# Interesting Question

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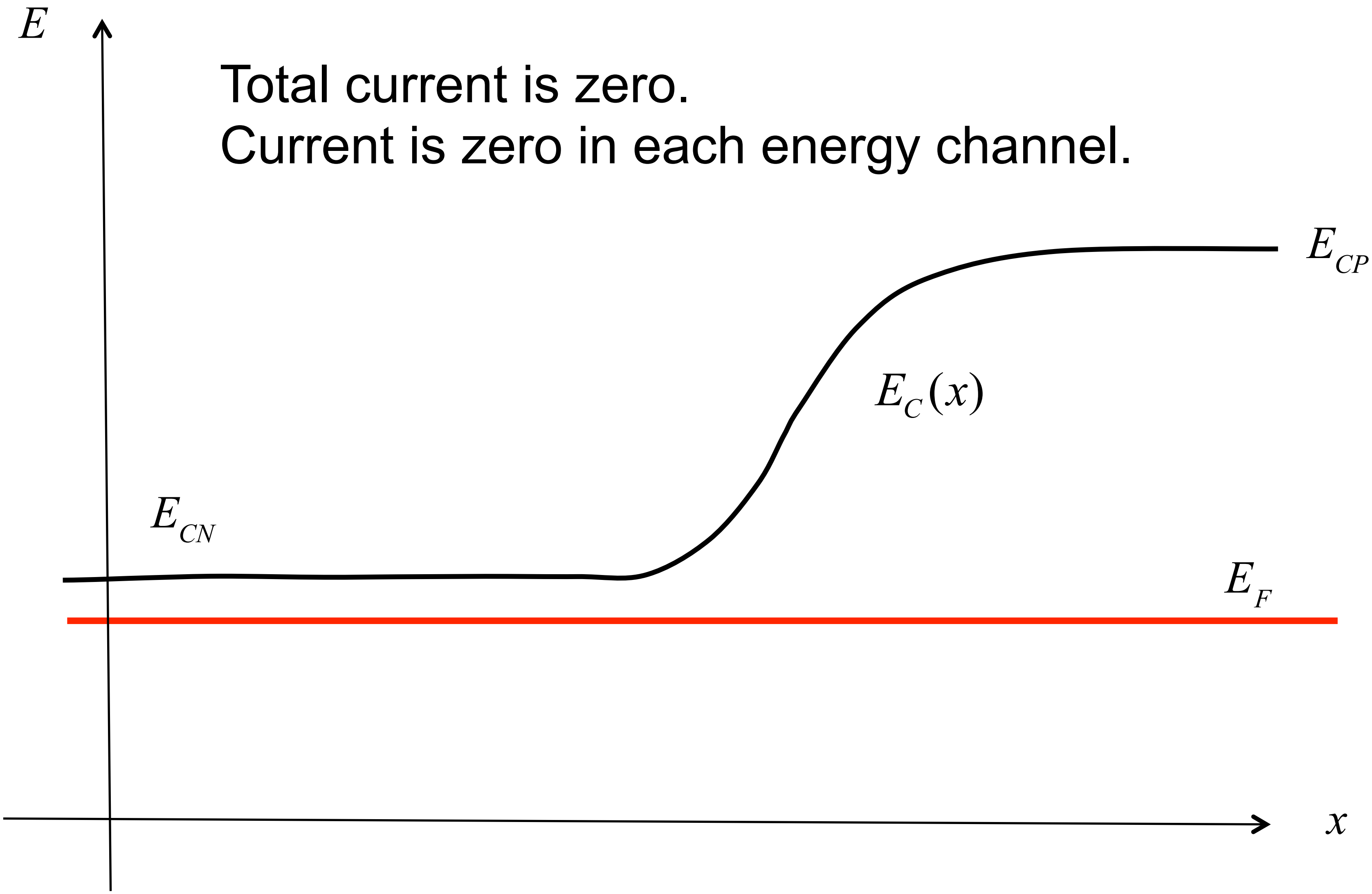
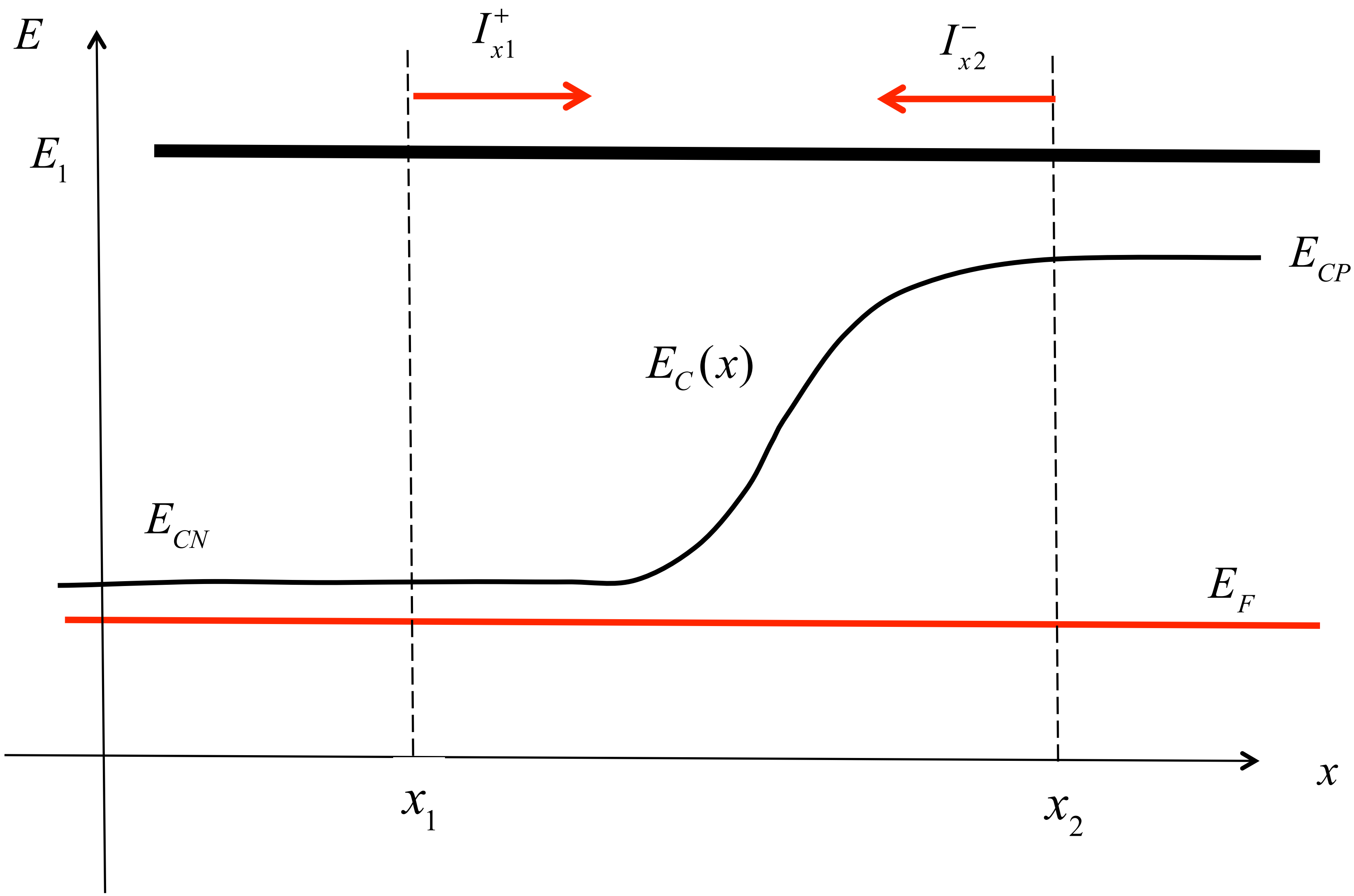
11/29/17

