NADH and $FADH_2$ from glycolysis and citric acid cycle arrive at the electron transport chain, where they are both oxidized. Electrons from NADH and $FADH_2$ are passed to protein complexes located in the inner membrane of the mitochondria. The electron transport chain consists of four protein complexes labeled I through IV and several mobile electron carriers, labeled Q and Cyt c (Figure 6.19).

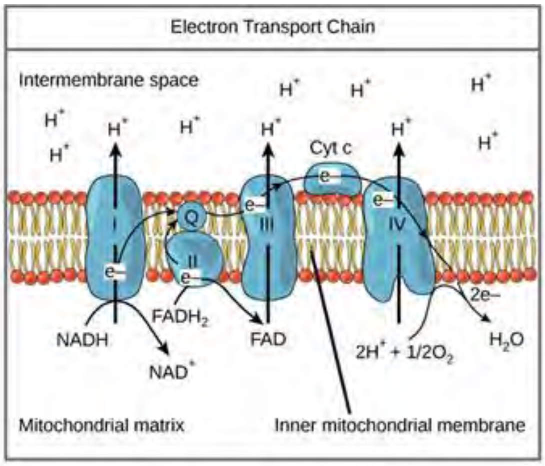

Figure 6.19 The electron transport chain is a series of electron transporting proteins embedded in the inner mitochondrial membrane that shuttles electrons from NADH and $FADH_2$ to molecular oxygen. (credit: Modified by Elizabeth O'Grady original work of Clark et al. / [Biology 2E OpenStax)](https://openstax.org/)

As each electron is transferred through the electron transport chain, some of the electron's energy is transferred to the protein complexes. The potential energy can be used by the protein complexes to pump hydrogen ions across the inner mitochondrial membrane against their concentration gradient using active transport (Figure 6.18). The ions are pumped into the intermembrane space, which creates a hydrogen ion gradient that will be used in chemiosmosis.

In the fourth protein complex, the electrons are accepted by oxygen, the terminal acceptor. It takes four electrons to split one molecule of oxygen. Each oxygen atom then accepts two electrons and two hydrogen ions from the electron transport chain and is reduced to water (Figure 6.18). If no oxygen was present in the mitochondrion, the electrons could not be removed from the system, and the entire electron transport chain would back up and stop. Without the electron transport chain, new ATP would not be synthesized during oxidative phosphorylation, and the cell would ultimately die from a lack of energy. This is the reason we must inhale oxygen.

CONCEPTS IN ACTION - Watch this video to learn about the electron transport chain.

Chemiosmosis

As electrons are passed through the electron transport chain, the energy released is used to establish a hydrogen ion concentration gradient. Because of their charge, hydrogen ions can only diffuse across the inner membrane of the mitochondria through integral transport proteins. **ATP synthase**, an integral protein and an enzyme, acts as a tiny generator which allows hydrogen ions to easily diffuse across the inner membrane (Figure 6.20). The movement of hydrogen ions through ATP synthase regenerates ATP from ADP plus inorganic phosphate. The flow of hydrogen ions across the membrane through ATP synthase is called **chemiosmosis**.

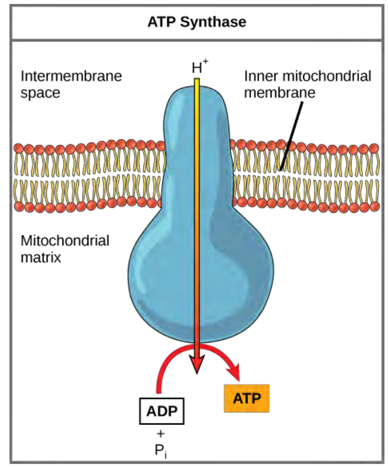

Figure 6.20 ATP synthase is a complex, molecular machine that uses a proton (H_+) gradient to form ATP from ADP and inorganic phosphate (P_i). (Credit: modification of work by Klaus Hoffmeier / Biology 2E OpenStax)

The energy generated from the electron transport chain and chemiosmosis (Figure 6.21) generates 90 percent of the ATP made during aerobic glucose catabolism. Chemiosmosis and the electron transport chain are also used during the light reactions of photosynthesis. Both these processes will be discussed again when we get to chapter 7.

