4.2 Terminal Characteristics of Junction Diodes

Reading Assignment: *pp. 173-179*

Now that we understand **ideal** diodes, let's consider the kind of diode that we **can** make—the ***p-n* junction diode**!

HO: The Junction Diode

We can describe **most** of the junction diode curve with an exact **mathematical** expression!

HO: The Junction Diode Equation

Let's look closer at this junction diode equation—there are **alternative ways** to express it!

HO: The Junction Diode Forward Bias Equation

Now we can analyze some(!) **circuits** with junction diodes.

Example: A Junction Diode Circuit

Finally, let's consider the **rate** at which diodes **absorb energy**!

HO: Diode Power Dissipation

The Junction Diode Curve

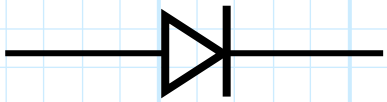
Junction diodes are **real** diodes!

We can **build** them and we can **buy** them and we can **insert** them in real **working** circuits!

In many ways, **junction** diodes are **similar** to **ideal** diodes.

But—in many **other** ways—junction diodes are **profoundly** different from their ideal counterpart.

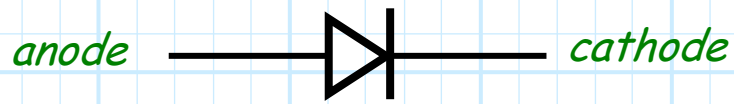
First, we note that a junction diode has a very **similar circuit symbol:**



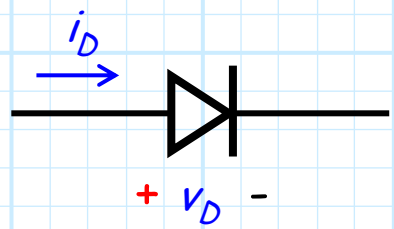
Thus, the junction diode is **asymmetric**!

Symbol and notation

The **names** of each terminal are **identical** to that of the ideal diode:



Likewise, the current-voltage **notations** are **very** similar (but **not** exact!) to the ideal diode:

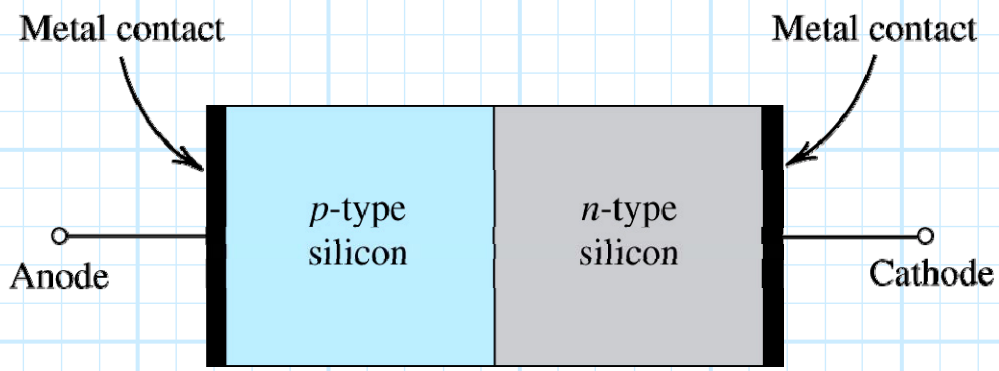


Why they call it a junction diode

Q: *You say that we can actually **make** these junction diodes? Of **what** are they made?*

A: They are made from **two types** of semiconductor material (usually **Silicon**), called ***p*-type** and ***n*-type**.

The region where the *p*-type Silicon and the *n*-typed Silicon touch is known as the ***p-n* junction**.



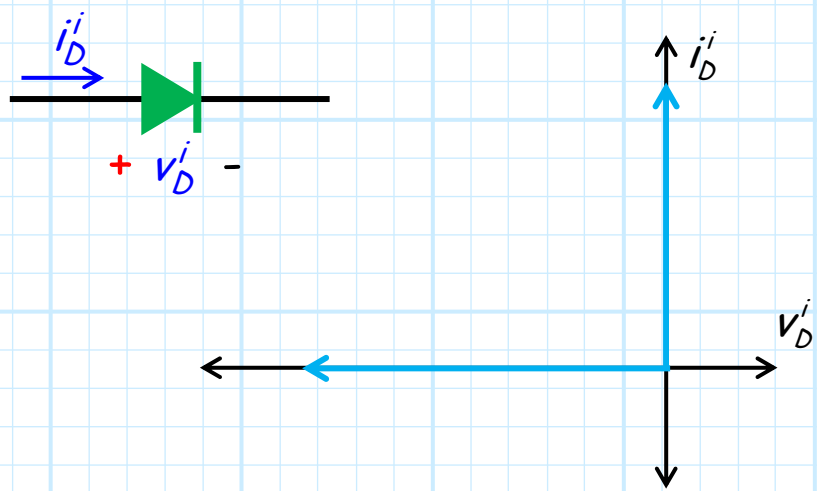
It is this ***p-n* junction** that gives junction diodes their **name**—and it is the **complex physical phenomena** that occur at the junction that gives the junction diode its **diode-like behavior**!

First recall the ideal diode

Q: *So what about its **device equation**—I suppose it is **non-linear**?*

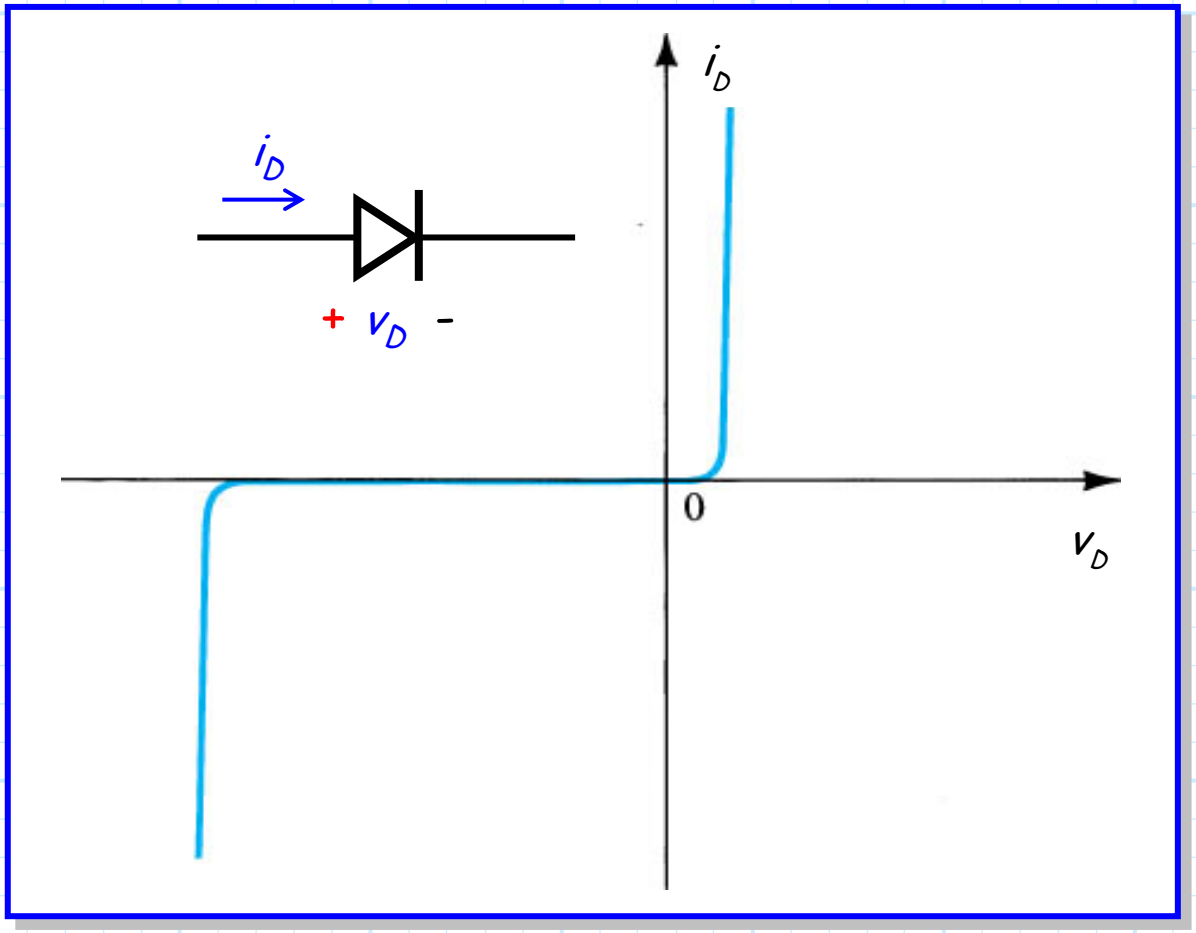
A: Absolutely!

Recall the behavior of the **ideal** diode could be plotted on the i,v plane as:



Now for the junction diode

Now, compare and contrast this with the behavior of a **junction diode**:



Note that **unlike** ideal diodes, this **junction** diode curve **is continuous**!

Trust me, you'll miss these annoying things

Q: *Great!*

*So we **don't** have those **annoying** piecewise linear equations, and we don't have those **annoying** conditions (i.e., inequalities), and most of all we don't have those **annoying bias modes**!?*

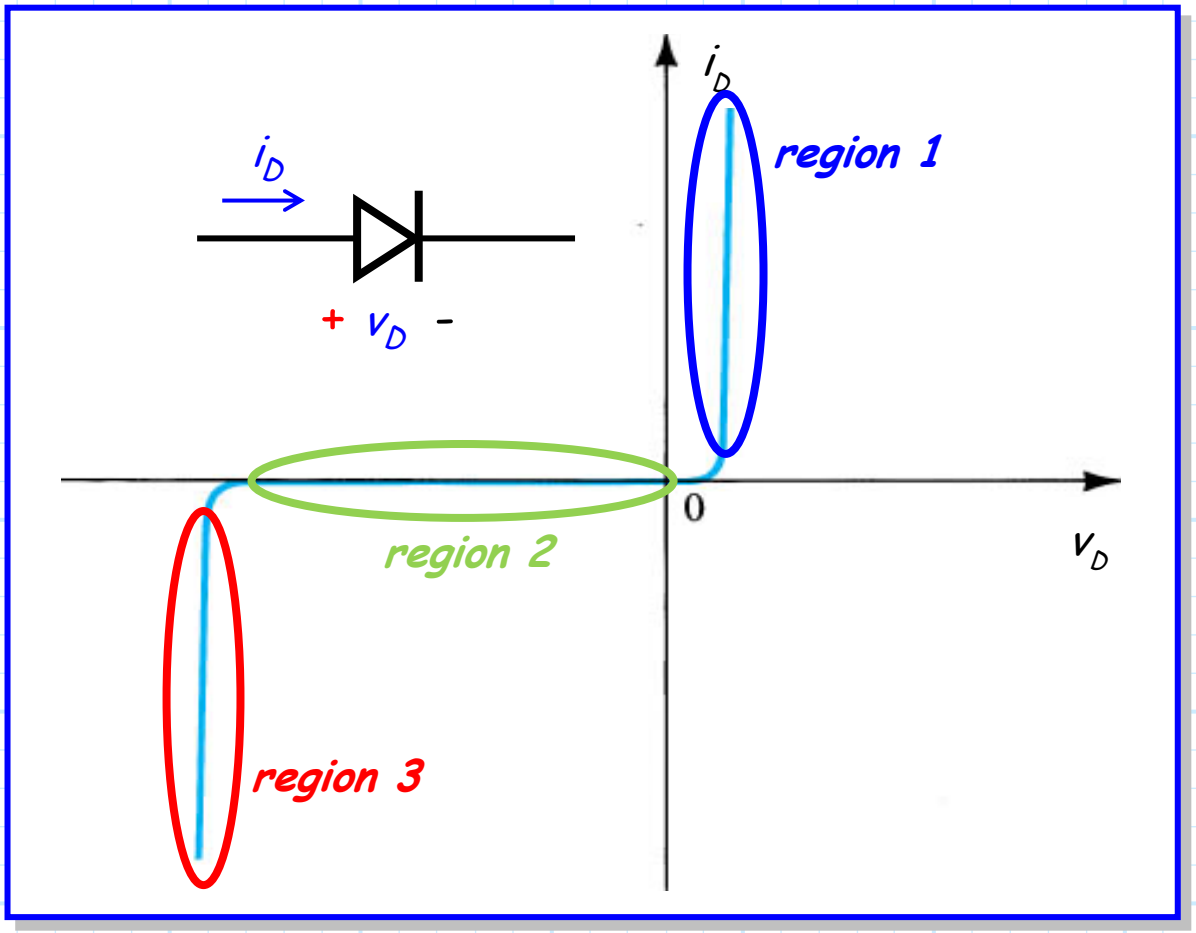
A: Yes **and** no.

