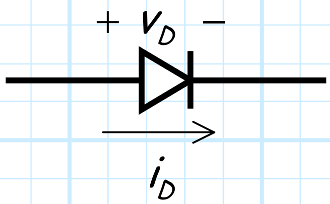
3.2 Terminal Characteristics of Junction Diodes (pp.147-153)



HO: The Junction Diode Curve

HO: The Junction Diode Equation

A. The Forward Bias Region

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

$$\approx I_s \, e^{v_D / nV_T} \qquad for \quad v_D \gg nV_T$$

Example: $I_s = 10^{-12}$, n=1

v_D(V)	i_D
0.4	
0.5	
0.6	
0.7	
0.8	
0.9	

$$v_D \simeq 0.7 \;\; V$$

a)

b)

HO: The Junction Diode Forward Bias Equation

HO: Example: A Junction Diode Circuit

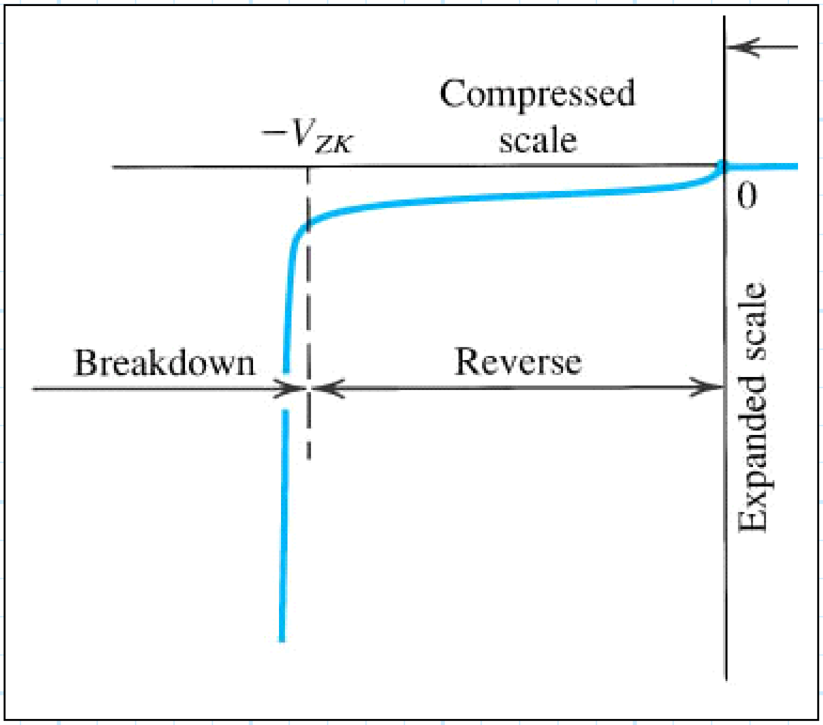
B. The Reverse Bias Region

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

$$\approx -I_s \qquad\qquad for \quad v_D \ll -nV_T$$

HO: Forward and Reverse Bias Approximations

C. The Breakdown Region


Compressed scale
$-V_{ZK}$
0
Breakdown
Reverse
Expanded scale

D. Power Dissipation in Junction Diodes

f.b. →

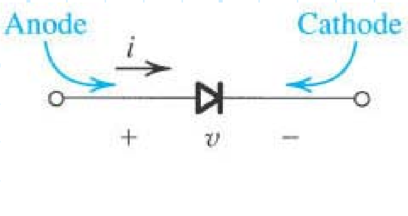
r.b →

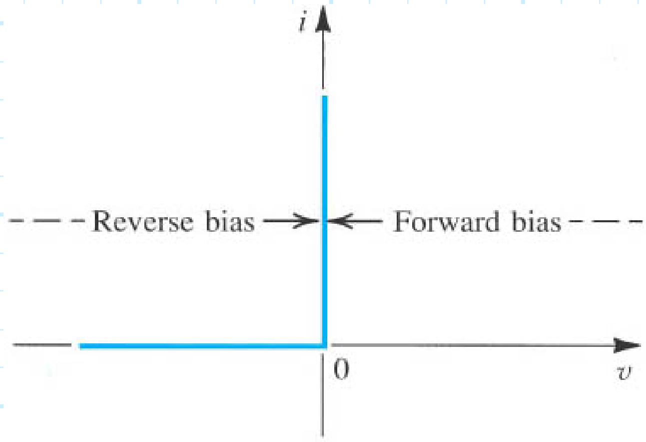
b.d →

The Junction Diode Curve

In many ways, **junction** diode (i.e., real diode) behavior is **similar** to that of ideal diodes. However, there are some important and profound **differences**!

