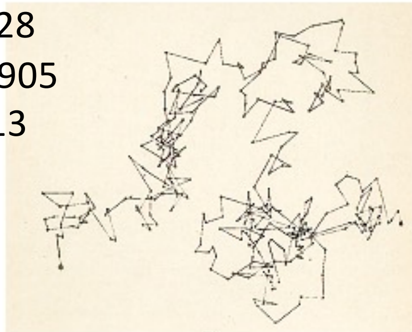
How much area would a bacterium (radius 1 um) explore using only thermal motion?

~ 0.2 um^2/sec

Motile bacteria mimic random walk

Brown: 1828
Einstein: 1905
Perrin: 1913



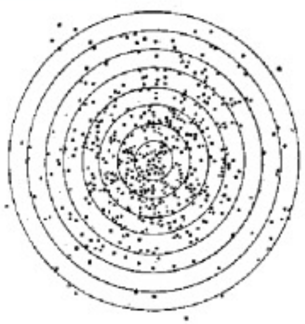
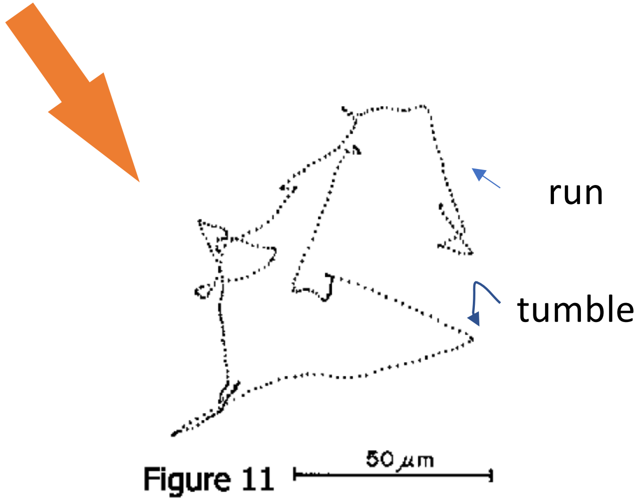


Fig 3. Brownian motion, after Jean Perrin [12]: An example of a trajectory (above) and statistical distribution of displacements (below, the circles correpond to fractions and multiples of the square root of the mean square displacement <X^2>)



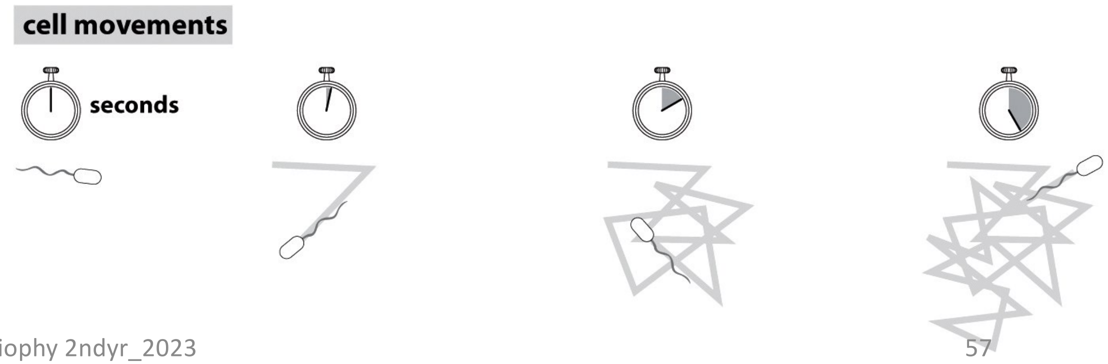


Figure 3.2d Physical Biology of the Cell (© Garland Science 2009)