We actually will find that all those annoying things you mentioned can actually **help** when analyzing circuits with junction diodes.

Thus, we tend to describe a **junction** diode in **ideal** diode terms!

3 Regions

For example, when we look at the **junction** diode curve, we can see **three** amorphous "**regions**", where the current/voltage relationships are distinctly different from each other.



Let's look at **each** of these three regions.

Region 1

In **this region** of the junction diode curve, we find that "significant" **positive current** (i.e., from anode to cathode) is flowing.

Likewise, we find that the **voltage** across the diode is a "**relatively" small**—but **positive**—value!

We will **find** that this "small" positive **voltage** (provided the junction diode current is significant) will be somewhere in the vicinity of **600 to 900 *mV***, for most junction diodes.

Moreover, we will see that this voltage is "**somewhat" constant**; it changes "**very little"** as the diode current increases.

➔ In other words, the curve in this region is "**nearly" vertical**!

Smells like forward bias

Q: *Hey! Doesn't this sound a little like a **forward biased ideal diode**?*

A: Indeed it **does**!

The current is positive, and the voltage is a (**approximately**) constant value that is **close** to a zero value.

Essentially, this **region** of the junction diode curve describes an **approximate** (i.e., non-ideal) version of the **forward bias mode**.

Thus, we call *region 1* of the *p-n* junction diode curve:

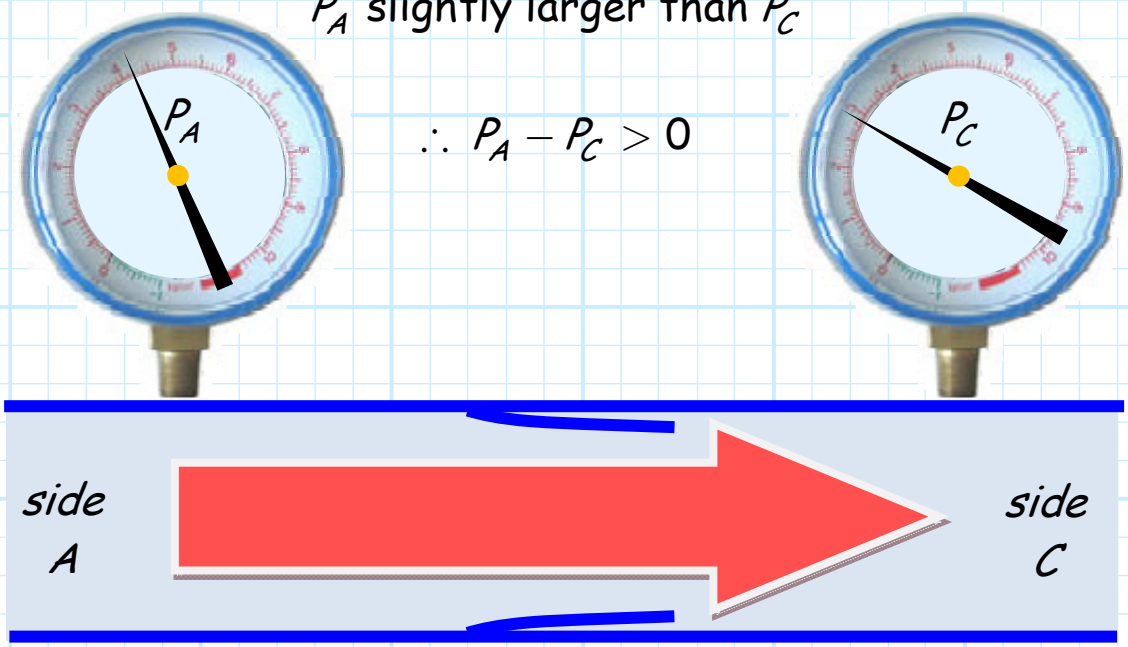
" The Forward Bias Region"

A mechanical analogy

From the standpoint of our **mechanical analogy**, it is if our flow valve requires a **little more pressure** at *side A* for it to **"pop-open"** and allow **current to flow**.

P_A slightly larger than P_C

$$\therefore\ P_A - P_C > 0$$



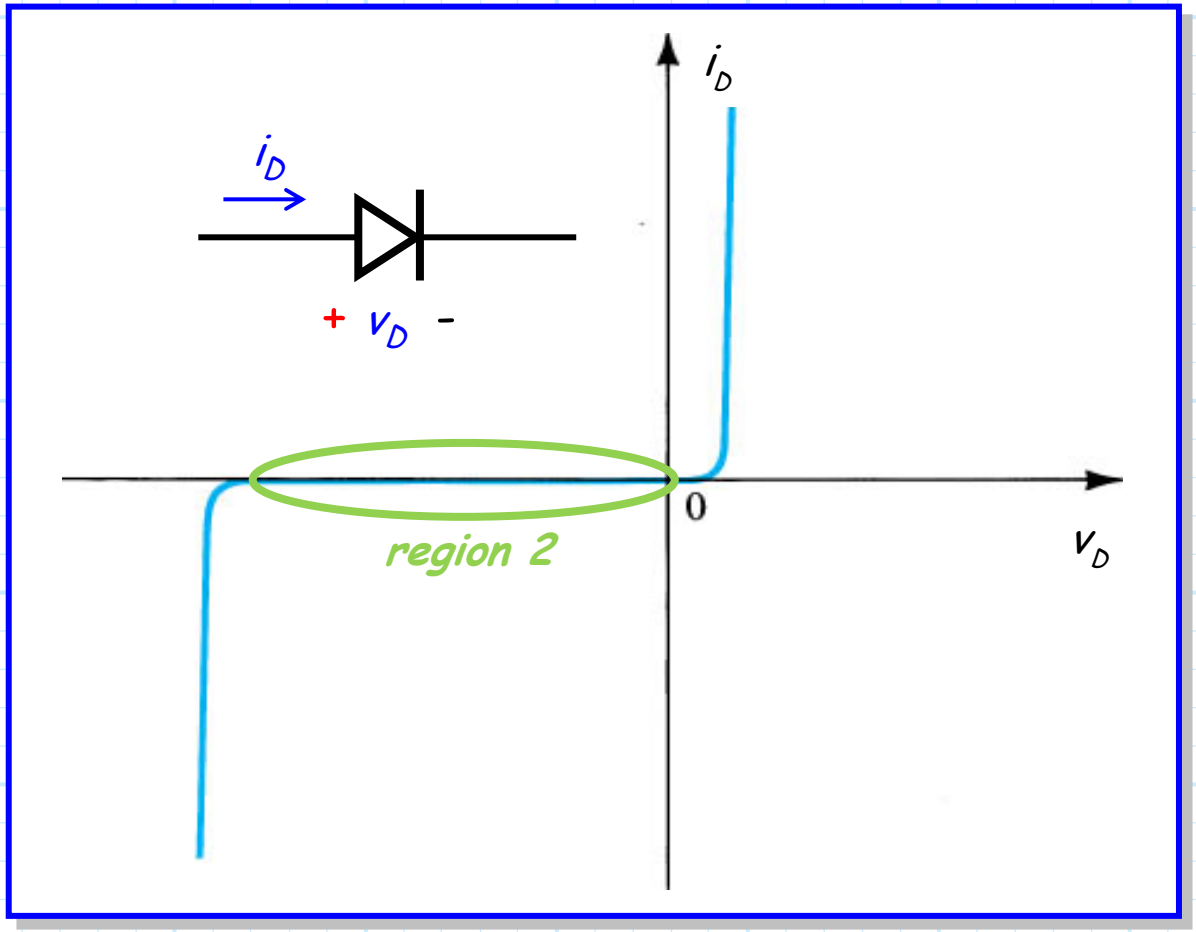
Similarly, we find that the **junction diode** requires a little more **potential** (i.e., voltage) at the **anode** in order for current to flow.

Region 2

In **this region** of the junction diode curve, we find that **almost no current** is flowing.

Q: *You say "almost" no current is flowing; doesn't this imply that there is **some** current flowing?*

A: Very astute—that's **exactly** what it implies!



There's negative current!

The *p-n* junction diode curve in this region **appears** to lie **precisely** on the v_D-axis; it **looks** like part of the $i_D = 0$ "curve".

But, appearances are deceiving, and if we look more closely, we find that it actually lies a "**tiny**" bit **below** the v_D-axis.

Q: ***Below*** *the* v_D*-axis!*

That means the current is ***negative****—it's flowing* ***from*** *the cathode* ***toward*** *the anode?*

A: Exactly correct!

But this **shouldn't** be too big of a **surprise**, as the voltage in this region of the junction diode curve is **negative** (i.e., non-positive).

Smells like reverse bias

Thus, in this region, the junction diode voltage is (mostly) **negative**, and the junction diode current is "**nearly**" zero.

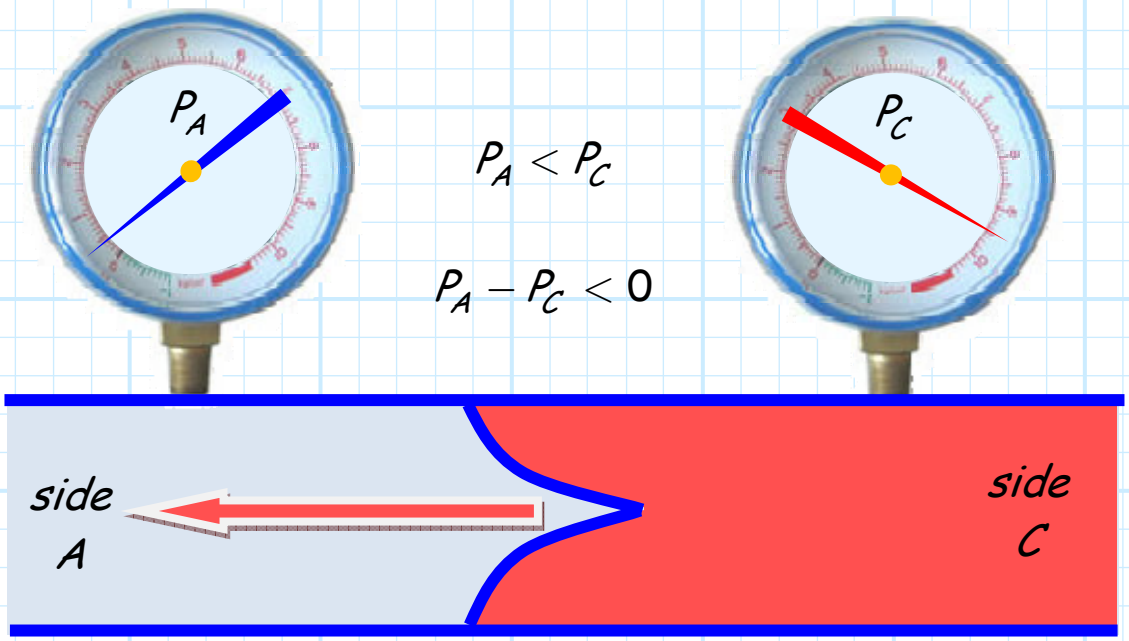
Essentially, this **region** of the junction diode curve describes an **approximate** (i.e., non-ideal) version of the **reverse bias mode**.

