# The synapse

How neurons communicate with each other at synapses. Chemical vs. electrical synapses.

## Key points

Neurons communicate with one another at junctions called synapses. At a synapse, one neuron sends a message to a target neuron—another cell.

Most synapses are chemical; these synapses communicate using chemical messengers. Other synapses are electrical; in these synapses, ions flow directly between cells.

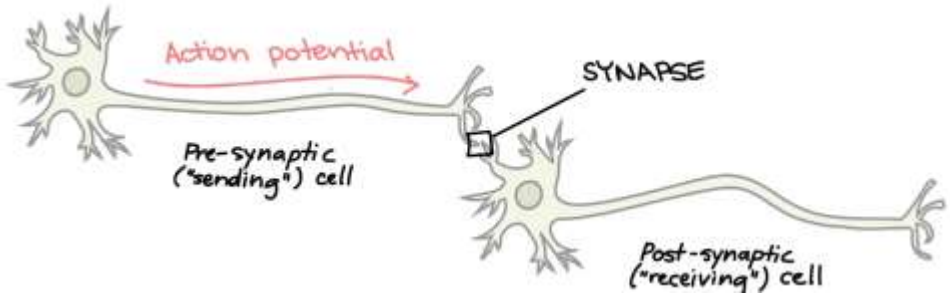
At a chemical synapse, an action potential triggers the presynaptic neuron to release neurotransmitters. These molecules bind to receptors on the postsynaptic cell and make it more or less likely to fire an action potential.

## Introduction

A single neuron, or nerve cell, can do a lot! It can maintain a resting potential—voltage across the membrane. It can fire nerve impulses, or action potentials. And it can carry out the metabolic processes required to stay alive.

A neuron's signalling, however, is much more exciting—no pun intended!—when we consider its interactions with other neurons. Individual neurons make connections to target neurons and stimulate or inhibit their activity, forming circuits that can process incoming information and carry out a response.

How do neurons "talk" to one another? The action happens at the synapse, the point of communication between two neurons or between a neuron and a target cell, like a muscle or a gland. At the synapse, the firing of an action potential in one neuron—the presynaptic, or sending, neuron—causes the transmission of a signal to another neuron—the postsynaptic, or receiving, neuron—making the postsynaptic neuron either more or less likely to fire its own action potential.




In this article, we'll take a closer look at the synapse and the mechanisms neurons use to send signals across it. To get the most out of this article, you may want to learn about neuron structure and action potentials first.

## Electrical or chemical transmission?

At the end of the 19th and beginning of the 20th century, there was a lot of controversy about whether synaptic transmission was electrical or chemical. Some people thought that signalling across a synapse involved the flow of ions directly from one neuron into another—electrical transmission. Other people thought it depended on the release of a chemical from one neuron, causing a response in the receiving neuron—chemical transmission.

We now know that synaptic transmission can be either

electrical or chemical—in some cases, both at the same synapse!

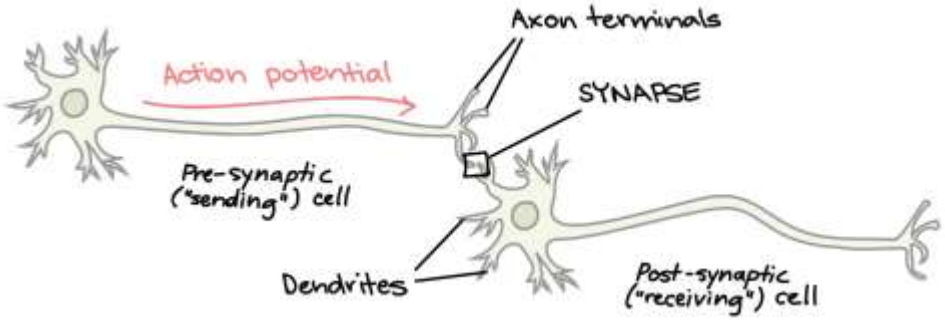
Chemical transmission is more common, and more complicated, than electrical transmission. So, let's take a look at chemical transmission first.

## Overview of transmission at chemical synapses

Chemical transmission involves release of chemical messengers known as neurotransmitters.

Neurotransmitters carry information from the presynaptic—sending—neuron to the post-synaptic—receiving—cell.

