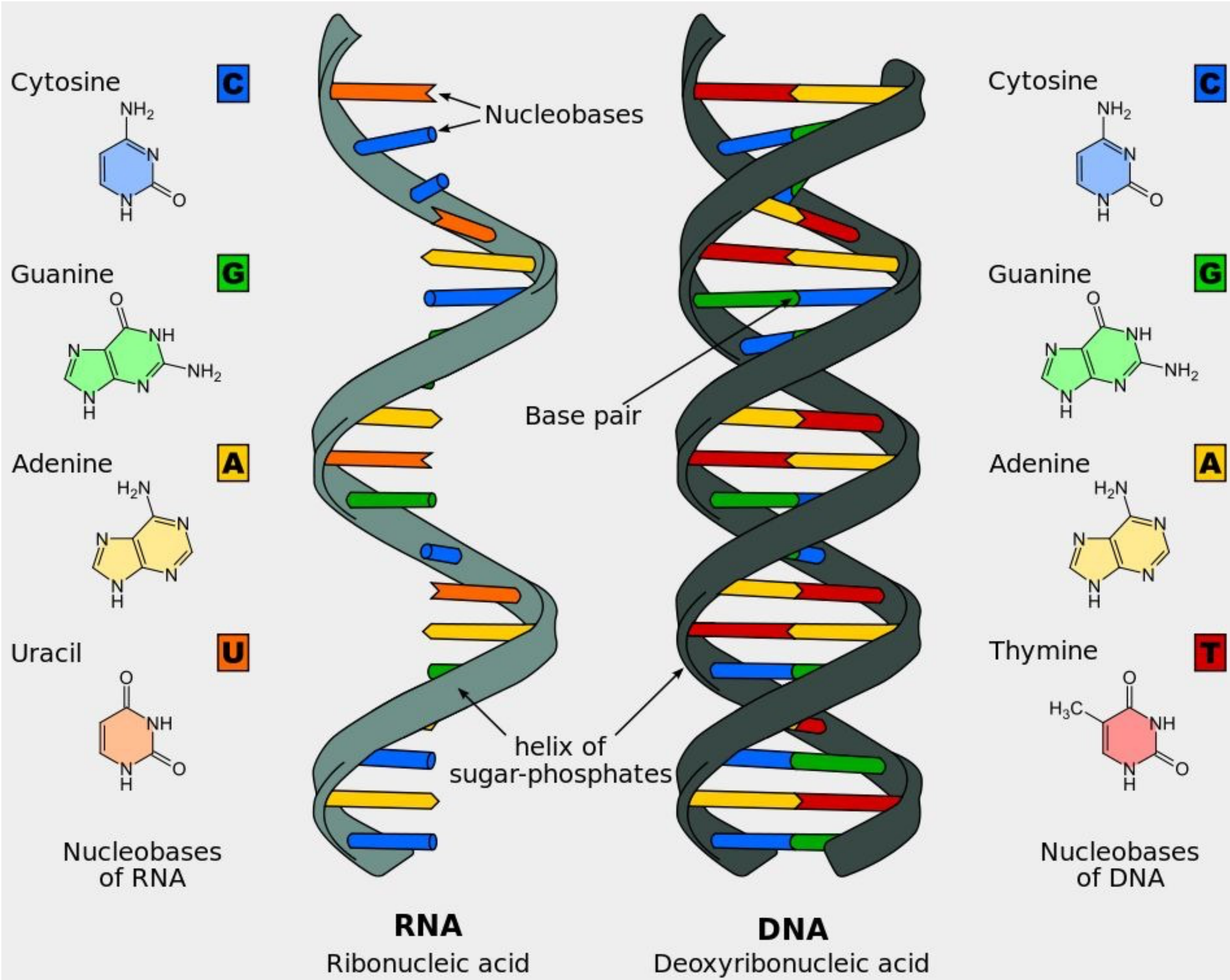
It must be precisely replicated in the cell division cycle.

At the molecular level

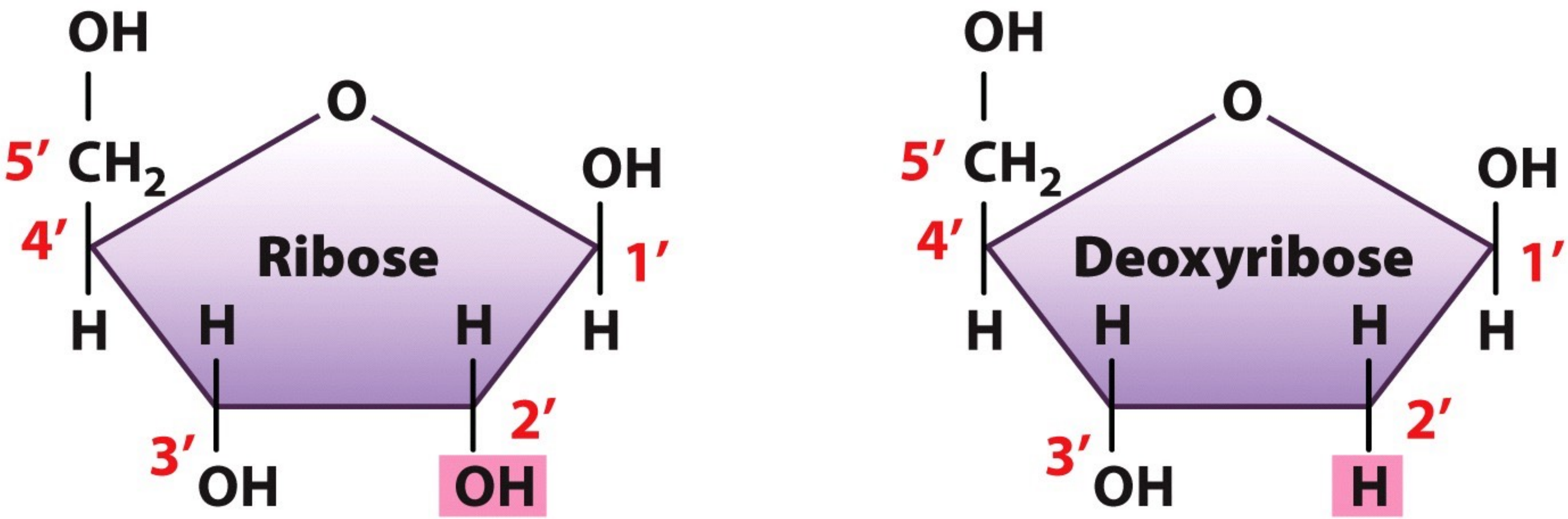
- **gene: "a sequence of DNA that gives rise to a functional gene product..." this product can (ultimately) be an RNA or a protein.**

This is a little different from our first definition of a gene in **lecture 4**, when we defined it as


DNA
Transcription
mRNA

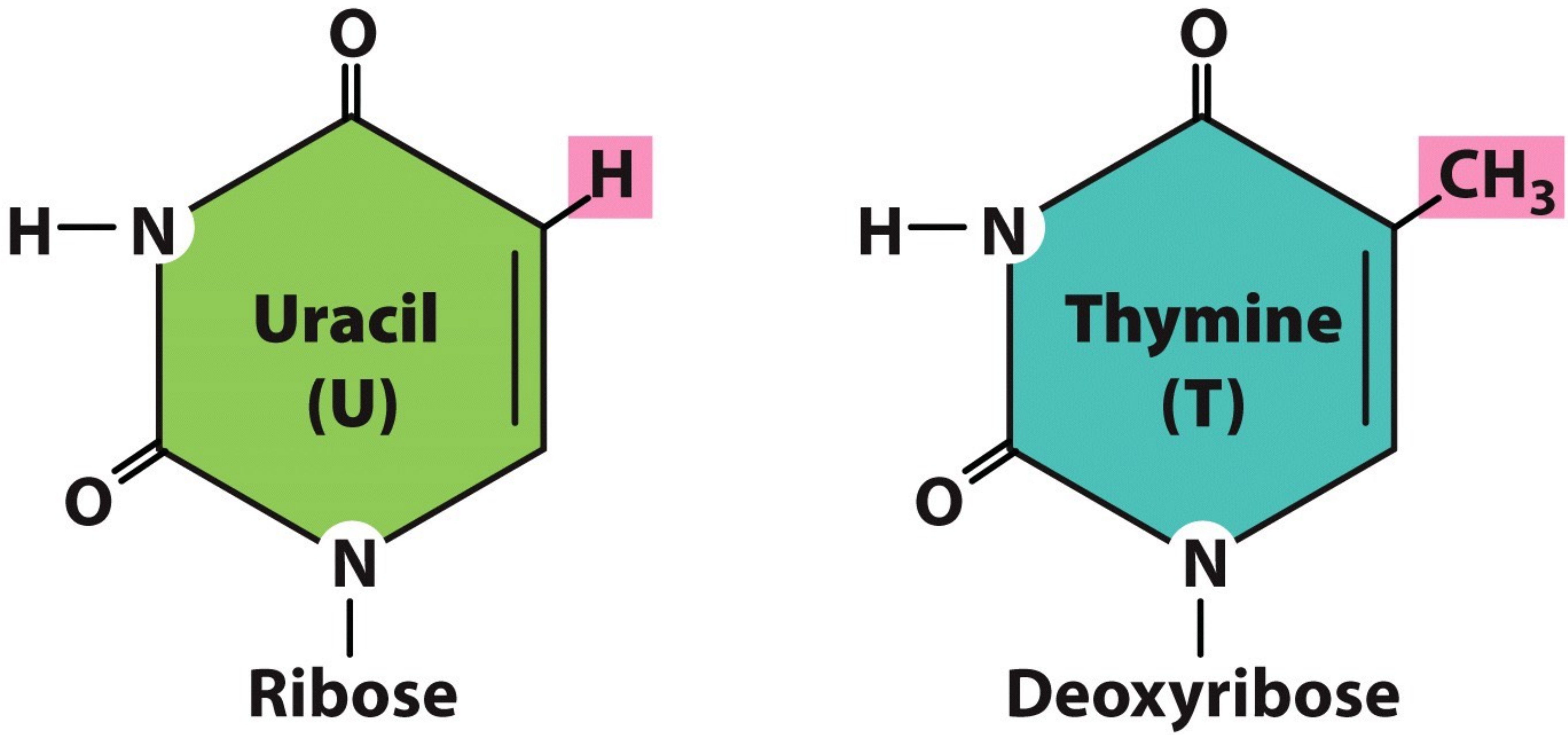


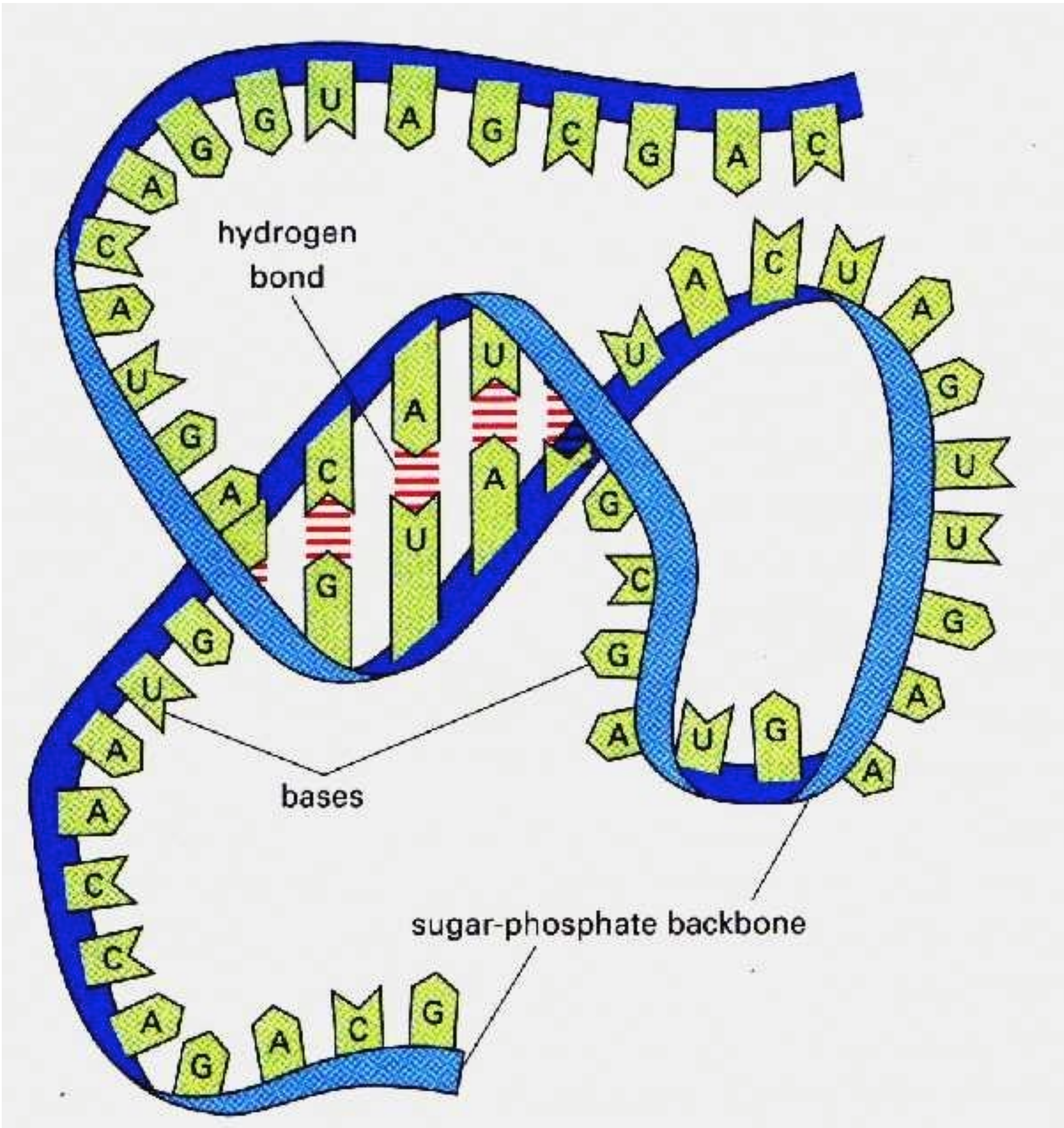
Cytosine
C
Guanine
G
Adenine
A
Uracil
U
Nucleobases
of RNA
Nucleobases
Base pair
helix of
sugar-phosphates
RNA
Ribonucleic acid
DNA
Deoxyribonucleic acid
Cytosine
C
Guanine
G
Adenine
A
Thymine
T
Nucleobases
of DNA



Ribose has a hydroxyl (–OH) group where deoxyribose has a hydrogen (–H).

Uracil has a hydrogen (–H) where thymine has a methyl ($-CH_3$) group.



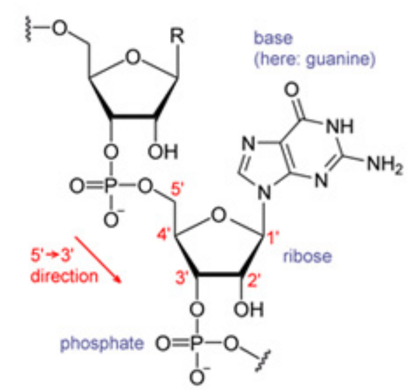


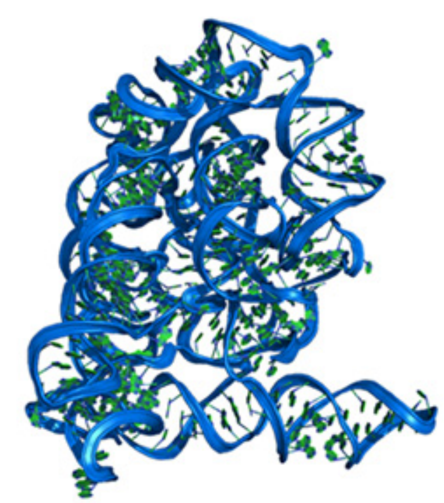
RNA is usually **single-stranded**.

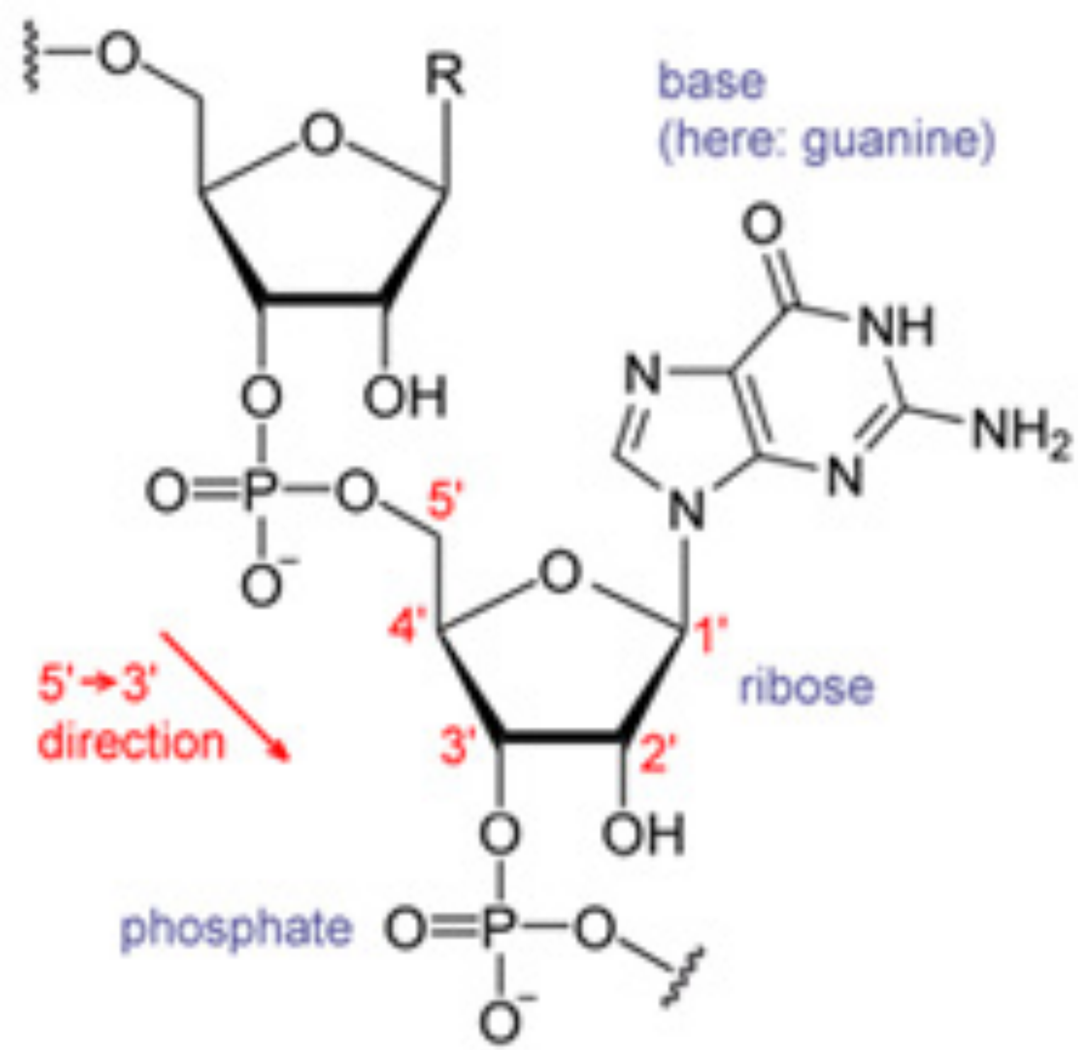
The sugar in RNA is **ribose**, not **deoxyribose**.

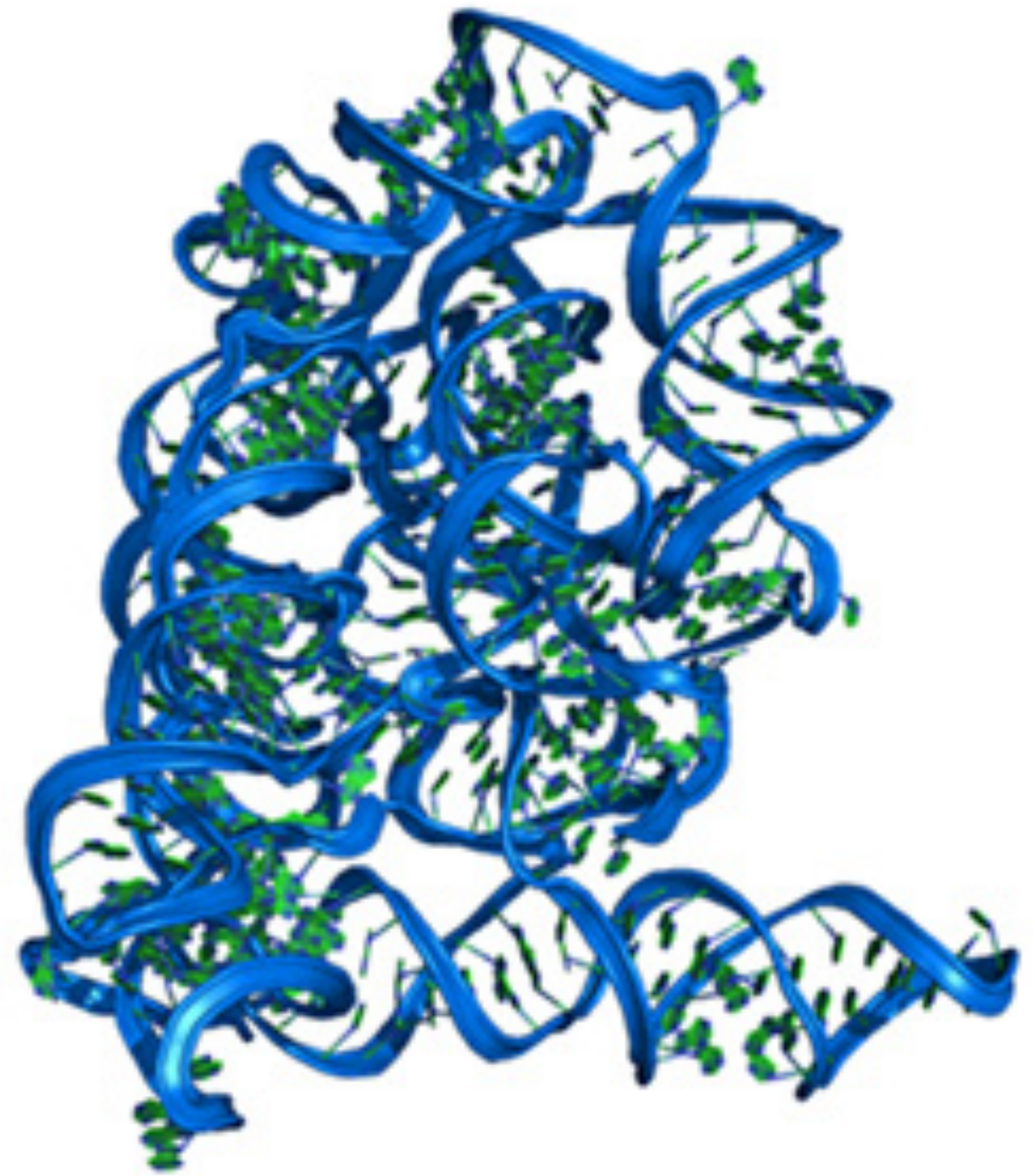
Wherever **thymine** is found in DNA, it is replaced by **uracil** in RNA.