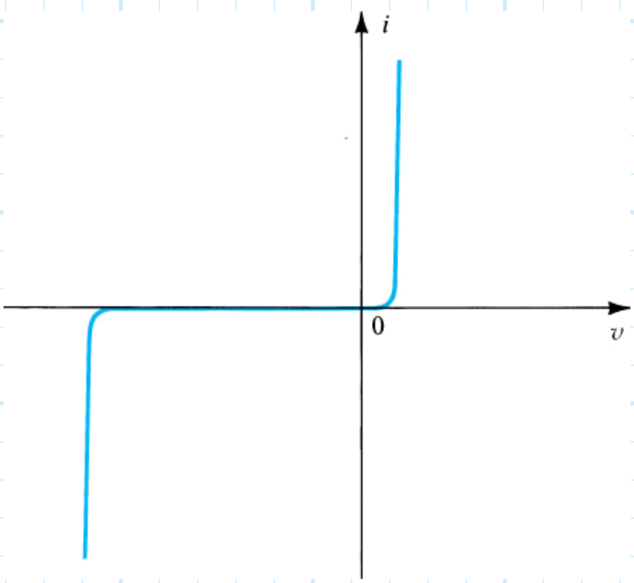
First, recall the **ideal** diode current voltage curve:

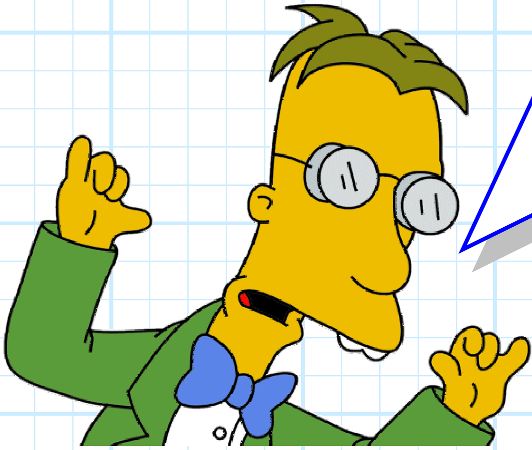




This curve is piece-wise linear, with two **unambiguous** regions—**reverse** bias (where $v < 0$ and $i = 0$), and **forward** bias (where $i > 0$ and $v = 0$).

Now consider the behavior of a **junction diode**:





*Please note that unlike the ideal diode, the **junction diode** curve:*

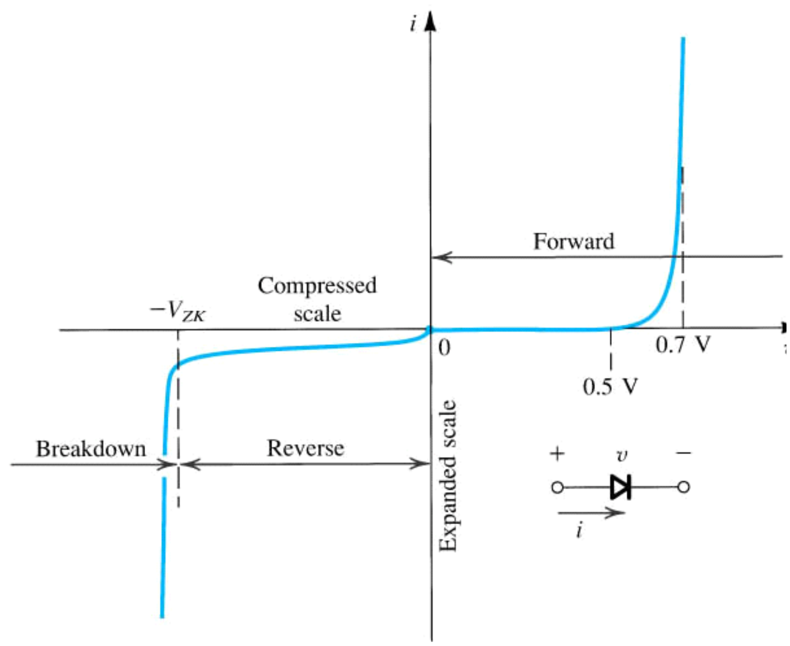
a) *is **continuous** (not piece-wise linear).*

b) *Has **three** apparent regions of operation (not two).*

c) *Has, therefore, **ambiguous** boundaries between regions (i.e., continuous **transitions** occur between regions—the curve has two "**knees**"!).*

By comparison to the ideal diode, we likewise define one region of the junction diode curve as the **forward bias** region, and another as the **reverse bias** region.

