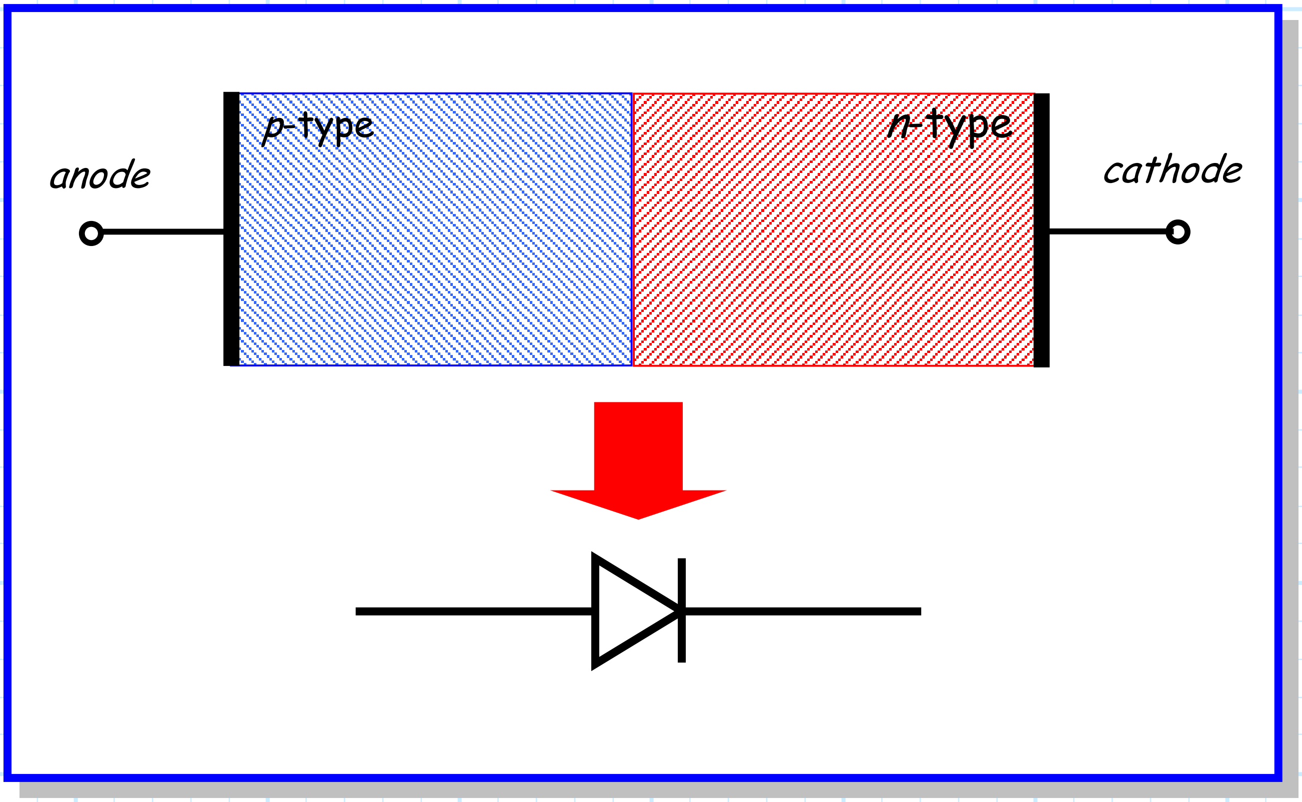
The *p-n* Junction Diode (Open Circuit)

We create a *p-n* junction diode simply by sticking together a hunk of ***p*-type** Silicon and a hunk of ***n*-type** Silicon!



Now, let's **think** about what happens here:

1) The **concentration** of holes in the anode is much greater than that of the cathode.

2) The **concentration** of free electrons in the cathode is much greater than that of the anode.

Diffusion is the result !

1) **Holes** begin to migrate (diffuse) across the junction from the **anode** to the **cathode**.

2) **Free electrons** begin to migrate (diffuse) across the junction from the **cathode** to the **anode**.