Swimming but mimicking random walk

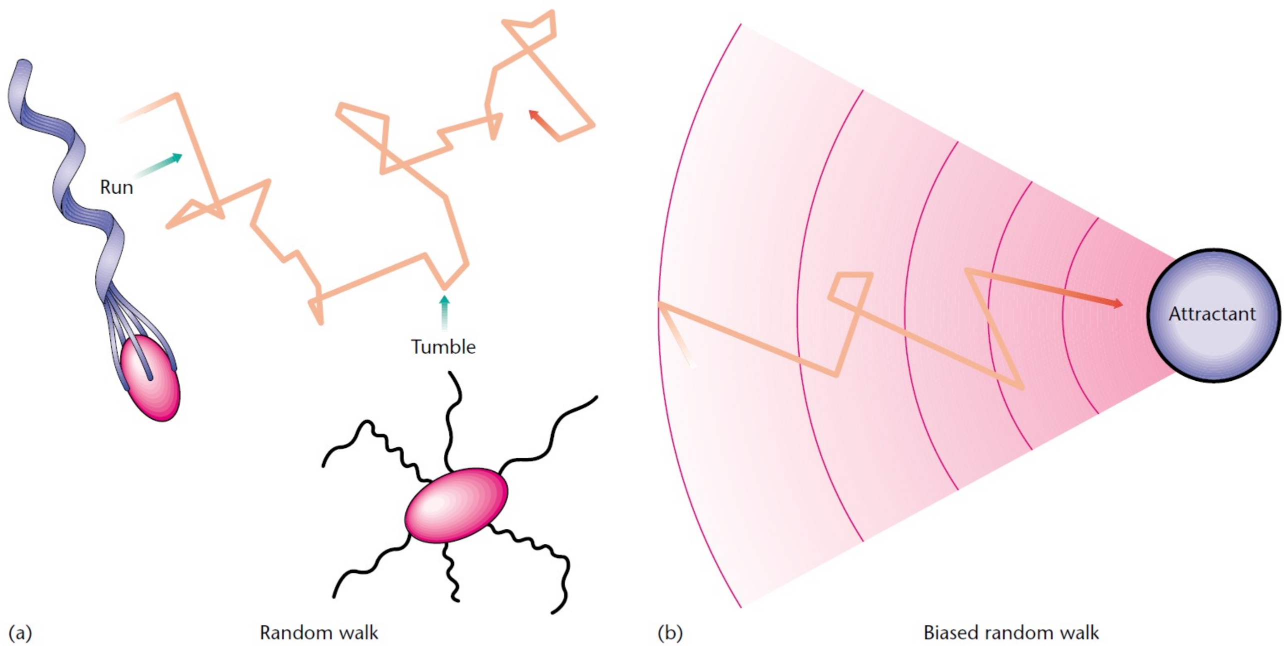
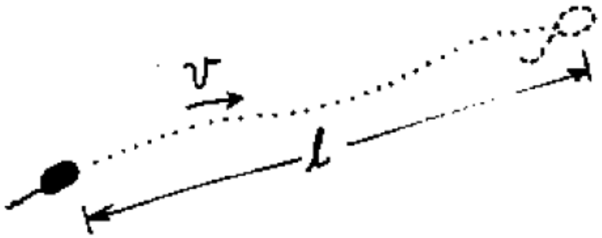


Figure 3 Swimming behaviour of *Escherichia coli* cells. (a) nonstimulated conditions; (b) stimulated conditions.

How long should it “run” to make this strategy useful?



to out-swim diffusion:

$$l \geqslant D/v$$

if $D = 10^{-5}\ cm^2/sec$, $v = .003\ cm/sec$

$$l \geqslant 30\ \mu$$

"If you don't swim that far you haven't gone anywhere."

Figure 20

1sec

growth (~1000 sec)

How much area would a bacterium (radius 1 um) explore using run length of 30um (1 sec steps)?

Use $$D = \frac{L^2}{2\Delta t}$$

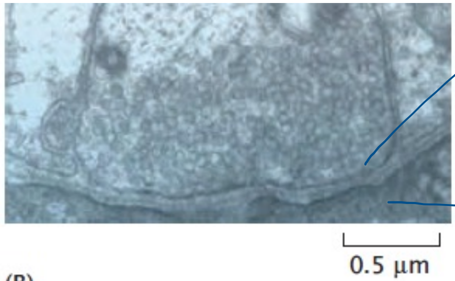
Estimate: Diffusion at the Synaptic Cleft The ideas introduced above can help us understand the dynamics of neurotransmitters at synapses. An example of the geometry of such a synapse is shown in Figure 3.32. Using exactly the same ideas as developed in the previous section, we can work out the time scale for neurotransmitters released at one side of the synapse to reach the receptors on the neighboring cell.