Thus, we call *region 2* of the *p-n* junction diode curve:

" The Reverse Bias Region"

Mechanical Analogy

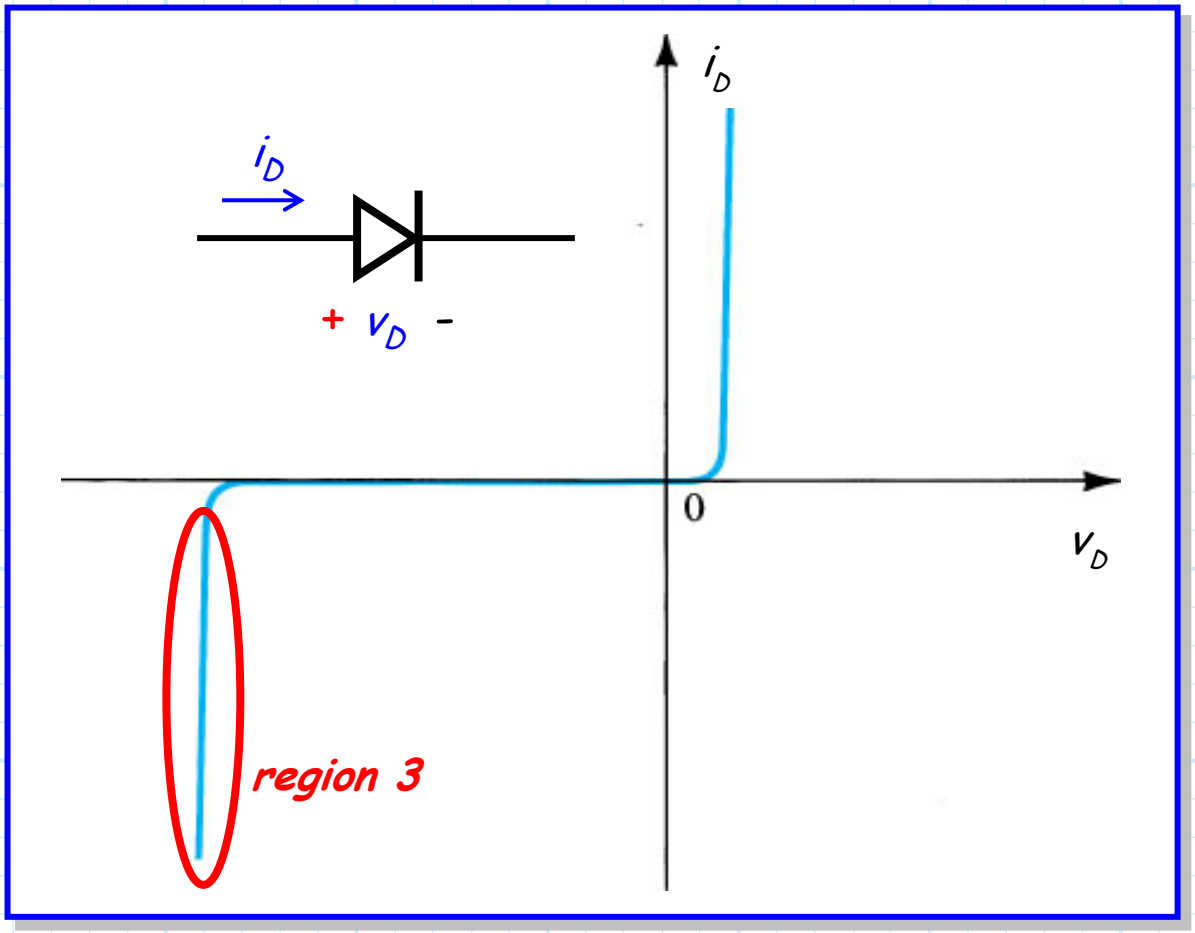
From the standpoint of our **mechanical analogy**, it is if our flow valve **leaks** (a tiny bit) when there is more pressure at the *side C* then *side A*—when the flow value is **shut**.



Similarly, **if** we find that the **junction diode** "leaks" a little current from anode to cathode, then its voltage is **negative**.

Region 3

In **this region** of the junction diode curve, we find that there is "**significant**" **negative current** flowing!



This negative current can be relatively "small", **or** it can be large—but it must be **negative**!

We've not seen this before!

Q: *What about the **voltage**?*

A: In this region, the diode voltage is "**very**" **negative** (e.g., -30 to -60 Volts!).

Moreover, this negative voltage is "approximately" **constant** with respect to current—more negative current causes only a "**tiny**" **change** in the diode **voltage**.

Q: *The voltage across the diode is "**nearly**" **independent** of the current through it—it sounds like a (negative) **voltage source**!*

A: **Very much** like one.

But remember, the current must be **negative**.

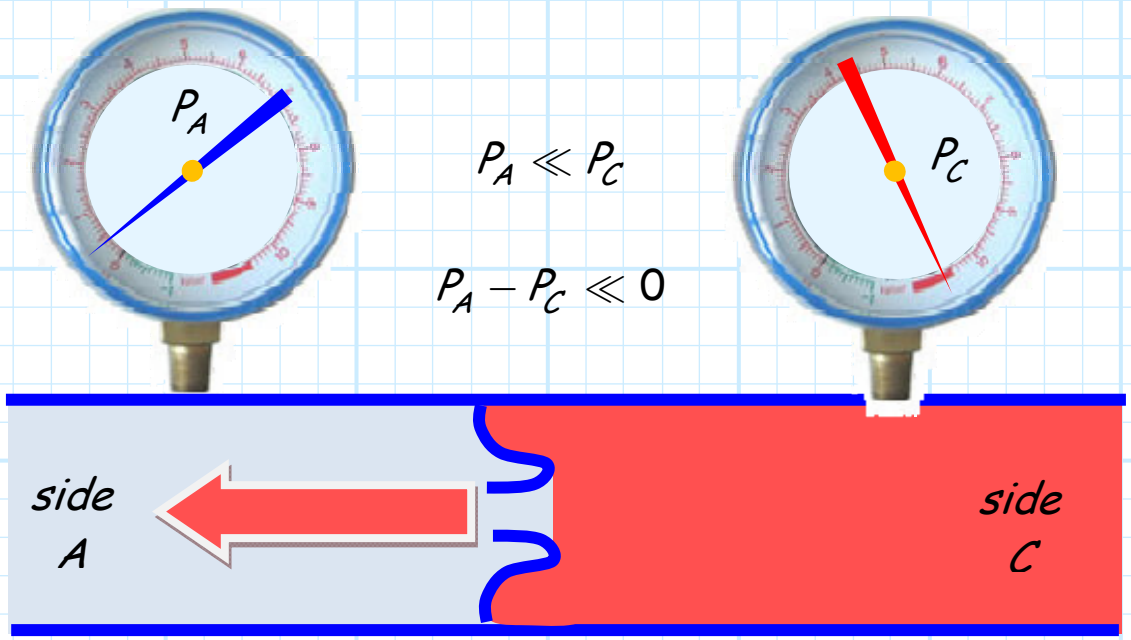
Q: *OK, I don't see how this is **anything** like **ideal** diode behavior.*

A: It's **not**! This is the **most** non-ideal of the three junction diode regions—it has **no** analogy to ideal diode behavior **what-so-ever**!

Mechanical Analogy

From the standpoint of our **mechanical analogy**, it is as if we have placed too much reverse pressure across our flow valve.

Instead of **leaking** just a bit, the valve sort of "**blows a gasket**", and the valve **pops open**. As a result, current flows in "significant" quantities from *side C* to *side A* !



The Breakdown region

Similarly, for the junction diode, if we place "**too much**" negative voltage across the device, "significant" **negative current** will begin to flow.

As a result, we call *region 3* of the *p-n* junction diode curve:

" The Breakdown Region Bias Region"

Q: *So, **if** a junction diode enters breakdown, it is **destroyed**?*

A: Nope! Not unless it **melts**.

It's not as bad as it sounds

Once we **reduce** the negative voltage, the junction diode will **revert back** to the "reverse bias region", or even the "forward bias region"—breakdown is **not as bad** as the **name** suggests!

Q: So, provide me with the **precise** mathematical boundaries, that **unambiguously** delineates when a junction diode is unequivocally in either:

1. Forward bias mode
2. Reverse bias mode
3. Breakdown mode

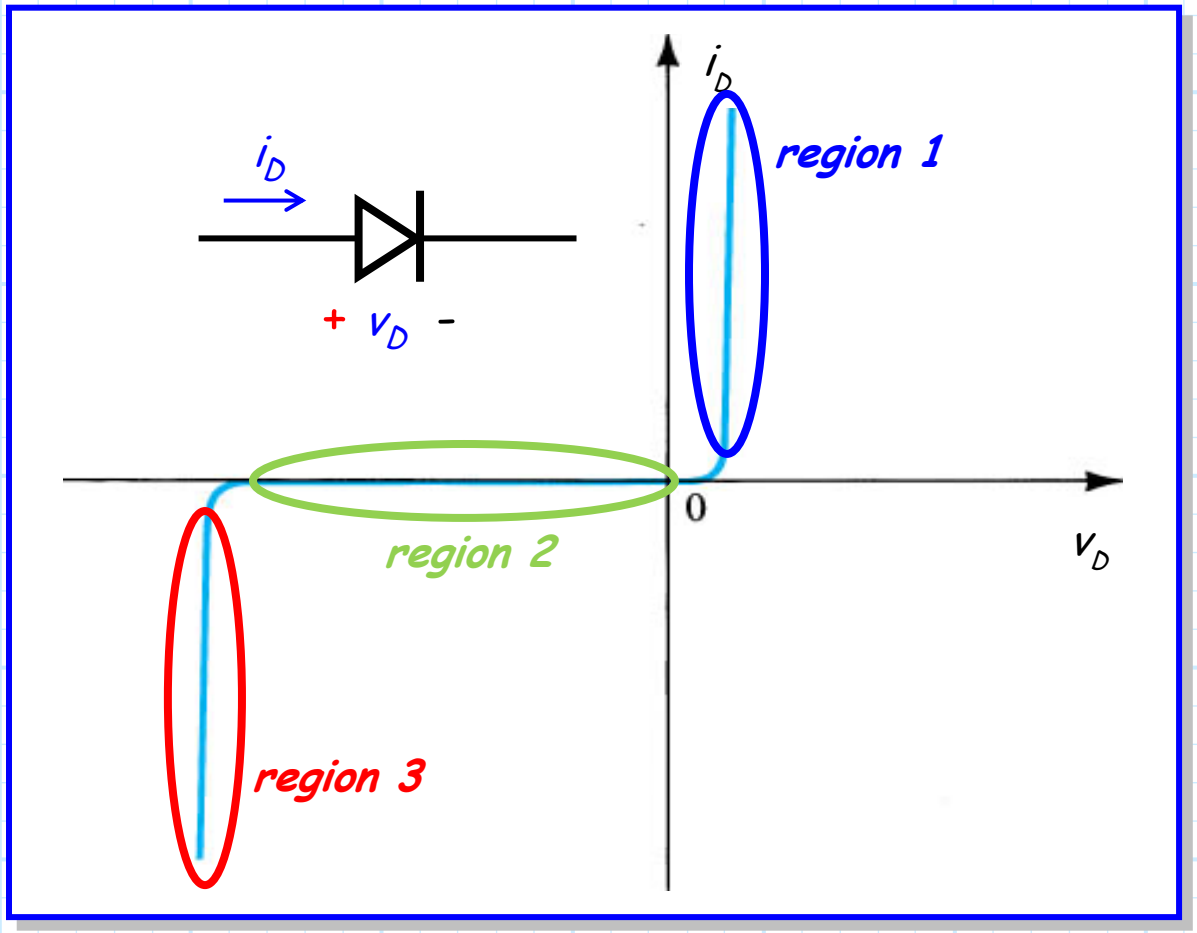
A: Whoa, whoa, whoa!!!!!!!