Q: *Oh, I see! This is **entropy** at work. This diffusion will occur until the concentration of holes and free electrons become **uniform** throughout the diode, right ?*

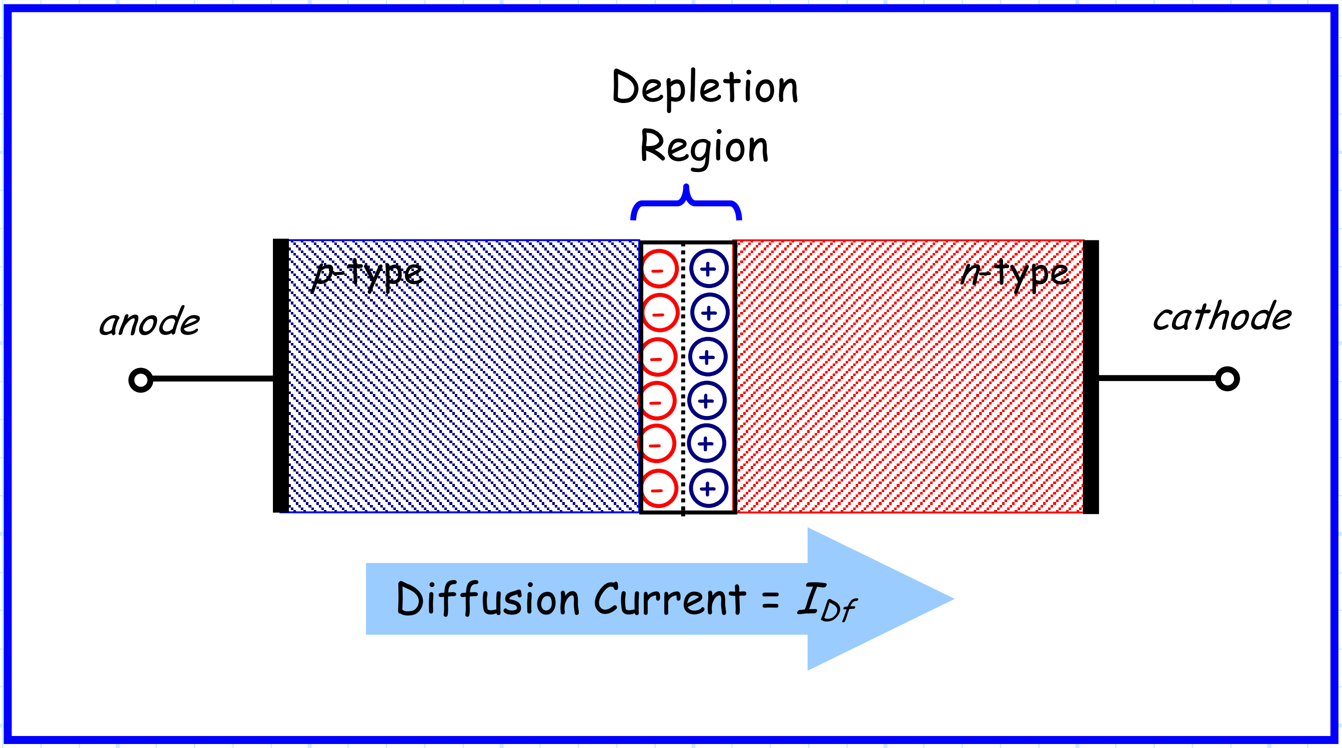
A: Not so fast ! There are **more** phenomena at work here than **just** diffusion !

For instance, **think** about what happens when holes **leave** the *p*-type Silicon of the anode, and the free electrons **leave** the *n*-type Silicon of the cathode:

→ They **uncover ions** !!!