The **third** region has **no similarity** with ideal diode behavior (i.e., this is a "new" region). We call this region **breakdown**.



Note that the breakdown region occurs when the junction diode voltage (from anode to cathode) is **approximately** less than or equal to a voltage value $-V_{ZK}$. The value V_{ZK} is known as the **zener breakdown voltage**, and is a fundamental performance parameter of any **junction** diode.

As we shall see later, the behavior of a junction diode in the forward and reverse bias region is a **predictable** result of **semiconductor physics**! As such we can write an **explicit** mathematical expression, simultaneously describing the behavior of a junction diode in **both** the forward and reverse bias regions (but **not** in breakdown!):

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

The Junction Diode Equation

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

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

Note: this equation describes diode behavior in the forward **and** reverse biased region **only** (i.e., **not** valid for **breakdown**).

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

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

1. I_s = **Saturation** (or scale) **Current**. Depends on diode material, size, and **temperature**.

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

2. V_T = **Thermal Voltage** = $\frac{kT}{q}$

Where:

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

$$\text{At } 20\ ^\circ C,\ V_T \approx 25\ mV$$

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 **always** assume that the **thermal voltage** V_T of **all** junction diodes is **25 mV** (i.e., $V_T = 25\text{ mV}$)!

3. n = a constant called the **ideality factor** (i.e. "fudge factor").

Typically, $1 \le n \le 2$

The Junction Diode Forward Bias Equation

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

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

provided that $v_D \gg 25\, mV$.

We can **invert** this approximation to alternatively express v_D in terms of diode current i_D:

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

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

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

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

Now, say a voltage v_1 across some junction diode results in a current i_1. Likewise, **different** voltage v_2 across this same diode a diode of course results in a **different** current i_2. We can define the difference between these two voltages as $\Delta v = v_2 - v_1$, and then using the above equation can express this voltage difference as:

$$
\begin{aligned}
\Delta v &= v_2 - v_1 \\
&= nV_T \ln\left(\frac{i_2}{I_S}\right) - nV_T \ln\left(\frac{i_1}{I_S}\right) \\
&= nV_T \ln\left(\frac{i_2}{I_S}\frac{I_S}{i_1}\right) \\
\Delta v &= nV_T \ln\left(\frac{i_2}{i_1}\right)
\end{aligned}
$$

Yikes! Look at what this equation says:

* 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.

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

$$n V_T \ ln\left[\frac{i_2}{i_1}\right] = v_2 - v_1$$

$$ln\left[\frac{i_2}{i_1}\right] = \frac{(v_2 - v_1)}{n V_T}$$

$$\frac{i_2}{i_1} = exp\left[\frac{(v_2 - v_1)}{n V_T}\right]$$

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

Q: *Stop wasting my time with these **pointless** derivations! Are these expressions even remotely **useful** !?!*

A: These expressions are often **very** useful! Frequently, instead of explicitly providing **device parameters** n and I_s, a junction diode is specified by stating n, and then a statement of the specific diode current resulting from a specific diode voltage.

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

"A junction diode with $n=1$ pulls 2mA of current at a voltage v_D=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.

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:

We know that n=1 and that i_D=2mA when v_D=0.6 V. Thus, we can use this information to solve for **scale current** I_S:

$$\begin{aligned} I_S\, e^{\frac{v_D}{nV_T}} &= i_D \\ I_S\, e^{\frac{0.6}{0.025}} &= 2 \\ I_S &= 2\, e^{\frac{-0.6}{0.025}} \\ I_S &= 7.55 \times 10^{-11}\, mA \end{aligned}$$

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:

$$\begin{aligned} i_D &= I_S\, e^{\frac{v_D}{nV_T}} \\ &= \left(7.55 \times 10^{-11}\right) e^{\frac{0.7}{0.025}} \\ &= 109.2\ mA \end{aligned}$$