# PN Junction in equilibrium

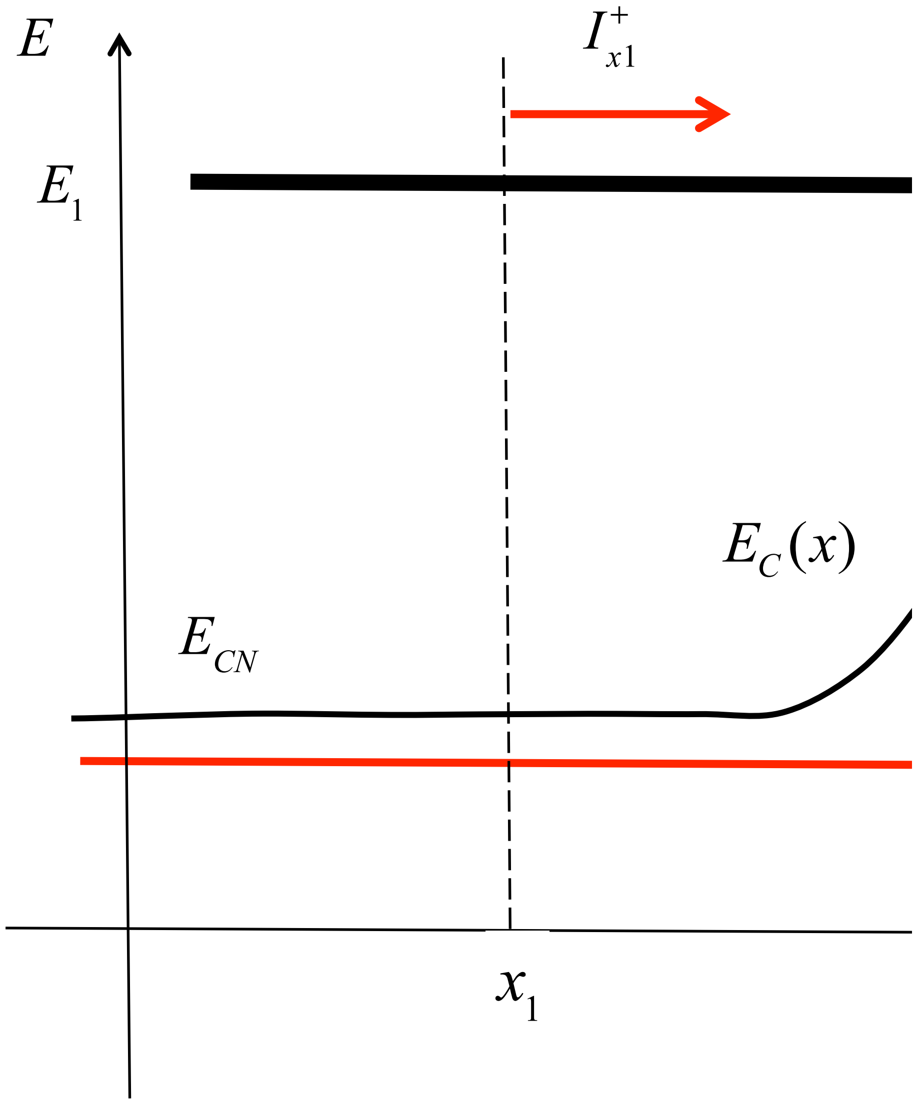
Total current is zero.
Current is zero in each energy channel.