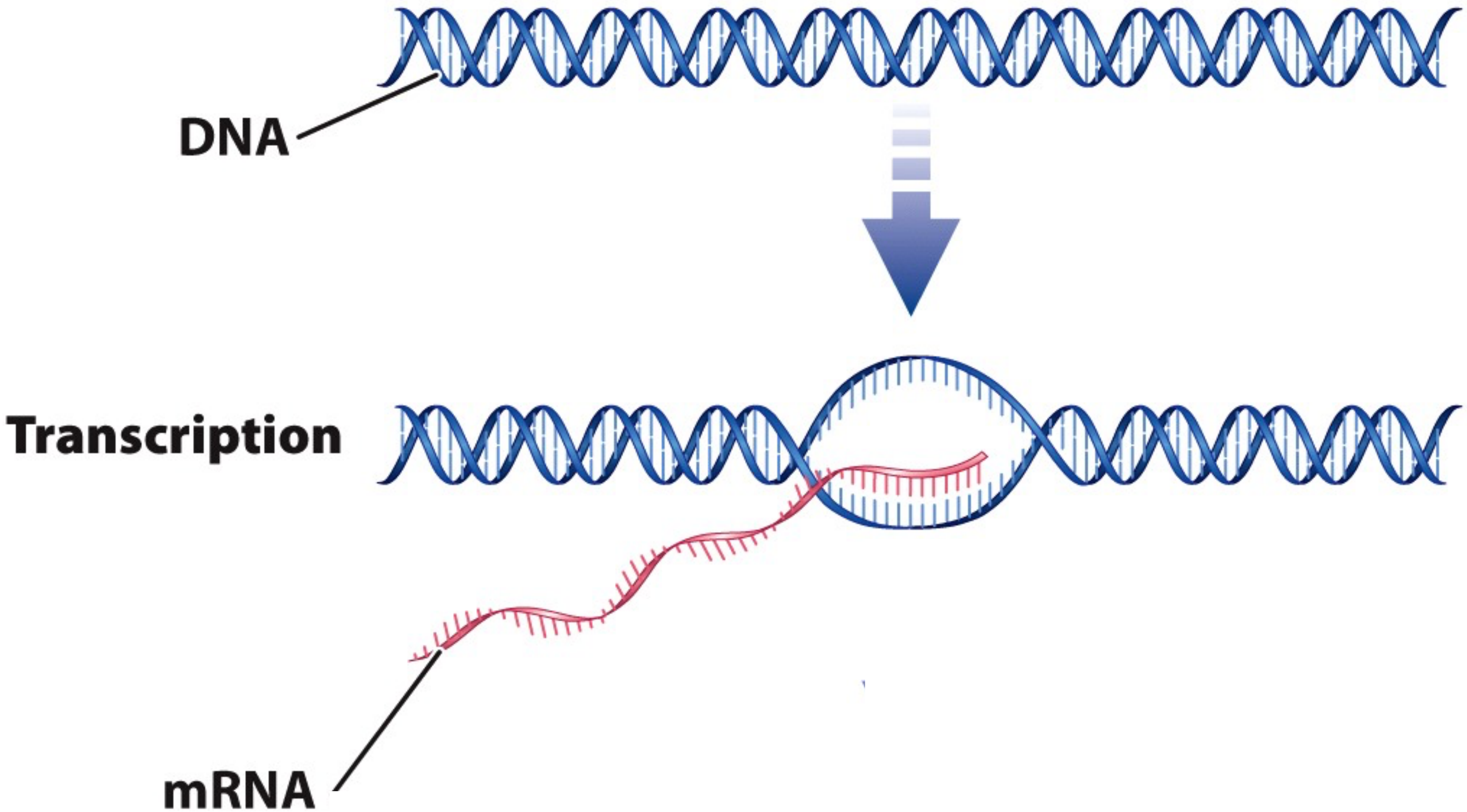
RNA can fold over and base-pair with itself.






base
(here: guanine)
ribose
phosphate
5'→3'
direction
1'
2'
3'
4'
5'

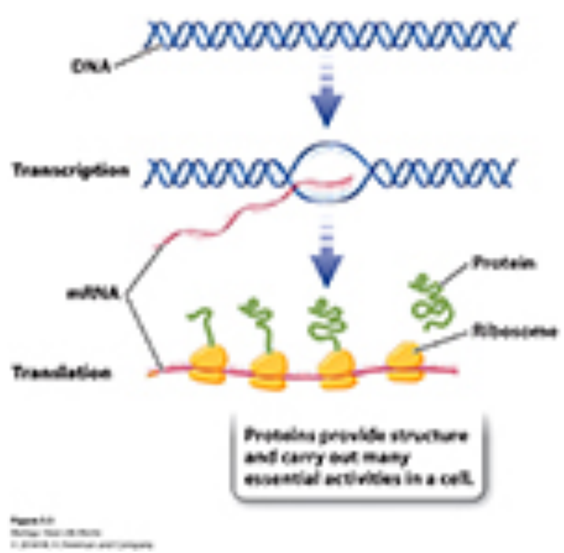



DNA
Transcription
mRNA

RNA comes in various forms/sequences, commensurate with function.

rRNA (81% by weight in *E. coli*; cellular RNA), which acts as nucleic acid scaffold for the ribosomes, which are the enzymes that copy the mRNA message into a polypeptide chain.

tRNA (15% by weight in *E. coli*; 60 different possible species), which is the link between the code of the **mRNA** and the **amino acids** of the **polypeptide**. The tRNA molecules specify the correct amino acid.

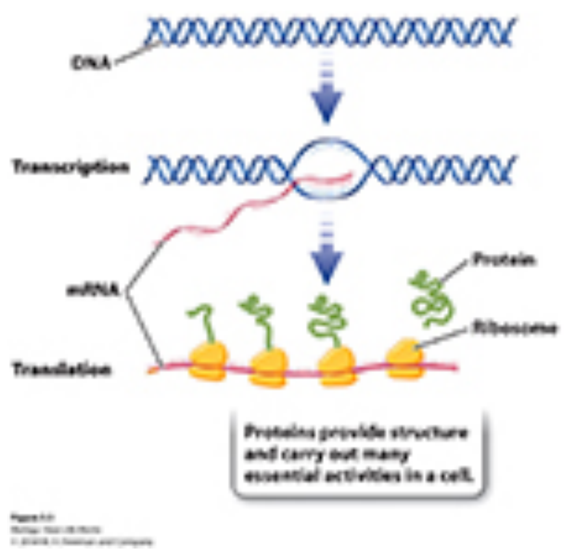


mRNA (4% by weight in *E. coli;* <u>transient</u> 0.5-10 minute to 24hr. life span), which is the transient information that is copied from the DNA.

RNA comes in various forms/sequences, commensurate with function.

rRNA (81% by weight in *E. coli*; cellular RNA), which acts as nucleic acid scaffold for the ribosomes, which are the enzymes that copy the mRNA message into a polypeptide chain.

tRNA (15% by weight in *E. coli*; 60 different possible species), which is the link between the code of the **mRNA** and the **amino acids** of the **polypeptide**. The tRNA molecules specify the correct amino acid.



mRNA (4% by weight in *E. coli;* <u>transient</u> 0.5-10 minute to 24hr. life span), which is the transient information that is copied from the DNA.

RNA comes in various forms/sequences, commensurate with function.

rRNA (81% by weight in *E. coli*; cellular RNA), which acts as nucleic acid scaffold for the ribosomes, which are the enzymes that copy the mRNA message into a polypeptide chain.

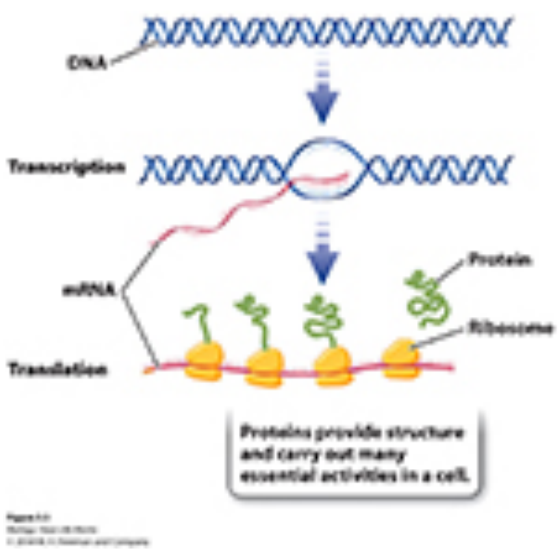
tRNA (15% by weight in *E. coli*; 60 different possible species), which is the link between the code of the **mRNA** and the **amino acids** of the **polypeptide**. The tRNA molecules specify the correct amino acid.

mRNA (4% by weight in *E. coli;* transient 0.5-10 minute to 24hr. life span), which is the transient information that is copied from the DNA.

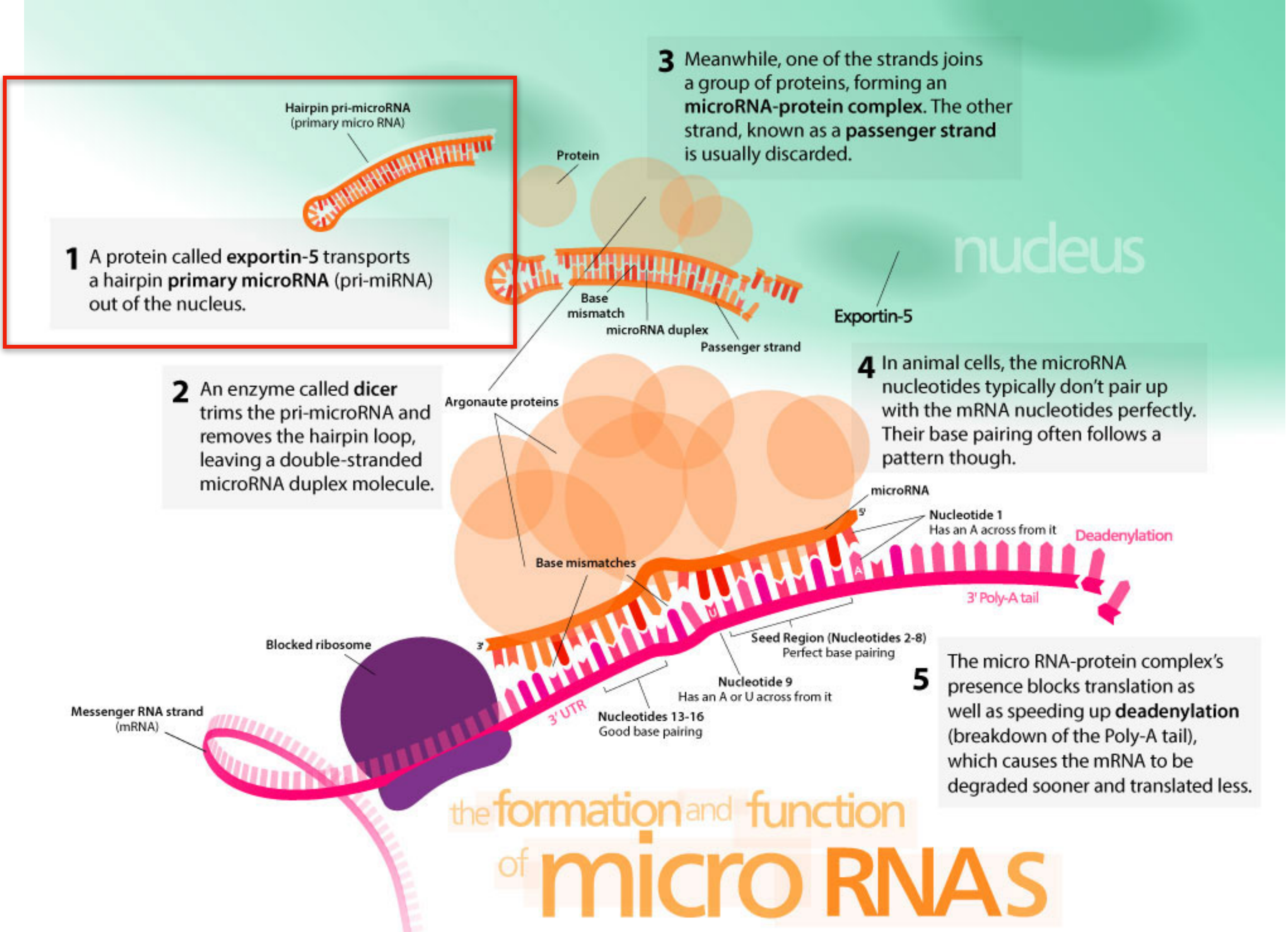
RNA comes in various forms/sequences, commensurate with function.

rRNA (81% by weight in *E. coli*; cellular RNA), which acts as nucleic acid scaffold for the ribosomes, which are the enzymes that copy the mRNA message into a polypeptide chain.

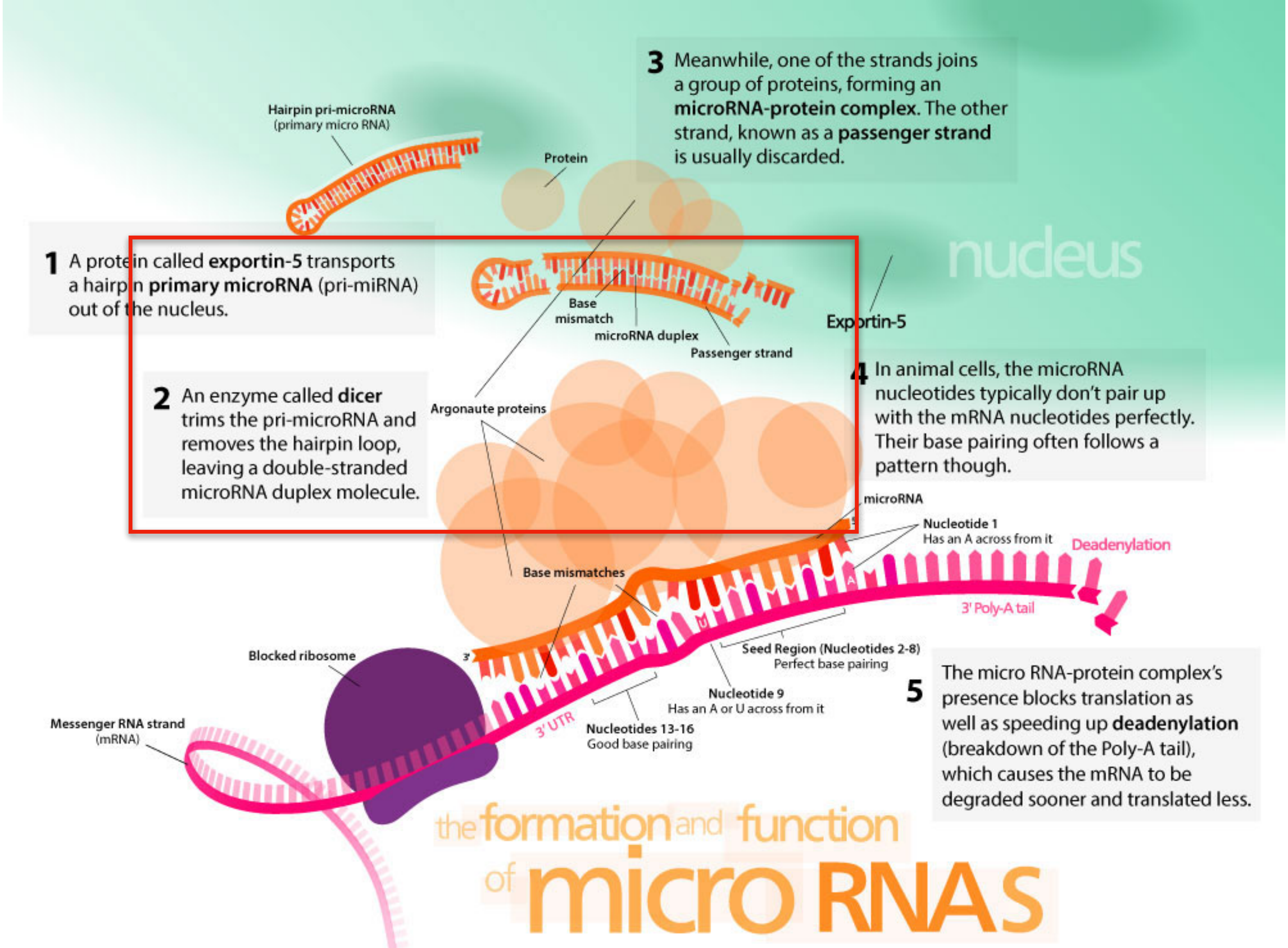
tRNA (15% by weight in *E. coli*; 60 different possible species), which is the link between the code of the **mRNA** and the **amino acids** of the **polypeptide**. The tRNA molecules specify the correct amino acid.



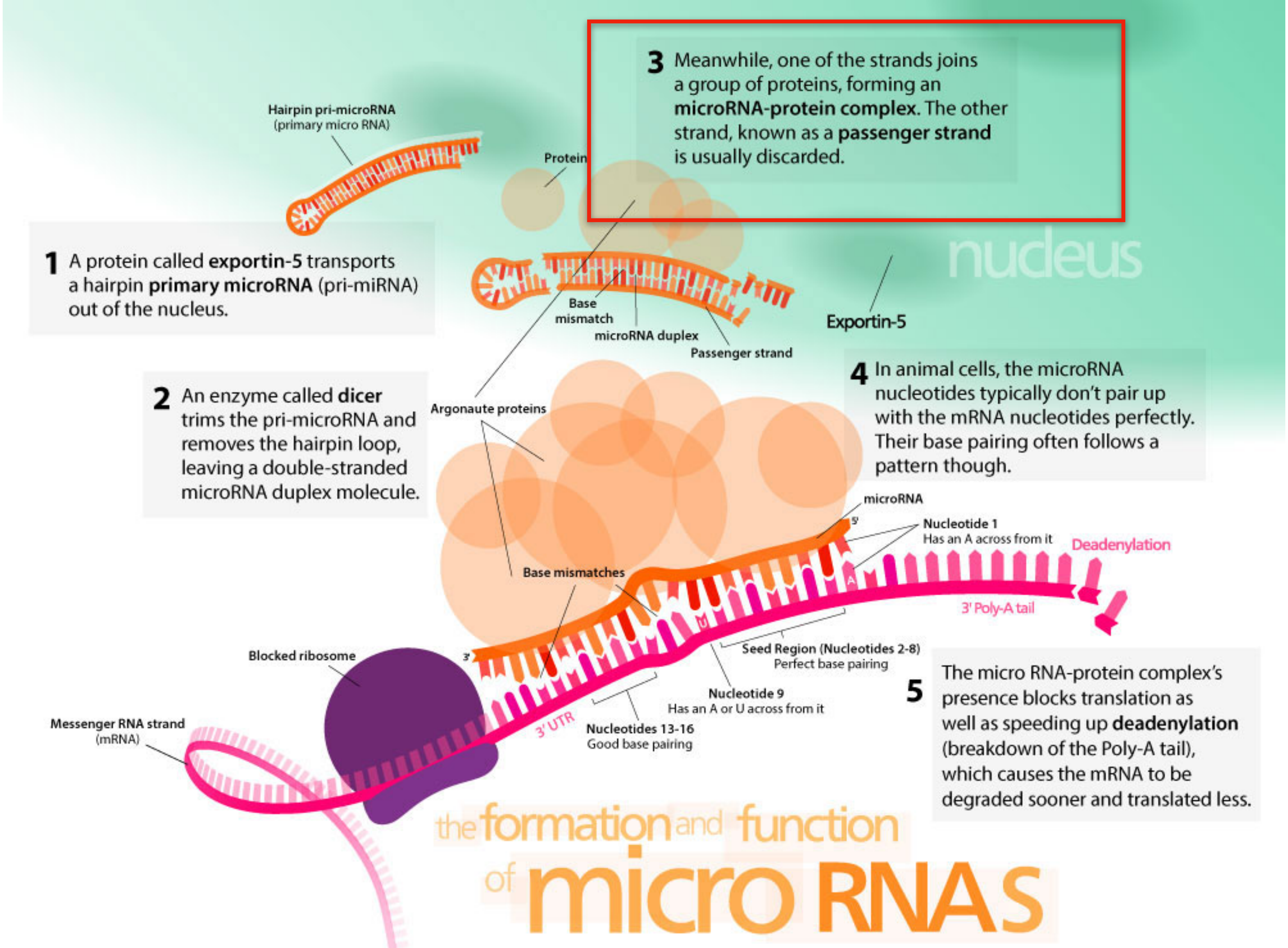
mRNA (4% by weight in *E. coli;* transient 0.5-10 minute to 24hr. life span), which is the transient information that is copied from the DNA.



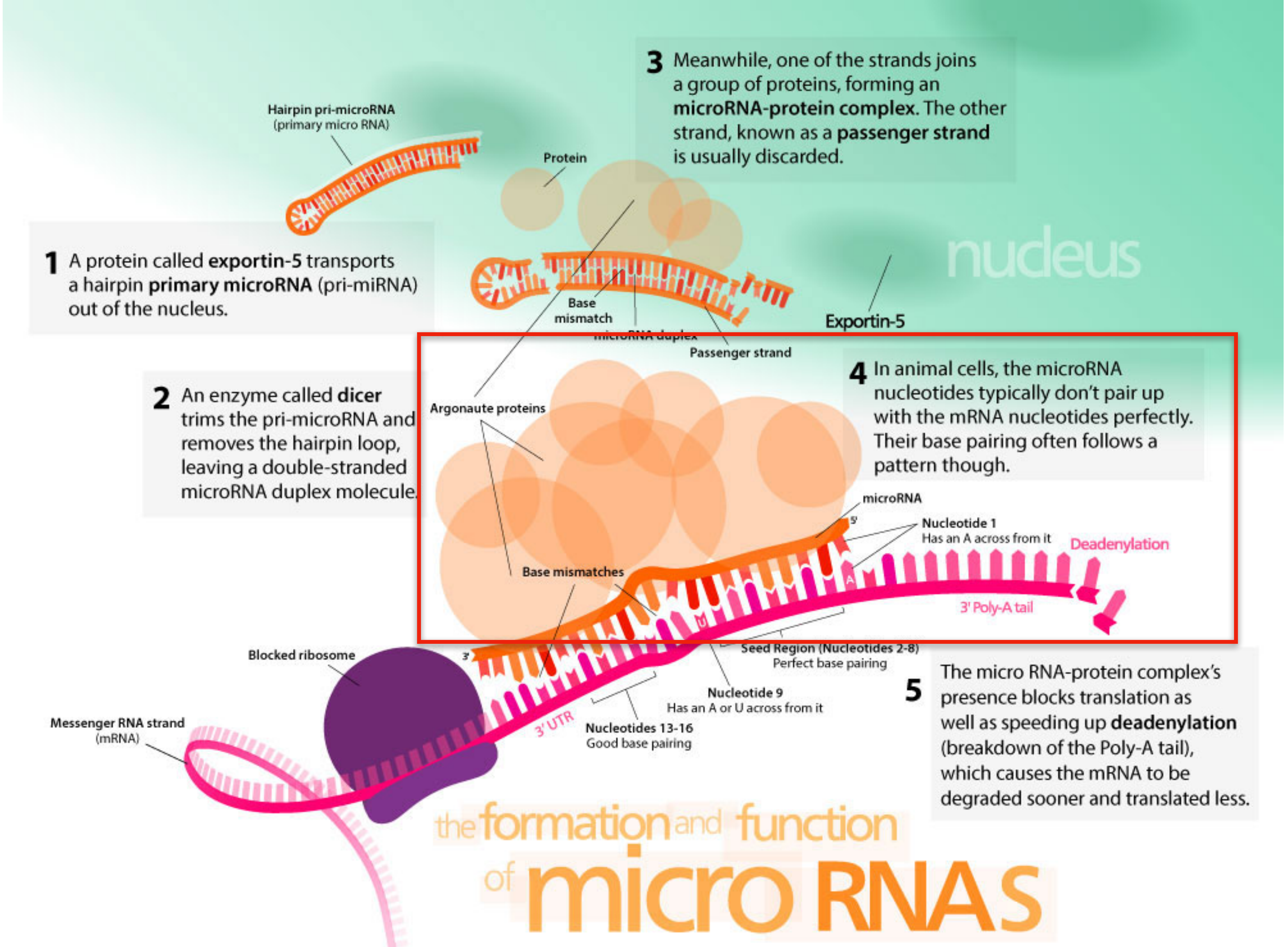
Adapted from Kelvinsong, Diagram of microRNA.



Adapted from Kelvinsong, Diagram of microRNA.