We **can't** do this—your thinking about this **all wrong**.

Remember, the junction diode curve is **continuous**; there are **no** well-defined **boundaries** between the "forward bias region" of this continuous curve, **or** the "reverse bias region" of this continuous curve, **or** the "breakdown region" of this continuous curve.

Ambiguity

There are **"regions"** of this continuous curve where specific characteristics **can** be ascribed (e.g., diode current is positive), but where one region ends and another starts is a bit **ambiguous**.



For example

For **example**, let's say we measure the **voltage** across and **current** through **three** identical junction diodes that occupy three **different locations** in an **operating** DC circuit.

For the **first** junction diode we measure:

$$v_{D1} = 0.67\ V \qquad and \qquad i_{D1} = 231\ mA$$

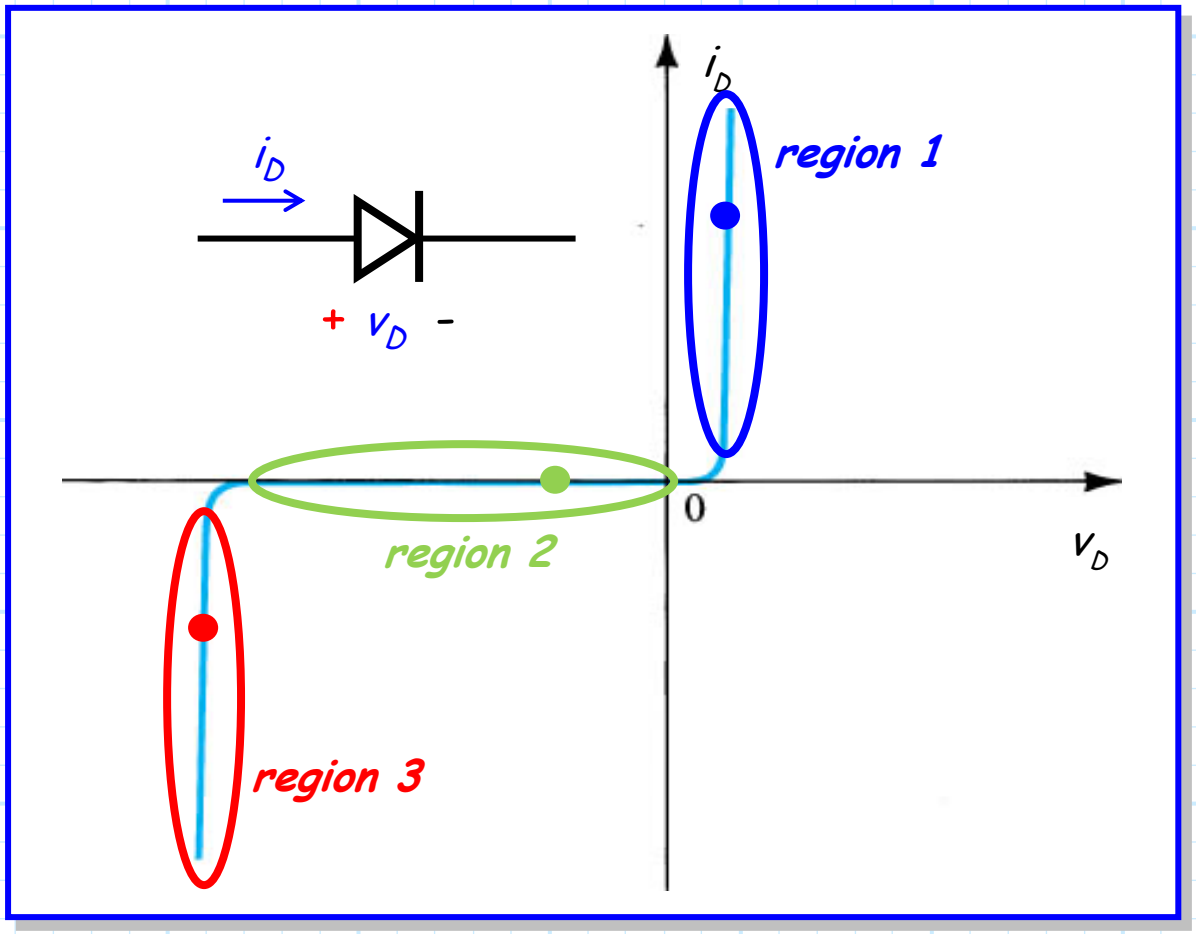
For the **second** we measure:

$$v_{D2} = -12.7\ V \qquad and \qquad i_{D2} = -12\ \mu A$$

And for the **third**:

$$v_{D3} = -52.0\ V \qquad and \qquad i_{D3} = -69.1\ mA$$

Clearly!



What regions mean

Hopefully it is clear to you that:

the **first** junction diode measurement lies in the "***forward bias region*** " of the continuous junction diode curve,

the second measurement lies in the "***reverse bias region***" of the continuous junction diode curve,

and the third measurement lies in the "***breakdown region***" of the continuous junction diode curve.

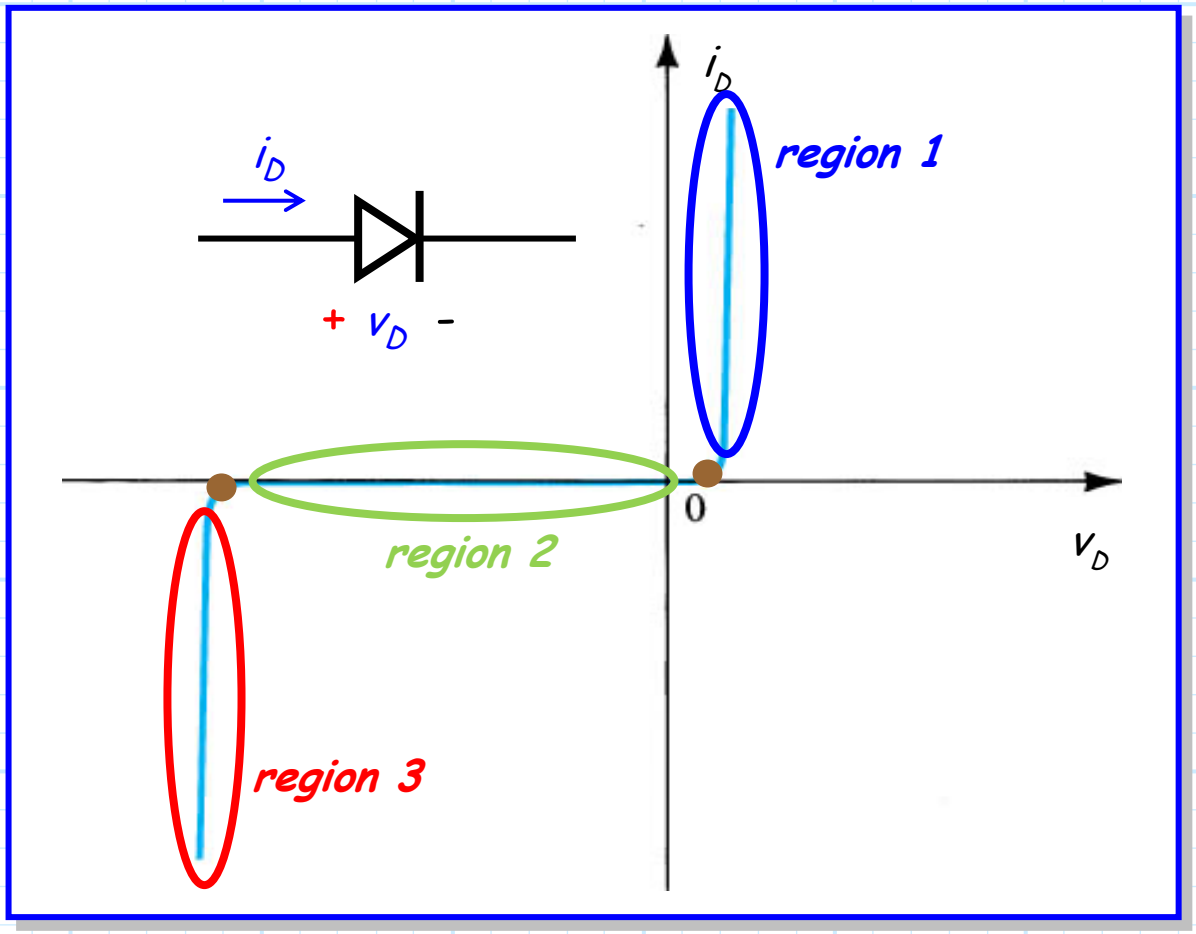
Here's the problem

Now consider **two more** measurements:

$$v_{D4} = 0.31\,V \qquad and \qquad i_{D4} = 0.07\ mA$$

$$v_{D5} = -51.7\,V \qquad and \qquad i_{D5} = -0.23\ mA$$

Neither of these two points lie unambiguously in any of the 3 "regions", rather they lie in the **transition "knee"** between two regions.



Those darn bunny ears

The fourth measurement is **sort of** between the forward and reverse bias "regions", while the fifth is **kind of** between the breakdown and reverse bias regions.

We could argue, for example, that the forth measurement is **simultaneously** in the forward **and** reverse bias region, or we could argue that it lies in **neither**.

Basically, the problem is determining when **"tiny"** becomes **"significant"**, and vice versa.

Q: *So what's the **point?** You've been **"bunny-earing"** almost every phrase in the handout: "almost", "tiny", "significant", "nearly", "too much"— are we studying circuits or **poetry?***

A: We engineers often find **approximations** to be quite helpful in solving difficult problems, even if they do introduce **"a little" error**.

Get used to it

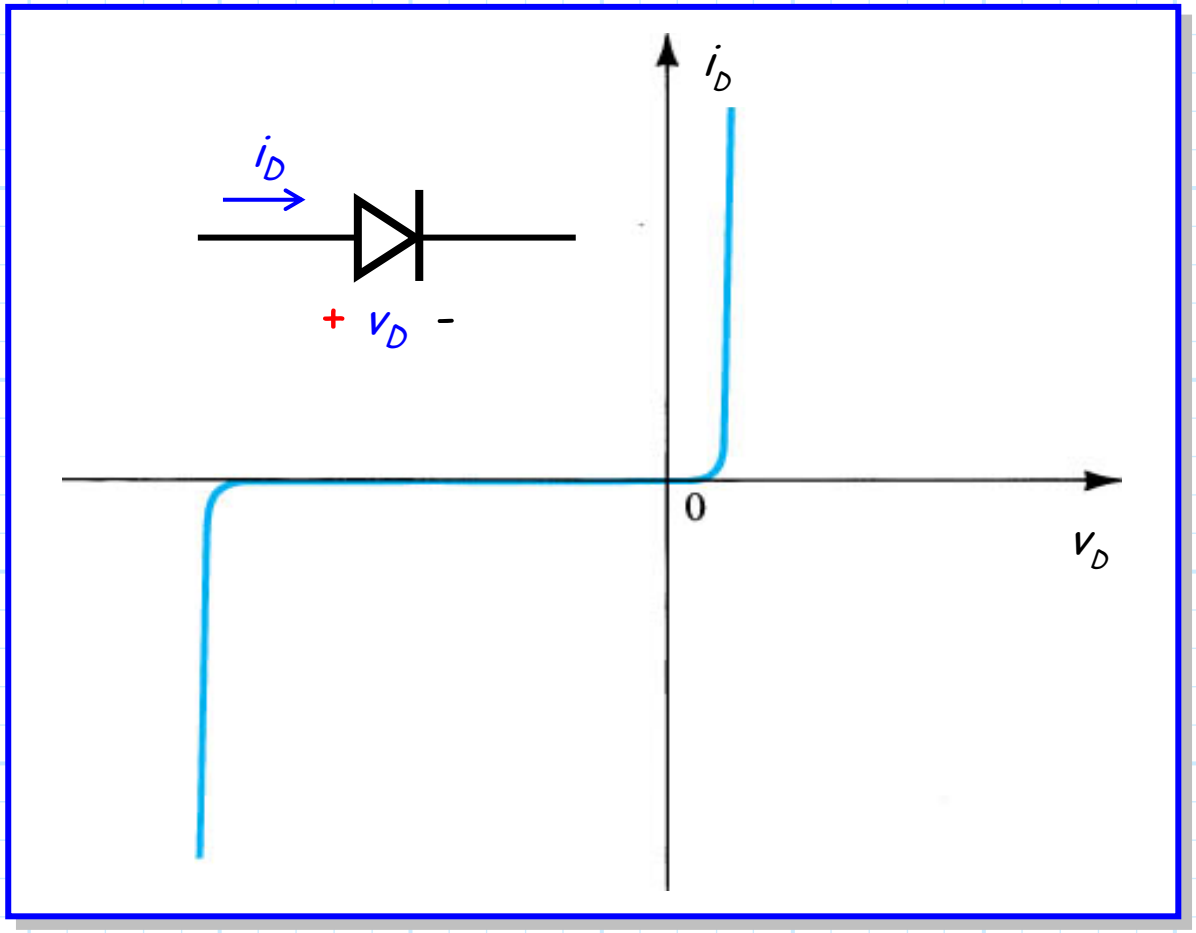
But, this **ambiguity** about what kind of error is "acceptable" can **frustrate** students—what if this error results in lost **points** on an exam?