# Consider 1 specific energy channel



# On the n-side




$$I_{x1}^{+} = \frac{D(x_1, E_1)\,dE}{2} f_o(E_1)\,\upsilon^{+}(x_1, E_1)$$

$$I_{x1}^{+} = \frac{D(x_1, E_1)\,dE}{2} f_o(E_1)\frac{\upsilon(x_1, E_1)}{2}$$

$$I_{x1}^{+} \propto \sqrt{E_1 - E_{CN}}\, f_o(E_1)\sqrt{E_1 - E_{CN}}$$

$$I_{x1}^{+} \propto (E_1 - E_{CN})\, f_o(E_1)$$

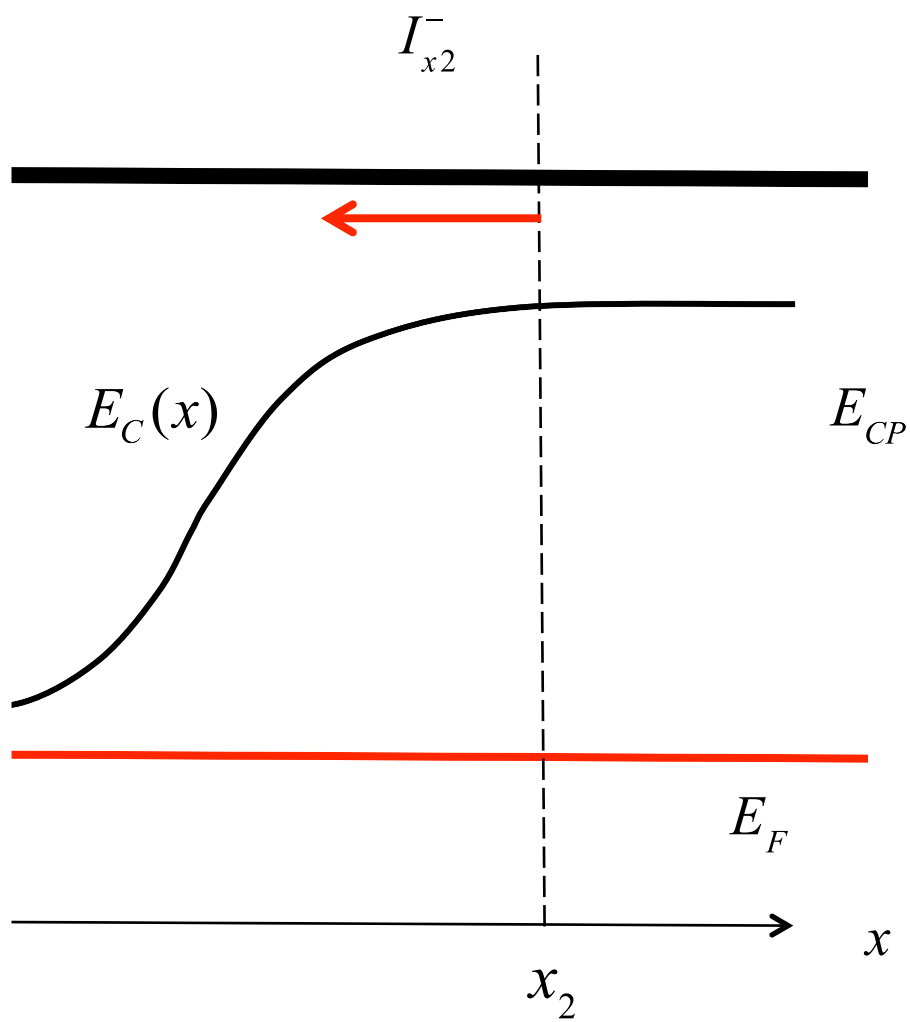
# On the p-side

$$I_{x2}^{-} = \frac{D(x_2, E_1)\,dE}{2} f_o(E_1)\,\upsilon^1(x_2, E_1)$$

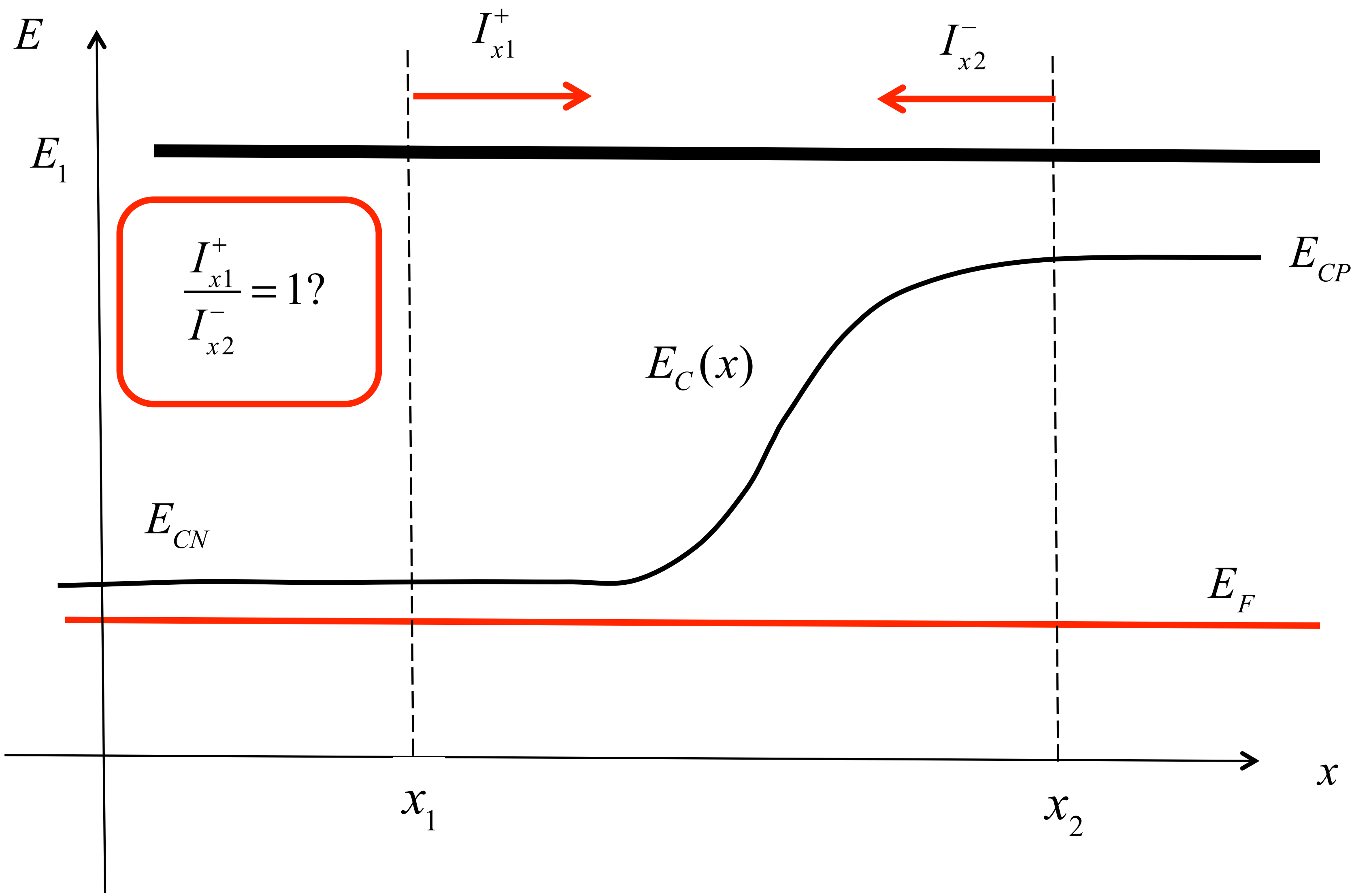
$$I_{x2}^{-} = \frac{D(x_2, E_1)\,dE}{2} f_o(E_1)\frac{\upsilon(x_2, E_1)}{2}$$

$$I_{x2}^{-} \propto \sqrt{E_1 - E_{CP}}\, f_o(E_1)\sqrt{E_1 - E_{CP}}$$

$$I_{x2}^{-} \propto (E_1 - E_{CP})\, f_o(E_1)$$



# Are these two currents equal?



# Ratio of currents

$$I_{x1}^{+} \propto \left(E_1 - E_{CN}\right) f_o\left(E_1\right)$$

$$I_{x2}^{-} \propto \left(E_1 - E_{CP}\right) f_o\left(E_1\right)$$

Why is the current ratio > 1?

$$\frac{I_{x1}^{+}}{I_{x2}^{-}} \propto \frac{\left(E_1 - E_{CN}\right) f_o\left(E_1\right)}{\left(E_1 - E_{CP}\right) f_o\left(E_1\right)} = \frac{\left(E_1 - E_{CN}\right)}{\left(E_1 - E_{CP}\right)}$$

$$\frac{I_{x1}^{+}}{I_{x2}^{-}} \propto \frac{\left(E_1 - E_{CN}\right)}{\left(E_1 - E_{CN} - qV_{bi}\right)} > 1$$

How can the current be zero?

# Question

But we know that the current in the channel at energy, E1, must be zero.

What is wrong with our argument?