To be concrete, consider the diffusion of acetylcholine across a synaptic cleft with a size of roughly 20 nm. Given a diffusion constant for acetylcholine of $\approx 100\ \mu\text{m}^2/\text{s}$, the time for these molecules to diffuse across the cleft is

$$t = L^2/D \approx \frac{400\ \text{nm}^2}{10^8\ \text{nm}^2/\text{s}} \approx 4\ \mu\text{s}. \tag{3.20}$$

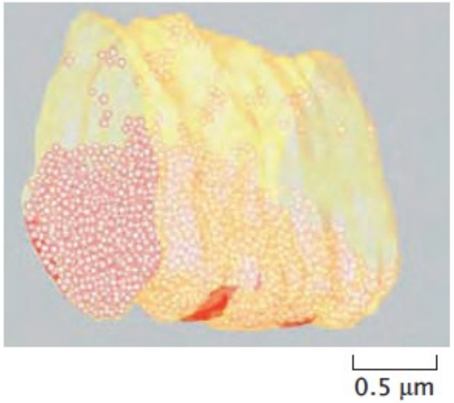
ESTIMATE

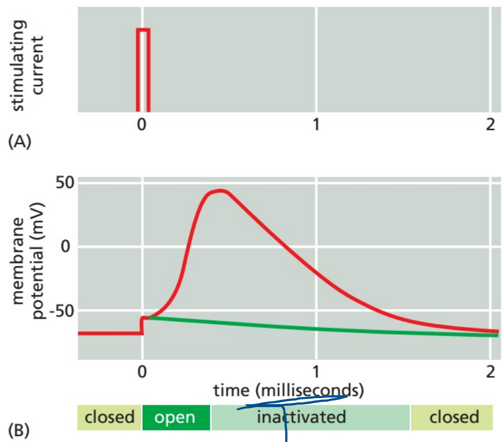
cell 1

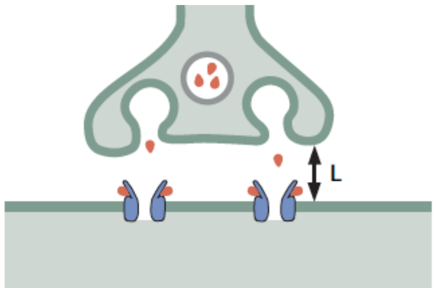


2

(B)







2 **Figure 3.32:** Geometry of the

Temporal scales

Slow to fast processes

- Development
- Early development
- Bacterial cell division
- Cell movement
- Protein synthesis
- Transcription
- Gating of ion channels
- Enzyme catalysis

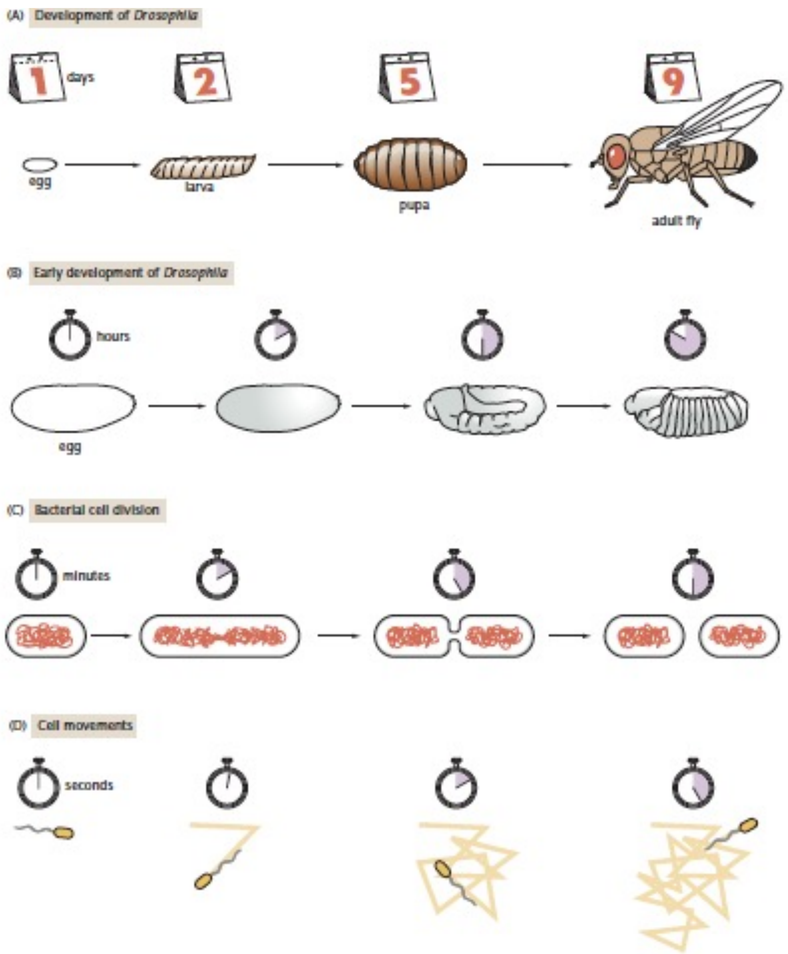


Figure 3.2: Hierarchy of biological time scales. Cartoon showing range of time scales associated with different biological