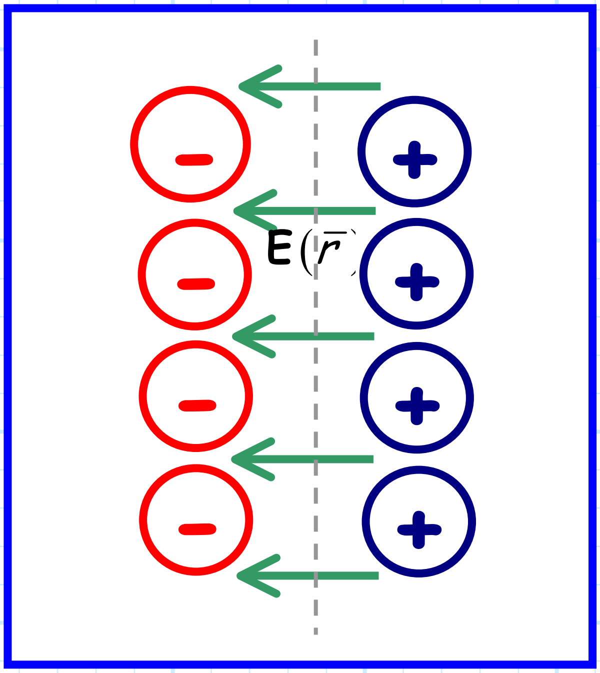
As a result, the **charge density** of the **anode** along the junction becomes **negative**, and the charge density of the **cathode** along the junction becomes **positive**.

This region of uncovered ions along the junction is known as the **depletion region**.



Now, something **really** interesting occurs!

The uncovered ions of opposite polarity generate an **electric field** across the junction.



Recall that an electric field exerts a **force** on charge particles—charged particles like **holes** and **free electrons**!

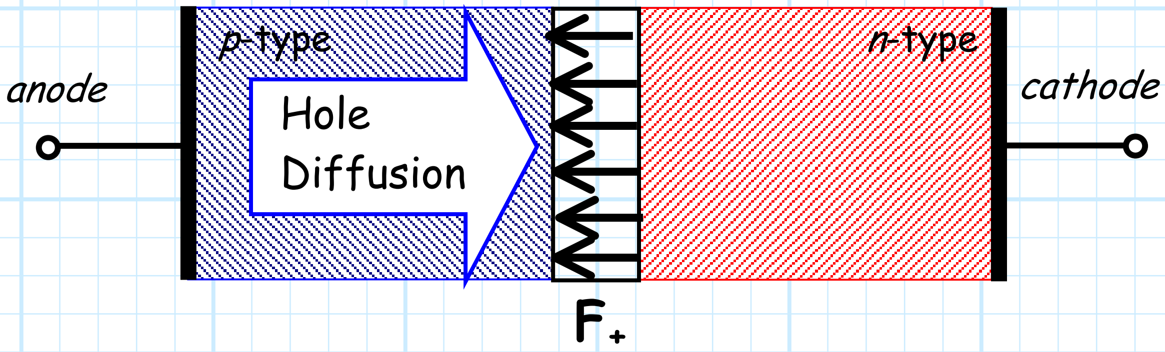
Let's see what this force **is** on both holes and free electrons:

For **holes:**

Using the **Lorentz force equation**, we find that the force vector $\mathbf{F}_+$ on a **hole** (with charge $Q_+ = -e$) located at position $\bar{r}$ is:

$$\mathbf{F}_+ = Q_+ \mathbf{E}(\bar{r})$$

Note that since the electric field vector in the depletion region is pointing from **right to left** (i.e., from the *n*-type Si cathode to the *p*-type Si cathode), and since the "charge" Q_+ of a hole is **positive**, the force vector likewise extends from **right to left**:



Look what happens! The electric field in the depletion region applies a **force** on the holes that is **opposite** of the direction of **hole diffusion**!