You'll have to learn to **accept** some ambiguity as we learn about **junction diodes**.

WE **must** make approximations in order to "easily" analyze junction diode circuits, and these **approximations** will use the **definable characteristics** of these **three regions** of the junction diode curve!

The Junction Diode Equation

Q: *OK, you have explained the relationship between junction diode current and junction diode voltage using this elegant **plot**:*



Here's the math

*But, **I'm** an engineer; **I** need to determine **numbers**—values like* $i_D = 234\,mA$ *and* $v_D = 0.68V$ *.*

➔ *I need the **mathematical** relationship between* i_D *and* v_D*!*

A: You sure do! The relationship between the **current** through a **junction diode** (i_D) and the **voltage** across it (v_D) is:

$$i_D = I_s\left(e^{v_D/nV_T} - 1\right) \quad \text{for} \quad v_D > -V_{ZK}$$

Q: *Good **golly**! Just what do those **dog-gone** parameters* n, I_s, V_{ZK} *and* V_T *mean?*

A: Similar to the resistance value R of a resistor, or the capacitance C of a capacitor, there are **three** parameters that specify the performance of a **junction diode**.

Device parameters

Specifically, the three parameters are:

1. $I_s \doteq$ **Saturation** (or scale) **Current**. This value depends on diode material, size, and most of all—**temperature**. This value typically doubles for every 10 degree C increase in temperature!

Typical values range from **10^{-8} to 10^{-15} Amps** (i.e., **tiny**)!

2. $n \doteq$ a constant called the **ideality factor** (i.e. a "fudge factor").

Typically, this ideality factor is between **one and two** (i.e., $1 \le n \le 2$), but is usually **close to one** (e.g., $n = 1.2$).

If the ideality factor is not specified, then we use the nominal value of $n = 1.0$.

Thermal voltage is not a device parameter

3. $V_{ZK} \doteq$ **Zener Breakdown Voltage.** When the junction diode is operating in the **breakdown** region, the diode voltage is **approximately** $v_D = -V_{ZK}$.

For **example**, if the zener breakdown voltage of a junction diode is $V_{ZK} = 37V$ then, when in **breakdown**, that junction diode will exhibit a voltage of $v_D = -37V$.

Q: *What about this parameter V_T? Why did you not include it among the three* ***device parameters?***

A: The **thermal voltage** $\doteq V_T$ is **not** a device parameter, it is a **physical** parameter.

Lots of physics

Specifically, the thermal voltage is determined from three important **physical values**:

$$V_T = \text{Thermal Voltage} = \frac{kT}{q}$$

Where:

k = Boltzman's Constant
T = Diode Temperature ($^\circ$K)
q = Charge on an electron (coulombs)

At **room temperature** (approximately 20 $^\circ C$), we find the thermal voltage has a value of:

$$\boxed{V_T \approx 25\ mV \quad \text{at } 20\ ^\circ C,}$$

IMPORTANT NOTE!: Unless **otherwise** stated, we will **assume** that each and every junction diode is at **room temperature** (i.e., $T = 20^\circ\ C$).

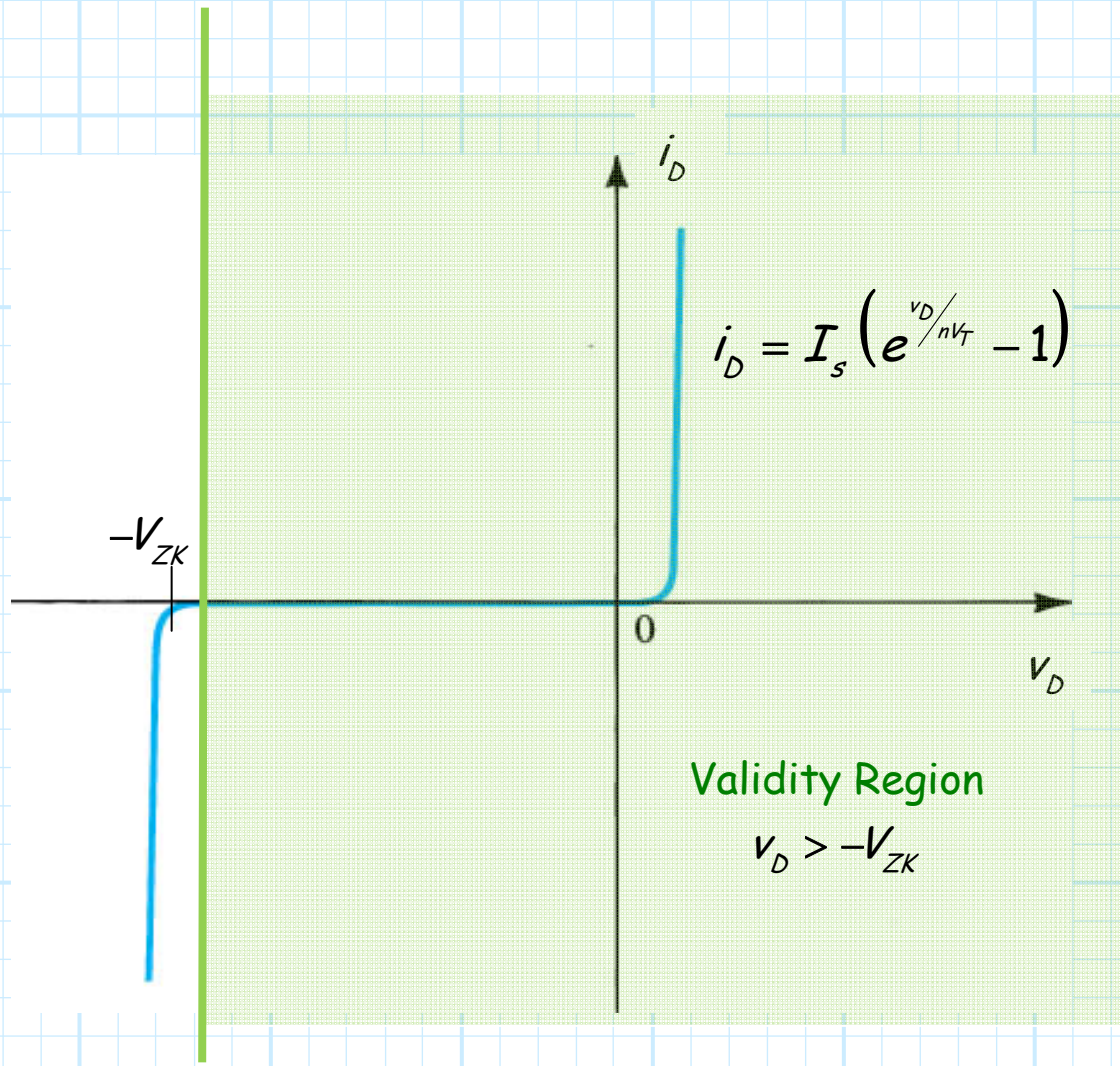
Thus, we will almost **always** assume that the **thermal voltage** V_T of **all** junction diodes is **25 mV** (i.e., $V_T = 25$ mV)!

Not if its in breakdown

Q: *The junction diode equation appears to be* ***conditional****—it includes the statement:*

"for $v_D > -V_{ZK}$"

A: That's correct; the equation is **not valid** in the breakdown region!



Correct for *almost* everything!

Q: *So you're saying that the equation:*

$$i_D = I_s \left(e^{\frac{v_D}{nV_T}} - 1 \right)$$

is valid for both the ***reverse*** *and* ***forward*** *bias regions?*

A: **Both** those regions—**and** the **transition region** between them!!!!

This junction diode equation is valid for **any** and **all** junction diode voltages that are significantly **larger than** $-V_{ZK}$.

This first term is diffusion current

Now, let's **look closer** at the equation:

$$i_D = I_s\left(e^{\frac{v_D}{nV_T}} - 1\right)$$

We rewrite it explicitly with **two terms**:

$$i_D = I_s e^{\frac{v_D}{nV_T}} - I_s$$

These two terms each have a very important **physical meaning**.

The **first** term is called the **diffusion current** i_{diff}:

$$i_{diff} = I_s e^{\frac{v_D}{nV_T}}$$

Note that diffusion current **is** a function of junction diode **voltage** v_D!

The second is drift current

The **second** term is called the **drift current** i_{drift}:

$$i_{drift} = -I_s$$

Three things to note about drift current:

1. Drift current is **negative**—it flows from cathode to anode!
2. Drift current is **very small** (e.g., nano-amps or smaller).
3. Drift current is a **constant**—it is **independent** of junction diode voltage v_D!

Thus, we can express **junction diode current** as:

$$\begin{aligned} i_D &= i_{diff} + i_{drift} \\ &= I_s e^{\frac{v_D}{nV_T}} - I_s \end{aligned}$$

Consider diffusion current

Now let's examine **diffusion current**, as it very much **depends** on diode voltage!

Let's consider **three** cases:

1. the junction diode voltage is several times **lower** (i.e., more negative) than the thermal voltage $V_T = 0.025\,V$. I.E.:

$$\frac{V_D}{V_T} = \frac{V_D}{0.025} \ll -1$$

2. the junction diode voltage is **zero**.

3. the junction diode voltage is several times **higher** (i.e., more positive) than the thermal voltage $V_T = 0.025\,V$. I.E.:

$$\frac{V_D}{V_T} = \frac{V_D}{0.025} \gg 1$$

If the voltage is negative

Note that the diffusion current is **exponentially related** to the junction diode voltage:

$$i_{diff} = I_s e^{\frac{v_D}{nV_T}}$$

Now for the **first case**, where the junction diode voltage is **negative** by a value several time the thermal voltage.

Let's assume, **for example**, that the junction diode voltage is:

$$v_D = -10\,V_T = -0.25\,V$$

This voltage is **barely** "south of" zero, yet look what it does to diffusion current (assume n =1):

$$i_{diff} = I_s e^{\frac{-10V_T}{V_T}} = I_s e^{-10}$$

Almost no diffusion current!

Remember, scale current I_s is a **really** small value, and e^{-10} is likewise a **really** small value.

> The product of a **really** small number and another **really** small number is a **really, really** small number!!

In other words, the diode **diffusion** current is **essentially zero if** the junction diode voltage is **negative**!

Thus, for this **first case**, we find that the junction diode current is:

$$i_D \cong 0 + i_{drift} = i_{drift} = -I_s \qquad for \quad \frac{v_D}{V_T} \ll -1$$

Thus, there is a **tiny amount** of current flowing from **cathode** to **anode**!

Smells like the reverse bias region

Q: *Hey!* ***You*** *said that there was the* ***same*** *tiny amount of negative current flowing when in the* ***reverse bias*** *"region"!*

A: That's right!