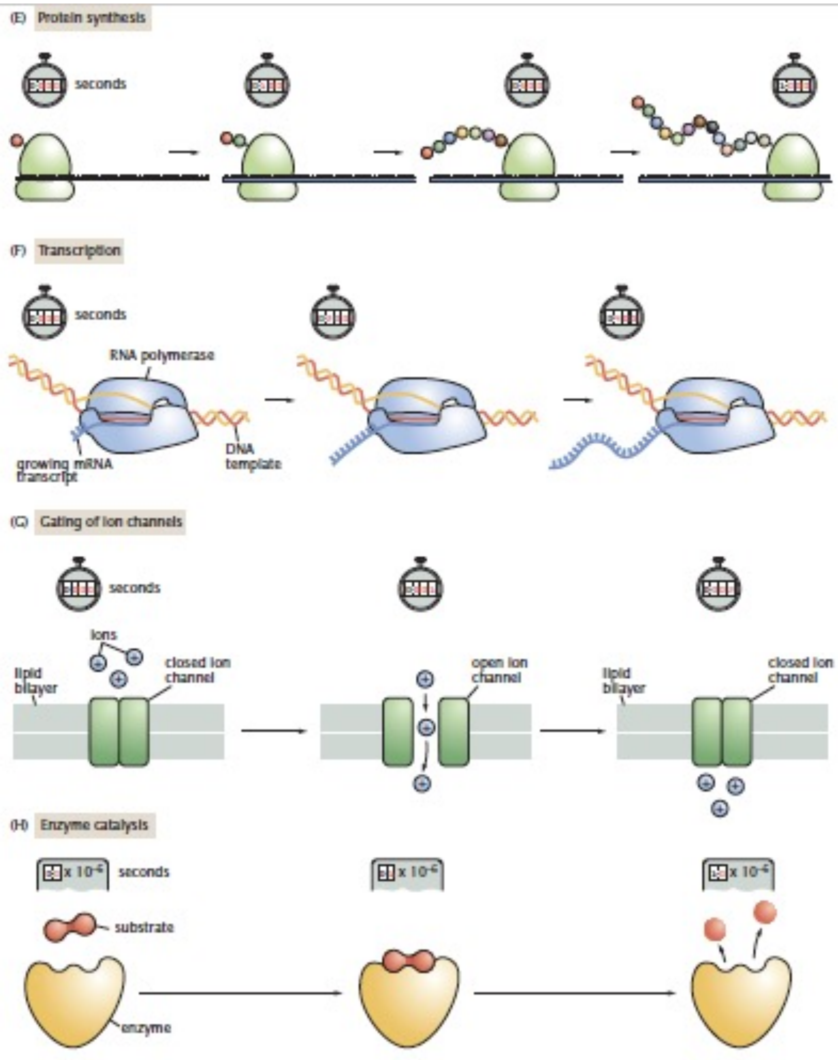
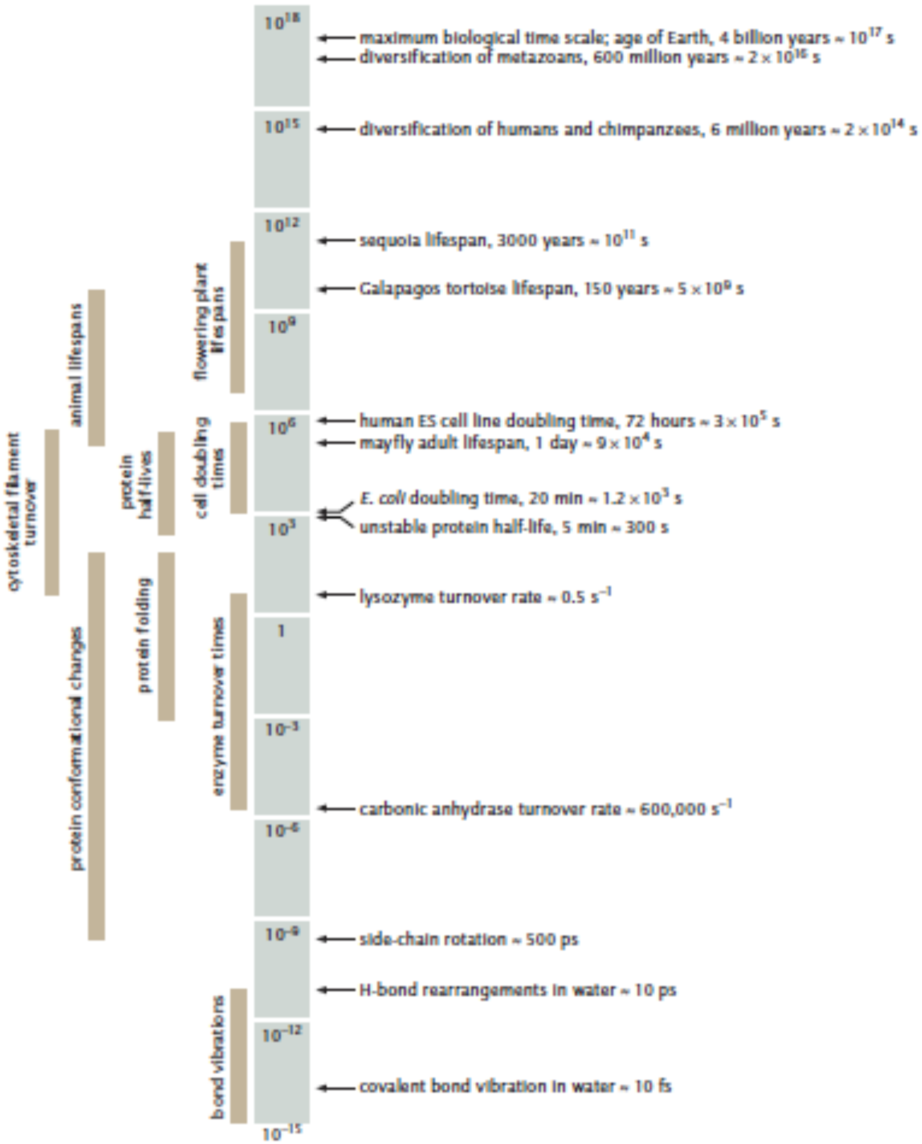
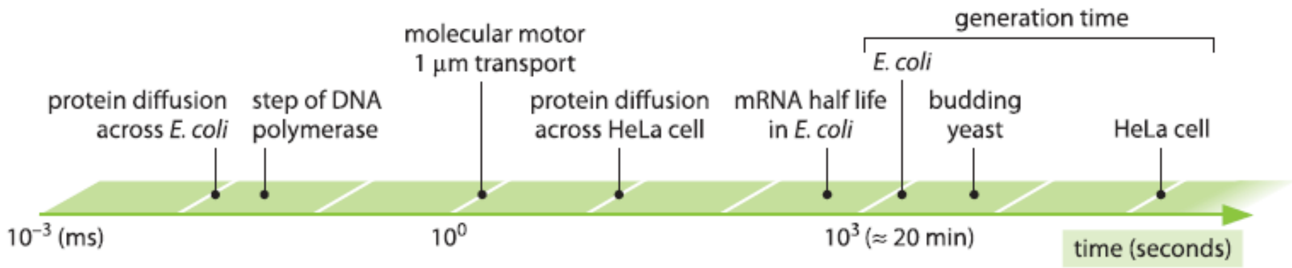