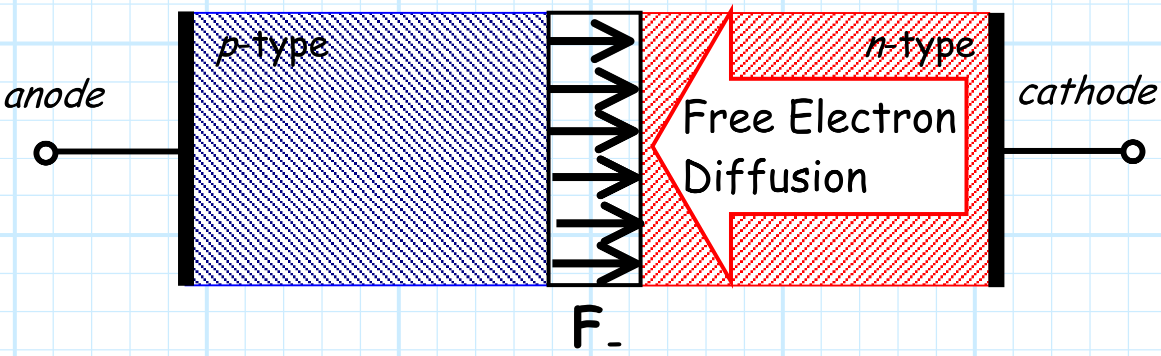
In other words, the electric field begins to "**hold back**" the tide of holes attempting to **diffuse** into the *n*-type cathode region.

For free electrons:

Now, let's see what effect this electric field has on **free electrons**. Using the **Lorentz force equation**, we find that the **force** vector $\mathbf{F}_-$ on a free electron (with charge $Q_- = e$) located at position $\bar{r}$ is:

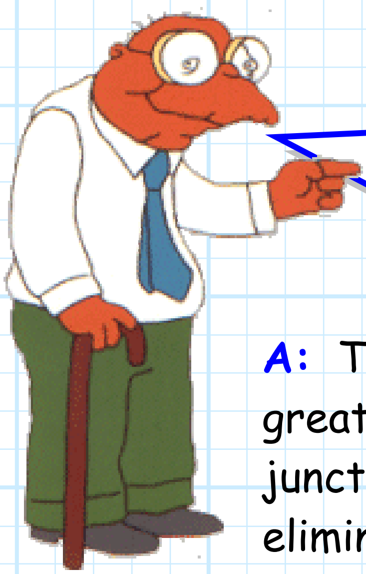
$$\mathbf{F}_- = Q_- \mathbf{E}(\bar{r})$$

Note that since the electric field vector in the depletion region is pointing from **right to left** (i.e., from the *n*-type Si to the *p*-type Si), and since the charge Q_- of a free electron is **negative**, the force vector extents in the opposite direction of $\mathbf{E}(\bar{r})$--from **left to right**:



Look what happens! The **electric field** in the depletion region likewise applies a **force** on the **free electrons** that is **opposite** of the direction of free electron **diffusion**!

In other words, the electric field begins to "**hold back**" the tide of **free electrons** attempting to **diffuse** into the *p*-type anode region .



Q: *So, does this electric field **stop** all diffusion across the junction ? Is the diffusion current I_{Df} therefore **zero**?*

A: Typically **NO!** The electric field will greatly **reduce** the diffusion across the junction, but only in **certain** cases will it eliminate I_{Df} entirely (more about **that** later!).

The **amount** of diffusion that occurs for a given electric field $\mathbf{E}(\bar{r})$ is dependent on how **energetic** the particles (holes and free-electrons) are!

Recall that these particles will have **kinetic energy** due to heat. If this energy is sufficiently **large**, a particle can still diffuse **across** the *p-n* junction!

To see why, consider the amount of **energy** E it would take to move a charged particle **through** this electric field. Recall from EECS 220 that this energy is:

$$E = -Q\int_C \mathbf{E}(\bar{r}) \cdot \overline{d\ell}$$

For our case, Q is the **charge** on a particle (hole or free electron), and **contour** C is a path that extends **across** the depletion region.

Moreover, we recall that this expression can be simplified by using **electric potential**, i.e.,

$$V = -\int_C \mathbf{E}(\bar{r}) \cdot \overline{d\ell}$$

Where V is the difference in **potential energy** (per coulomb) between a charge at either end of contour C. This of course tells us how much **work** must be done (per coulomb) to move a charge from **one end** of the contour to the **other**.