And in the reverse bias region, the diode voltage is **negative**.

This case describes the **reverse bias region**—the **diffusion** current is **zero**.

Voltage is zero

For the **second case** (where the diode voltage is **zero**), we find that the **diffusion** current is:

$$i_{diff} = I_s e^{\frac{0}{V_T}} = I_s e^0 = I_s$$

When $v_D = 0$, the **diffusion** current is **equal** to the **scale** current I_s!

Q: *Wow!*

*Current flows through a junction diode **when no voltage** is placed across it?*

A: **Not so fast** my friend!

The currents cancel

When the junction diode voltage is **zero**, we find that the **diffusion** current is **non-zero**:

$$i_{diff} = I_s$$

And of course the **drift** current (being independent of v_D) is its **non-zero** value:

$$i_{drift} = -I_s$$

But the diode current i_D is the **sum** of these two currents:

$$i_D = i_{diff} + i_{drift} = I_s - I_s = 0 \qquad for\ v_D = 0$$

The diffusion current for this case is "equal but **opposite**" the drift current—the net result is **no current flow**!

Voltage is postive

Now, for the **final case**, the junction diode voltage is several times **larger** (more positive) than the thermal voltage.

Let's assume (**for example**) that:

$$v_D = +10\,V_T = +0.25\,V$$

The resulting **diffusion** current is:

$$i_{diff} = I_s e^{\frac{+10V_T}{V_T}} = I_s e^{+10}$$

Note that e^{+10} is a **very big number**!

As a result, the magnitude of the diffusion current is **orders-of-magnitude** larger than drift current $\left|i_{diff}\right| \gg \left|i_{drift}\right|$, such that we can **ignore the drift current** term:

$$i_D = i_{diff} + i_{drift} \cong i_{diff} = I_s e^{\frac{v_D}{nV_T}} \qquad for \quad \frac{v_D}{V_T} \gg 1$$

How do we make diffusion current large?

Q: *So you're saying the diffusion current is very large?*

A: Nope!

Remember the scale current I_s is **exceedingly small** (e.g., pico-amps).

Thus for this example ($v_D = +0.25\,V$), we find that although the resulting **diffusion** current is many orders-of-magnitude larger than I_s, it is still **not particularly significant**.

Q: *Yikes!*

*Is there **no way** to get a **significant** junction diode current?*

A: Note we used as our example $v_D = +0.25\,V$, this voltage is just **slightly** "north" of zero!

Let's **continue to increase** the junction diode current and **see what happens**!

That woman used to terrify me

Example: $I_s = 10^{-13} A$, $n = 1$

v_D [Volts]	i_D
0.4 0.9	μA
0.5 0.05	mA
0.6 2.6	mA
0.7 140	mA
0.8 7.9	A
0.9 431.1	A → I'm melting!

Look **closely** at what occured!

At $v_D = 0.5\,V$, the diode current was an **insignificant** 50 μA.

Yet, when the junction diode voltage is increased by **just** another 400 mV—to a value $v_D = 0.9\,V$—the junction diode current increases to an **implausible** 431 Amps!

Some surprisingly useful approximations

Therefore, we conclude that a junction diode with **"significant"** but **"plausible"** current will exhibit a diode voltage in the **narrow region** between "about" 600 and 800 mV:

$$0.6\ V < v_D < 0.8\ V \qquad \text{for significant yet plausible } i_D$$

Q: *That's **not much** of variation; why don't we just call it $v_D = 0.7\ V$ and be done with it?*

A: We often do just **exactly that**!

A **simple** but surprisingly **accurate approximation** for the **forward bias** region of a junction diode is:

$$v_D \cong 0.7\ V \qquad \text{for significant yet plausible } i_D$$

Don't forget: It's an APPROXIMATION!

Some important things to **note** about this approximation:

1. It's just an **approximation**!

The junction diode voltage is **not exactly** 700 mV, it's just somewhere **near** (i.e., $\pm 100\ mV$) this value.

If the diode current is relatively **small,** then the junction diode voltage will be **slightly less** than 0.7 V; relatively **large**, and it will be **slightly more** than 0.7 V.

2. This is a **subjective** approximation.

Some engineers (and text books) use a value of **0.65 V**, while others might use 0.6 V or 0.75 V.

The Junction Diode Forward Bias Equation

For the **forward bias region**, we have learned that the diode current i_D can be related to the diode voltage v_D using the following **approximation**:

$$i_D = I_S \left(e^{\frac{v_D}{nV_T}} - 1 \right) \approx I_S \, e^{\frac{v_D}{nV_T}},$$

provided that $v_D / V_T \gg 1$.

An advantage of this approximation is that we can easily **invert** it, so that we can express **voltage** v_D in terms of junction diode **current** i_D:

$$I_S e^{\frac{v_D}{nV_T}} = i_D$$

$$e^{\frac{v_D}{nV_T}} = \frac{i_D}{I_S}$$

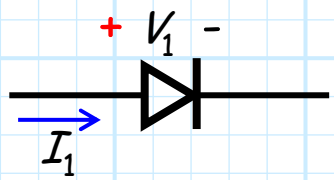
$$\frac{v_D}{nV_T} = \ln\left(\frac{i_D}{I_S} \right)$$

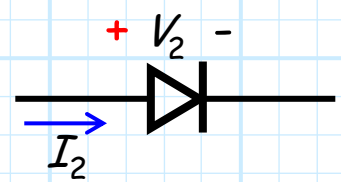
$$v_D = nV_T \ln\left(\frac{i_D}{I_S} \right)$$

You remember: log(x) – log(y) = log(x/y)

Now, say a voltage $v_D = V_1$ across some junction diode results in a current $i_D = I_1$.

Likewise, a **different** voltage $v_D = V_2$ across this **very same** diode will (of course) result in a **different** current $i_D = I_2$.





We can define the **difference** between these two voltages as $\Delta v_D = V_2 - V_1$, and then using the "inverted" forward bias equation to express this voltage difference as:

$$\begin{aligned}
\Delta v_D &= V_2 - V_1 \\
&= nV_T \ln\left(\frac{I_2}{I_S}\right) - nV_T \ln\left(\frac{I_1}{I_S}\right) \\
&= nV_T \ln\left(\frac{I_2}{I_S}\frac{I_S}{I_1}\right) \\
\Delta v_D &= nV_T \ln\left(\frac{I_2}{I_1}\right)
\end{aligned}$$

Where the heck did I_s go?

Yikes! **Look** at what this equation says: $\Delta v_D = nV_T \ln\left(\frac{I_2}{I_1}\right)$

* The **difference** in the two voltages is dependent on the **ratio** of the two currents.

* This voltage difference is **independent** of scale current I_s.

For **example**, say that the second current is 10 times the first:

$$I_2 = 10 I_2$$

Assuming $n = 1$, we find that the **difference** in junction diode voltage is:

$$\Delta v_D = nV_T \, ln\left(\frac{I_2}{I_1}\right) = V_T \, ln(10) = 0.058V$$

Think about what this means!

58mV per decade

It means that each time we increase the junction diode current one whole **order-of-magnitude**, the junction diode voltage increases just a **measly 58** mV!

Thus, if a junction diode with a voltage $v_D = 0.6V$ exhibits a current of 1.0 mA, we can **quickly** determine the diode voltage for a current of 10mA, 100 mA, 1.0 A and 10.0 A:

$i_D\,(mA)$	$v_D\,(V)$
1.0	**0.6**
10.0	**0.658** = 0.6 + (1)0.058
100.0	**0.716** = 0.6 + (2)0.058
1,000.0	**0.774** = 0.6 + (3)0.058
10,000.0	**0.832** = 0.6 + (4)0.058

Really, you'll thank me later

We can likewise **invert** the above equation and express the ratio of the two currents in terms of the difference of the two voltages:

$$nV_T \ln\left[\frac{I_2}{I_1}\right] = V_2 - V_1$$

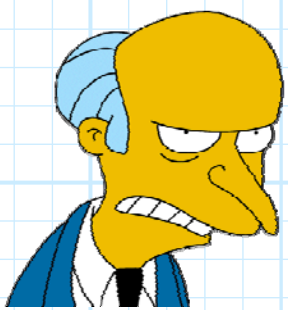
$$\ln\left[\frac{I_2}{I_1}\right] = \frac{V_2 - V_1}{nV_T}$$

$$\frac{I_2}{I_1} = \exp\left[\frac{V_2 - V_1}{nV_T}\right]$$

Again, we find that this expression is **independent** of scale current ***I_s!***

Note that we can alternatively express these equations as:

$$V_2 = V_1 + nV_T \ln\left(\frac{I_2}{I_1}\right) \qquad \text{and} \qquad I_2 = I_1 \exp\left[\frac{V_2 - V_1}{nV_T}\right]$$



Q: *Stop wasting our time with these **pointless** derivations!*

A: On the contrary, these expressions are often **very** useful!

The test point—as good as knowing I_s

Frequently, instead of explicitly providing **device parameters** n and I_s, a junction diode is specified by stating n, and then one specific **test point** for that diode.

A "test point" is simply **one current** ($i_D = I_{test}$) and the corresponding diode **voltage measurement** ($v_D = V_{test}$) from that junction diode.

For **example**, a junction diode might be specified as:

*"A junction diode with n =1 pulls **2mA** of current at a diode voltage **0.6 V**."*

In other words, we are given the **test point** $I_{test} = 2.0\ mA$ and $V_{test} = 0.6\ V$.

The above statement **completely specifies** the performance of this particular junction diode—we can now determine the current flowing through this diode for **any** other value of diode voltage v_D.

Likewise, we can find the voltage across the diode for **any** other diode current value i_D.

You're welcome!

Q: *Just how do we do **that**?*

A: Using the "pointless" expressions derived earlier, where $I_1 = I_{test}$ and $V_1 = V_{test}$, we can find these alternate **forward bias expressions**:

$$v_D = V_{test} + nV_T \ln\left(\frac{i_D}{I_{test}}\right) \quad \text{and} \quad i_D = I_{test} \exp\left[\frac{v_D - V_{test}}{nV_T}\right]$$

Note that **neither** expression involves I_s !

So for **example**, say we wish to find the current through the junction diode specified above when a potential difference of v_D = 0.7 V is placed across it.

We have **two** options for finding this current…

Option 1: Find I_S first

We know that $n = 1$ and that $i_D = 2.0\ mA$ when $v_D = 0.6\ V$.

Thus, we can use this information to solve for **scale current** I_S:

$$I_S\, e^{\frac{v_D}{nV_T}} = i_D$$

$$I_S\, e^{\frac{0.6}{0.025}} = 2$$

$$I_S = 2\, e^{\frac{-0.6}{0.025}}$$

$$I_S = 7.55 \times 10^{-11}\ mA$$

Now, we use the forward-biased junction diode equation to determine the current through this device at the new voltage of $v_D = 0.7\ V$:

$$i_D = I_S\, e^{\frac{v_D}{nV_T}}$$

$$= \left(7.55 \times 10^{-11}\right) e^{\frac{0.7}{0.025}}$$

$$= 109.2\ mA$$

Option 2: Use the test point directly!

Here, we **directly** determine the current at $v_D = 0.7$ using one of the expressions derived earlier in **this** handout!

Using the **test point** $I_{test} = 2.0\ mA$ and $V_{test} = 0.6\ V$, we can state the relationship between current i_D as and voltage v_D as:

$$i_D = I_{test}\ \exp\left[\frac{v_D - V_{test}}{nV_T}\right] = 2.0\ \exp\left[\frac{v_D - 0.6}{nV_T}\right]\ mA$$

For $v_D = 0.7\ V$ we can therefore find current i_2 as:

$$i_2 = 2.0\ \exp\left[\frac{0.7 - 0.6}{0.025}\right] = 109.2\ mA$$

Option 2 (using the equations we derived in this handout) is obviously **quicker** and **easier** (note in option 2 we did **not** have to deal with **annoying numbers** like **7.55 x 10^{-11}** !).