Option 2

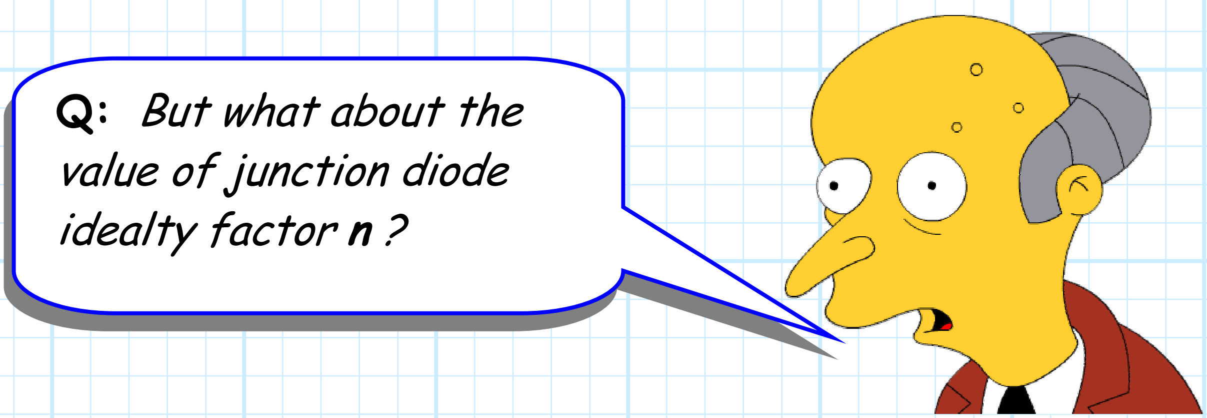
Here, we directly determine the current at $v_D = 0.7$ using one of the expressions derived earlier in **this** handout! Using i_1=2 mA, v_1 =0.6, and v_2 =0.7 V we can find current i_2 as:

$$\frac{i_2}{i_1} = exp\left[\frac{(v_2 - v_1)}{nV_T}\right]$$

$$\begin{aligned} i_2 &= i_1\, exp\left[\frac{(v_2 - v_1)}{nV_T}\right] \\ &= 2\, exp\left[\frac{(0.7 - 0.6)}{0.025}\right] \\ &= 109.2\ mA \end{aligned}$$

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 7.55×10^{-11} !).

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 $\mathbf{v_D=0.7\ V}$.



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

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 $\boldsymbol{v_D}$**=0.7 V**. We will **assume** that n=1, since no other information about that parameter was given.

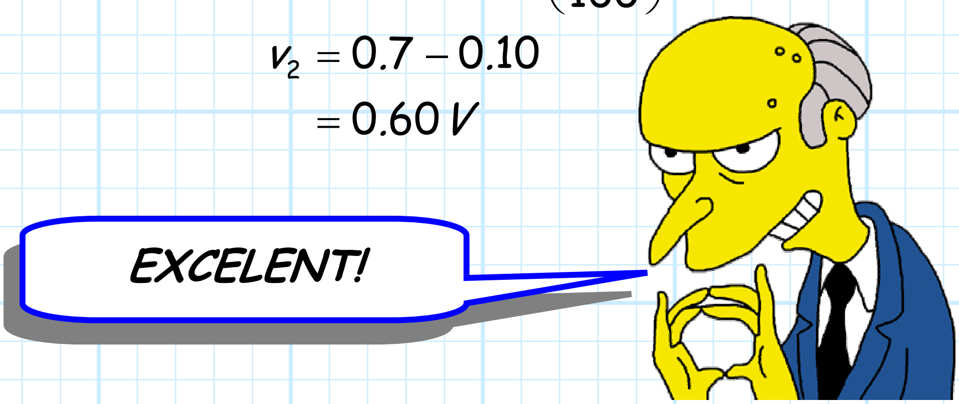
Thus, using v_1 =0.7, i_1 =100mA, and i_2 =2 mA, we can determine the value of v_2:

$$v_2 - v_1 = n V_T \ln\left(\frac{i_2}{i_1}\right)$$

$$v_2 - 0.7 = (0.025) \ln\left(\frac{2}{100}\right)$$

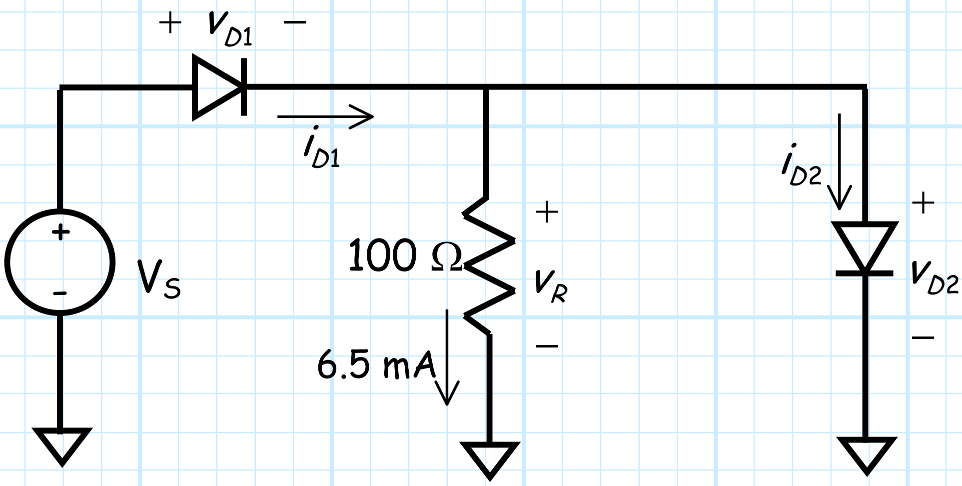
$$v_2 = 0.7 - 0.10$$

$$= 0.60 \, V$$



Example: A Junction Diode Circuit

Consider the following circuit with two junction diodes:



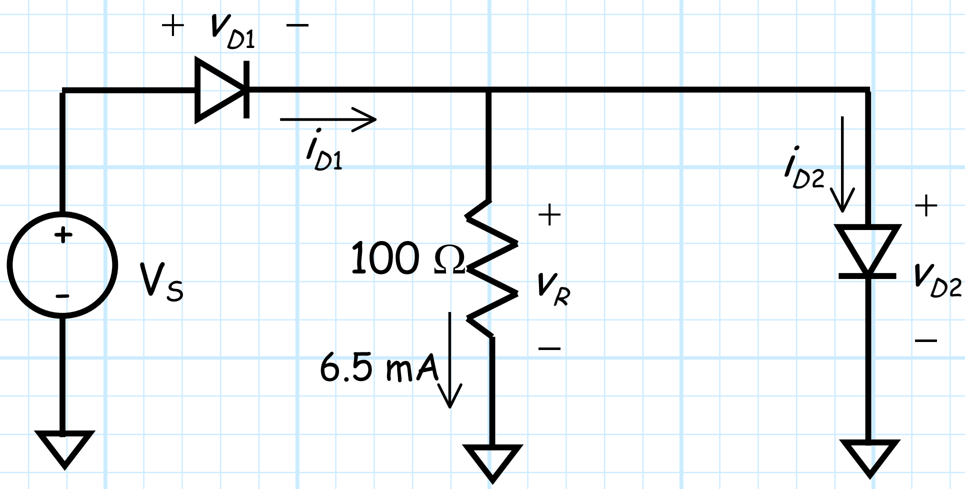
The diodes are identical, with n = 1 and $I_S = 10^{-14}$ A.

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, the voltage across that resistor is:

$$v_R =$$

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, is the **same** value:

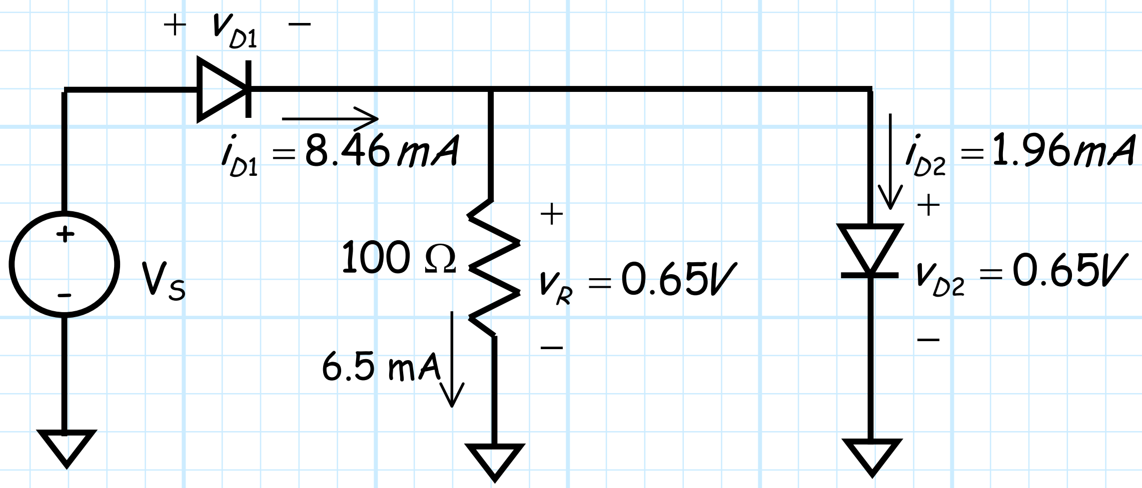
$$v_{D2} =$$

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 through the resistor, we know (using KCL) the current through D_1 :