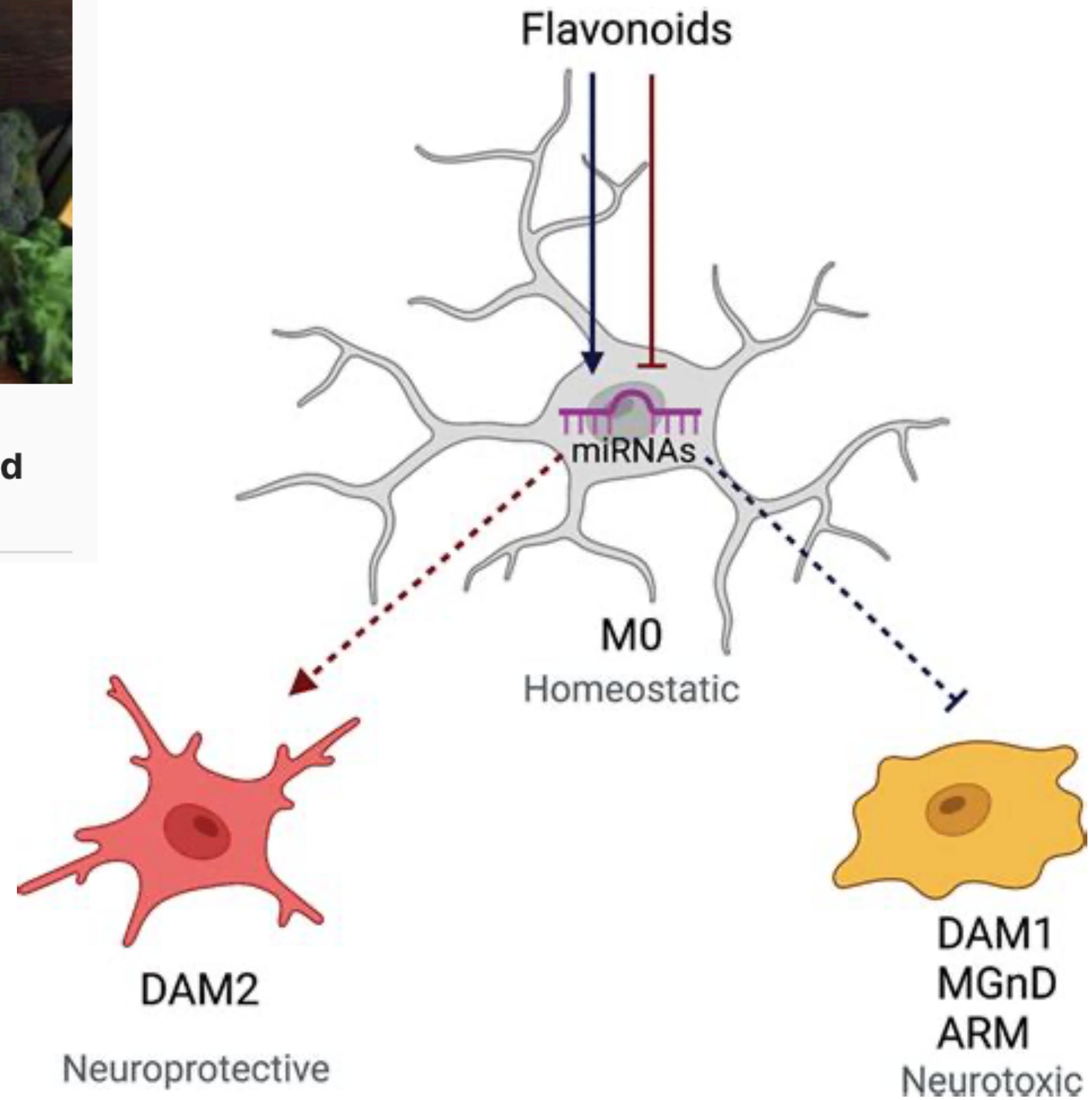
Adapted from Kelvinsong, Diagram of microRNA.

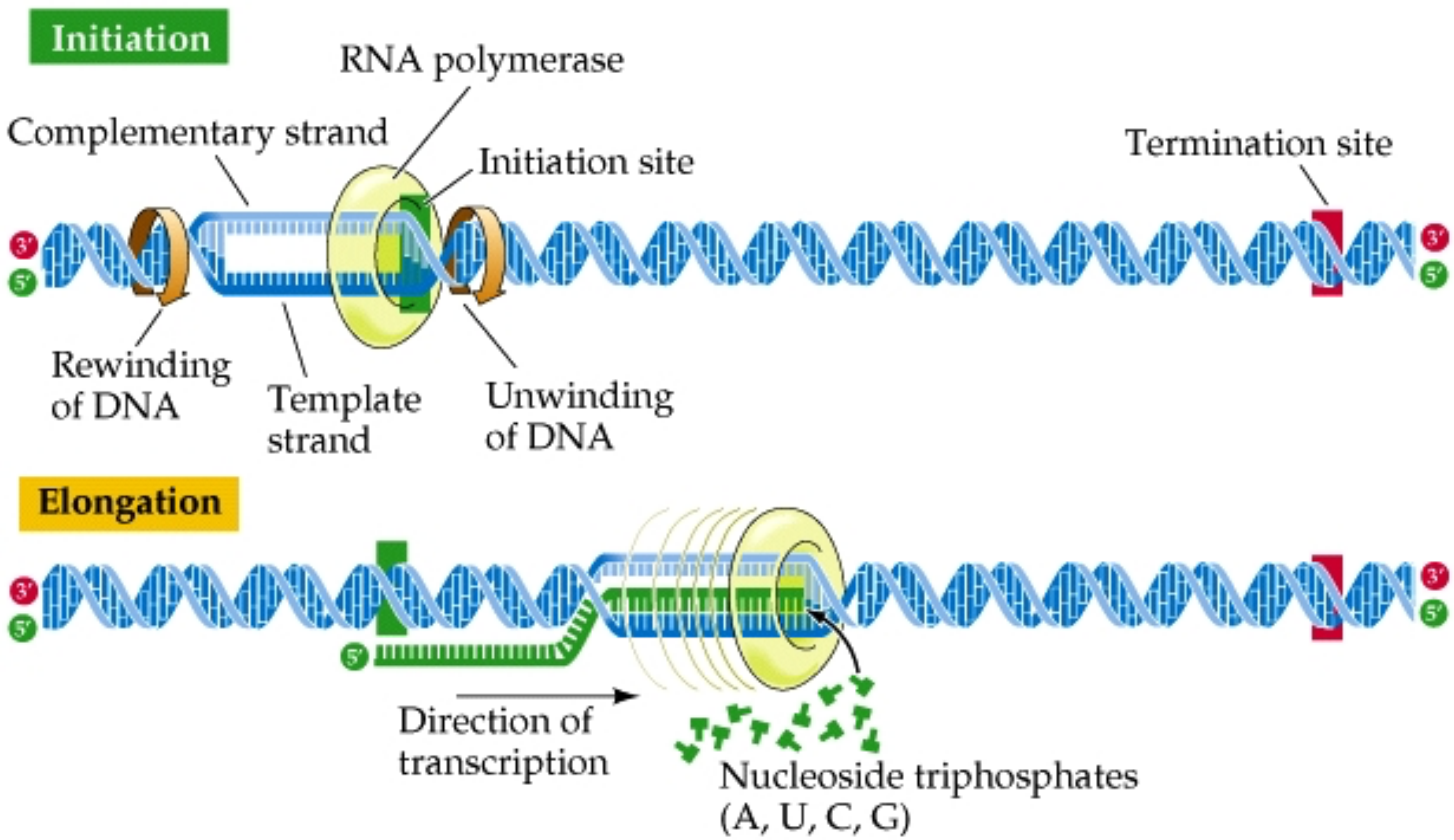


Adapted from Kelvinsong, Diagram of microRNA.

Flavonols may slow your cognitive decline

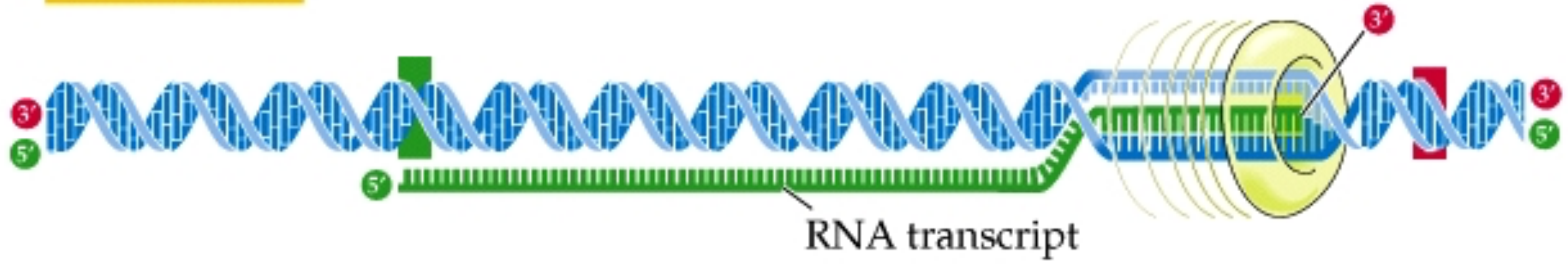
A study shows that eating more flavonoids — the antioxidants found in many vegetables, fruits, tea and wine — may slow your rate of memory loss

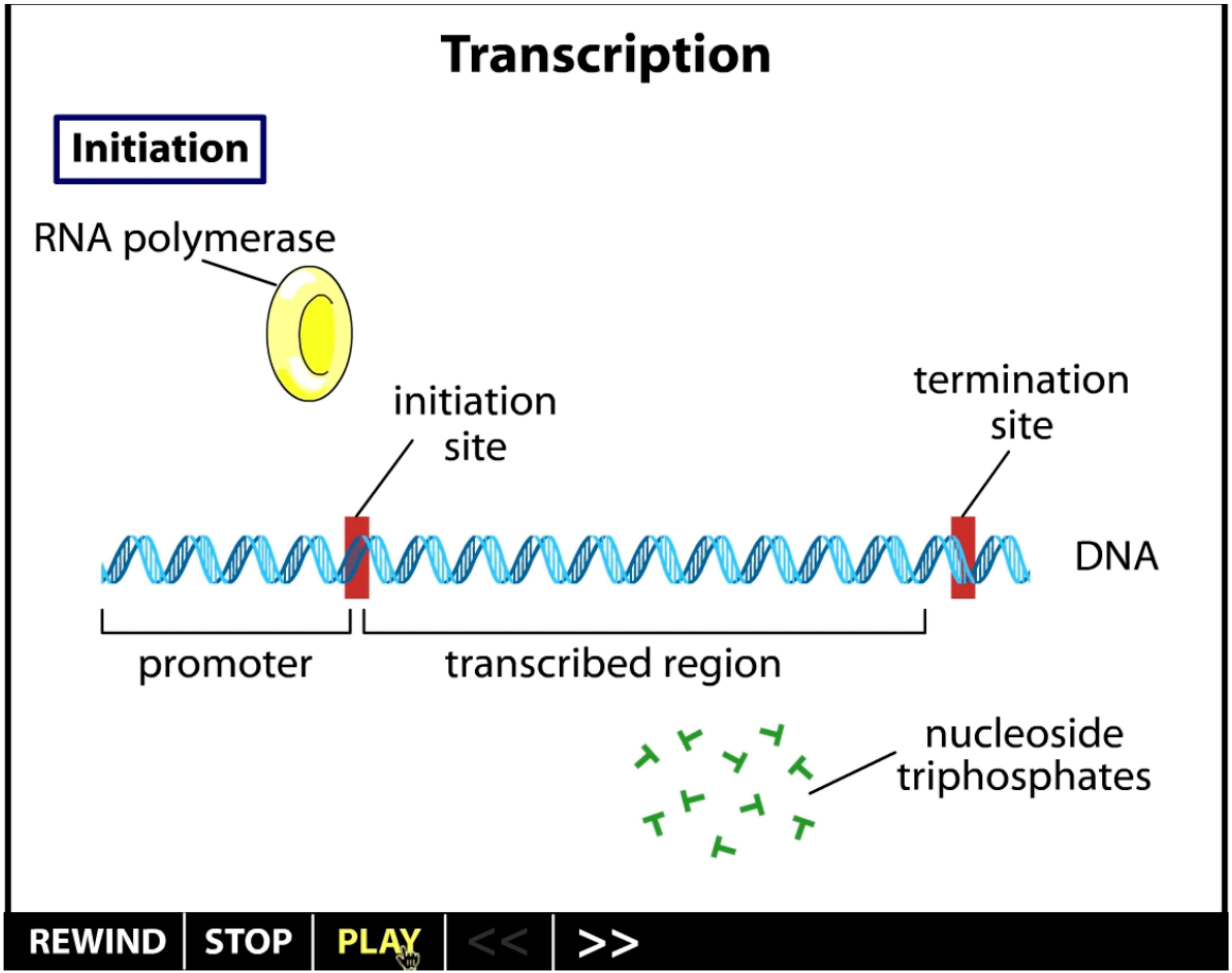


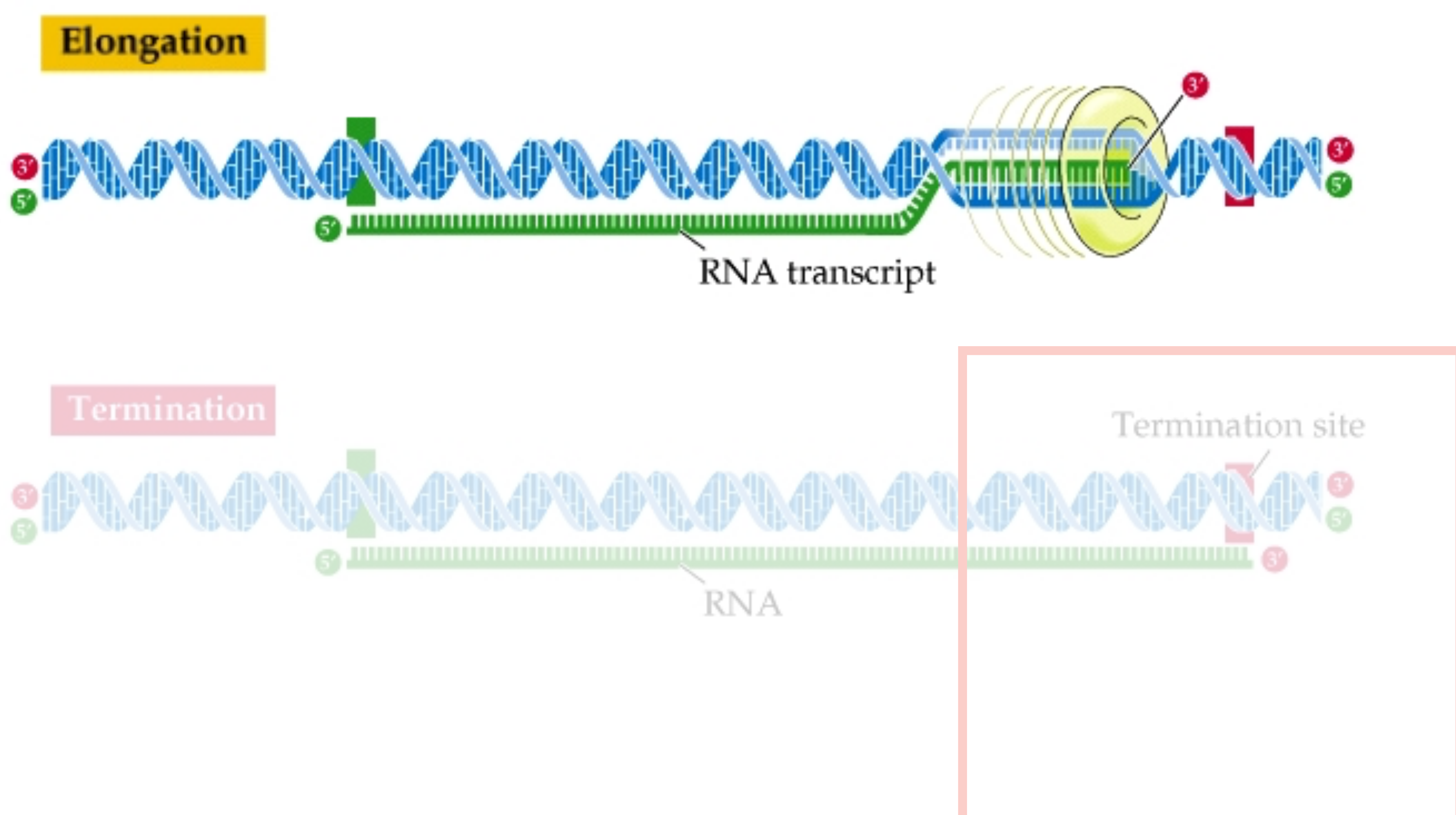


Initiation
RNA polymerase
Complementary strand
Initiation site
Termination site
3′
5′
Rewinding of DNA
Template strand
Unwinding of DNA
Elongation
5′
Direction of transcription
Nucleoside triphosphates (A, U, C, G)

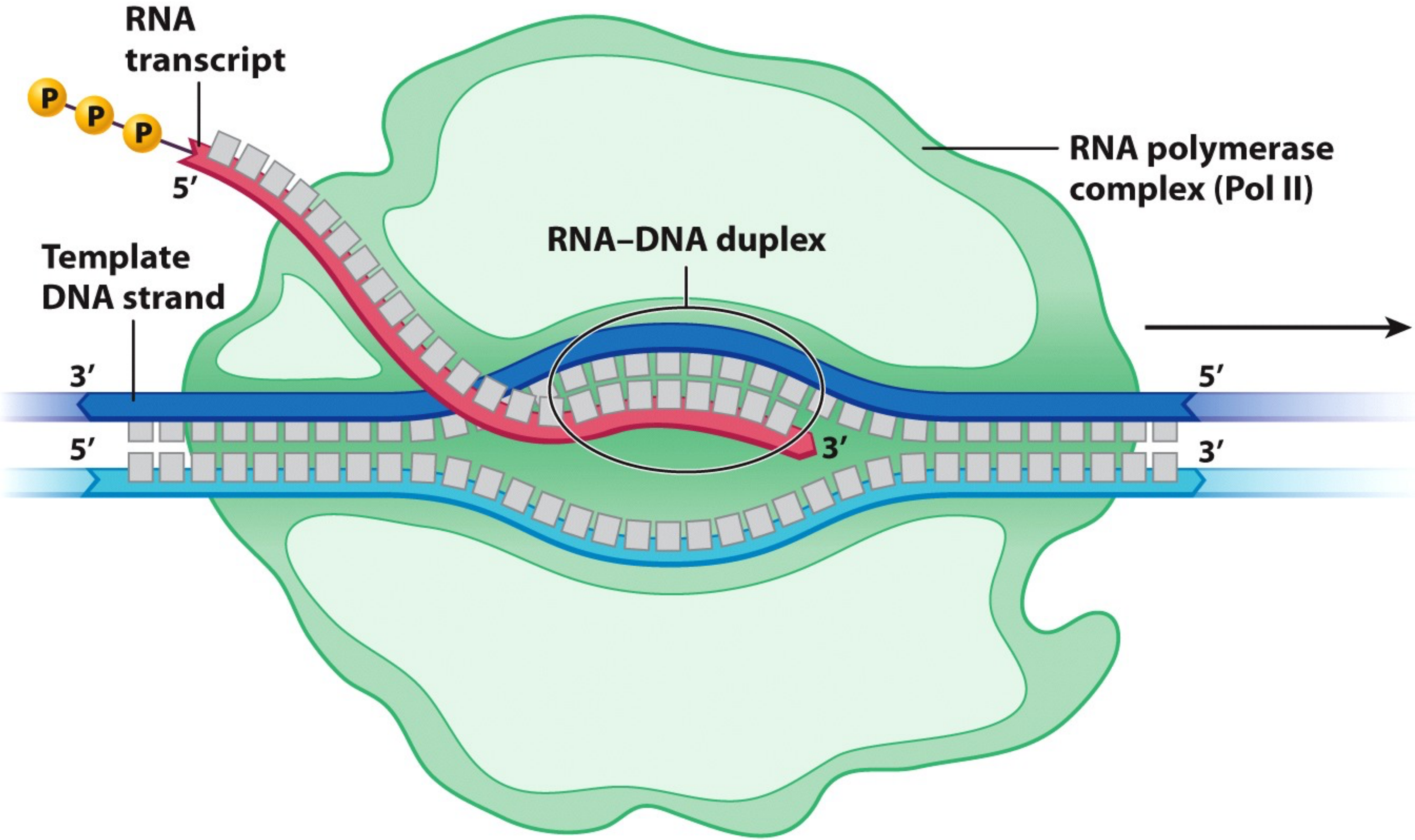
Elongation



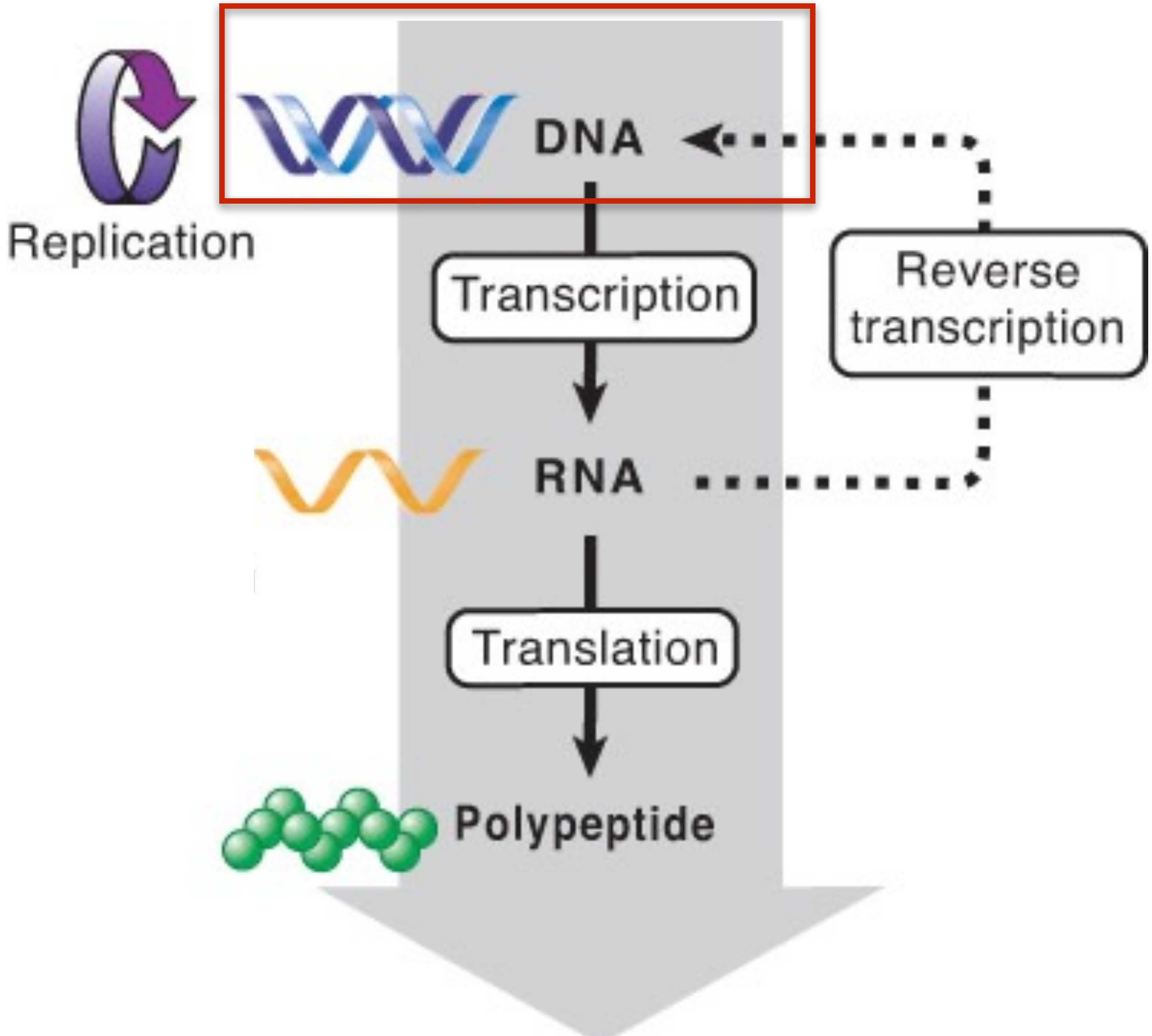

Transcription
Initiation
RNA polymerase
initiation site
termination site
DNA
promoter
transcribed region
nucleoside triphosphates
REWIND
STOP
PLAY
<<
>>