Often then just assume you know that n = 1 and V_{test} = 0.7 V

Finally, we should also note that junction diodes are often specified **simply** as " a **2mA diode**" or "a **10 mA diode**" or "a **100 mA diode**".

These statement **implicitly** provide the diode current at the **standard** diode test voltage of V_{test} = 0.7 V.

Q: *But what about the value of junction diode idealty factor **n** ?*

A: If **no** value of n is provided (and there is not sufficient information given to determine it), we typically just **assume** that n =**1**.

Release the hounds

For **example**, consider the following problem:

*"Determine the voltage across a **100 mA junction diode** when there is 2 mA of current flowing through it."*

A "**100 mA junction diode**" simply means a junction diode that will have a current of 100 mA flowing through it (i_D = 100 mA) **if** the voltage across it is v_D = **0.7 V**.

We will **assume** that n =1, since no other information about that parameter was given.

Thus, using V_{test} = 0.7 V, I_{test} =100 mA, we can determine the diode voltage v_D when i_D = 2.0 mA:

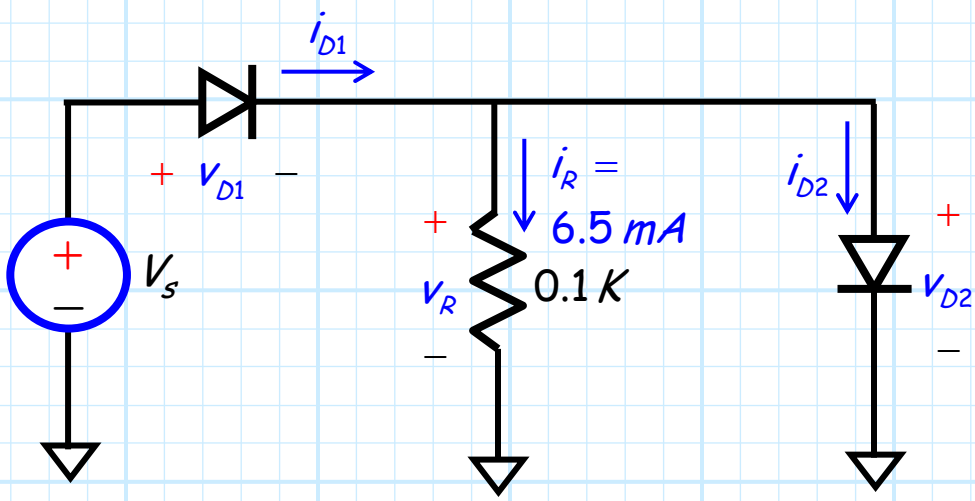
$$
\begin{aligned}
v_D &= V_{test} + nV_T \ln\left(\frac{i_D}{I_{test}}\right) \\
&= 0.7 + (0.025)\ln\left(\frac{2}{100}\right) \\
&= 0.7 - 0.10 \\
&= 0.60\,V
\end{aligned}
$$

*Why, these expressions are **not** pointless at all.*

*They turn out to be—**EXCELENT!***

Example: A Junction Diode Circuit

Consider the following circuit with two **junction diodes**:



The diodes are **identical**, with $n = 1$ and $I_S = 10^{-14}$ A.

Q: *If the current through the resistor is 6.5 mA, what is the voltage of source V_S ??*

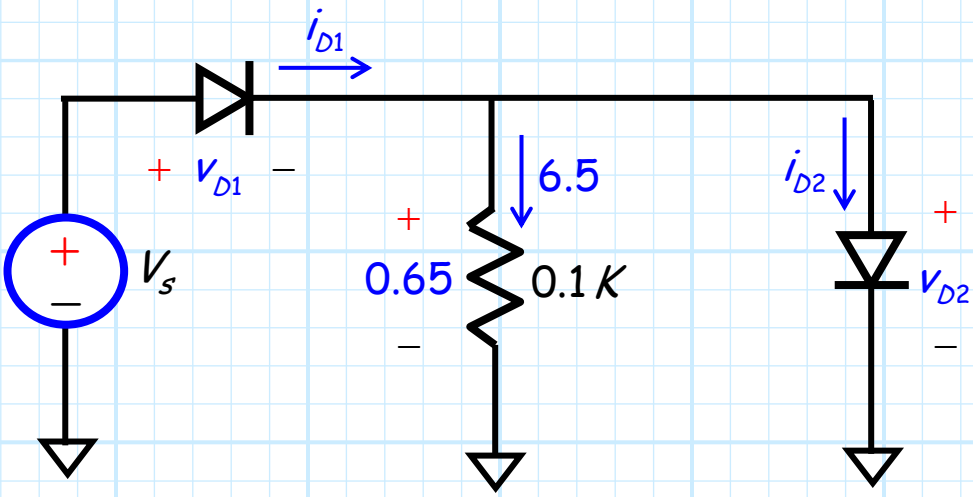
A: This is a **difficult** problem to solve ! Certainly, we cannot just write:

$$V_S =$$

and then the answer. Instead, let's just determine **what we can**, and see what happens !

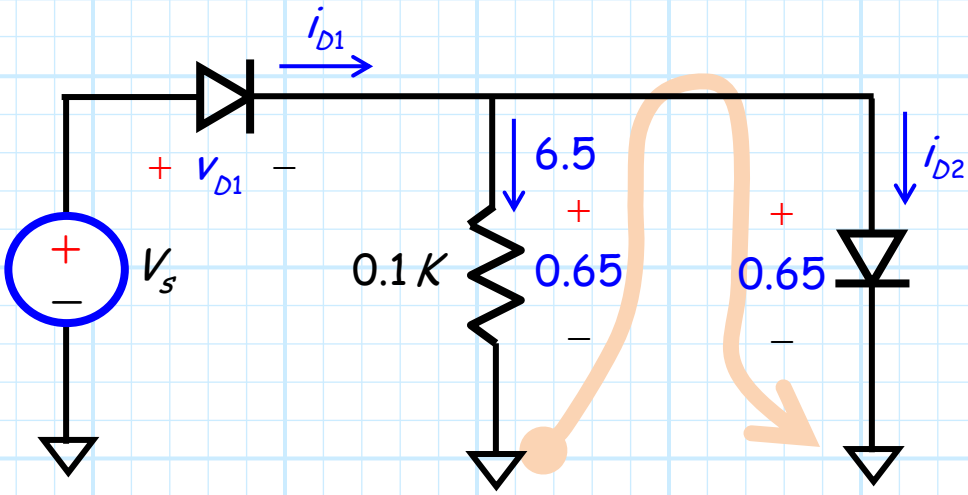
1) If 6.5 *mA* flows through a 0.1 K resistor, we find from Ohm's law that the voltage across that resistor is:

$$v_R = i_R R = (6.5)0.1 = 0.65\,V$$



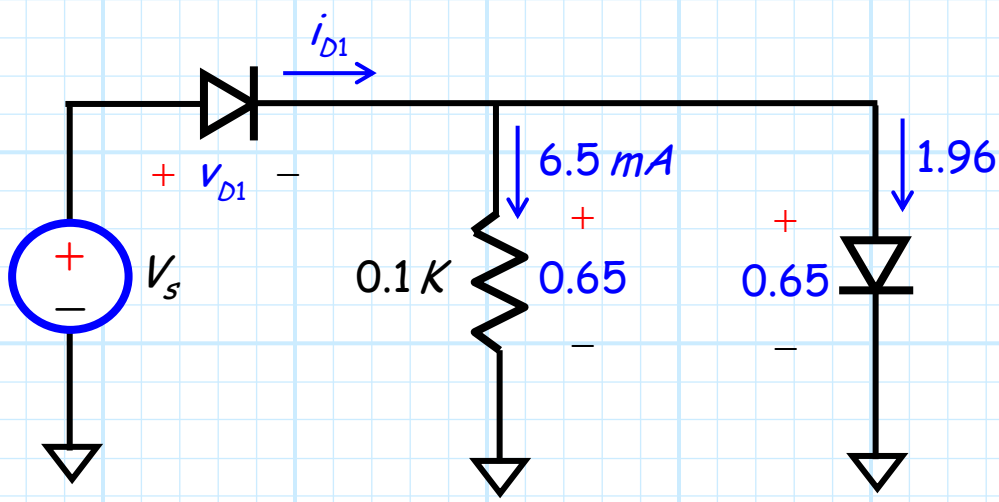
2) If the voltage across the resistor is 0.65 *V*, then the voltage across the diode D_2 , which is **parallel** to the resistor, can be determined from **KVL** to be the **same** value:

$$v_{D2} = v_R = 0.65\,V$$



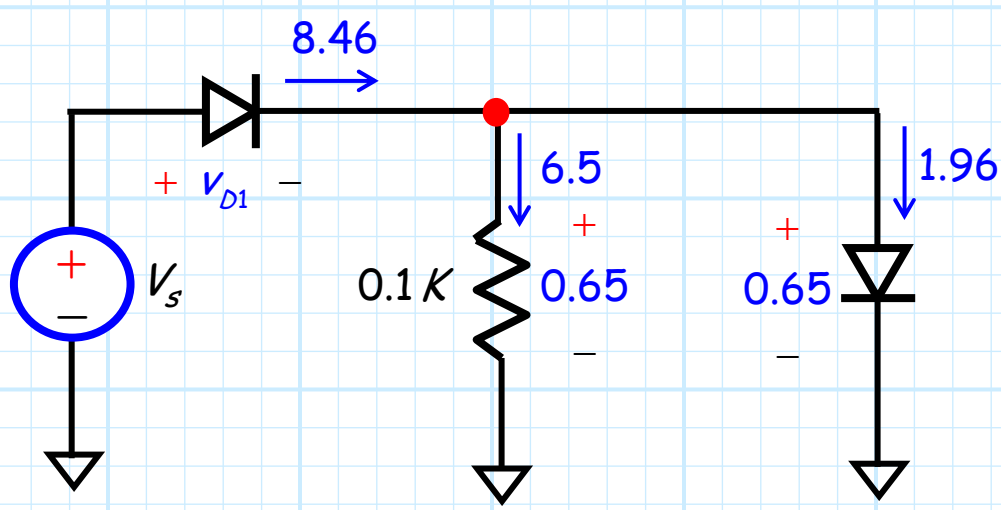
3) If we know the **voltage** across a *p-n* junction diode, then we also know its **current** !

$$i_{D2} = I_S \, exp\left[\frac{v_{D2}}{nV_T}\right] = 10^{-14} \, exp\left[\frac{0.650}{0.025}\right] = 1.96 \; mA$$



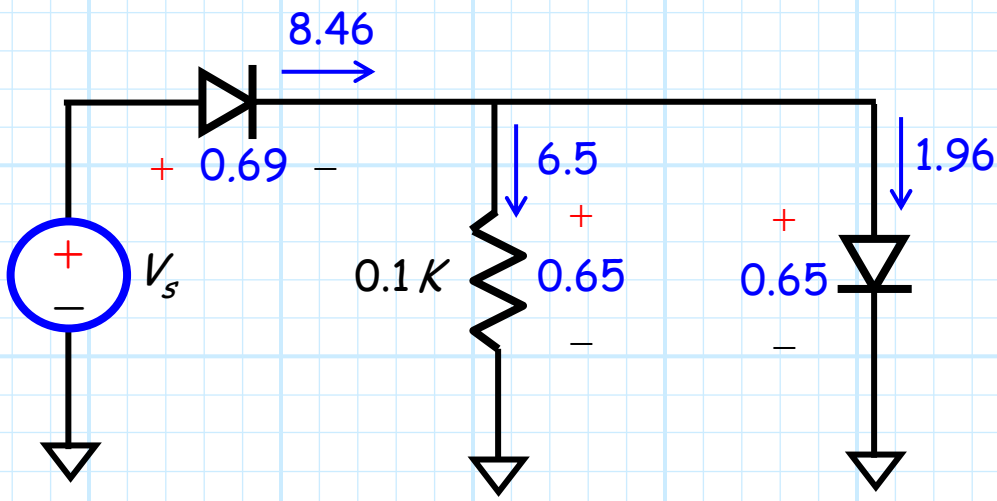
4) If we know i_{D2} and the current i_R through the resistor, we likewise know (using **KCL**) the current through D_1 :

$$\begin{aligned} i_{D1} &= i_R + i_{D2} \\ &= 6.5 + 1.96 \\ &= 8.46 mA \end{aligned}$$