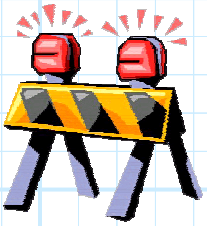
Of course V has units of **Volts**, but its more descriptive unit is **joules/coulomb**—energy per unit charge.

Therefore, the energy required to move a charge Q along some contour C can **likewise** be expressed as:

$$E = QV$$

Now, for our particular problem, the charge Q is either the charge of a **free electron** (Q_-) or the charge of a **hole** (Q_+).

The **voltage** (i.e., potential difference) across the depletion region is called the **barrier voltage** V_B (sometimes denoted V_0):



$$V_B = -\int_{C_{dr}} \mathbf{E}(\bar{r}) \cdot \overline{d\ell}$$

where the contour C_{dr} describes some contour **across** the depletion region.

Typically, we find that when the junction diode is **open** circuited (i.e., v_D=0 and i_D=0), this barrier voltage is approximately—**0.7 V** !

Thus, we find that the **energy** required for a **hole** to **diffuse** across the depletion region is:

$$E_B = Q_+ V_B$$

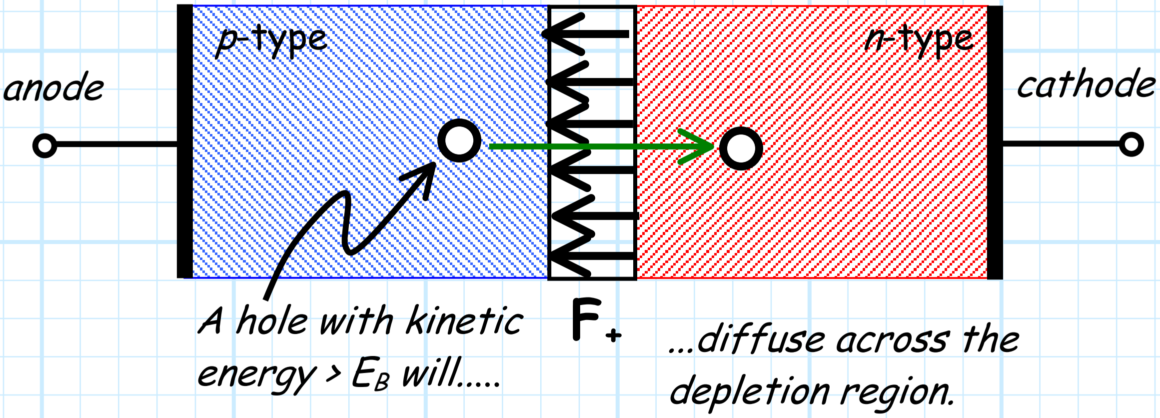
While the **energy** required for a **free electron** to **diffuse** across the depletion region is:

$$E_B = -Q_- V_B$$

Note that both these energies are the **same** (positive) value!

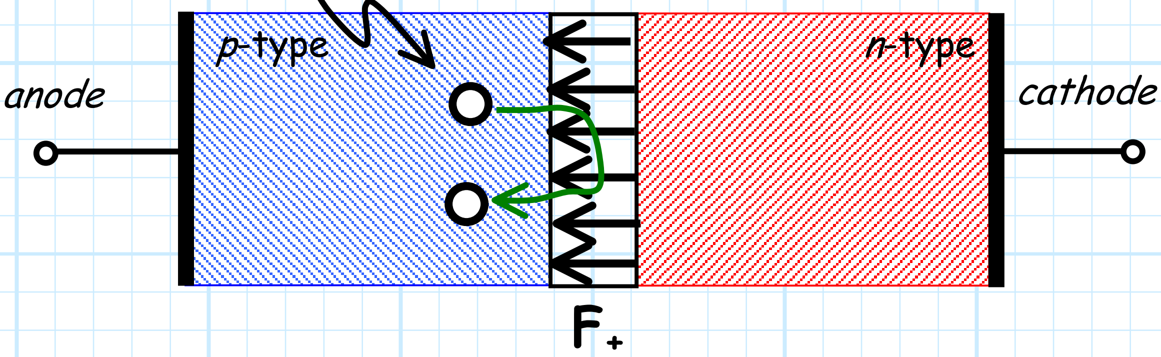
OK, here's the **important part**:

A. **If** the particle has kinetic energy **greater** than E_B, it can **diffuse** across the depletion region.



B. **If** the particle has kinetic energy **less** than E_B, then the electric field will "push" it **back** into either the *p*-type anode region (for holes) or the *n*-type cathode region (for free electrons).