Figure 3.2: Continued.



10^{18}
maximum biological time scale; age of Earth, 4 billion years ≈ 10^{17} s
diversification of metazoans, 600 million years ≈ 2×10^{16} s
10^{15}
diversification of humans and chimpanzees, 6 million years ≈ 2×10^{14} s
10^{12}
sequoia lifespan, 3000 years ≈ 10^{11} s
Galapagos tortoise lifespan, 150 years ≈ 5×10^{9} s
10^{9}
10^{6}
human ES cell line doubling time, 72 hours ≈ 3×10^{5} s
mayfly adult lifespan, 1 day ≈ 9×10^{4} s
E. coli doubling time, 20 min ≈ 1.2×10^{3} s
unstable protein half-life, 5 min ≈ 300 s
10^{3}
lysozyme turnover rate ≈ 0.5 s^{-1}
1
10^{-3}
carbonic anhydrase turnover rate ≈ 600,000 s^{-1}
10^{-6}
10^{-9}
side-chain rotation ≈ 500 ps
H-bond rearrangements in water ≈ 10 ps
10^{-12}
covalent bond vibration in water ≈ 10 fs
10^{-15}
cytoskeletal filament turnover
animal lifespans
protein conformational changes
protein half-lives
protein folding
flowering plant lifespans
cell doubling times
enzyme turnover times
bond vibrations



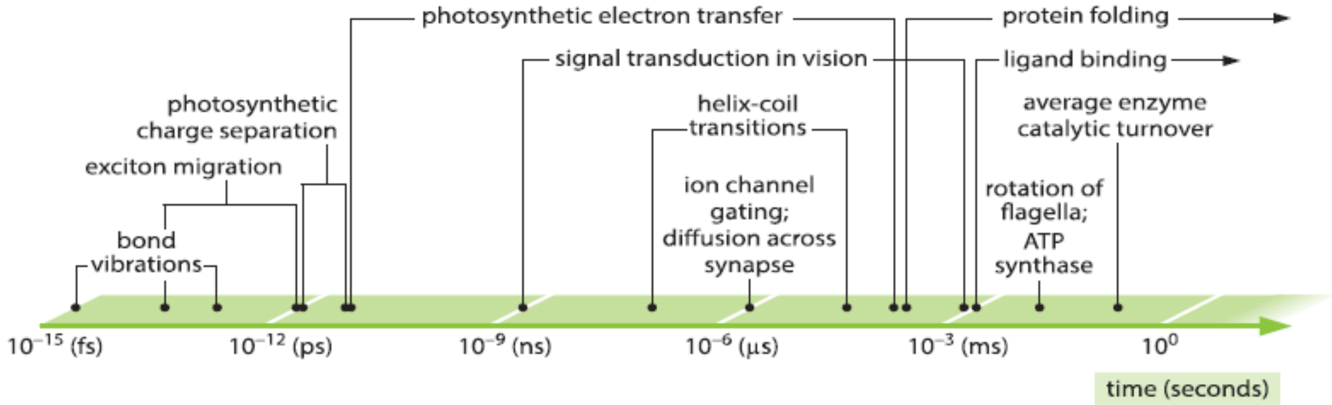


Figure 1: Range of characteristic time scales of central biological processes. Upper axis shows the longer timescales from protein diffusion across a bacterial cell to the generation time of a mammalian cell. The lower axis shows the fast timescales ranging from bond vibrations to protein folding and catalytic turnover durations.

Estimate: Ion Transport Rates in Ion Channels An ion channel embedded in the cell membrane can be thought of as a tube with a diameter of approximately $d = 0.5\,\text{nm}$ (size of hydrated ion) and a length $l = 5\,\text{nm}$ (width of the lipid bilayer). With these numbers in hand, and a typical value of the diffusion constant for small ions (e.g. sodium), $D \approx 2000\,\mu\text{m}^2/\text{s}$, we can estimate the flux of ions through the channel, assuming that their motion is purely diffusive.