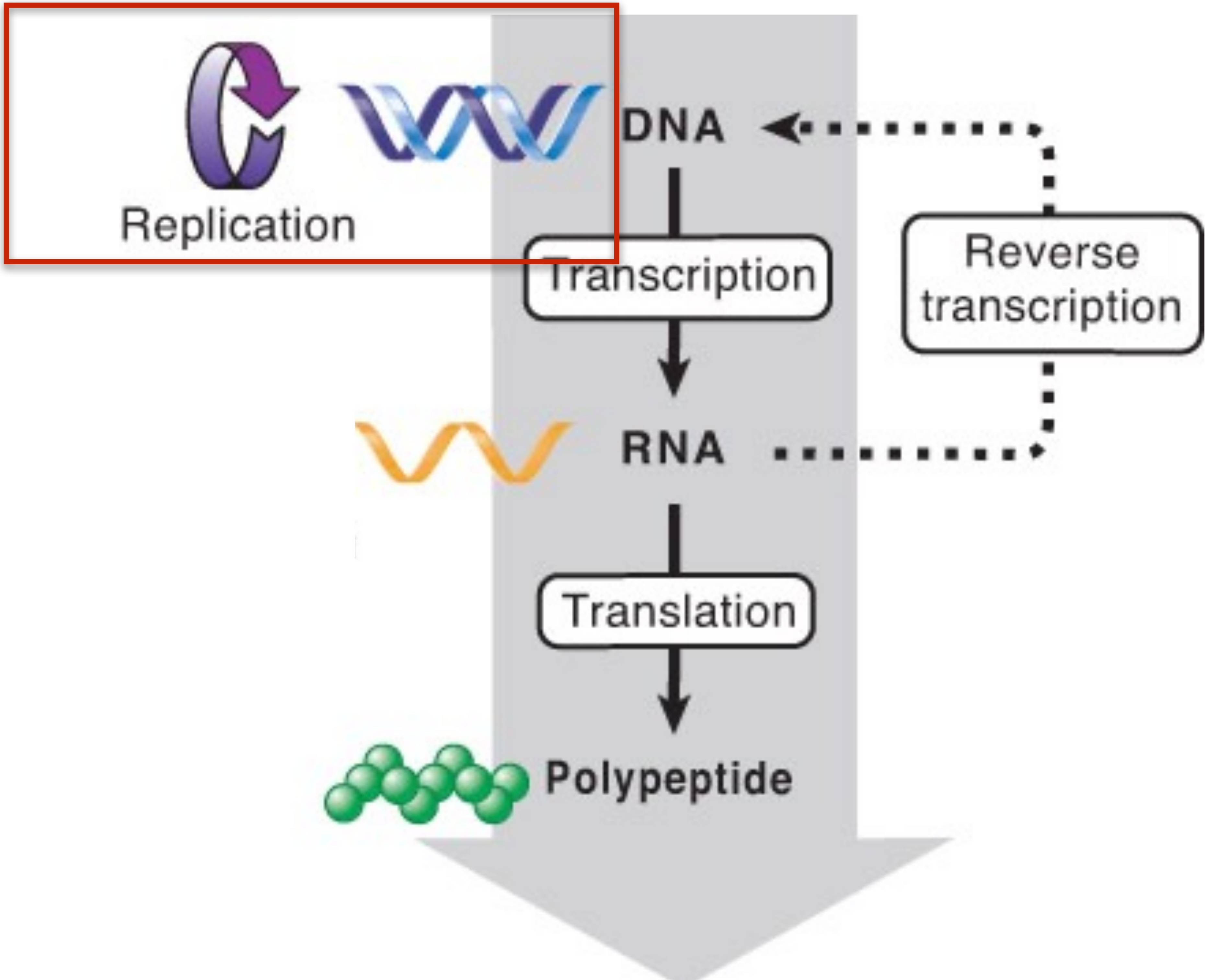
Elongation
3′
3′
5′
3′
5′
5′
RNA transcript
Termination
Termination site
3′
5′
3′
5′
5′
3′
RNA



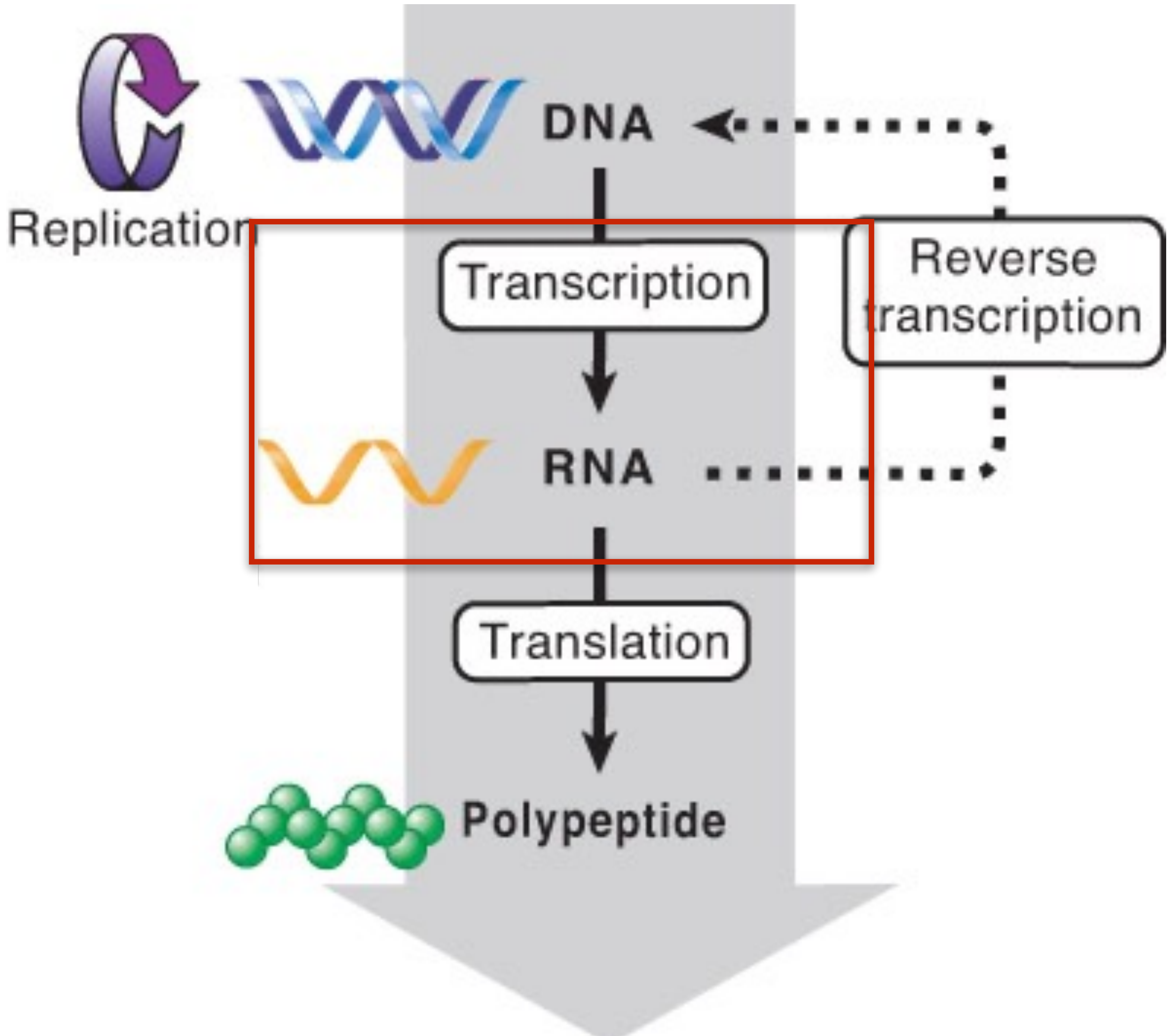
RNA transcript
P
P
P
5′
RNA polymerase complex (Pol II)
RNA–DNA duplex
Template DNA strand
3′
5′
5′
3′
3′



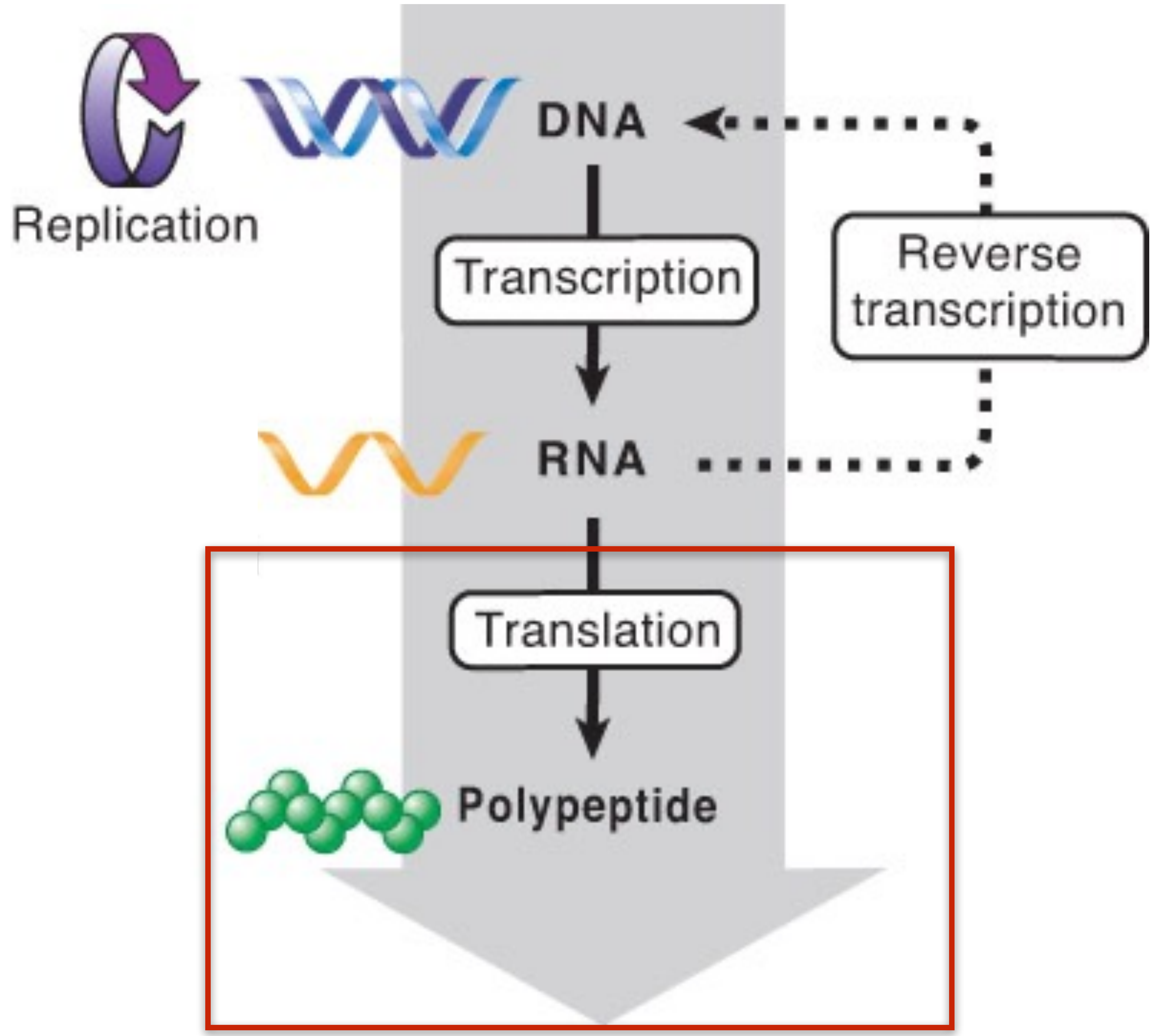
Information in nucleic acid can be perpetuated or transferred, but the transfer of information into a polypeptide is irreversible.



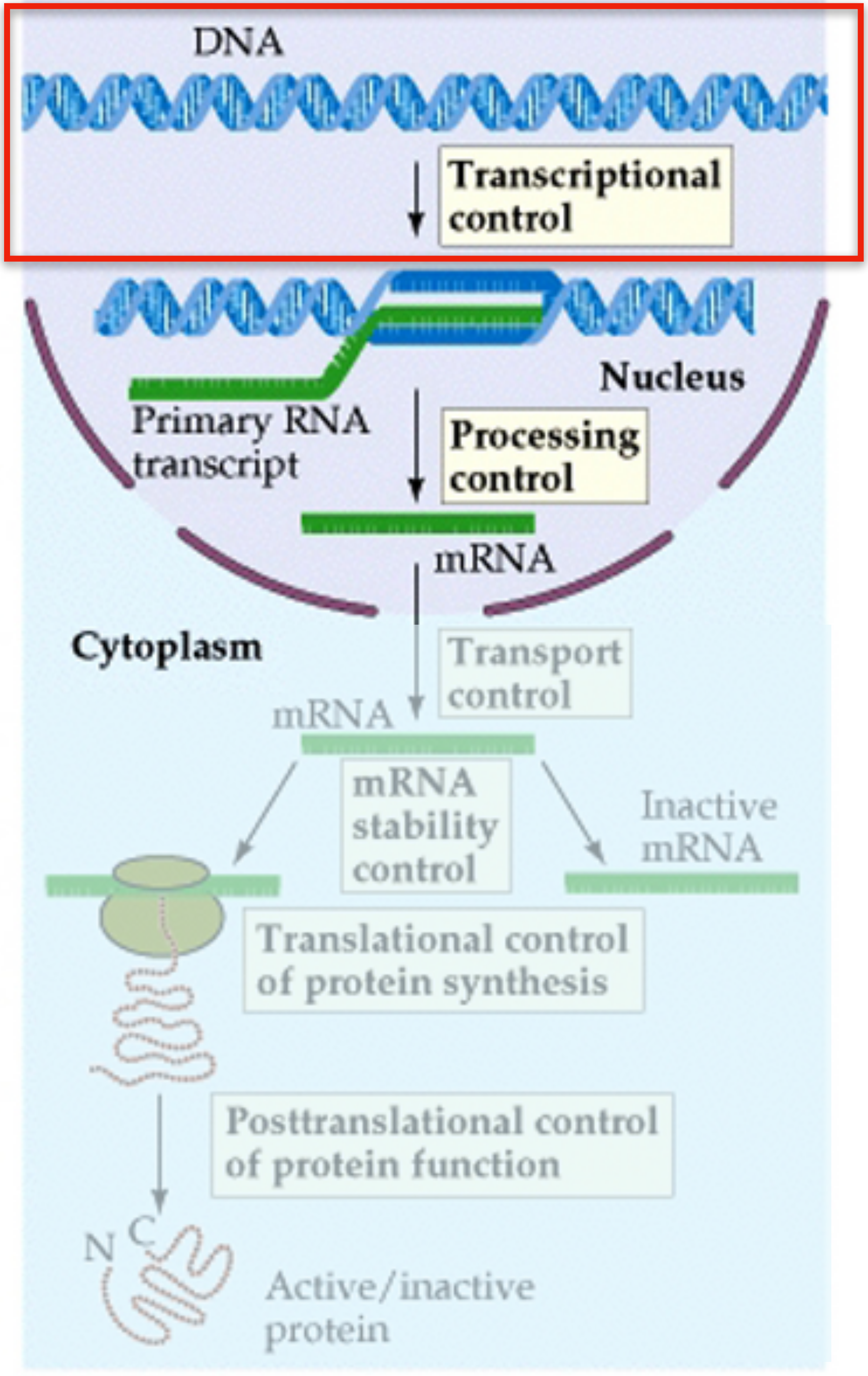
Information in nucleic acid can be perpetuated or transferred, but the transfer of information into a polypeptide is irreversible.

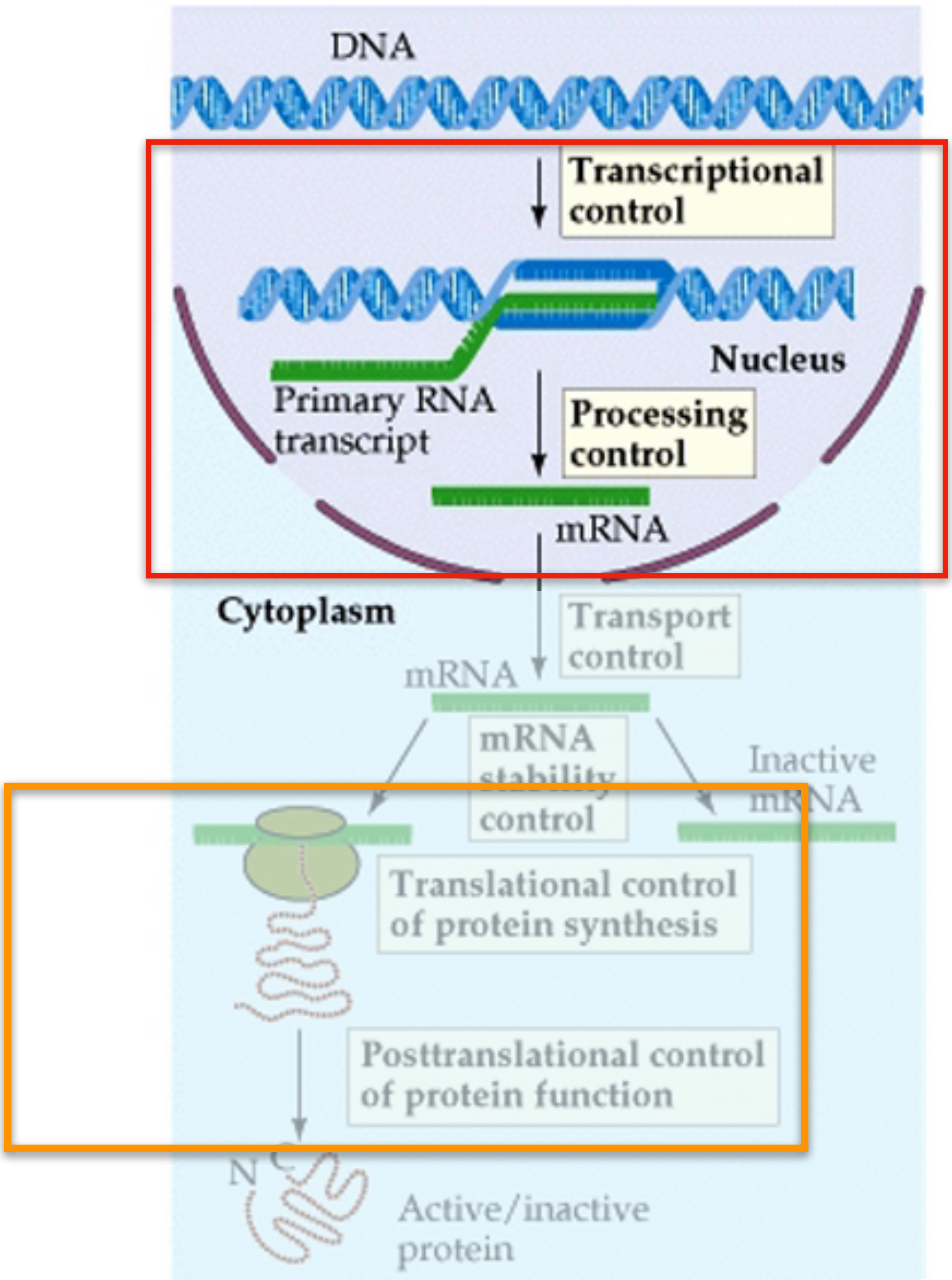


Information in nucleic acid can be perpetuated or transferred, but the transfer of information into a polypeptide is irreversible.