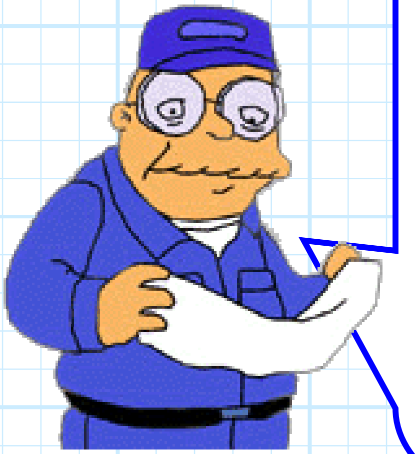
A hole with kinetic energy < E_B will.....



...be pushed back by the electric field (it will ***not*** *diffuse across the depletion region)!*

Thus, the diffusion current I_{Df} across the *p-n* junction will depend on three things:

1. **The majority particle concentration.** -The more holes or free electrons there are, the more particles will diffuse across the junction.
2. **The barrier voltage V_B.** – A lower barrier means less kinetic energy is required to diffuse across the depletion region, resulting in more.
3. **The diode temperature** – Higher temperature means holes and electrons have more kinetic energy and thus are more likely to diffuse across the depletion region.



Q: *Wait a minute! We've examined the behavior of holes in the p-type region and free electrons in the n-type region. These are the* ***majority*** *carriers for each of those Silicon types.*

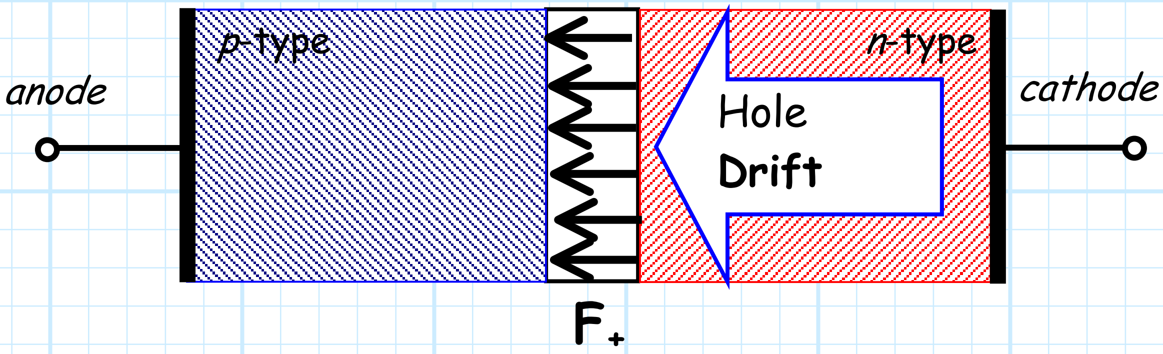
There are also ***minority*** *carriers present in each side. What does the electric field in the depletion region do to* ***them****?*

A: A great question! We will find that the electric field will have a profoundly **different** effect on **minority** carriers!

For **holes:**

Recall that the electric field in the depletion region applies a force on **positive** charges (holes) that is directed **from** the *n*-type (cathode) region **into** the *p*-type (anode) region.

This force of course **pushes** the holes in the *p*-type anode (the *majority* carriers) **back into** the *p*-type region. **However**, the same force will **pull** holes from the *n*-type region (the **minority** carriers) **into** the *p*-type region!



Any unsuspecting **minority** hole that "drifts" into the depletion region will from the *n*-type side will be **pulled** into the *p*-type side! Note that this result is **independent** of the kinetic energy of the particle—it takes **no** energy to "fall **downhill**".