ESTIMATE

Coupled transcription, translation in prokaryotes

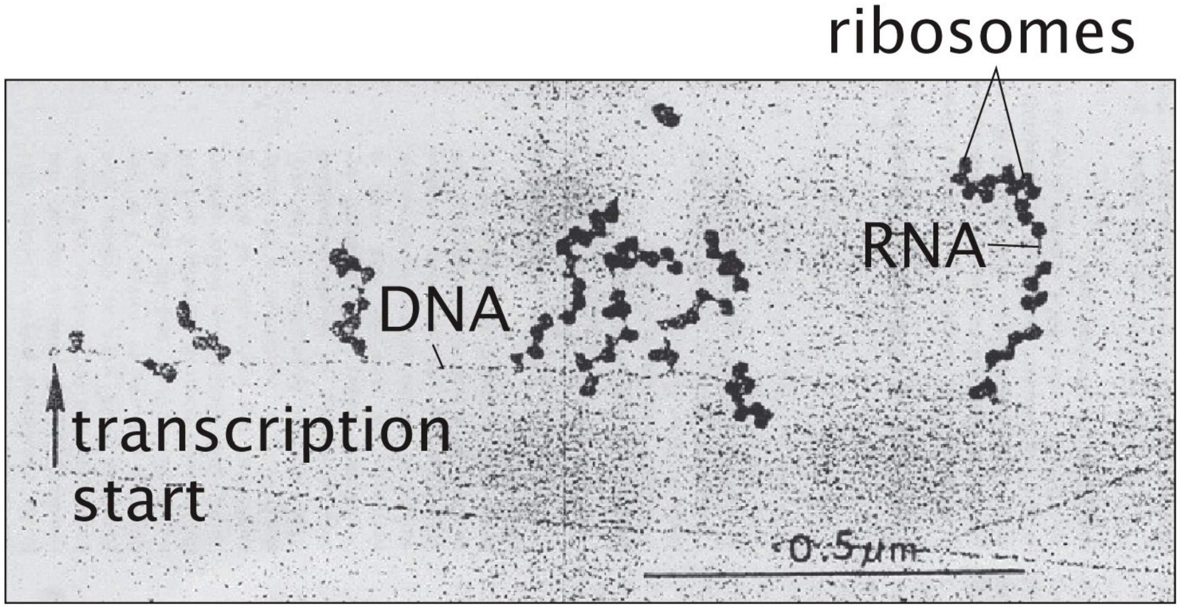


Figure 3.13 Physical Biology of the Cell, 2ed. (© Garland Science 2013)

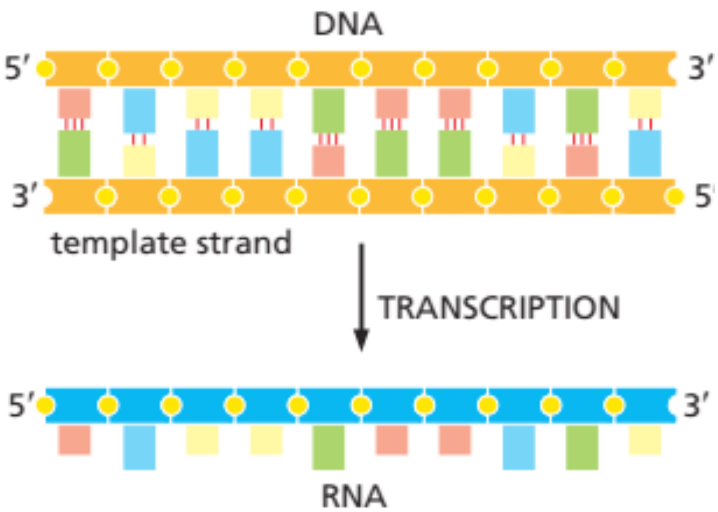
transcription ~45 bases/sec:
translation ~15 residues/sec

Science
. 2006 Mar 17;311(5767):1600-3.
doi: 10.1126/science.1119623.

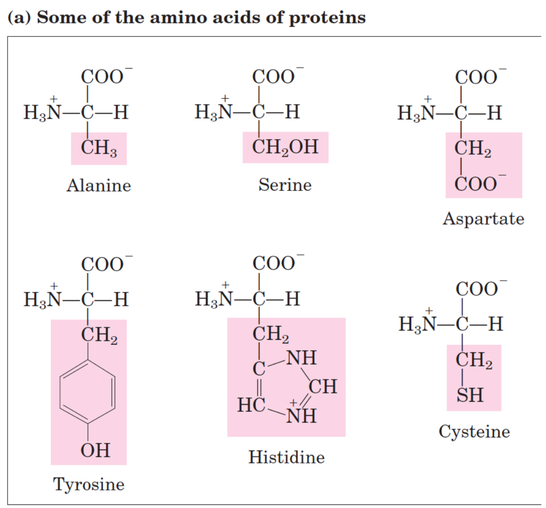
Probing gene expression in live cells, one protein molecule at a time