$$i_{D1} =$$

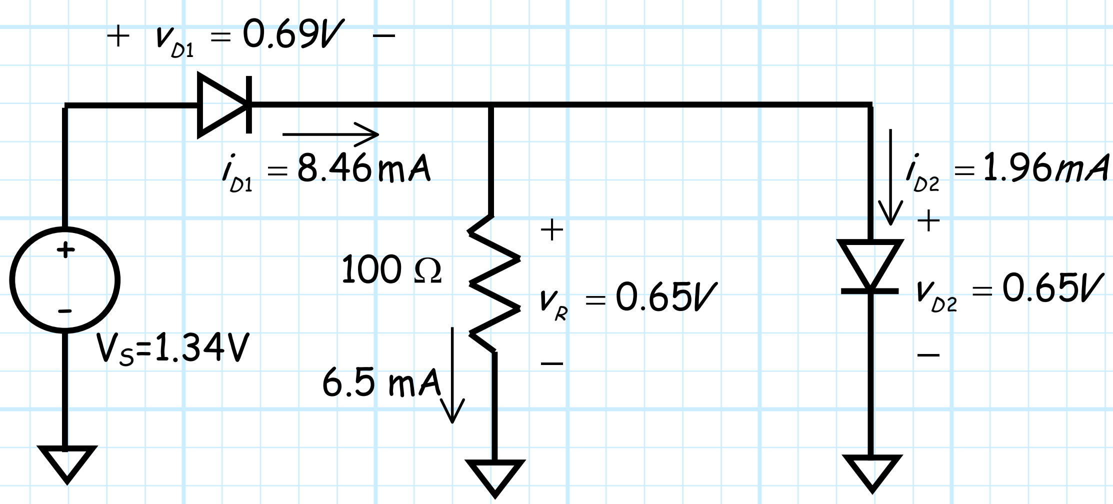


5) If we know the current through a junction diode, then we can find the voltage across it:

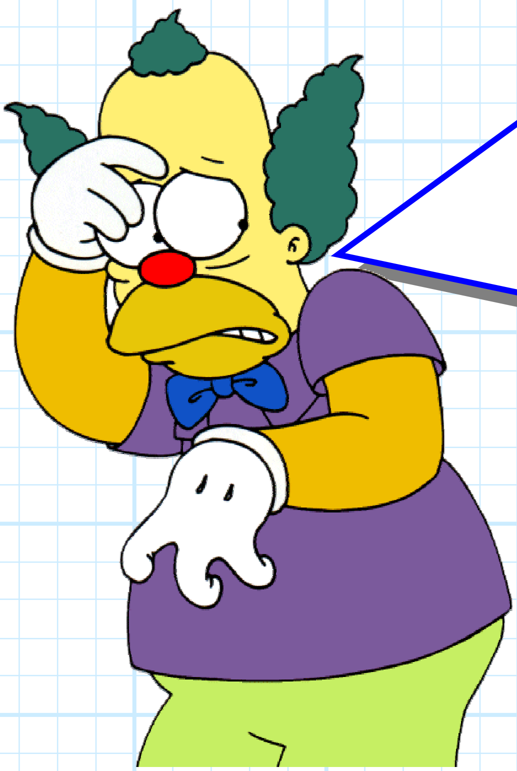
$$v_{D1} = nV_T \ln\left(\frac{i_{D1}}{I_S}\right) = 0.025 \ln\left(\frac{0.00846}{10^{-14}}\right) = 0.69\,V$$

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

$$V_S =$$



Forward and Reverse Bias Approximations



Q: *Man, am I ever **befuddled**! Is the behavior of a junction diode in the **forward biased** region described as **this**:*

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

*or as **this**:*

$$i_D = I_s e^{v_D/nV_T} \quad ?$$

*or as **this***

$$i_D > 0 \quad \text{and} \quad v_D = 0.7 \text{ V} \quad ???$$

A: Actually, **all three** of the above statements are true (or, at least, **approximately** so)!