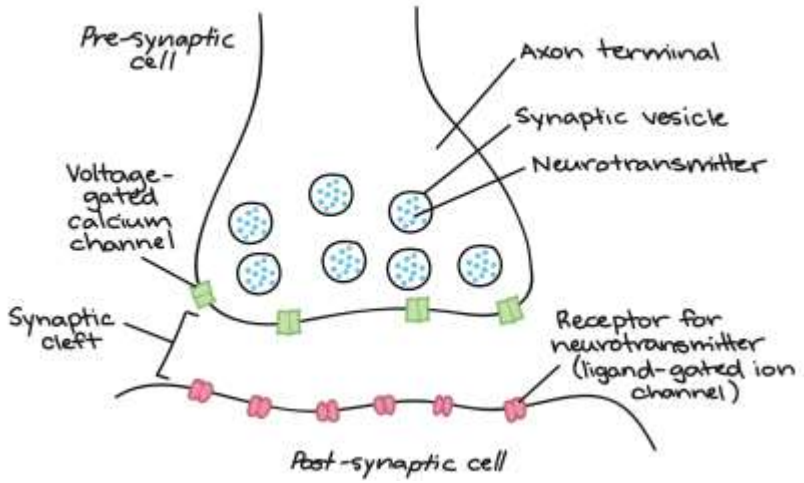
As you may remember from the article on neuron structure and function, synapses are usually formed between nerve terminals—axon terminals—on the sending neuron and the cell body or dendrites of the receiving neuron.



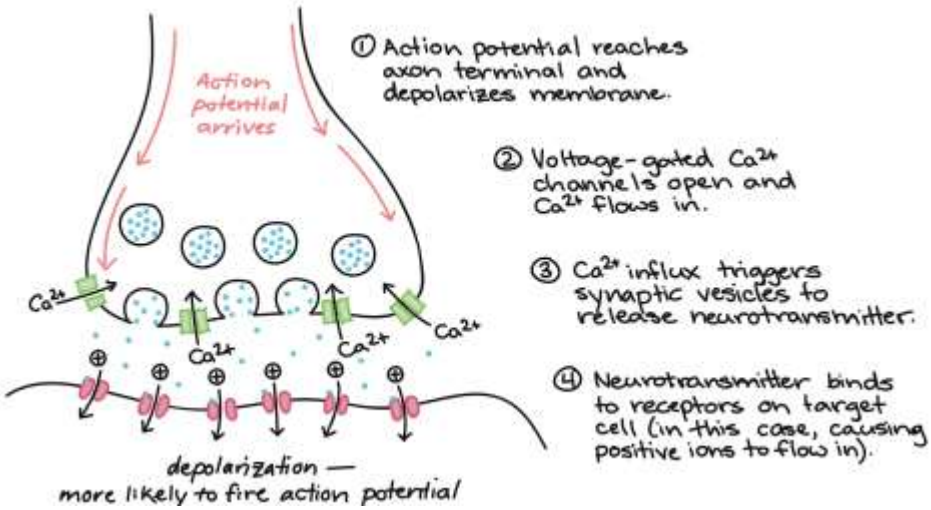

A single axon can have multiple branches, allowing it to make synapses on various postsynaptic cells. Similarly, a single neuron can receive thousands of synaptic inputs from many different presynaptic—sending—neurons.

Inside the axon terminal of a sending cell are many synaptic vesicles. These are membrane-bound

spheres filled with neurotransmitter molecules. There is a small gap between the axon terminal of the presynaptic neuron and the membrane of the postsynaptic cell, and this gap is called the synaptic cleft.




When an action potential, or nerve impulse, arrives at the axon terminal, it activates voltage-gated calcium channels in the cell membrane. CA, which is present at a much higher concentration outside the neuron than inside, rushes into the cell. The CA allows synaptic vesicles to fuse with the axon terminal membrane, releasing neurotransmitter into the synaptic cleft.



The molecules of neurotransmitter diffuse across the synaptic cleft and bind to receptor proteins on the postsynaptic cell. Activation of postsynaptic receptors leads to the opening or closing of ion channels in the cell membrane. This may be depolarizing—make the inside of the cell more positive—or hyperpolarizing—make the inside of the cell more negative—depending on the ions involved.