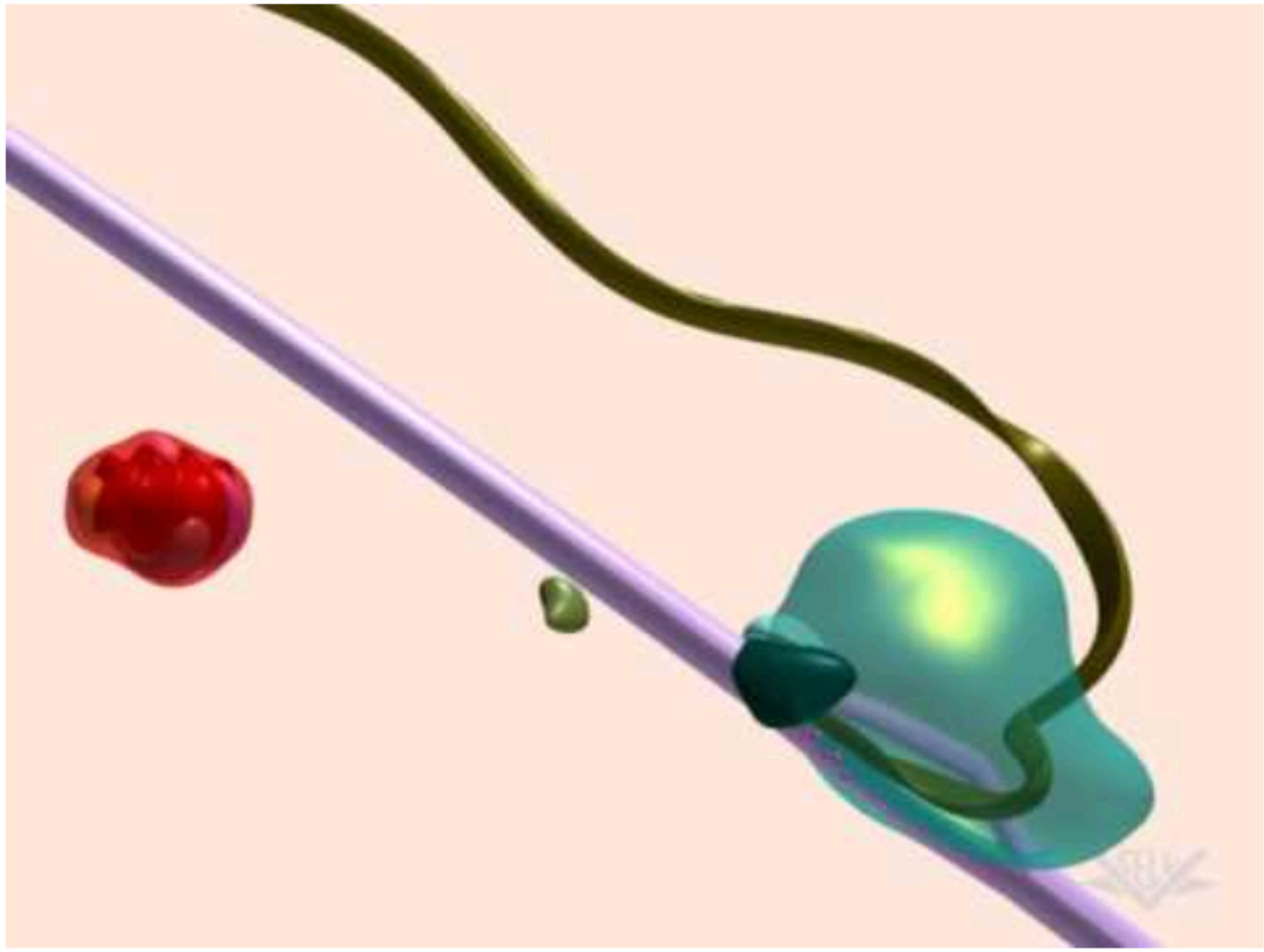


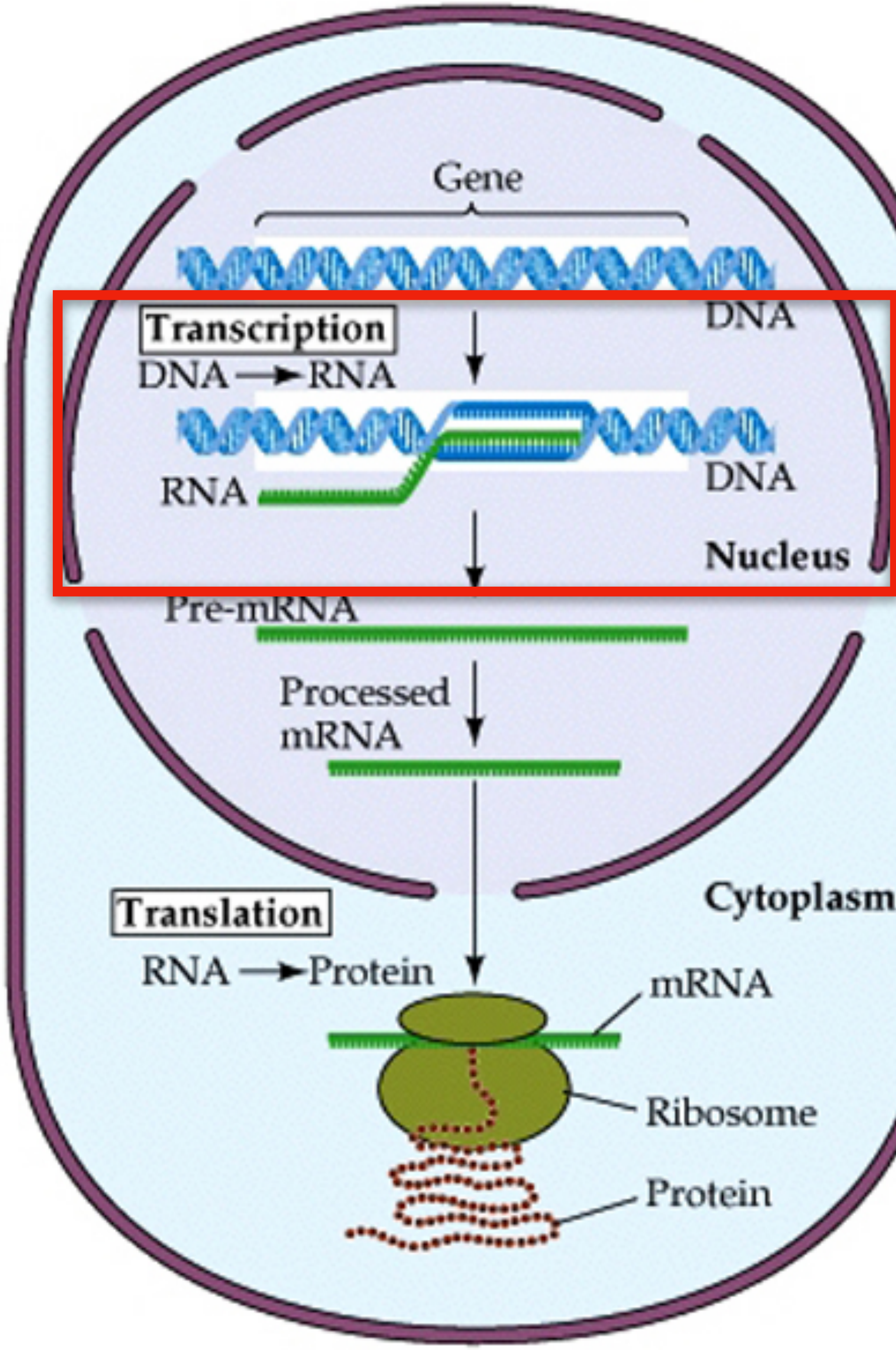
Information in nucleic acid can be perpetuated or transferred, but the transfer of information into a polypeptide is irreversible.

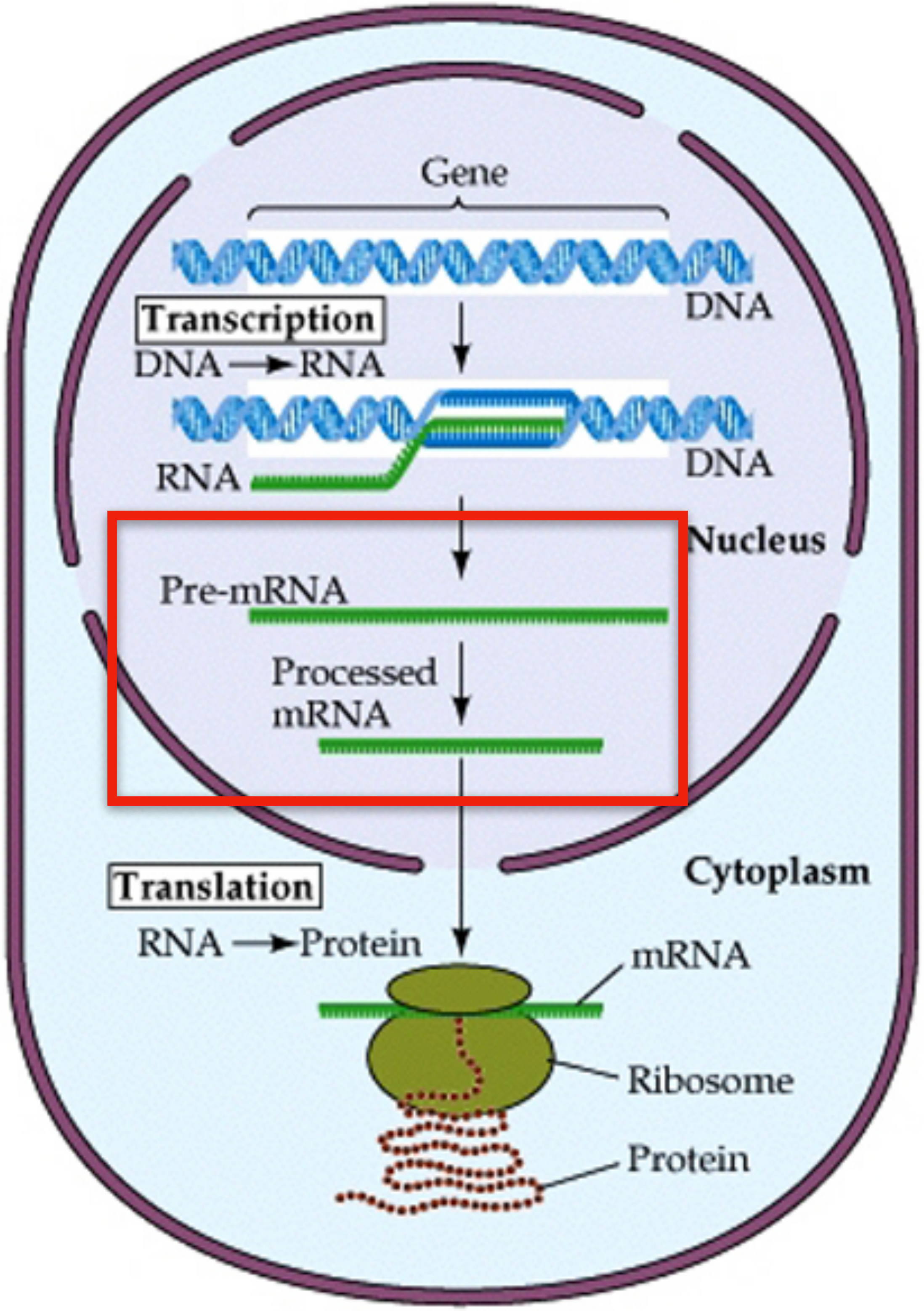

DNA
Transcriptional control
Nucleus
Primary RNA transcript
Processing control
mRNA
Cytoplasm
Transport control
mRNA
mRNA stability control
Inactive mRNA
Translational control of protein synthesis
Posttranslational control of protein function
N
C
Active/inactive protein



DNA
Transcriptional control
Nucleus
Primary RNA transcript
Processing control
mRNA
Cytoplasm
Transport control
mRNA
mRNA stability control
Inactive mRNA
Translational control of protein synthesis
Posttranslational control of protein function
N
C
Active/inactive protein




Gene
DNA
Transcription
DNA → RNA
RNA
DNA
Nucleus
Pre-mRNA
Processed
mRNA
Cytoplasm
Translation
RNA → Protein
mRNA
Ribosome
Protein


Gene
DNA
Transcription
DNA → RNA
RNA
DNA
Nucleus
Pre-mRNA
Processed
mRNA
Cytoplasm
Translation
RNA → Protein
mRNA
Ribosome
Protein

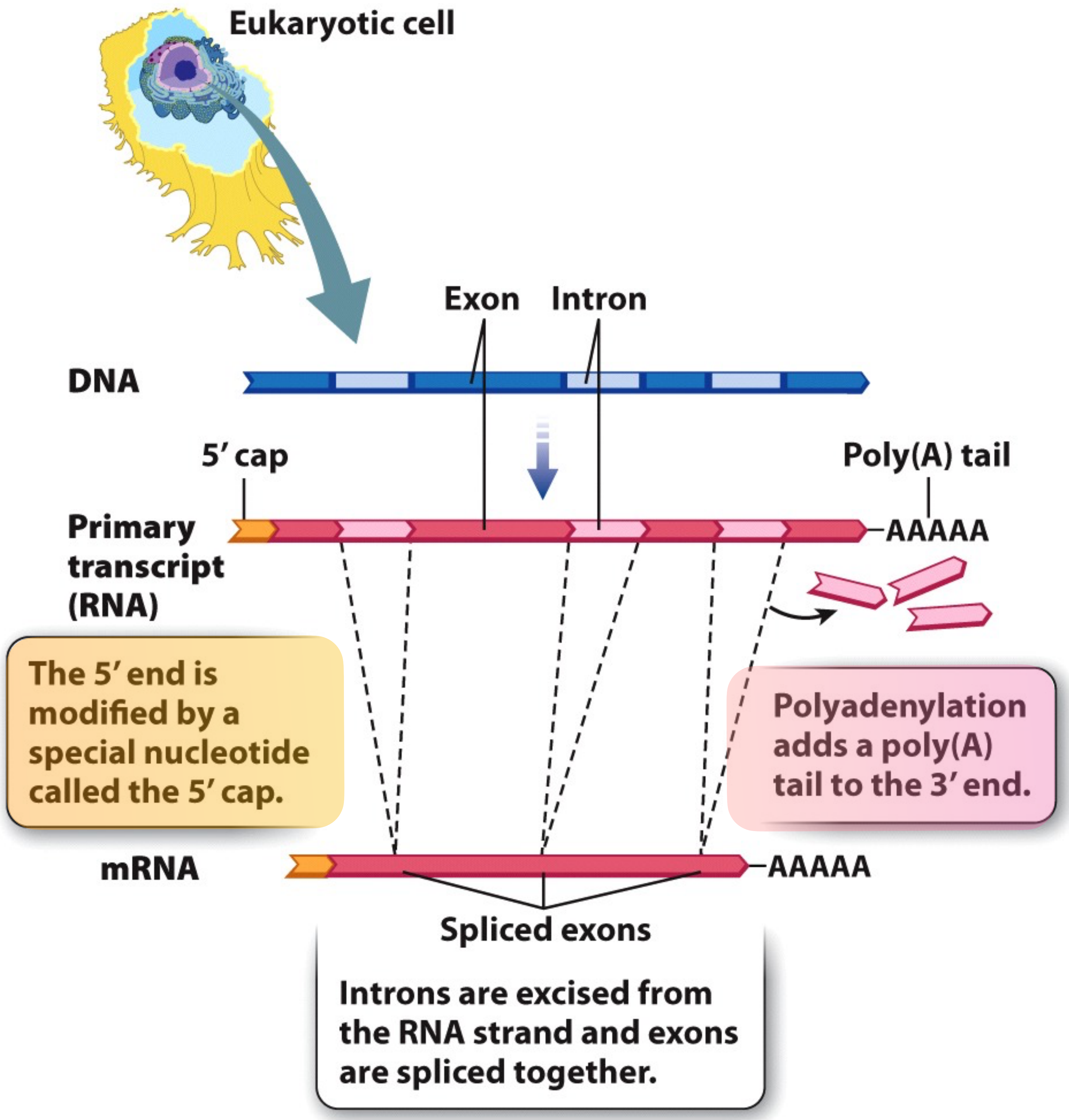
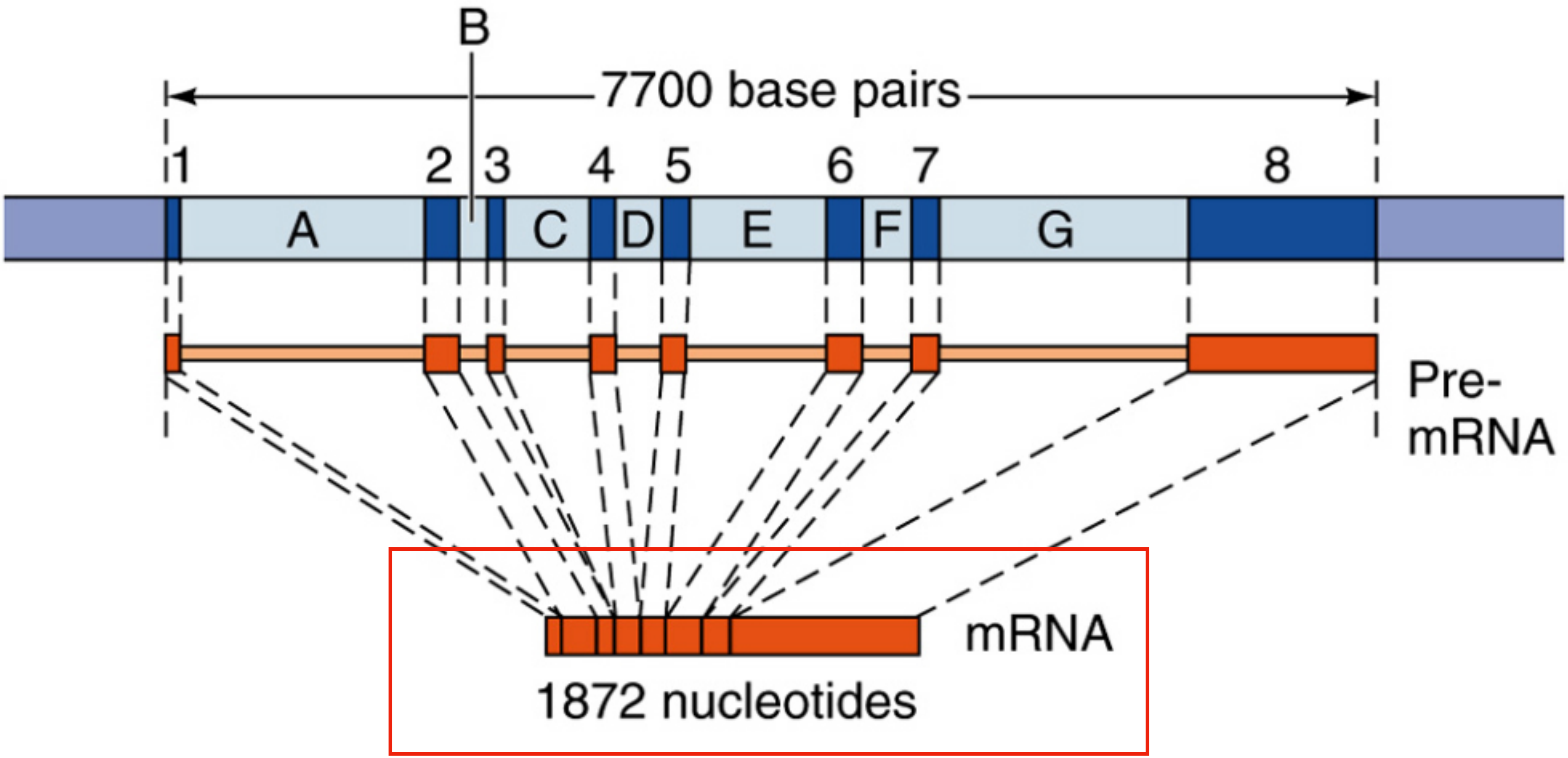


Figure 3.22
Biology: How Life Works


B
7700 base pairs
1
2
3
4
5
6
7
8
A
C
D
E
F
G
Pre-
mRNA
mRNA
1872 nucleotides

1 error in 1x 10^9 (1 in 1,000,000,000) bases replicated

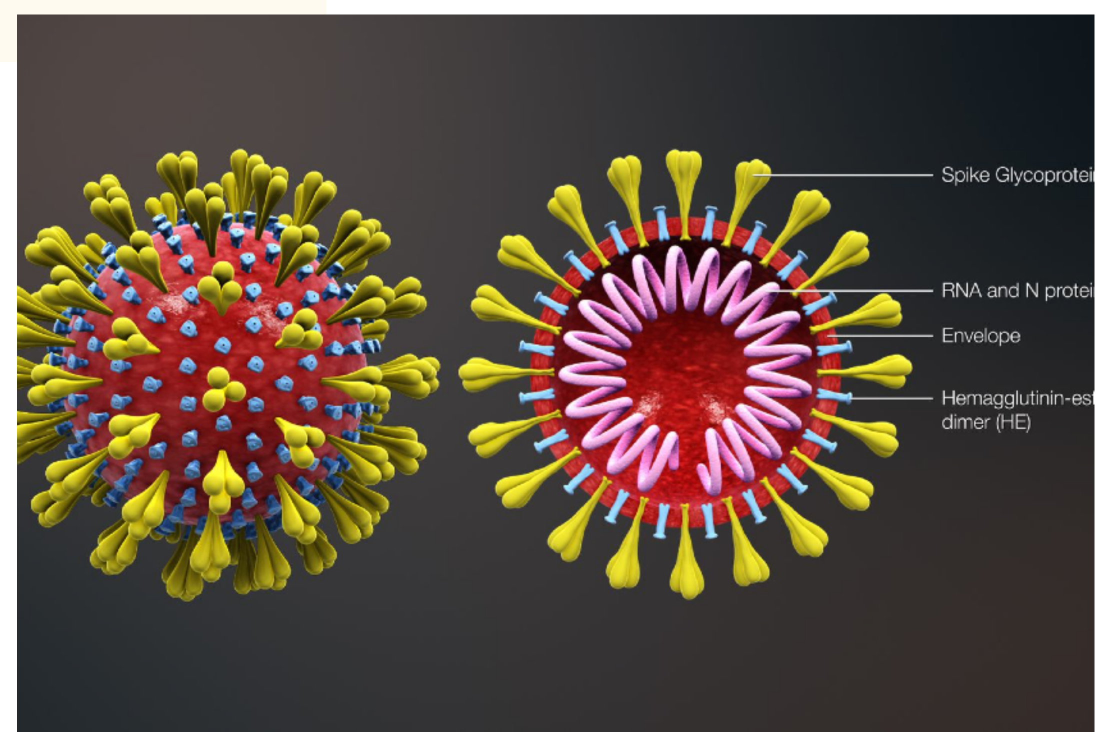
1 error in 1x 10^4 (1 in 10,000) bases replicated