Let's **review** what we know about the junction diode in forward and revered bias:

1. First, we know that if the diode is **not** in breakdown, the relationship between current and voltage can be precisely described as:

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

Q: *Here's where I get confused. Is this equation valid for reverse bias,* ***or*** *is it valid for forward bias?*

A: The above expression **is** valid for forward bias, **and** it is valid for reverse bias, **and** it is also valid for the transition region between forward and reverse bias!

In other words, the above equation is a **very accurate** description of the junction diode behavior—with the important **exception** of when the junction diode is in **breakdown**.

2. Now, lets **simplify** the previous expression further, **separately** examining the cases when the junction diode is in forward bias (i.e., $v_D \gg nV_T$), and reverse bias (i.e., $-V_{ZK} < v_D \ll -nV_T$).

For the **forward bias** case, we find that:

$$e^{v_D / nV_T} \gg 1 \qquad \text{if } v_D \gg nV_T$$

Therefore, we can approximate the junction diode behavior in **forward bias** mode as:

$$i_D \approx I_s \, e^{v_D / nV_T} \quad \text{for} \quad v_D \gg nV_T \text{ (i.e., forward biased)}$$

Likewise, for the **reverse bias** case, we find that:

$$e^{v_D / nV_T} \ll 1 \quad \text{if } v_D \ll -nV_T$$

Therefore, we can approximate the junction diode behavior in **reverse bias** mode as:

$$i_D \approx -I_s \quad \text{for} \quad -V_{ZK} < v_D \ll -nV_T \text{ (i.e., reversed biased)}$$

Combining, we can approximate the expression at the top of the previous page as:

$$i_D \approx \begin{cases} I_s \, e^{v_D / nV_T} & \text{for} \quad v_D \gg nV_T \text{ (i.e., forward biased)} \\ -I_s & \text{for} \quad -V_{ZK} < v_D \ll -nV_T \text{ (i.e., reversed biased)} \end{cases}$$

3. We can now simplify these expressions even **further**! We rewrite the above approximation for forward bias so that the junction diode **voltage** is a function of junction diode current:

$$I_s e^{v_D / nV_T} = i_D$$

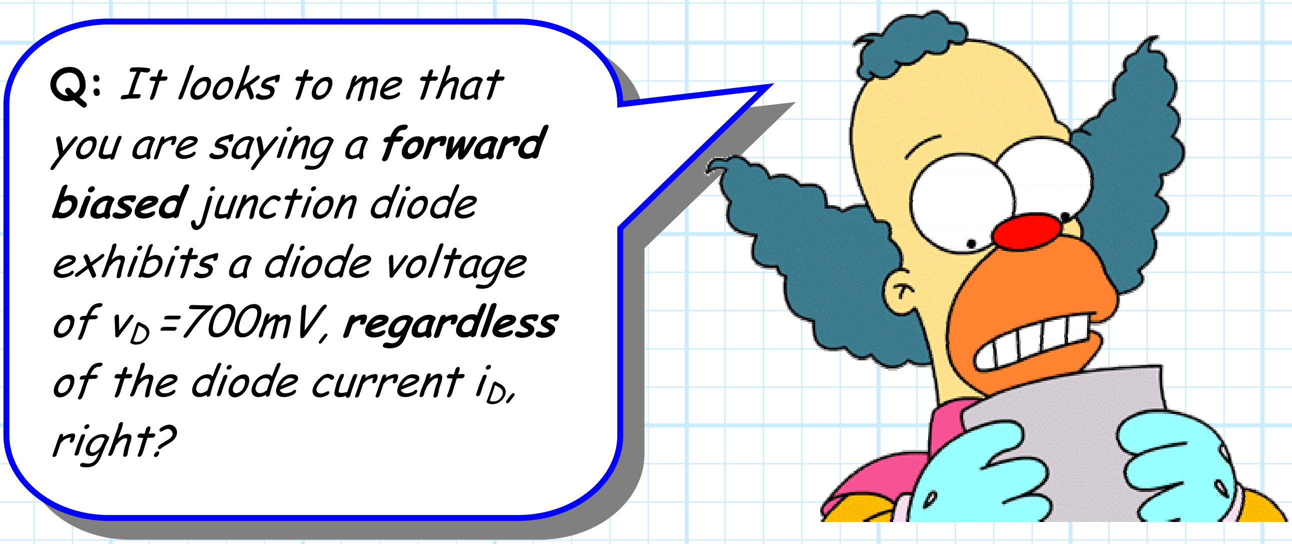
$$e^{v_D / nV_T} = \frac{i_D}{I_s}$$

$$\frac{v_D}{nV_T} = ln\left[\frac{i_D}{I_s}\right]$$

$$v_D = nV_T \, ln\left[\frac{i_D}{I_s}\right]$$

As a previous example demonstrated, as we vary the value of diode **current** i_D from microamps to kiloamps, the diode voltage will vary **only** a few hundred millivolts, from about 0.5 V to 0.9 V.