In some cases, these effects on channel behaviour are direct: the receptor is a ligand-gated ion channel, as in the diagram above. In other cases, the receptor is not an ion channel itself but activates ion channels through a signalling pathway. See the article on neurotransmitters and receptors for more info.

## Excitatory and inhibitory postsynaptic potentials

When a neurotransmitter binds to its receptor on a receiving cell, it causes ion channels to open or close. This can produce a localized change in the membrane potential—voltage across the membrane—of the receiving cell.

In some cases, the change makes the target cell more likely to fire its own action potential. In this case, the shift in membrane potential is called an excitatory postsynaptic potential, or EPSP.
In other cases, the change makes the target cell less likely to fire an action potential and is called an inhibitory post-synaptic potential, or IPSP.
An EPSP is depolarizing: it makes the inside of the cell more positive, bringing the membrane potential closer to its threshold for firing an action potential. Sometimes, a single EPSP isn't large enough bring the neuron to threshold, but it can sum together with other EPSPs to trigger an action potential.
IPSPs have the opposite effect. That is, they tend to

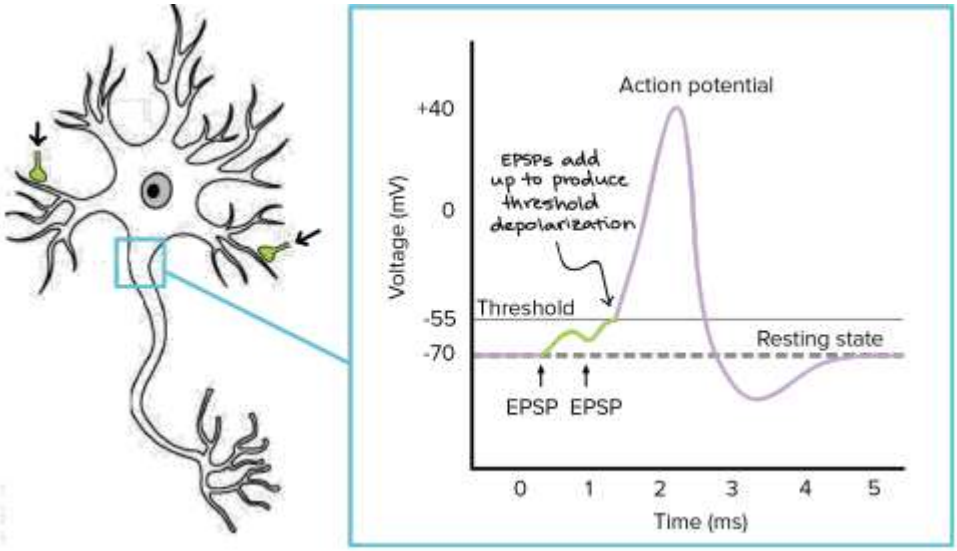
keep the membrane potential of the postsynaptic neuron below threshold for firing an action potential. IPSPs are important because they can counteract, or cancel out, the excitatory effect of EPSPs.

## Spatial and temporal summation

How do EPSPs and IPSPs interact? Basically, a postsynaptic neuron adds together, or integrates, all of the excitatory and inhibitory inputs it receives and "decides" whether to fire an action potential.
The integration of postsynaptic potentials that occur in different locations—but at about the same time—is known as spatial summation.

The integration of postsynaptic potentials that occur in the same place—but at slightly different times—is called temporal summation.

For instance, let's suppose that excitatory synapses are made on two different dendrites of the same postsynaptic neuron, as shown below. Neither synapse can produce an EPSP quite large enough to bring the membrane potential to threshold at the axon hillock—the place where the action potential is triggered, boxed below. If both sub threshold EPSPs occurred at the same time, however, they could sum, or add up, to bring the membrane potential to threshold.

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On the other hand, if an IPSP occurred together with the two EPSPs, it might prevent the membrane potential from reaching threshold and keep the neuron from firing an action potential. These are examples of spatial summation.

What about temporal summation? A key point is that postsynaptic potentials aren't instantaneous: instead, they last for a little while before they dissipate. If a presynaptic neuron fires quickly twice in row, causing two EPSPs, the second EPSP may arrive before the first one has dissipated, bumping the membrane potential above threshold. This is an example of temporal summation.