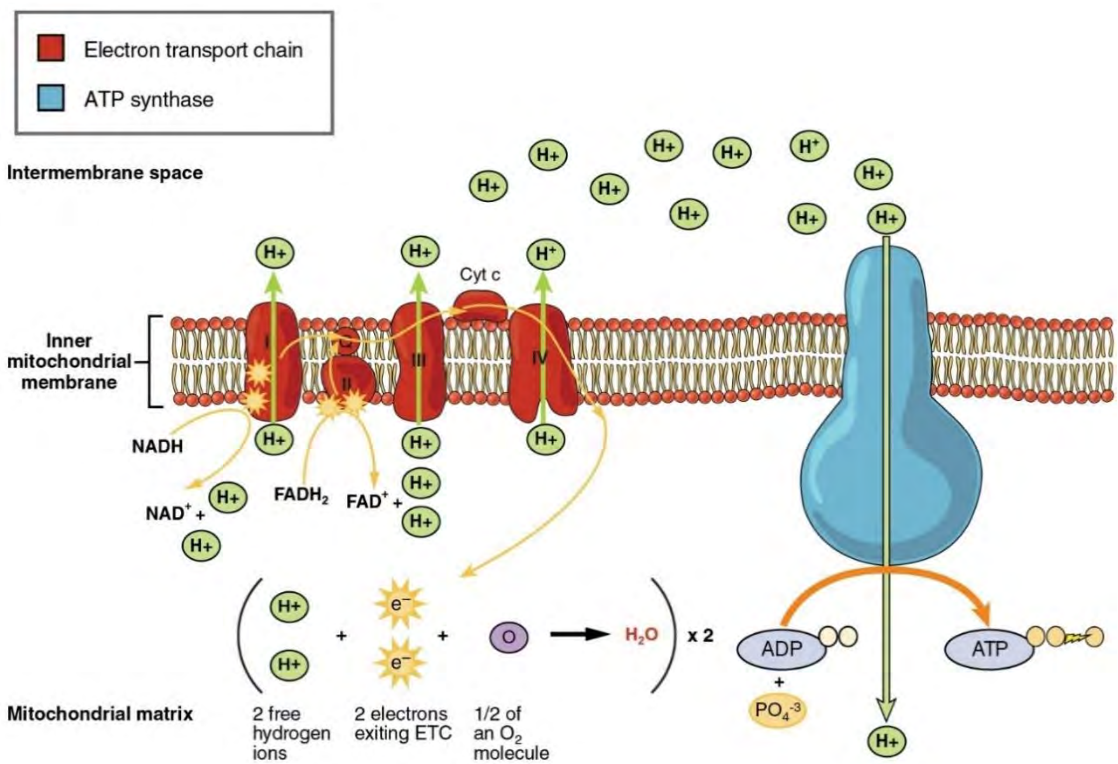

Figure 6.21 Shows the electron transport chain and chemiosmosis (credit: Betts et al. / Anatomy and Physiology OpenStax)

ATP Yield

The number of ATP molecules generated from glucose catabolism varies. For example, different species vary in the number of hydrogen ions that the electron transport chain can pump through the membrane. This variation impacts the hydrogen ion concentration gradient and, therefore, the rate of ATP synthesis. Another difference stems from the electron carriers' ability to cross the mitochondrial membrane. The NADH generated from glycolysis cannot easily enter the mitochondria. As a result, electrons from NADH produced during glycolysis are picked up on the inside of the mitochondria by either NAD^+ or FAD. Fewer ATP molecules are generated when FAD acts as a carrier. It is estimated that for every NADH molecule that arrives at the electron transport chain, approximately two to three molecules of ATP can be synthesized. For everyone molecule of $FADH_2$ oxidized at the electron transport chain, the cell can synthesize one to two molecules of ATP. NADH results in more ATP because it delivers its electrons to protein complex I and they travel through the entire electron transport chain. $FADH_2$, in contrast, delivers its electrons to protein complex II and they only travel through part of the transport chain.

When accounting for the total number of ATP produced per glucose molecule, it is important to remember the following points:

- A net of two ATP is produced through glycolysis (four produced, but two are consumed during the energy-consuming stage).
- A net of two ATP is produced through the citric acid cycle.
- A net of 28 molecules of ATP is produced during oxidative phosphorylation. Approximately 25 ATP molecules from the oxidation of NADH and three molecules of ATP from the oxidation of $FADH_2$ (see Figure 6.22).

Check your knowledge

Are the following options active or passive transport?

- Chemiosmosis
- Proteins moving H+ into the intermembrane space (outer matrix)
- Sodium/Potassium pump
- Sugar dissolving in a glass of water.

Answers: passive, active, active, passive