How do we explain current = 0?

# Solution

# Directed current vs. position

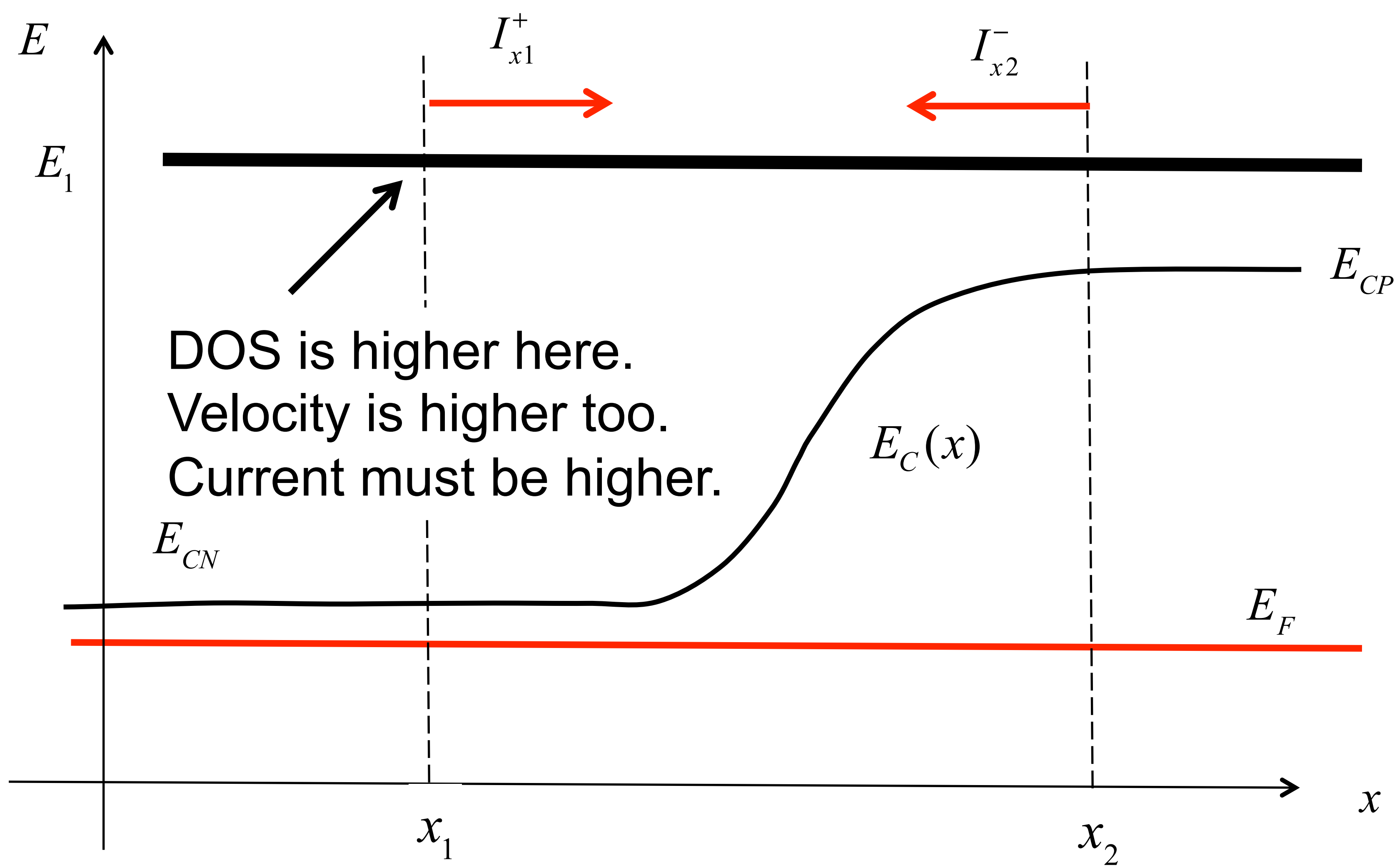
Current is electron density times electron velocity

Electron density: $n\left(E_1\right)dE = D\left(E_1\right)f_o\left(E_1\right) \propto \sqrt{E_1 - E_C\left(x\right)}$