Thus, we can assume that if any appreciable current is flowing from junction diode anode to junction diode cathode (i.e., forward bias condition), the junction diode voltage will be **approximately** (i.e., within a few hundred millivolts) **0.7 V**.



A: NO! This is **not** what I am saying! As is evident in the previous two equations, the junction diode current in forward bias is directly **dependent** on diode current—as the **current** increases, the **voltage** increases! For each possible diode **current**, there is a **specific** (and different) diode **voltage**.

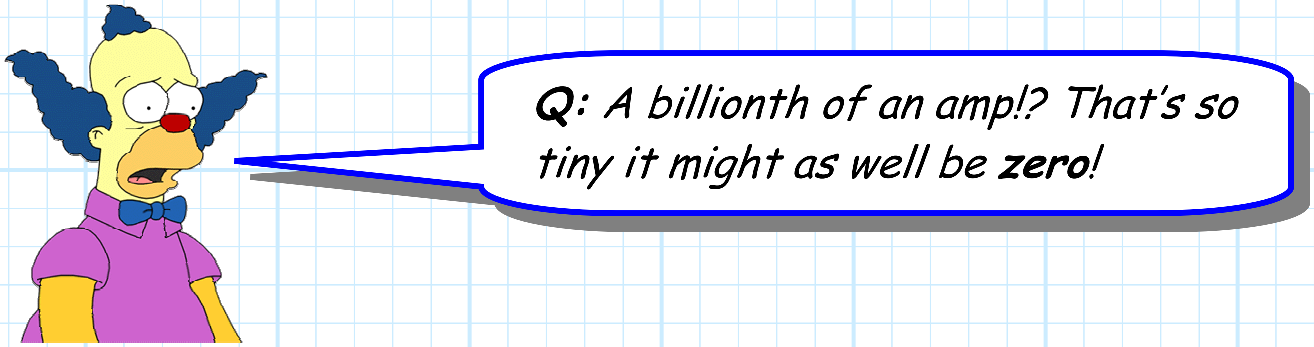
* However, we find that this increase is **logarithmically** related to diode current, such that the voltage increases very **slowly** with increasing current—it takes a **bunch** of additional junction diode current to increase the junction diode voltage even a **small** amount.

* Thus, we are simply saying that for all appreciable (and plausible) diode currents, the junction diode voltage will be within of few hundred millivolts of, say, 700 mV.

* As a result, $v_D = 0.7$ V is not a bad **approximation** for **forward biased** junction diodes!

Now, we can likewise simplify further our approximation for a **reverse biased** junction diode. Recall that we now approximate the reverse bias diode current as $i_D = -I_s$.

However, recall that the diode saturation current I_s is a very small value, typically 10^{-8} to 10^{-15} Amps!



A: Precisely! The reverse bias current value $i_D = -I_s$ is so small that we can approximate it as **zero**:

$$i_D \approx 0 \qquad \text{if} \qquad -V_{ZK} < v_D \ll -nV_T \quad \text{(reverse bias)}$$

Thus, we arrive at an **even simpler** (albeit **less** accurate) approximation of junction diode behavior in forward and reverse bias:

$$v_D \approx 0.7 \qquad \text{if} \qquad i_D > 0 \quad \text{(forward bias)}$$

$$i_D \approx 0 \qquad \text{if} \qquad -V_{ZK} < v_D < 0 \quad \text{(reverse bias)}$$

*Each of the **three** expressions examined in this handout can be used to describe the behavior of junction diodes in **forward** and/or **reverse** bias. The **first** expression we examined is the **most** accurate, but it is likewise the most mathematically **complex**. Conversely, the **third** expression above is the **simplest**, but is likewise the **least** accurate.*

*We will find that **all** three of the expressions are **useful** to us, depending on **what** specifically we are attempting to determine, and how **accurately** we need to determine it!*