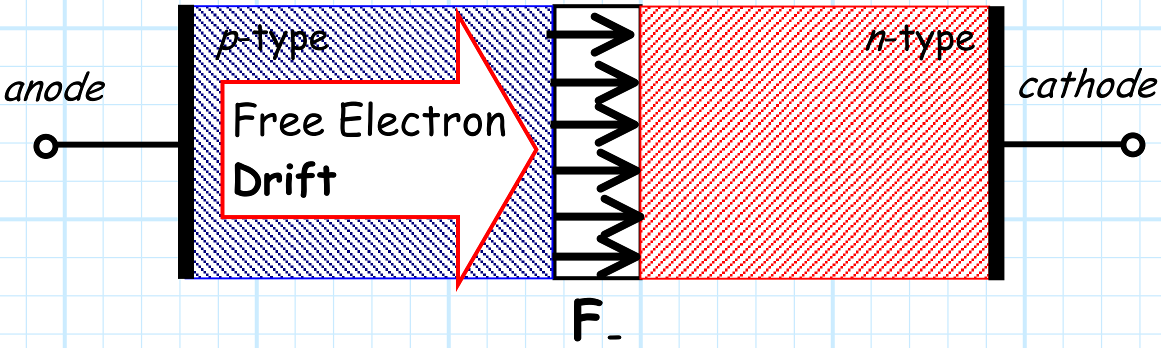
This movement of charge is completely **due** to the force applied by the **electric field**—this is **drift current** I_s!

Now, for **free electrons:**

Recall also that the electric field in the depletion region applies a force on **negative** charges (free electrons) that is directed **from** the *p*-type (anode) region **into** the *n*-type (cathode) region.

This force of course **pushes** the free electrons in the *n*-type region (the **majority** carriers) **back into** the *n*-type region.

However, the same force will **pull** free electrons from the *p*-type region (the **minority** carriers) into the *n*-type region!

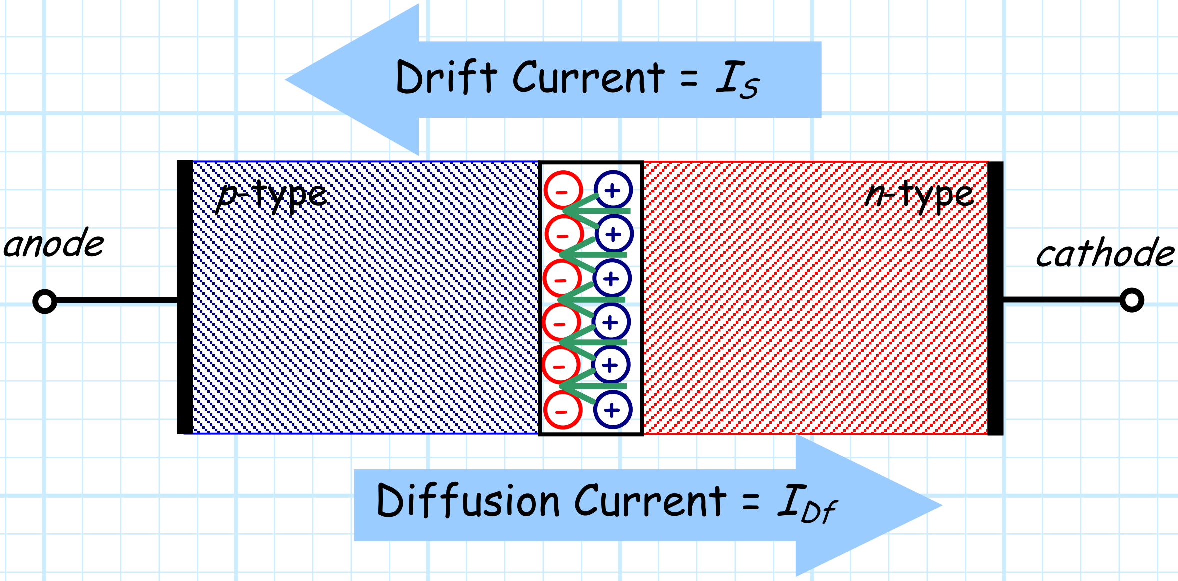


Any unsuspecting **minority** free electron that "drifts" into the depletion region will from the *p*-type side will be **pulled** into the *n*-type side! Note that this result is **independent** of the kinetic energy of the particle—it takes **no** energy to "fall **downhill**".