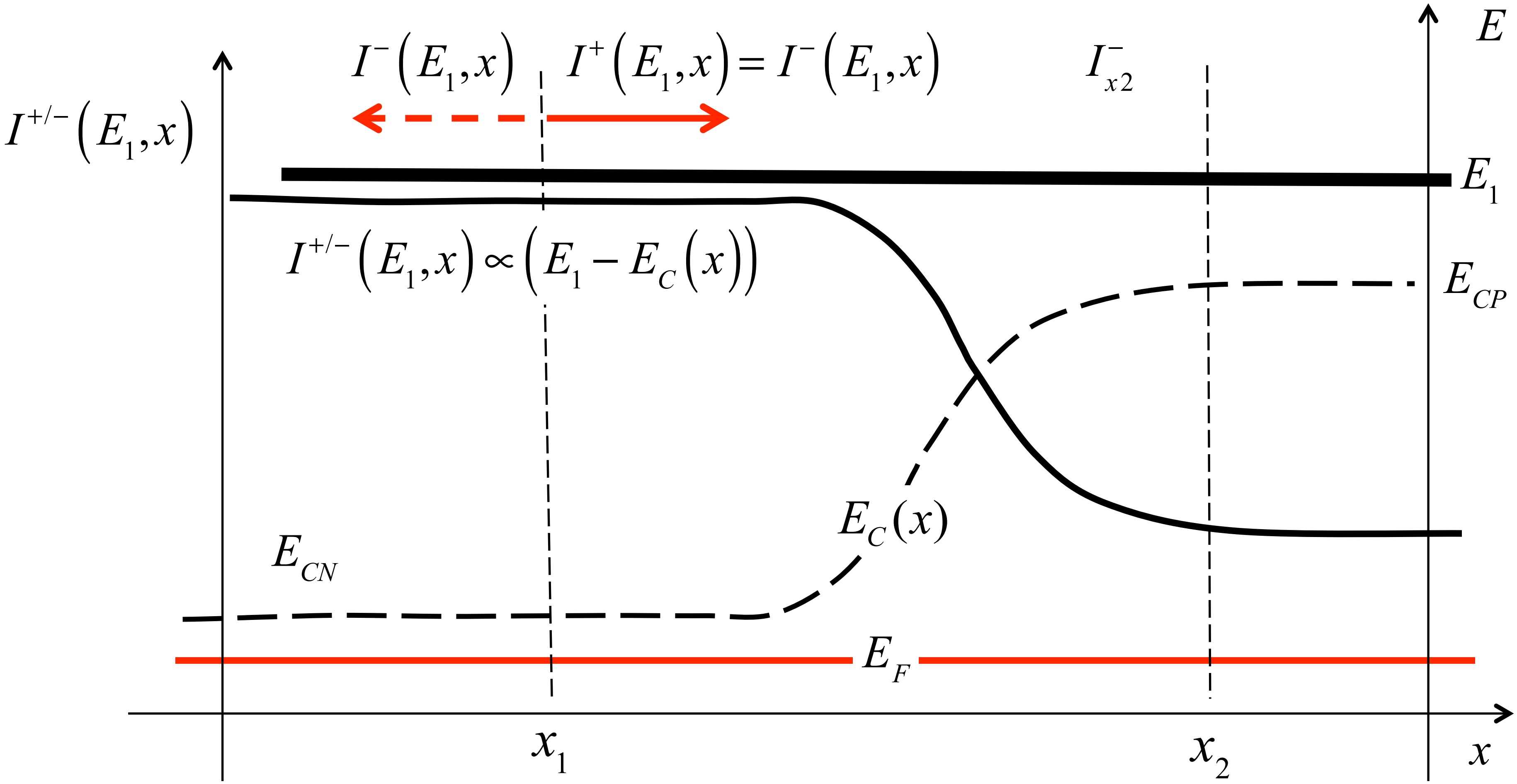
Velocity of electrons : $\upsilon\left(E_1\right) = \sqrt{\frac{2\left(E_1 - E_C\left(x\right)\right)}{m^*}}$