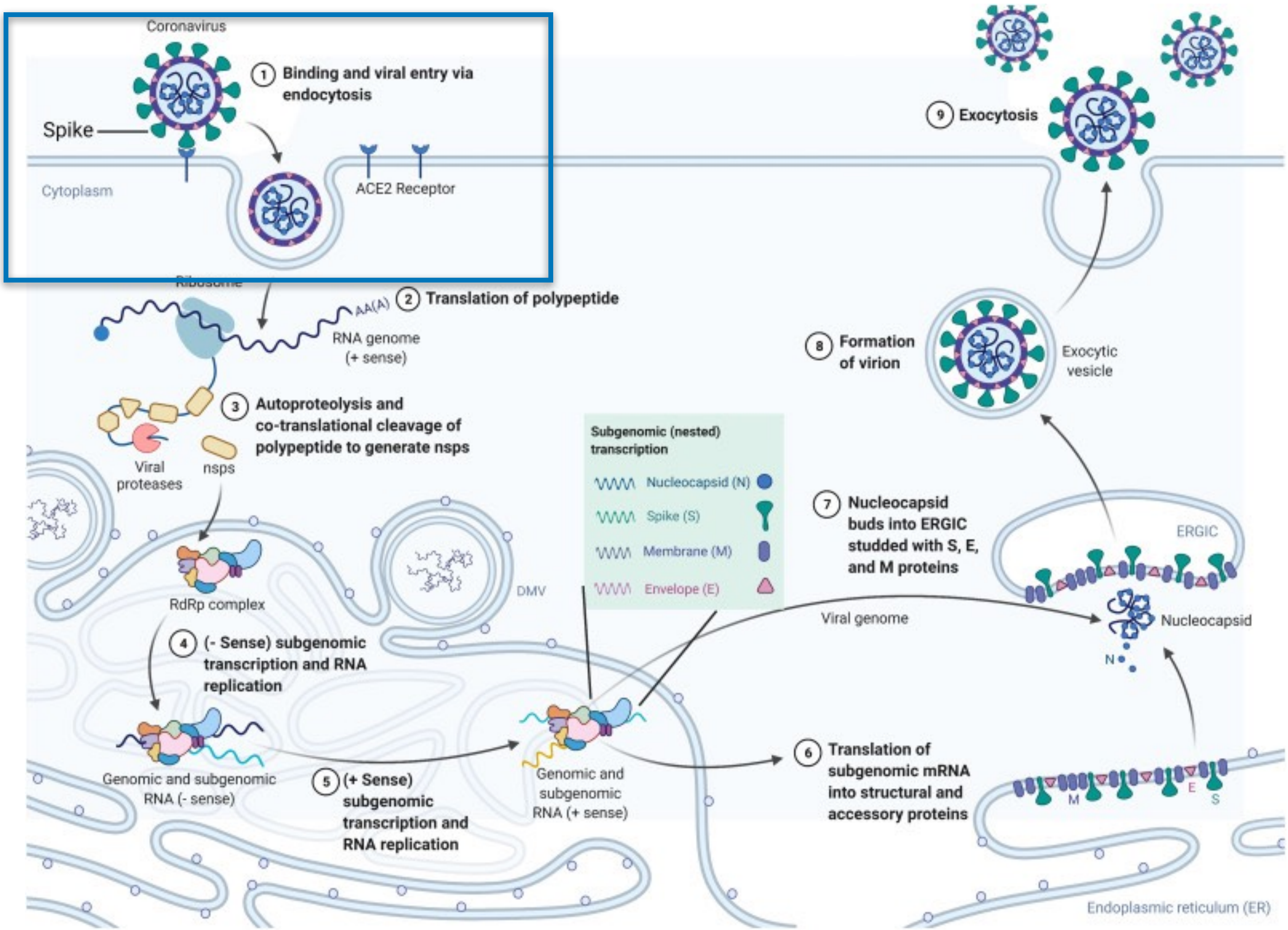
e.g HIV

e.g SarsCoV-2

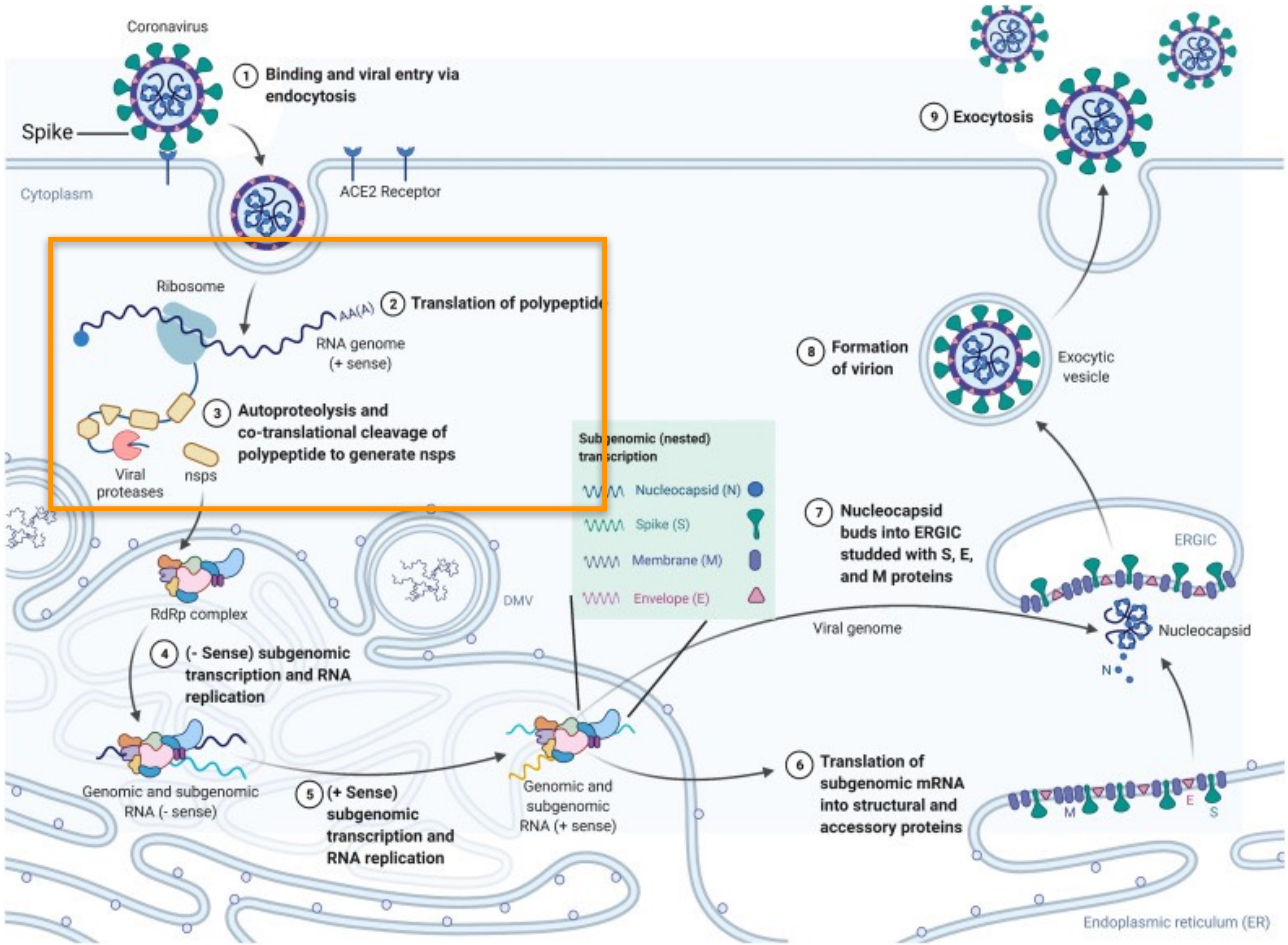
Fig. 1

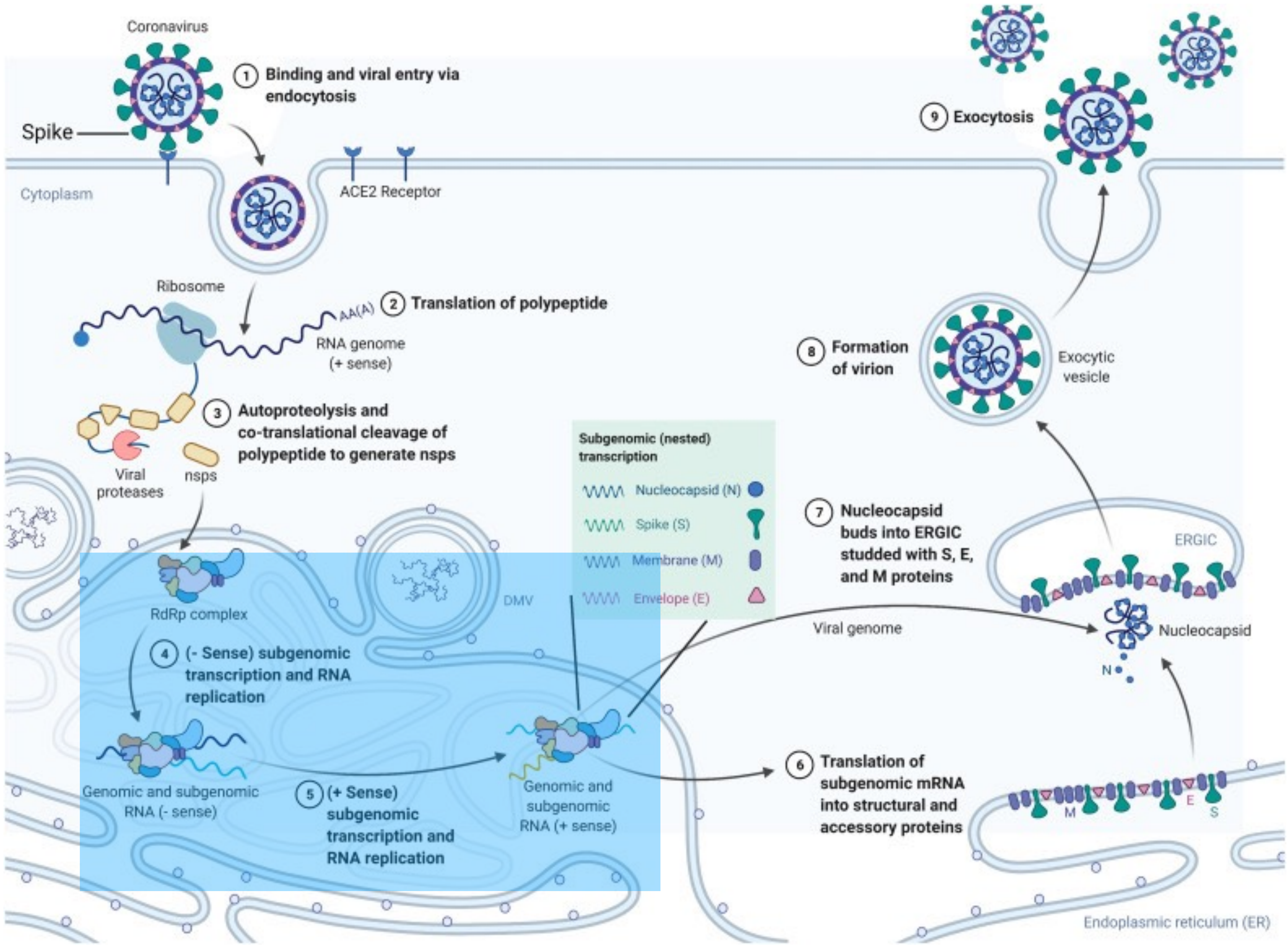
Genomic organization of representative α, β, and γ CoVs. An illustration of the MHV genome is depicted at the *top*. The expanded regions below show the structural and accessory proteins in the 3′ regions of the HCoV-229E, MHV, SARS-CoV, MERS-CoV and IBV. Size of the genome and individual genes are approximated using the legend at the *top* of the diagram but are not drawn to scale. *HCoV-229E* human coronavirus 229E, *MHV* mouse hepatitis virus, *SARS-CoV* severe acute respiratory syndrome coronavirus, *MERS-CoV* Middle East respiratory syndrome coronavirus, *IBV* infectious bronchitis virus



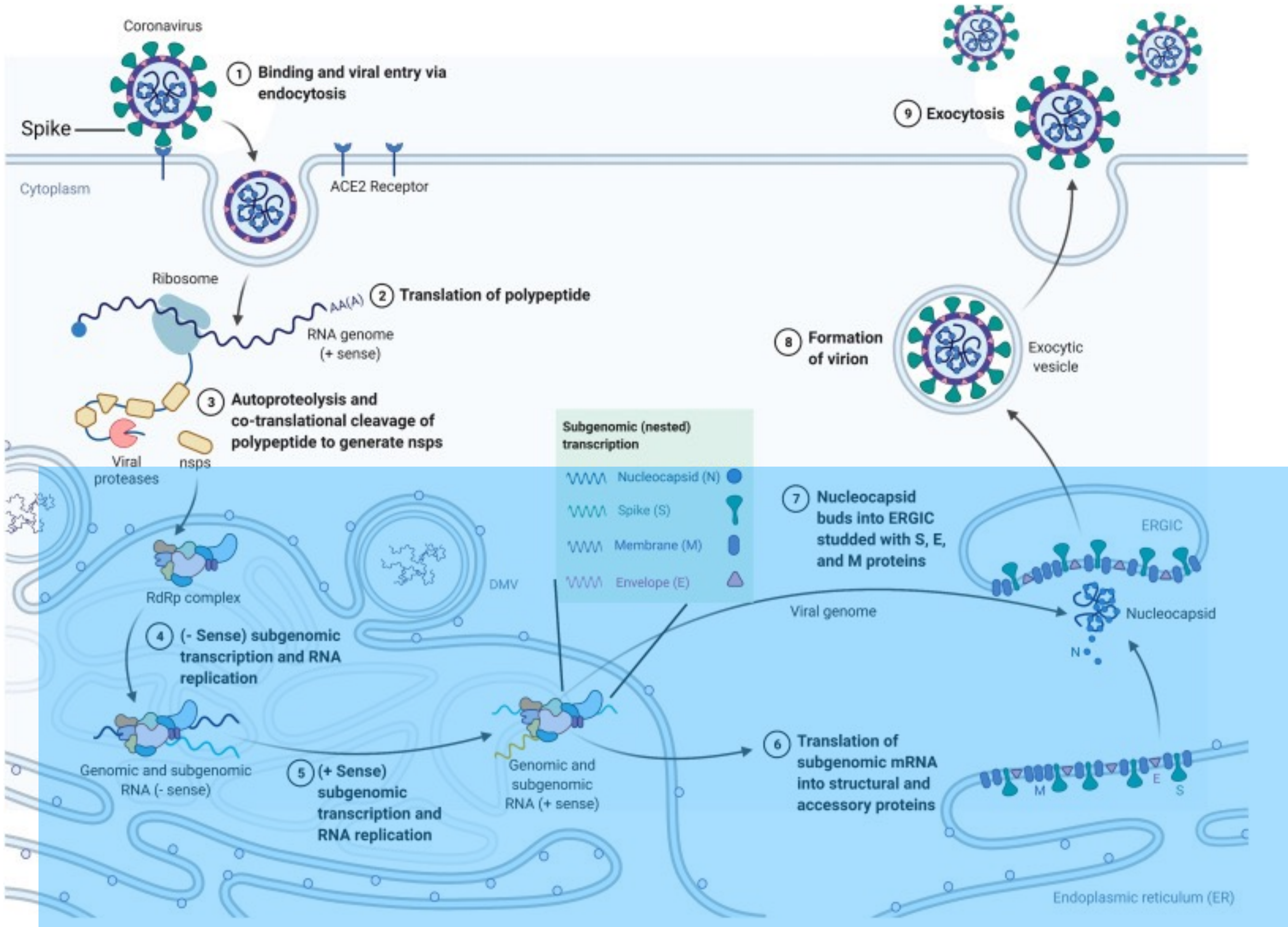


Coronavirus
1 Binding and viral entry via endocytosis
Spike
Cytoplasm
ACE2 Receptor
2 Translation of polypeptide
AA(A)
RNA genome (+ sense)
3 Autoproteolysis and co-translational cleavage of polypeptide to generate nsps
Viral proteases
nsps
RdRp complex
DMV
4 (- Sense) subgenomic transcription and RNA replication
Genomic and subgenomic RNA (- sense)
5 (+ Sense) subgenomic transcription and RNA replication
Genomic and subgenomic RNA (+ sense)
Subgenomic (nested) transcription
Nucleocapsid (N)
Spike (S)
Membrane (M)
Envelope (E)
6 Translation of subgenomic mRNA into structural and accessory proteins
7 Nucleocapsid buds into ERGIC studded with S, E, and M proteins
ERGIC
Viral genome
Nucleocapsid
N
M
E
S
8 Formation of virion
Exocytic vesicle
9 Exocytosis
Endoplasmic reticulum (ER)

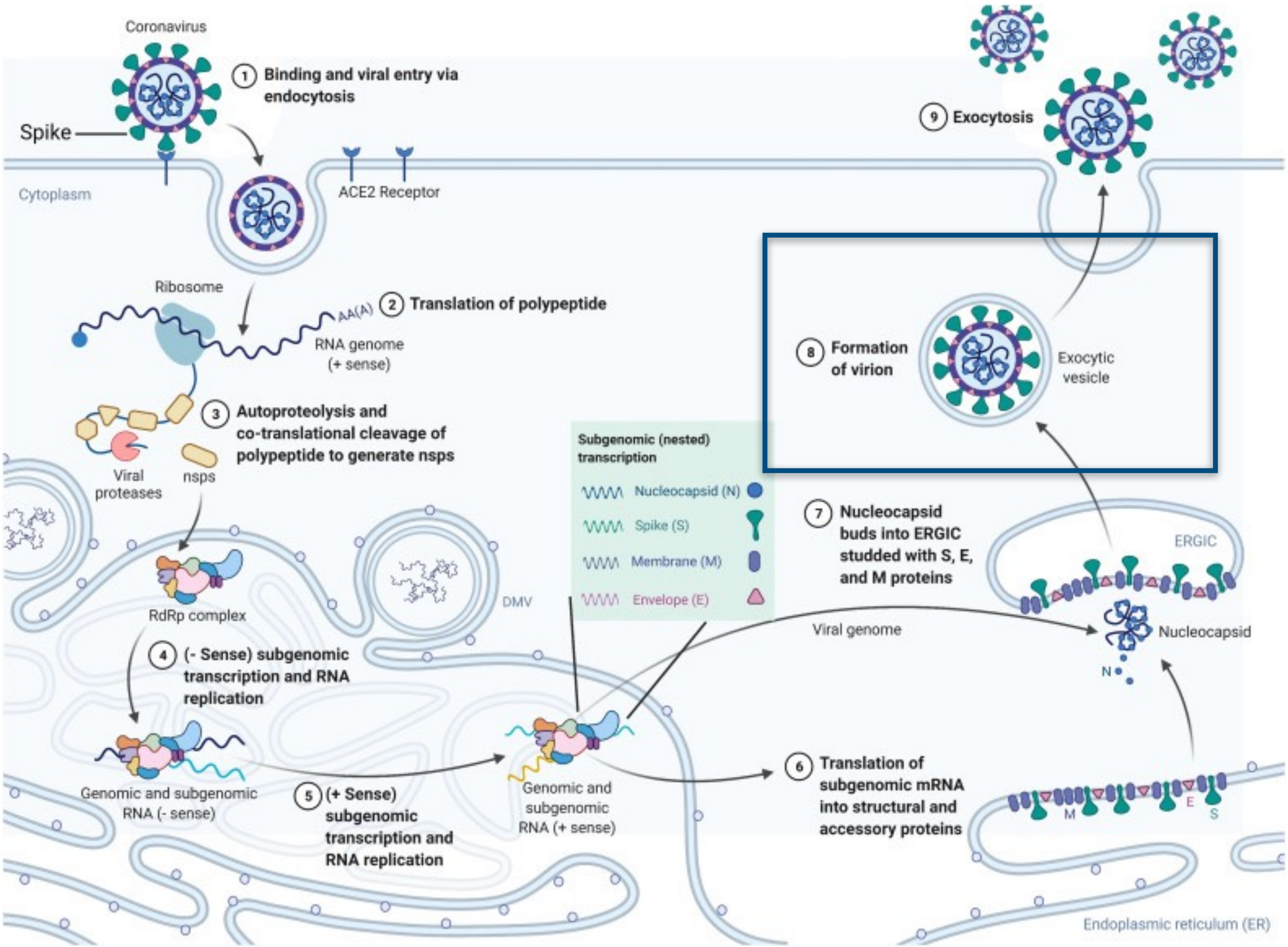

Coronavirus
Spike
1 Binding and viral entry via endocytosis
Cytoplasm
ACE2 Receptor
Ribosome
2 Translation of polypeptide
AA(A)
RNA genome (+ sense)
3 Autoproteolysis and co-translational cleavage of polypeptide to generate nsps
Viral proteases
nsps
RdRp complex
DMV
4 (- Sense) subgenomic transcription and RNA replication
Genomic and subgenomic RNA (- sense)
5 (+ Sense) subgenomic transcription and RNA replication
Genomic and subgenomic RNA (+ sense)
Subgenomic (nested) transcription
Nucleocapsid (N)
Spike (S)
Membrane (M)
Envelope (E)
Viral genome
6 Translation of subgenomic mRNA into structural and accessory proteins
7 Nucleocapsid buds into ERGIC studded with S, E, and M proteins
ERGIC
Nucleocapsid
N
M
E
S
8 Formation of virion
Exocytic vesicle
9 Exocytosis
Endoplasmic reticulum (ER)



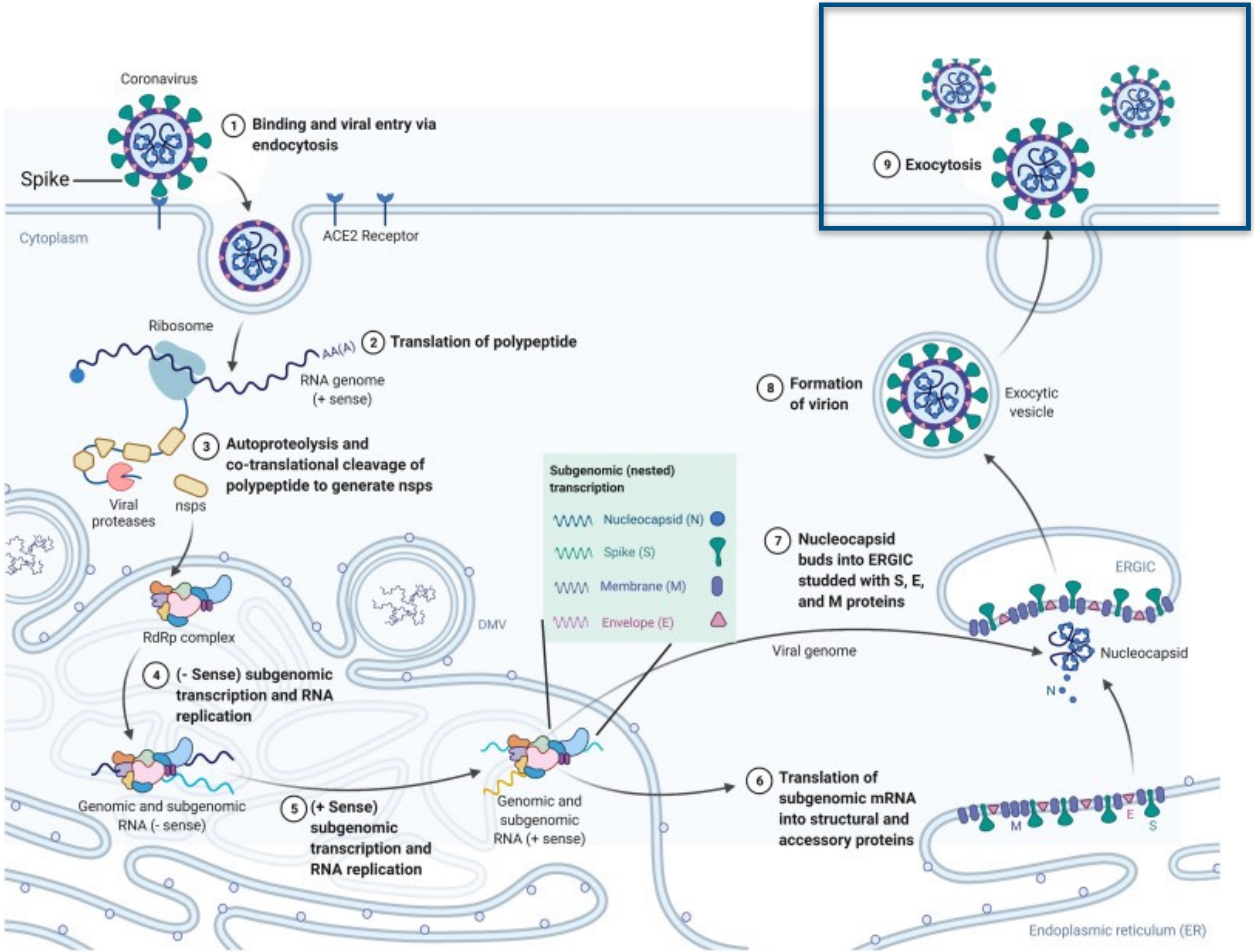
Coronavirus
Spike
1 Binding and viral entry via endocytosis
ACE2 Receptor
Cytoplasm
Ribosome
2 Translation of polypeptide
AA(A)
RNA genome (+ sense)
3 Autoproteolysis and co-translational cleavage of polypeptide to generate nsps
Viral proteases
nsps
RdRp complex
DMV
4 (- Sense) subgenomic transcription and RNA replication
Genomic and subgenomic RNA (- sense)
5 (+ Sense) subgenomic transcription and RNA replication
Genomic and subgenomic RNA (+ sense)
Subgenomic (nested) transcription
Nucleocapsid (N)
Spike (S)
Membrane (M)
Envelope (E)
Viral genome
6 Translation of subgenomic mRNA into structural and accessory proteins
7 Nucleocapsid buds into ERGIC studded with S, E, and M proteins
ERGIC
Nucleocapsid
N
M
E
S
8 Formation of virion
Exocytic vesicle
9 Exocytosis
Endoplasmic reticulum (ER)



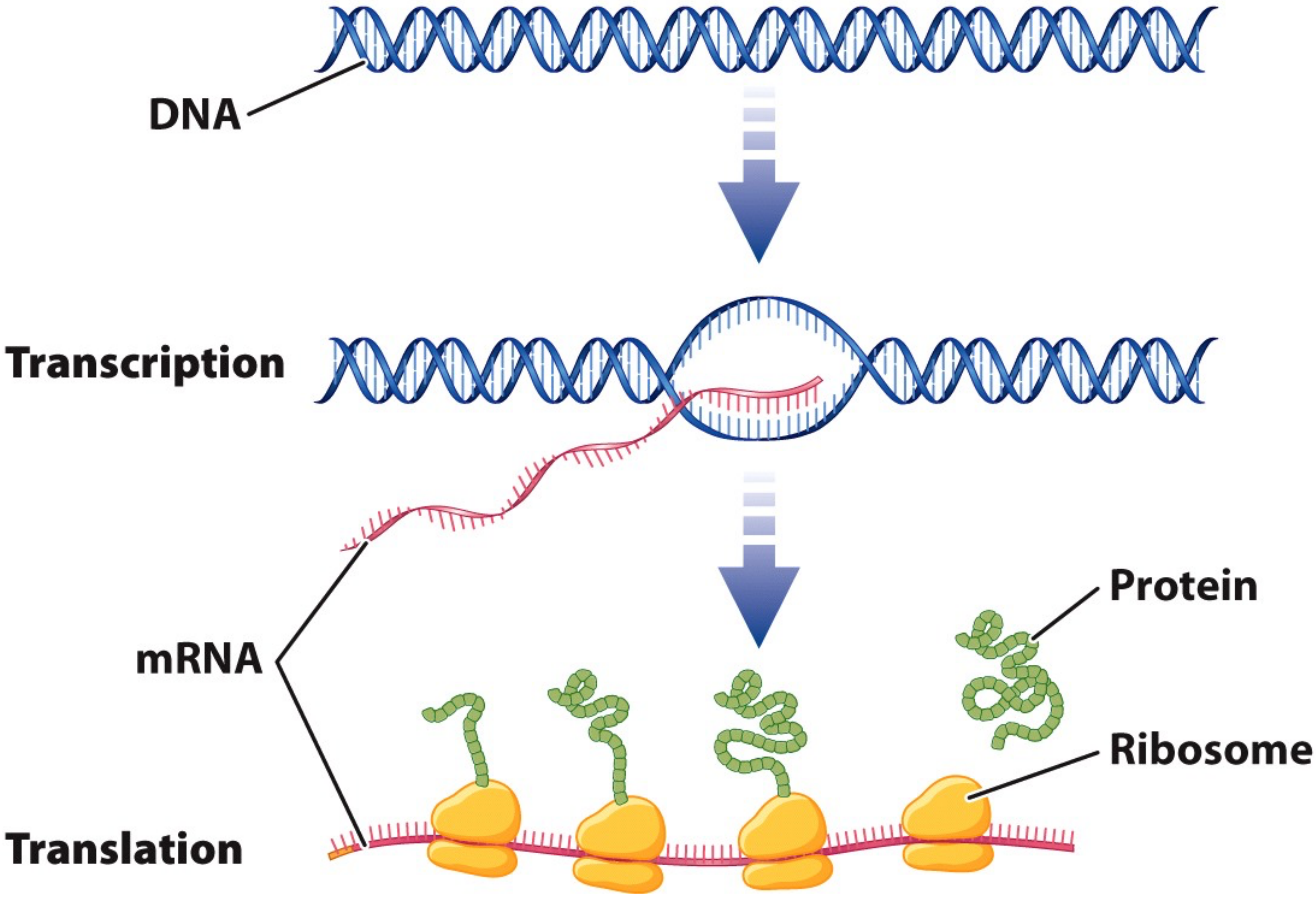
Coronavirus
Spike
1 Binding and viral entry via endocytosis
Cytoplasm
ACE2 Receptor
Ribosome
2 Translation of polypeptide
AA(A)
RNA genome (+ sense)
3 Autoproteolysis and co-translational cleavage of polypeptide to generate nsps
Viral proteases
nsps
RdRp complex
DMV
4 (- Sense) subgenomic transcription and RNA replication
Genomic and subgenomic RNA (- sense)
5 (+ Sense) subgenomic transcription and RNA replication
Genomic and subgenomic RNA (+ sense)
Subgenomic (nested) transcription
Nucleocapsid (N)
Spike (S)
Membrane (M)
Envelope (E)
Viral genome
6 Translation of subgenomic mRNA into structural and accessory proteins
M
E
S
7 Nucleocapsid buds into ERGIC studded with S, E, and M proteins
ERGIC
Nucleocapsid
N
8 Formation of virion
Exocytic vesicle
9 Exocytosis
Endoplasmic reticulum (ER)