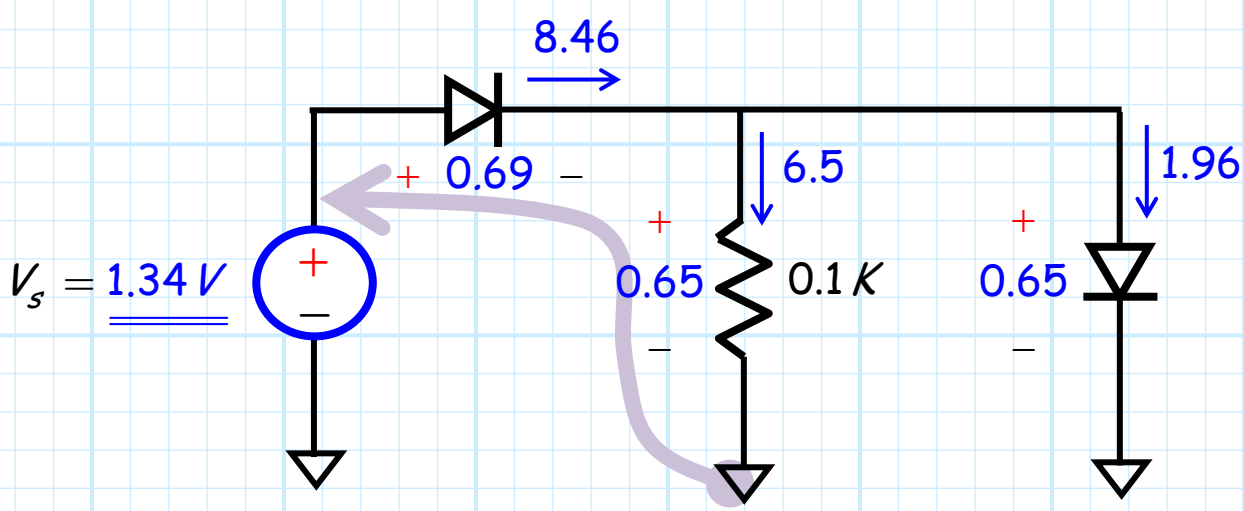
5) If we know the **current** through a junction diode, then we can find the **voltage** across it:

$$v_{D1} = nV_T \ln\left(\frac{i_{D1}}{I_S}\right) = 0.025 \ln\left(\frac{0.00846}{10^{-14}}\right) = 0.69V$$



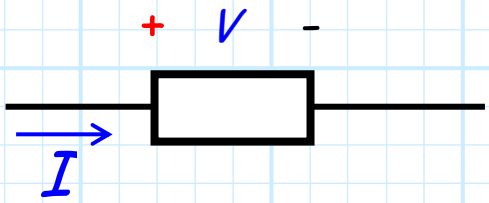
6) Finally, if we know v_{D1} and v_{D2}, we can find V_S using KVL:

$$V_S = v_{D1} + v_{D2} = 0.69 + 0.65 = 1.34\,V$$



Diode Power Dissipation

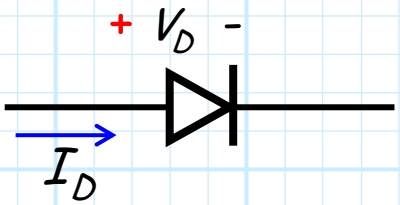
We know that for a **two-terminal** device, the **absorbed power** is simply equal to the **product** of the **voltage** across and **current** through the device:



$$P_A = V\,I$$

For **this** notation, a **positive** result is the power **absorbed** by the device, so that a **negative** value indicates that the device is a **source** of power!

As a result, the power **absorbed** by a **junction diode** is:



$$P_A = V_D\,I_D$$

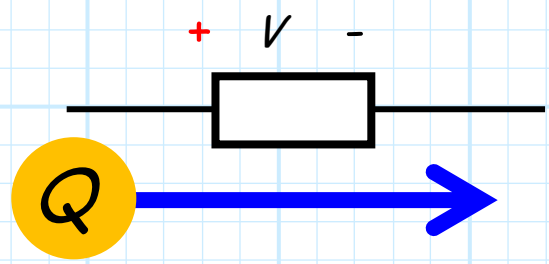
It's not a device equation!

Q: *Wait a second!*

*I know that this is the "right equation" for a **resistor**; is it just a **coincidence** that it also "works" for a **junction diode**?*

A: The **fact** that the absorbed power is the product of the current through and voltage across a two-terminal device is one that is **independent** of that device—it is **not a device equation**!

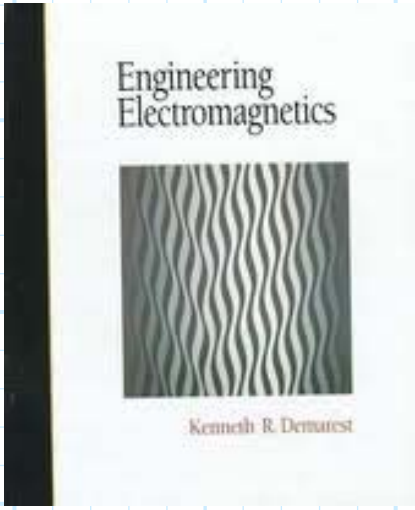
When some **charge** Q moves through the device—any device—from one terminal to the other, the **potential energy** of this charge either **decreases** or **increases**.



Volts: Joules per Coulomb

Q: *Buy **how much** does its energy increase or decrease?*

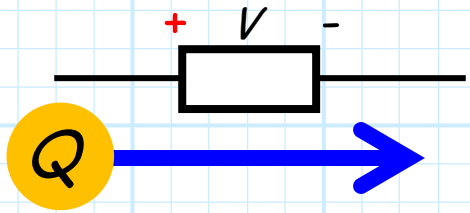
A: That's what the **voltage** across the device (e.g., V_D) **tells us**!



Remember, the units of volts is **Joules/Coulomb**—the change in potential **energy** for every **Coulomb of charge**!

So, for **example**, if a device voltage is **3.0 volts**, then when one Coulomb of charge passes from the plus terminal to the minus terminal, its **potential energy** will be **reduced by 3.0 Joules**!

Or more **generally**, if a charge Q moves through a device with voltage V across it, the **potential energy** of that charge will be **changed** by an amount equal to the **product** $Q\ V$.



$$\Delta\mathcal{E} = QV$$

Makes the device nice and toasty

Q: *Yikes! Just where does that energy **go**?*

*Conservation of energy says it must go **somewhere!***

A: That's exactly correct!

The reduction in potential energy must be **"absorbed"** by the device.

This absorbed energy must then be **dissipated** (changed into another form) in some manner.

Generally speaking, this absorbed energy is turned into **heat**!

Trust me; just don't arrive late

Q: *But how do we know the amount of **charge** Q that moves through the device?*

A: Charge move through the device at a **continual rate**—a rate defined as **Coulombs/second**.

Of course this rate of charge flow (in **C/s**) is otherwise known as **current** I (in **Amps**)!

Thus, the **product** of Volts and Current flow thus provides us with the **rate of energy absorption**:

$$V\left(\frac{Jolues}{Coulomb}\right)\cdot I\left(\frac{Coulombs}{second}\right)=V\cdot I\left(\frac{Joules}{second}\right)$$

The difference between miles and miles/hour

Q: *Joules **per second**?*

*I thought we were talking about **energy** (in **just** Joules)!*

A: The product of V and I provides us with the **rate** at which the device—any device—must **absorb energy**.

Just like the rate of **current** flow is **Coulombs/sec**, this provides us with the rate of **energy flow** is **Joules/sec**.

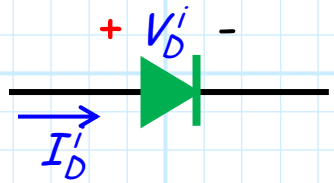
We of course call this **rate** of energy flow, **power**.

$$1\,Watt = 1\frac{Joules}{second}$$

So let's consider all this with respect to **diodes**.

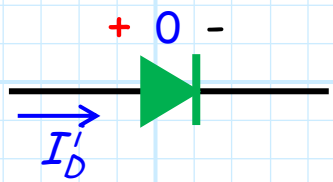
The ideal diode is just *so* ideal!

First let's look at an **ideal** diode:



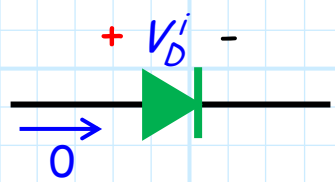
$$P_A = V_D^i \, I_D^i$$

If in **forward bias**, we know that the **ideal** diode **voltage is zero** ($V_D^i = 0$), so that the absorbed power is likewise **zero**!



$$P_A = (0) \, I_D^i = 0$$

And, in **reverse bias**, we know that the **ideal** diode **current is zero** ($I_D^i = 0$), so that the absorbed power is as well!



$$P_A = V_D^i \, (0) = 0$$

➔ An **ideal** diode absorbs **no energy**—yet another characteristic that makes this device **ideal**!

Forward Bias region is nice and warm

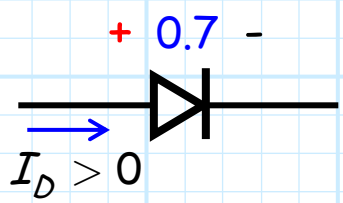
Q: *What about **junction** diodes?*

A: If a junction diode is operating in the **forward bias region**, then we know that:

a) the diode **voltage** is within a few hundred milli-volts of **0.7 *V***.

b) the diode **current** is "significant yet plausible".

As a result, we find that a **junction** diode operating in the **forward** bias region will absorb energy at some "moderate" rate!



$$P_A \cong 0.7\, I_D$$

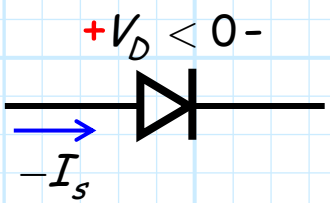
Cooler than the other side of the pillow

If a **junction** diode is operating in the **reverse bias region**, we know that:

a) The diode **current** will be negative and **extremely small**.

b) The diode voltage will be **negative**.

As a result, we find that a **junction** diode operating in the **reverse** bias region will absorb energy at an **extremely small** rate—essentially **zero**!



$$P_A = V_D\left(-I_s\right) \cong 0$$

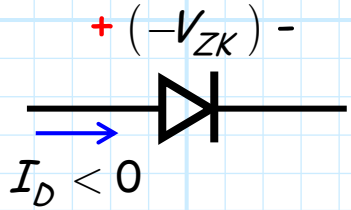
Houston, we have a problem

If a **junction** diode is operating in the **breakdown** region, we know that:

a) the diode current will be **negative**, and will be **significant**.

b) The diode voltage will be a **large, negative** value $-V_{ZK}$.

As a result, we find that a junction diode operating in the **breakdown region** might absorb energy at a **very large rate**!



$$P_A = -V_{ZK}\, I_D > 0$$

Q: *Is this **bad**?*

A: It can be!

A junction diode (or any device, for that matter) absorbing energy at a **large rate** must then **dissipate** this energy at a large rate—it must dissipate the **heat** created!

I'm melting!

Q: *Why, **what happens** if it doesn't?*

A: If energy is absorbed **faster** than the **heat is dissipated**, the **temperature** of the device will **rise**.

If **equilibrium** is not reached—if the rate of heat dissipation does **not** become **equal** to the rate of energy absorption—then the device will quite literally "go up in **smoke**"!

Thus, **breakdown** is the most **problematic** of the three **junction** diode **regions** with respect to **power dissipation**—without a good thermal **"sink"**, our junction diode might well be **destroyed**!