## Signal termination

A synapse can only function effectively if there is some way to "turn off" the signal once it's been sent. Termination of the signal lets the postsynaptic cell return to its normal resting potential, ready for new signals to arrive.

For the signal to end, the synaptic cleft must be cleared of neurotransmitter. There are a few different ways to get this done. The neurotransmitter may be broken down by an enzyme, it may be sucked back up into the presynaptic neuron, or it may simply diffuse away. In some cases, neurotransmitter can also be "mopped up" by nearby glial cells—not shown in the diagram below.

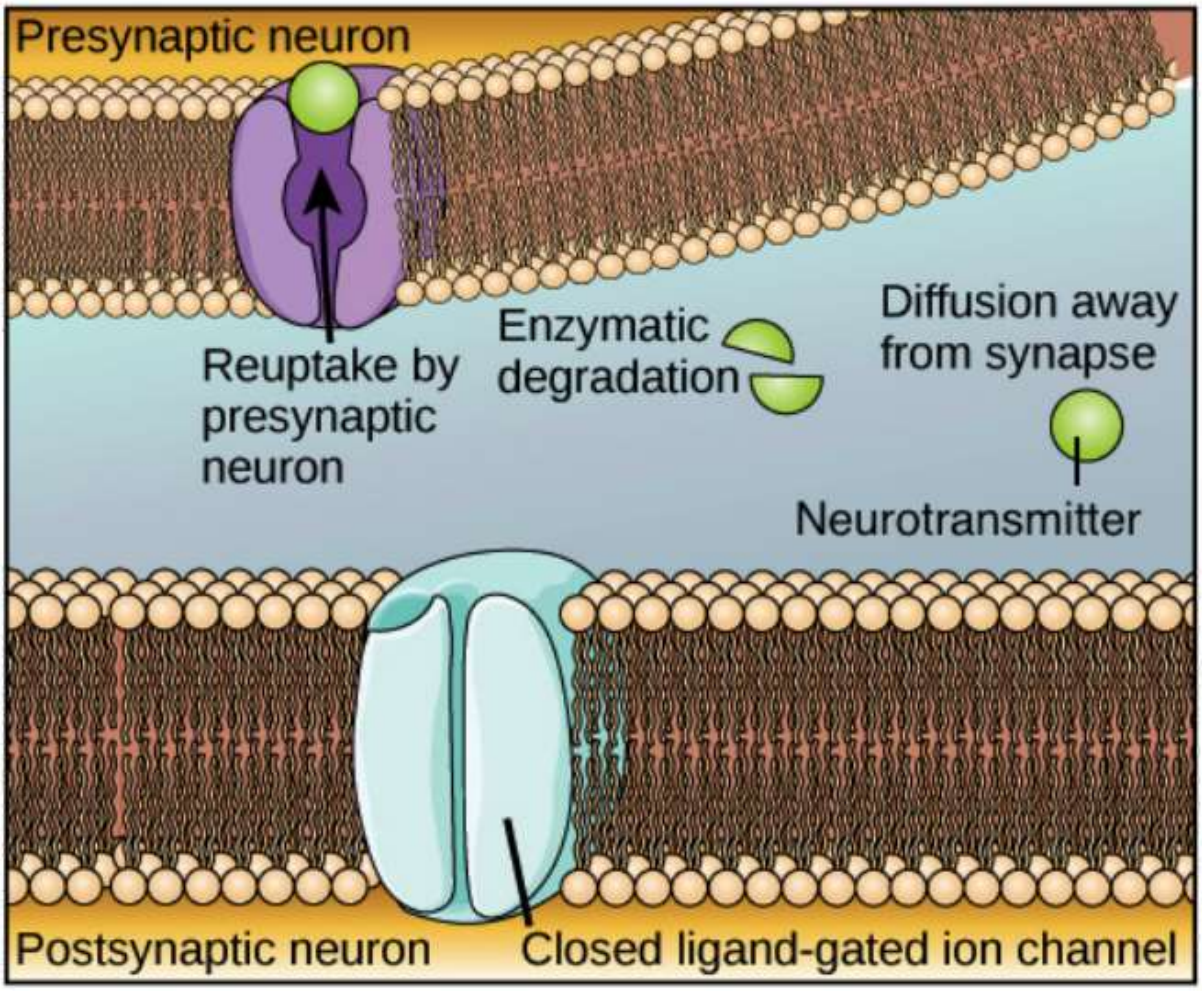



Image credit: modified from Nervous system: Figure 9 by OpenStax College, Biology, adapted by Robert Bear and David Rintoul, CC BY 4.0