This movement of charge is completely due to the force applied by the **electric field**—this is also **drift current** I_S!

There are two very important **differences** between **drift** and **diffusion** currents in a *p-n* junction diode:

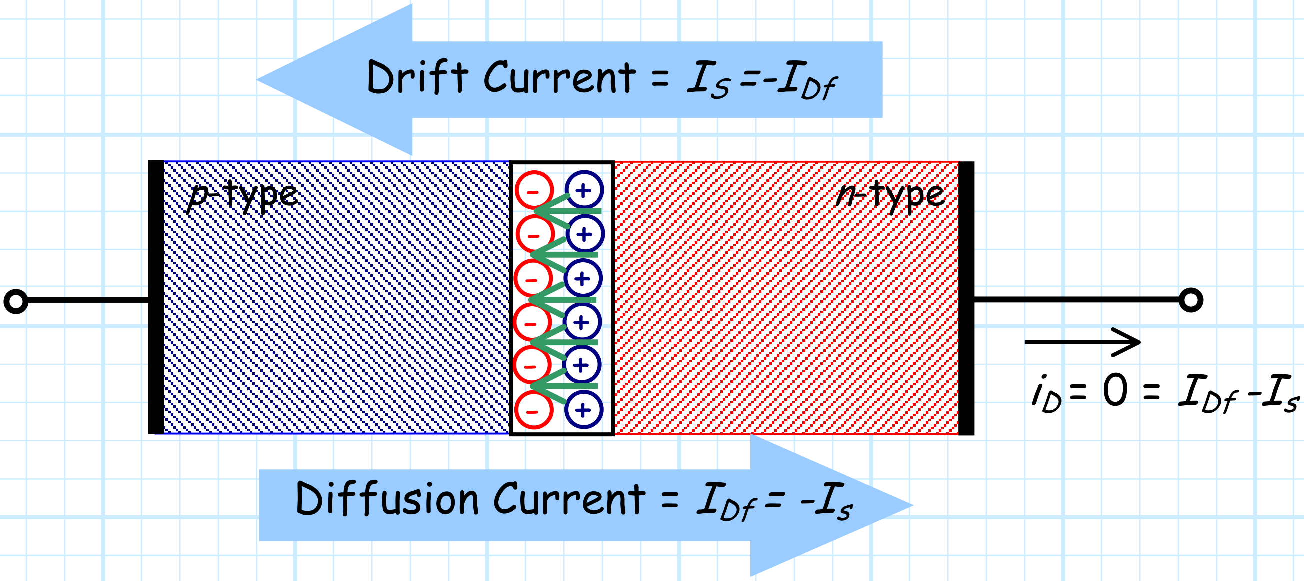
1. **Drift and Diffusion current flow in opposite directions –** The Diffusion current I_{Df} flows across the *p-n* junction from anode to cathode, while Drift current I_S flows across the *p-n* junction from cathode to anode.



2. Diffusion current depends on the barrier voltage V_B, but Drift Current does not. – As the barrier voltage increases, fewer and fewer of the majority carriers will have sufficient kinetic energy to cross the depletion region—the **diffusion** current will **decrease**.

Conversely, minority carriers require **no energy** to be swept across the depletion region by the electric field, the value of the **barrier voltage is irrelevant** to the value of drift current I_S.

Now, for an open-circuited (i.e., **disconnected**) junction diode, the **total current** i_D through the device **must be zero (i_D=0)**. In other words, the diffusion current I_{Df} must be **equal but opposite** that of the drift current I_S, such that $I_{Df} - I_S = 0$:



This is the **equilibrium** state of a **disconnected** junction diode. We find that typically this drift/diffusion current is **very small**, generally 10^{-8} to 10^{-12} Amps!