Coronavirus
Spike
1 Binding and viral entry via endocytosis
Cytoplasm
ACE2 Receptor
Ribosome
2 Translation of polypeptide
AA(A)
RNA genome (+ sense)
3 Autoproteolysis and co-translational cleavage of polypeptide to generate nsps
Viral proteases
nsps
RdRp complex
DMV
4 (- Sense) subgenomic transcription and RNA replication
Genomic and subgenomic RNA (- sense)
5 (+ Sense) subgenomic transcription and RNA replication
Genomic and subgenomic RNA (+ sense)
Subgenomic (nested) transcription
Nucleocapsid (N)
Spike (S)
Membrane (M)
Envelope (E)
6 Translation of subgenomic mRNA into structural and accessory proteins
7 Nucleocapsid buds into ERGIC studded with S, E, and M proteins
ERGIC
Viral genome
Nucleocapsid
N
M
E
S
8 Formation of virion
Exocytic vesicle
9 Exocytosis
Endoplasmic reticulum (ER)



Coronavirus
Spike
1 Binding and viral entry via endocytosis
Cytoplasm
ACE2 Receptor
Ribosome
2 Translation of polypeptide
AA(A)
RNA genome (+ sense)
3 Autoproteolysis and co-translational cleavage of polypeptide to generate nsps
Viral proteases
nsps
RdRp complex
DMV
4 (- Sense) subgenomic transcription and RNA replication
Genomic and subgenomic RNA (- sense)
5 (+ Sense) subgenomic transcription and RNA replication
Genomic and subgenomic RNA (+ sense)
Subgenomic (nested) transcription
Nucleocapsid (N)
Spike (S)
Membrane (M)
Envelope (E)
Viral genome
6 Translation of subgenomic mRNA into structural and accessory proteins
M
E
S
7 Nucleocapsid buds into ERGIC studded with S, E, and M proteins
ERGIC
Nucleocapsid
N
8 Formation of virion
Exocytic vesicle
9 Exocytosis
Endoplasmic reticulum (ER)



Proteins provide structure and carry out many essential activities in a cell.

"Universal" Genetic Code

Second letter

First letter	U	C	A	G	Third letter
U	UUU UUC Phenyl-alanine UUA UUG Leucine	UCU UCC UCA UCG Serine	UAU UAC Tyrosine UAA Stop codon UAG Stop codon	UGU UGC Cysteine UGA Stop codon UGG Tryptophan	U C A G
C	CUU CUC CUA CUG Leucine	CCU CCC CCA CCG Proline	CAU CAC Histidine CAA CAG Glutamine	CGU CGC CGA CGG Arginine	U C A G
A	AUU AUC AUA Isoleucine AUG Methionine; start codon	ACU ACC ACA ACG Threonine	AAU AAC Asparagine AAA AAG Lysine	AGU AGC Serine AGA AGG Arginine	U C A G
G	GUU GUC GUA GUG Valine	GCU GCC GCA GCG Alanine	GAU GAC Aspartic acid GAA GAG Glutamic acid	GGU GGC GGA GGG Glycine	U C A G

Four possibilities for the first base, multiplied by four for the second, multiplied by four for the third yields… **64 possibilities**

“Universal” Genetic Code

First letter	Second letter: U	C	A	G	Third letter
U	UUU, UUC Phenyl-alanine; UUA, UUG Leucine	UCU, UCC, UCA, UCG Serine	UAU, UAC Tyrosine; UAA Stop codon; UAG Stop codon	UGU, UGC Cysteine; UGA Stop codon; UGG Tryptophan	U C A G
C	CUU, CUC, CUA, CUG Leucine	CCU, CCC, CCA, CCG Proline	CAU, CAC Histidine; CAA, CAG Glutamine	CGU, CGC, CGA, CGG Arginine	U C A G
A	AUU, AUC, AUA Isoleucine; AUG Methionine; start codon	ACU, ACC, ACA, ACG Threonine	AAU, AAC Asparagine; AAA, AAG Lysine	AGU, AGC Serine; AGA, AGG Arginine	U C A G
G	GUU, GUC, GUA, GUG Valine	GCU, GCC, GCA, GCG Alanine	GAU, GAC Aspartic acid; GAA, GAG Glutamic acid	GGU, GGC, GGA, GGG Glycine	U C A G

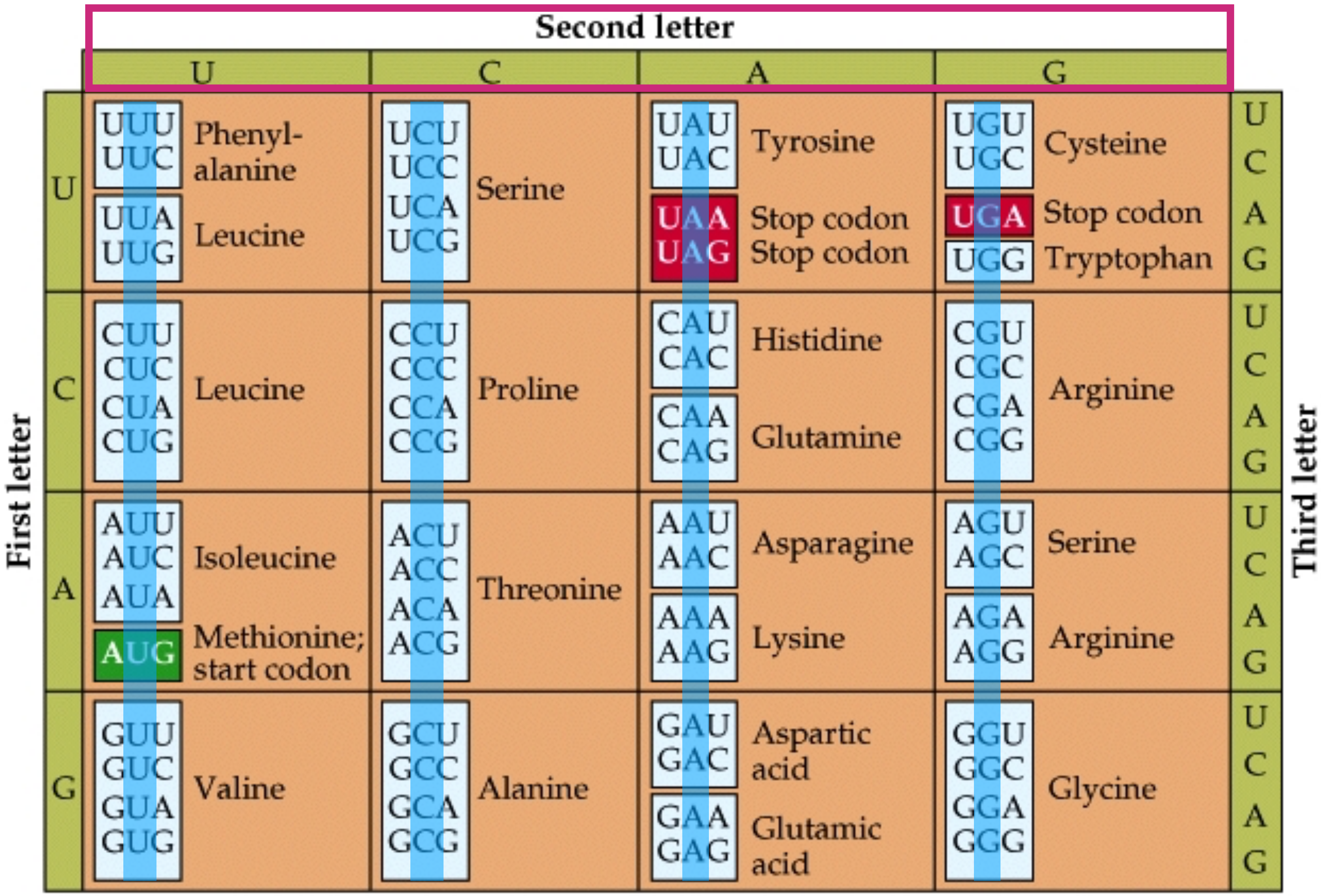
Four possibilities for the first base, multiplied by four for the second, multiplied by four for the third yields… **64 possibilities**

“Universal” Genetic Code

First letter	Second letter: U	Second letter: C	Second letter: A	Second letter: G	Third letter
U	UUU Phenyl-alanine	UCU Serine	UAU Tyrosine	UGU Cysteine	U
U	UUC Phenyl-alanine	UCC Serine	UAC Tyrosine	UGC Cysteine	C
U	UUA Leucine	UCA Serine	UAA Stop codon	UGA Stop codon	A
U	UUG Leucine	UCG Serine	UAG Stop codon	UGG Tryptophan	G
C	CUU Leucine	CCU Proline	CAU Histidine	CGU Arginine	U
C	CUC Leucine	CCC Proline	CAC Histidine	CGC Arginine	C
C	CUA Leucine	CCA Proline	CAA Glutamine	CGA Arginine	A
C	CUG Leucine	CCG Proline	CAG Glutamine	CGG Arginine	G
A	AUU Isoleucine	ACU Threonine	AAU Asparagine	AGU Serine	U
A	AUC Isoleucine	ACC Threonine	AAC Asparagine	AGC Serine	C
A	AUA Isoleucine	ACA Threonine	AAA Lysine	AGA Arginine	A
A	AUG Methionine; start codon	ACG Threonine	AAG Lysine	AGG Arginine	G
G	GUU Valine	GCU Alanine	GAU Aspartic acid	GGU Glycine	U
G	GUC Valine	GCC Alanine	GAC Aspartic acid	GGC Glycine	C
G	GUA Valine	GCA Alanine	GAA Glutamic acid	GGA Glycine	A
G	GUG Valine	GCG Alanine	GAG Glutamic acid	GGG Glycine	G

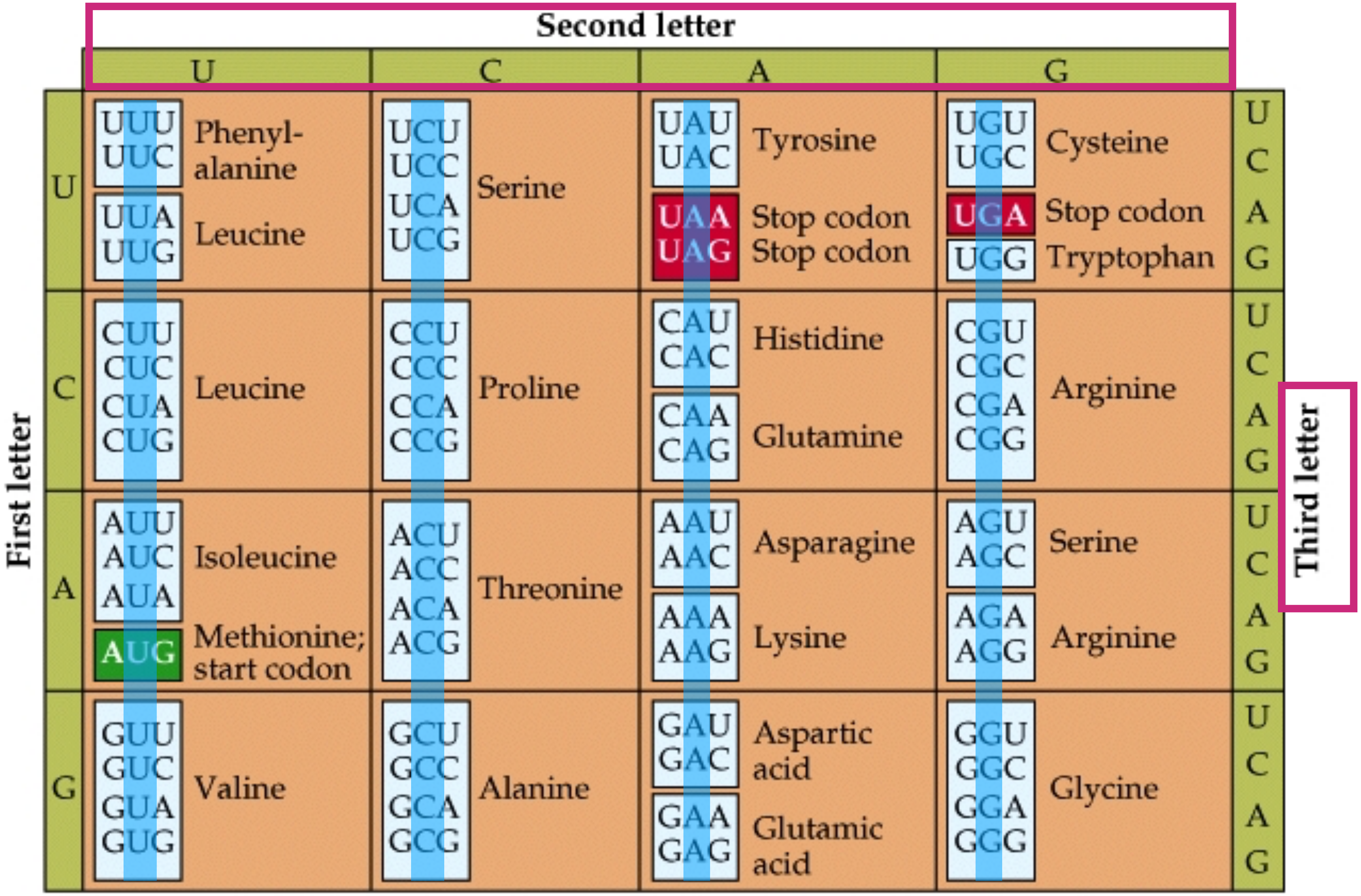
Four possibilities for the first base, multiplied by four for the second, multiplied by four for the third yields… **64 possibilities**

“Universal” Genetic Code



Four possibilities for the first base, multiplied by four for the second, multiplied by four for the third yields… **64 possibilities**

“Universal” Genetic Code



Four possibilities for the first base, multiplied by four for the second, multiplied by four for the third yields… **64 possibilities**

“Universal” Genetic Code

First letter	Second letter: U		C		A		G		Third letter
U	UUU UUC	Phenyl-alanine	UCU UCC UCA UCG	Serine	UAU UAC	Tyrosine	UGU UGC	Cysteine	U C
	UUA UUG	Leucine			UAA UAG	Stop codon Stop codon	UGA UGG	Stop codon Tryptophan	A G
C	CUU CUC CUA CUG	Leucine	CCU CCC CCA CCG	Proline	CAU CAC	Histidine	CGU CGC CGA CGG	Arginine	U C
					CAA CAG	Glutamine			A G
A	AUU AUC AUA	Isoleucine	ACU ACC ACA ACG	Threonine	AAU AAC	Asparagine	AGU AGC	Serine	U C
	AUG	Methionine; start codon			AAA AAG	Lysine	AGA AGG	Arginine	A G
G	GUU GUC GUA GUG	Valine	GCU GCC GCA GCG	Alanine	GAU GAC	Aspartic acid	GGU GGC GGA GGG	Glycine	U C
					GAA GAG	Glutamic acid			A G

Four possibilities for the first base, multiplied by four for the second, multiplied by four for the third yields… **64 possibilities**

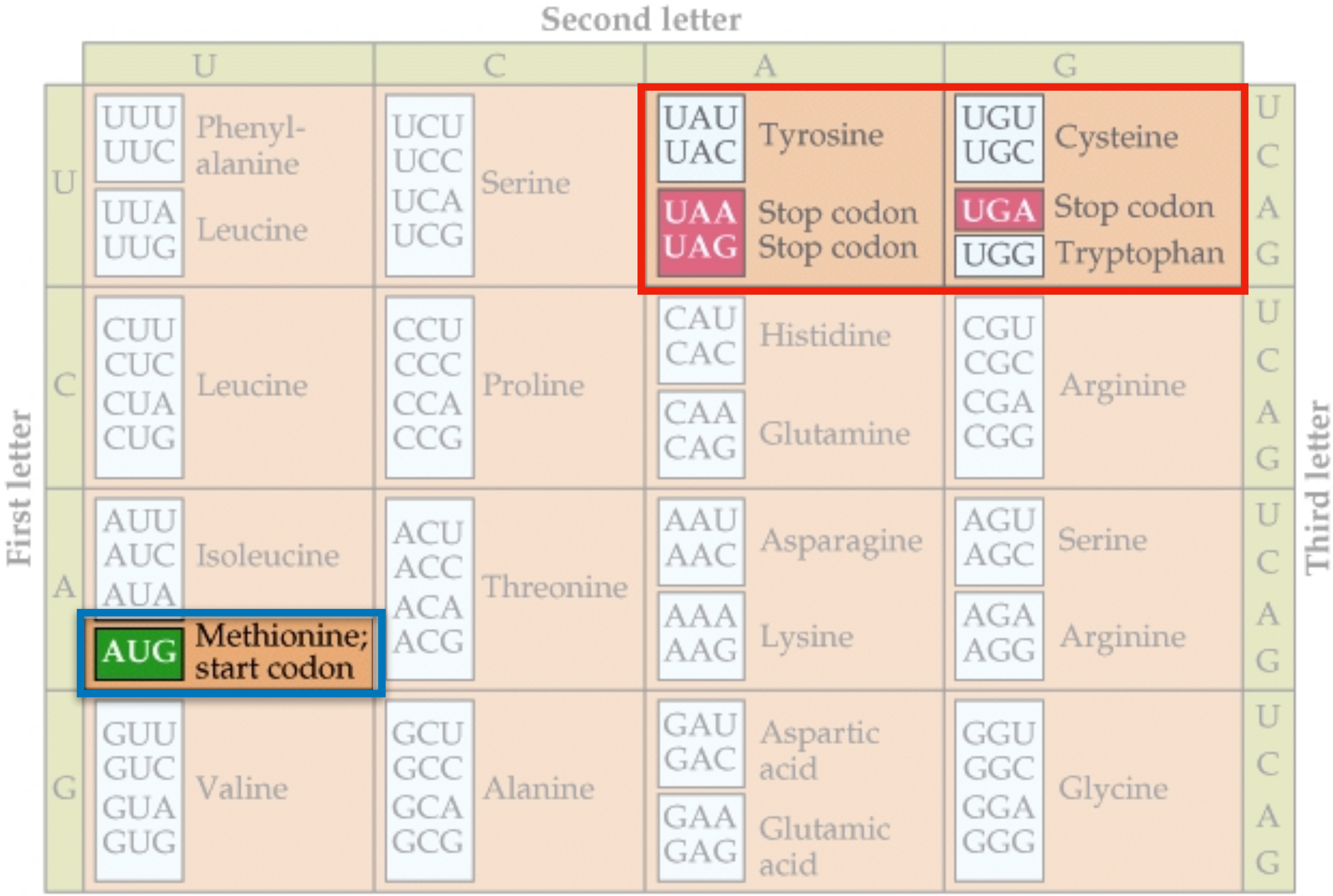
The “Universal” Genetic Code is a 3 base/letter code…

T / HER / EDC / ATG / OTT / HER / ATO / FFT / HEM / AT

TH / ERE / DCA / TGO / TTH / ERA / TOF / FTH / EMA / T

THE/ RED / CAT / GOT / THE / RAT / OFF / THE / MAT

“Universal” Genetic Code



AUG, which codes for the amino acid **methionine**, is called the ***start* codon**, which initiates the translational process.

Three of the possible codons are **STOP CODONS** (**UAA**, **UAG**, and **UGA**), which direct the ribosomes to STOP reading the mRNA; that is, they end translation.