Anything that interferes with the processes that terminate the synaptic signal can have significant physiological effects. For instance, some insecticides kill insects by inhibiting an enzyme that breaks down the neurotransmitter acetylcholine. On a more positive note, drugs that interfere with reuptake of the

neurotransmitter serotonin in the human brain are used as antidepressants, for example, Prozac.

## Chemical synapses are flexible

If you've learned about action potentials, you may remember that the action potential is an all-or-none response. That is, it either happens at its full strength, or it doesn't happen at all.

Synaptic signalling, on the other hand, is much more flexible. For instance, a sending neuron can "dial up" or "dial down" the amount of neurotransmitter it releases in response to the arrival of an action potential. Similarly, a receiving cell can alter the number of receptors it puts on its membrane and how readily it responds to activation of those receptors.

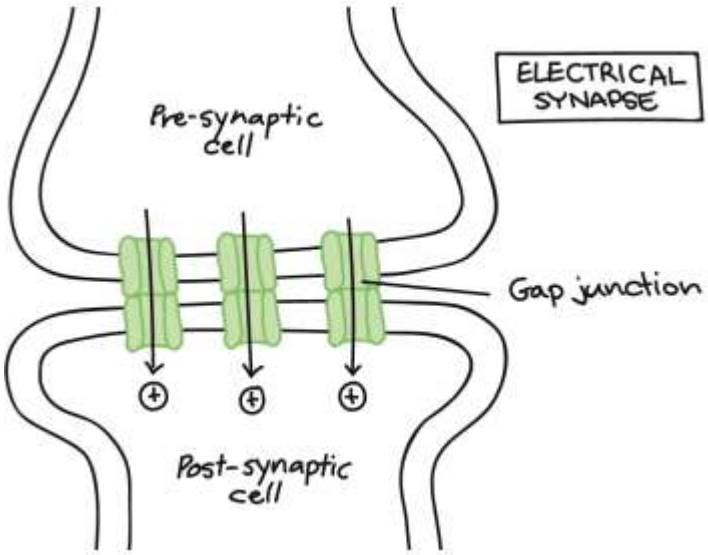
These changes can strengthen or weaken communication at a particular synapse.

Presynaptic and postsynaptic cells can dynamically change their signalling behaviour based on their internal state or the cues they receive from other cells. This type of plasticity, or capacity for change, makes the synapse a key site for altering neural circuit strength and plays a role in learning and memory. Synaptic plasticity is also involved in addiction.

In addition, different presynaptic and postsynaptic cells produce different neurotransmitters and neurotransmitter receptors, with different interactions and different effects on the postsynaptic cell. For more information, take a look at the article on neurotransmitters and receptors.

# Electrical synapses

At electrical synapses, unlike chemical synapses, there is a direct physical connection between the presynaptic neuron and the postsynaptic neuron. This connection takes the form of a channel called a gap junction, which allows current—ions—to flow directly from one cell into another.




Electrical synapses transmit signals more rapidly than chemical synapses do. Some synapses are both electrical and chemical. At these synapses, the electrical response occurs earlier than the chemical response.

What are the benefits of electrical synapses? For one thing, they're fast—which could be important, say, in a circuit that helps an organism escape from a predator. Also, electrical synapses allow for the synchronized activity of groups of cells. In many cases, they can carry current in both directions so that depolarization of a postsynaptic neuron will lead to depolarization of a presynaptic neuron. This kind of bends the definitions of presynaptic and postsynaptic!

What are the downsides of electrical synapses? Unlike chemical synapses, electrical synapses cannot turn an

excitatory signal in one neuron into an inhibitory signal in another. More broadly, they lack the versatility, flexibility, and capacity for signal modulation that we see in chemical synapses.