PubMed ID 16543458

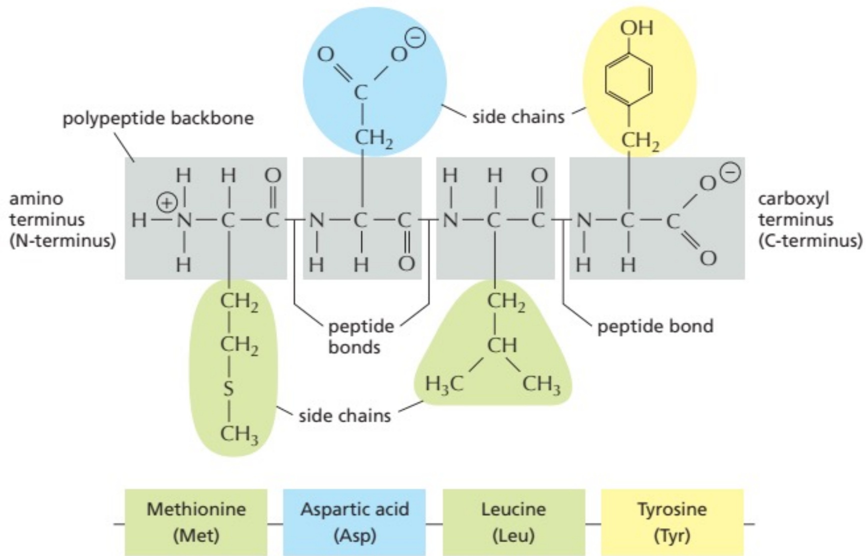
reminder



DNA
5′
3′
3′
5
template strand
TRANSCRIPTION
5′
3′
RNA



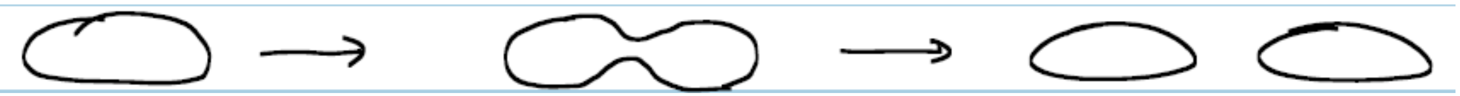
(a) Some of the amino acids of proteins
Alanine
Serine
Aspartate
Tyrosine
Histidine
Cysteine

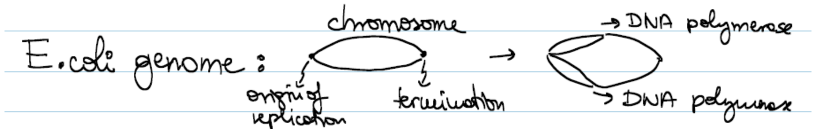


polypeptide backbone
side chains
amino terminus (N-terminus)
carboxyl terminus (C-terminus)
peptide bonds
peptide bond
side chains
Methionine (Met)
Aspartic acid (Asp)
Leucine (Leu)
Tyrosine (Tyr)

Beating the replication time

Cell division





Bacterial Cell division timescale: 1800 sec (fast), 3000 sec (slow)

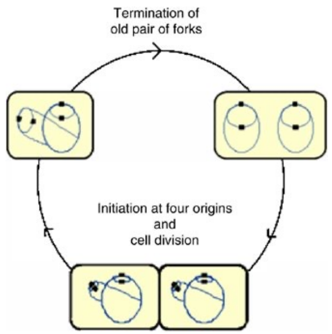
Genome length : $5x10^6$

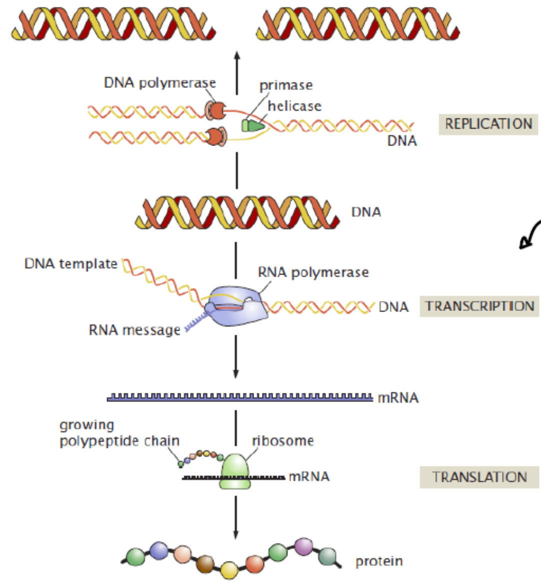
Time to replicate: Max expected: cell division time

Replication speed expected : 2700 (fast) or 600 bp/sec

Measured rate : 200-1000bp/sec

For fast growing : multiple origins





PBoC p90-93, 113