“Universal” Genetic Code
Mitochondrial Genetic Code

Second letter

First letter	U	C	A	G	Third letter
U	UUU UUC Phenyl-alanine UUA UUG Leucine	UCU UCC UCA UCG Serine	UAU UAC Tyrosine UAA Stop codon UAG Stop codon	UGU UGC Cysteine UGA Tryptophan UGG Tryptophan	U C A G
C	CUU CUC CUA CUG Leucine	CCU CCC CCA CCG Proline	CAU CAC Histidine CAA CAG Glutamine	CGU CGC CGA CGG Arginine	U C A G
A	AUU AUC AUA Isoleucine AUG Methionine; start codon	ACU ACC ACA ACG Threonine	AAU AAC Asparagine AAA AAG Lysine	AGU AGC Serine AGA Stop codon AGG Stop codon	U C A G
G	GUU GUC GUA GUG Valine	GCU GCC GCA GCG Alanine	GAU GAC Aspartic acid GAA GAG Glutamic acid	GGU GGC GGA GGG Glycine	U C A G

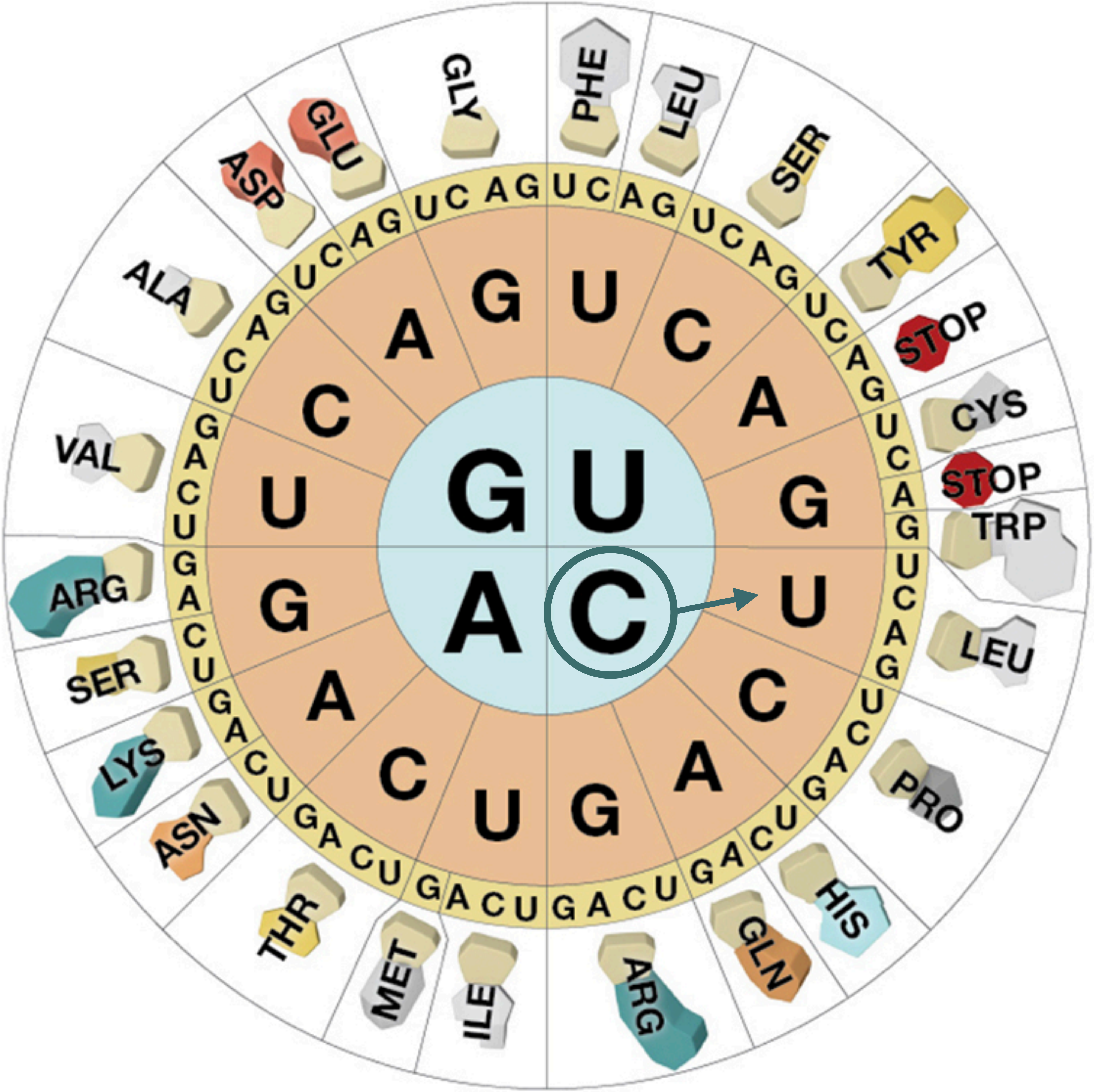
Four possibilities for the first base, x four for the second, x four for the third yields **64 possibilities options**

Only 20 amino acids, so the code is “redundant”

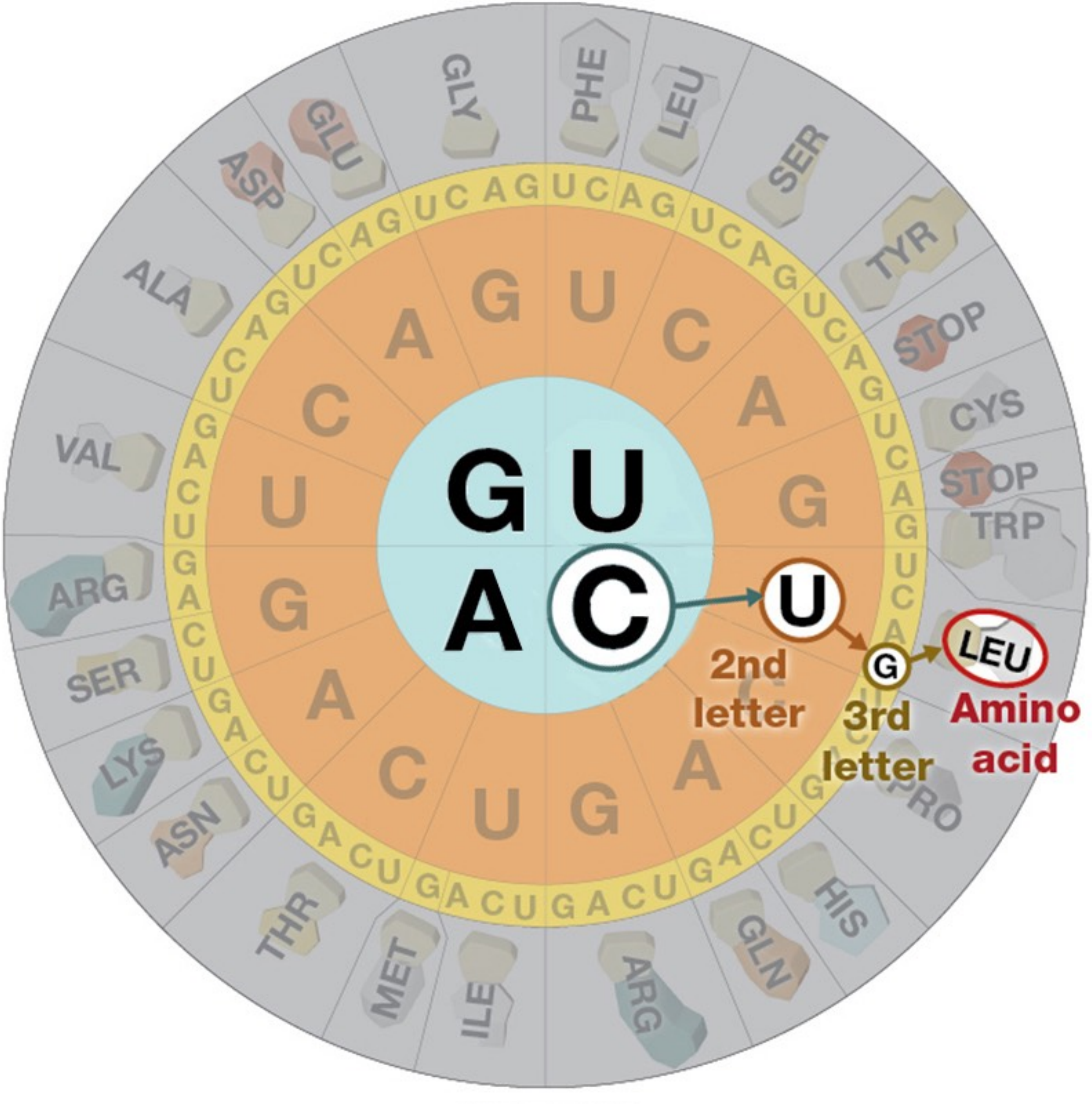
“Universal” Genetic Code

First letter	Second letter: U	Second letter: C	Second letter: A	Second letter: G	Third letter
U	UUU, UUC Phenyl-alanine UUA, UUG Leucine	UCU, UCC, UCA, UCG Serine	UAU, UAC Tyrosine UAA Stop codon UAG Stop codon	UGU, UGC Cysteine UGA Stop codon UGG Tryptophan	U C A G
C	CUU, CUC, CUA, CUG Leucine	CCU, CCC, CCA, CCG Proline	CAU, CAC Histidine CAA, CAG Glutamine	CGU, CGC, CGA, CGG Arginine	U C A G
A	AUU, AUC, AUA Isoleucine AUG Methionine; start codon	ACU, ACC, ACA, ACG Threonine	AAU, AAC Asparagine AAA, AAG Lysine	AGU, AGC Serine AGA, AGG Arginine	U C A G
G	GUU, GUC, GUA, GUG Valine	GCU, GCC, GCA, GCG Alanine	GAU, GAC Aspartic acid GAA, GAG Glutamic acid	GGU, GGC, GGA, GGG Glycine	U C A G

The genetic code is **redundant** but not **ambiguous.** This means that many amino acids have more than **one codon**, but only one amino acid is specified for any one codon.



G U
A C
G U C A G U C A G U C A G U C A
UCAG UCAG UCAG UCAG UCAG UCAG UCAG UCAG UCAG UCAG UCAG UCAG UCAG UCAG UCAG UCAG
PHE
LEU
SER
TYR
STOP
CYS
STOP
TRP
LEU
PRO
HIS
GLN
ARG
ILE
MET
THR
ASN
LYS
SER
ARG
VAL
ALA
ASP
GLU
GLY



G U
A C
U
G
LEU
2nd letter
3rd letter
Amino acid
GLY
PHE
LEU
SER
TYR
STOP
CYS
STOP
TRP
PRO
HIS
GLN
ARG
ILE
MET
THR
ASN
LYS
SER
ARG
VAL
ALA
ASP
GLU

“Universal” Genetic Code

Second letter

First letter	U	C	A	G	Third letter
U	UUU, UUC: Phenyl-alanine UUA, UUG: Leucine	UCU, UCC, UCA, UCG: Serine	UAU, UAC: Tyrosine UAA: Stop codon UAG: Stop codon	UGU, UGC: Cysteine UGA: Stop codon UGG: Tryptophan	U C A G
C	CUU, CUC, CUA, CUG: Leucine	CCU, CCC, CCA, CCG: Proline	CAU, CAC: Histidine CAA, CAG: Glutamine	CGU, CGC, CGA, CGG: Arginine	U C A G
A	AUU, AUC, AUA: Isoleucine AUG: Methionine; start codon	ACU, ACC, ACA, ACG: Threonine	AAU, AAC: Asparagine AAA, AAG: Lysine	AGU, AGC: Serine AGA, AGG: Arginine	U C A G
G	GUU, GUC, GUA, GUG: Valine	GCU, GCC, GCA, GCG: Alanine	GAU, GAC: Aspartic acid GAA, GAG: Glutamic acid	GGU, GGC, GGA, GGG: Glycine	U C A G

The genetic code is **redundant** but not **ambiguous.** This means that many amino acids have more than **one codon**, but only one amino acid is specified for any one codon.

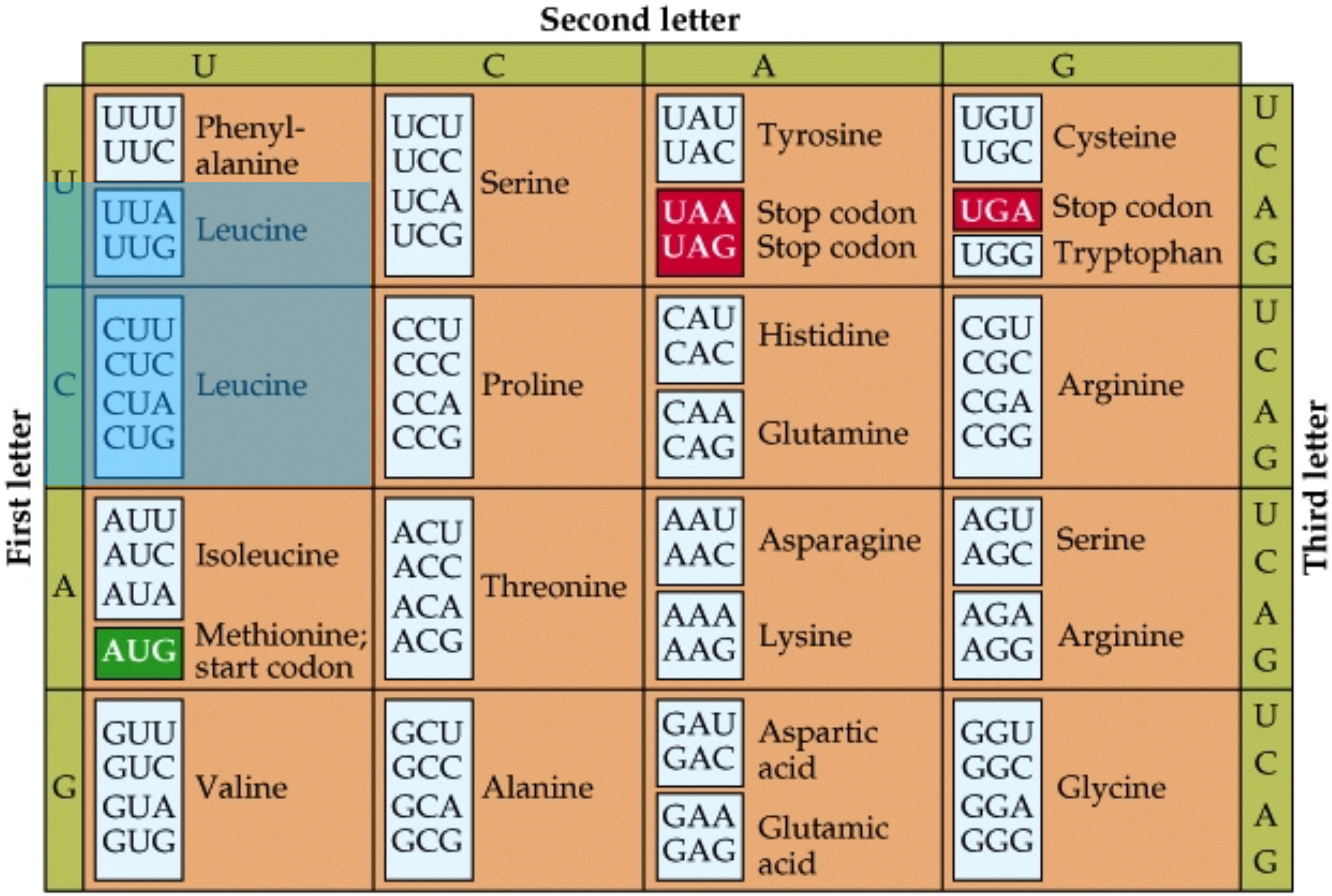
“Universal” Genetic Code

Second letter

First letter	U		C		A		G		Third letter
U	UUU UUC	Phenyl-alanine	UCU UCC UCA UCG	Serine	UAU UAC	Tyrosine	UGU UGC	Cysteine	U C
	UUA UUG	Leucine			UAA UAG	Stop codon Stop codon	UGA UGG	Stop codon Tryptophan	A G
C	CUU CUC CUA CUG	Leucine	CCU CCC CCA CCG	Proline	CAU CAC	Histidine	CGU CGC CGA CGG	Arginine	U C
					CAA CAG	Glutamine			A G
A	AUU AUC AUA	Isoleucine	ACU ACC ACA ACG	Threonine	AAU AAC	Asparagine	AGU AGC	Serine	U C
	AUG	Methionine; start codon			AAA AAG	Lysine	AGA AGG	Arginine	A G
G	GUU GUC GUA GUG	Valine	GCU GCC GCA GCG	Alanine	GAU GAC	Aspartic acid	GGU GGC GGA GGG	Glycine	U C
					GAA GAG	Glutamic acid			A G

The genetic code is **redundant** but not **ambiguous.** This means that many amino acids have more than **one codon**, but only one amino acid is specified for any one codon.

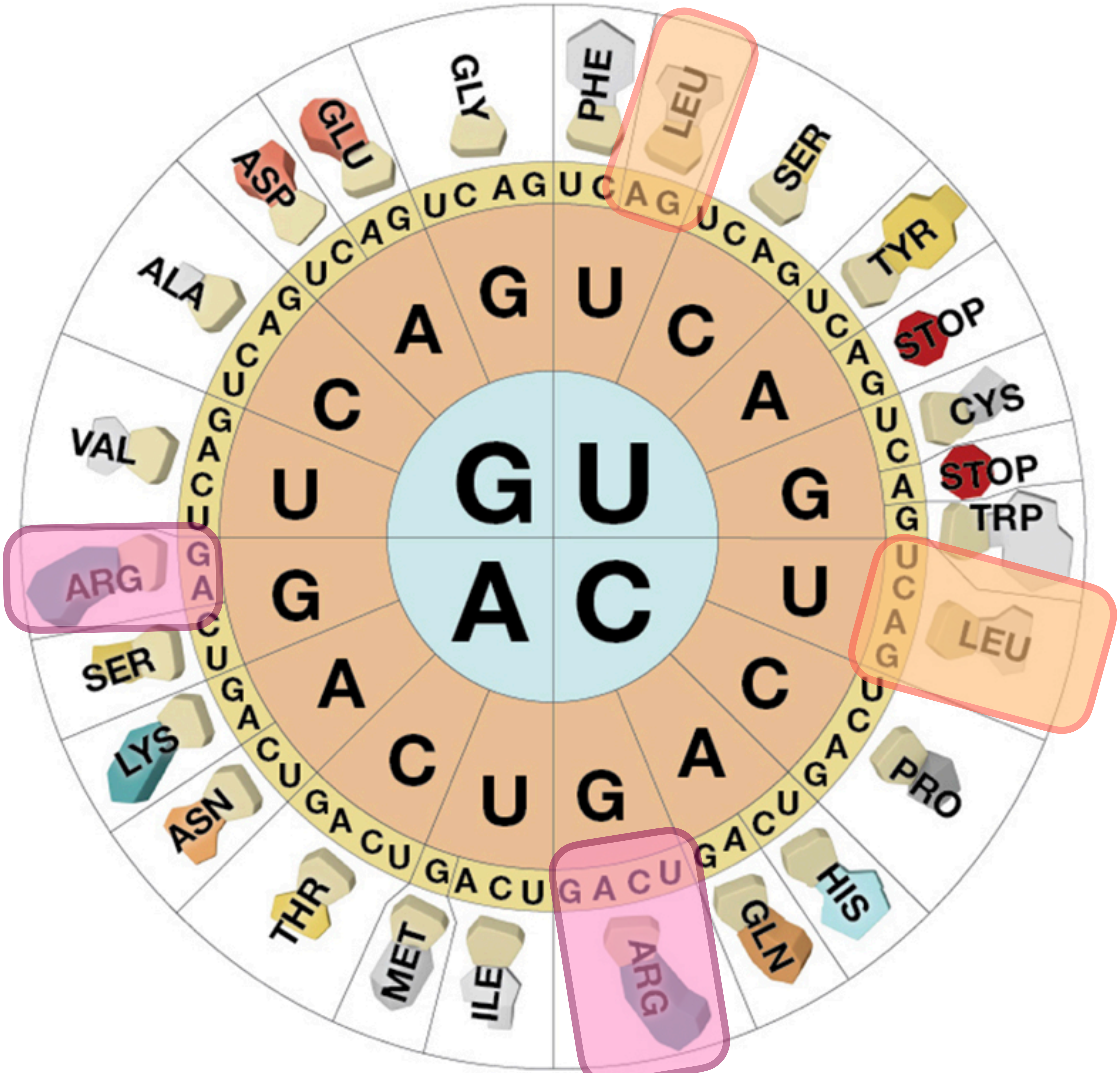
“Universal” Genetic Code



Second letter

First letter	U	C	A	G	Third letter
U	UUU UUC Phenyl-alanine; UUA UUG Leucine	UCU UCC UCA UCG Serine	UAU UAC Tyrosine; UAA Stop codon; UAG Stop codon	UGU UGC Cysteine; UGA Stop codon; UGG Tryptophan	U C A G
C	CUU CUC CUA CUG Leucine	CCU CCC CCA CCG Proline	CAU CAC Histidine; CAA CAG Glutamine	CGU CGC CGA CGG Arginine	U C A G
A	AUU AUC AUA Isoleucine; AUG Methionine; start codon	ACU ACC ACA ACG Threonine	AAU AAC Asparagine; AAA AAG Lysine	AGU AGC Serine; AGA AGG Arginine	U C A G
G	GUU GUC GUA GUG Valine	GCU GCC GCA GCG Alanine	GAU GAC Aspartic acid; GAA GAG Glutamic acid	GGU GGC GGA GGG Glycine	U C A G

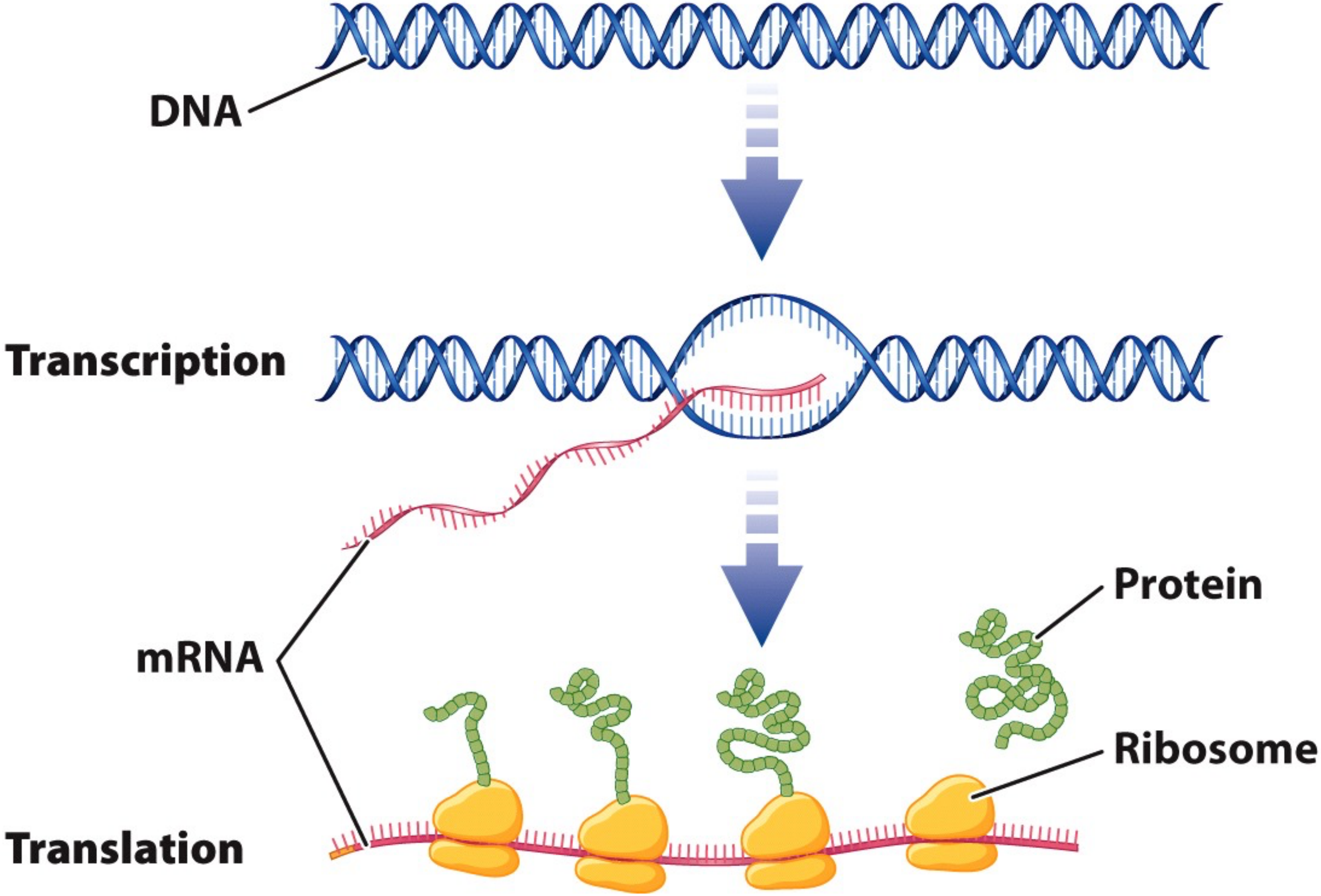
The genetic code is **redundant** but not **ambiguous.** This means that many amino acids have more than **one codon**, but only one amino acid is specified for any one codon.


G
U
A
C
PHE
LEU
SER
TYR
STOP
CYS
STOP
TRP
LEU
PRO
HIS
GLN
ARG
ILE
MET
THR
ASN
LYS
SER
ARG
VAL
ALA
ASP
GLU
GLY

“Universal” Genetic Code

First letter	Second letter: U	Second letter: C	Second letter: A	Second letter: G	Third letter
U	UUU UUC Phenyl-alanine UUA UUG Leucine	UCU UCC UCA UCG Serine	UAU UAC Tyrosine UAA Stop codon UAG Stop codon	UGU UGC Cysteine UGA Stop codon UGG Tryptophan	U C A G
C	CUU CUC CUA CUG Leucine	CCU CCC CCA CCG Proline	CAU CAC Histidine CAA CAG Glutamine	CGU CGC CGA CGG Arginine	U C A G
A	AUU AUC AUA Isoleucine AUG Methionine; start codon	ACU ACC ACA ACG Threonine	AAU AAC Asparagine AAA AAG Lysine	AGU AGC Serine AGA AGG Arginine	U C A G
G	GUU GUC GUA GUG Valine	GCU GCC GCA GCG Alanine	GAU GAC Aspartic acid GAA GAG Glutamic acid	GGU GGC GGA GGG Glycine	U C A G

The genetic code is **redundant** but not **ambiguous.** This means that many amino acids have more than **one codon**, but only one amino acid is specified for any one codon.



Proteins provide structure and carry out many essential activities in a cell.