Current: $I^{+/-}\left(E_1, x\right) \propto n\left(E_1, x\right)dE\,\upsilon\left(E_1, x\right) \propto \left(E_1 - E_C\left(x\right)\right)$

# Consider one specific energy channel

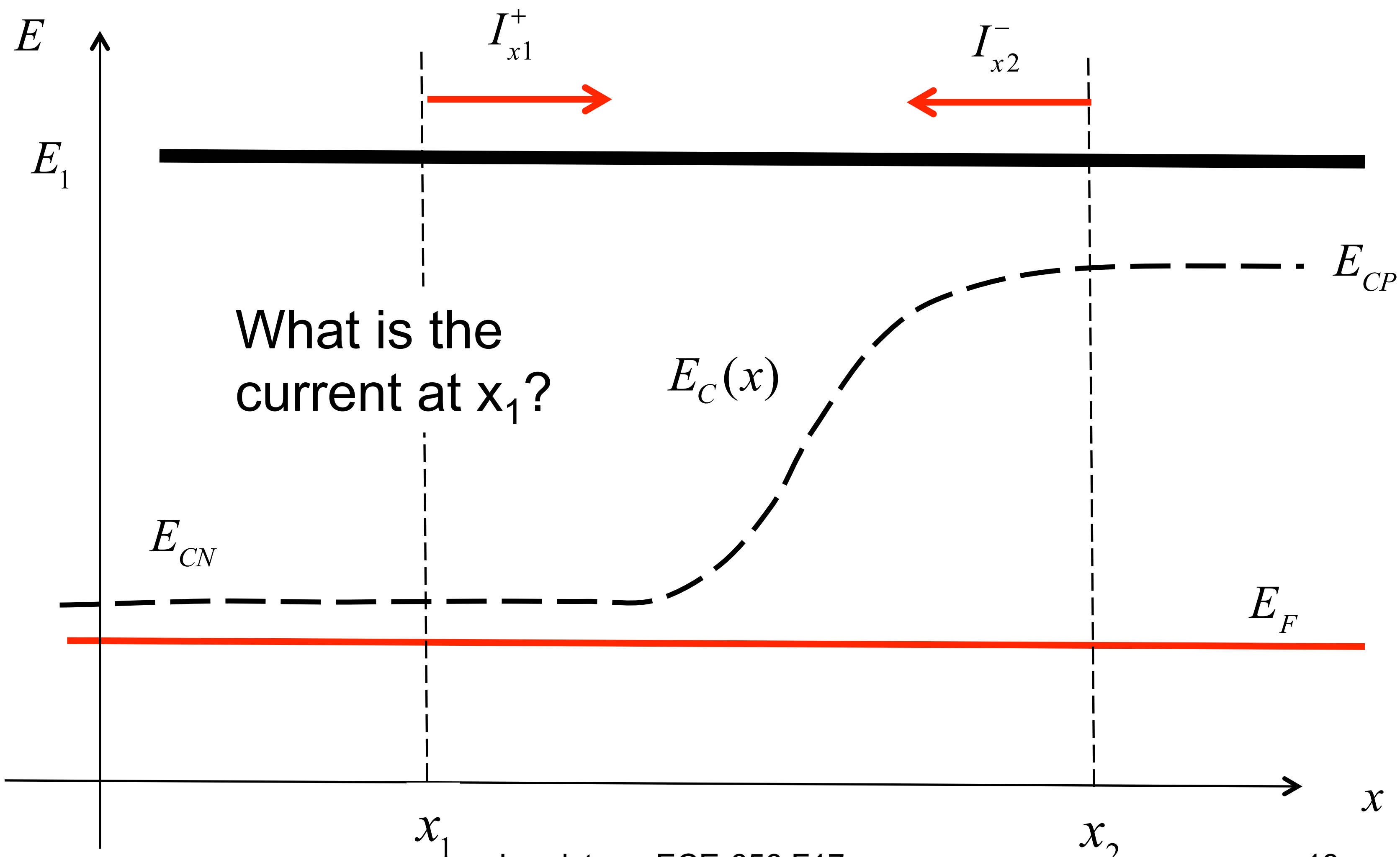


# Position-dependent current

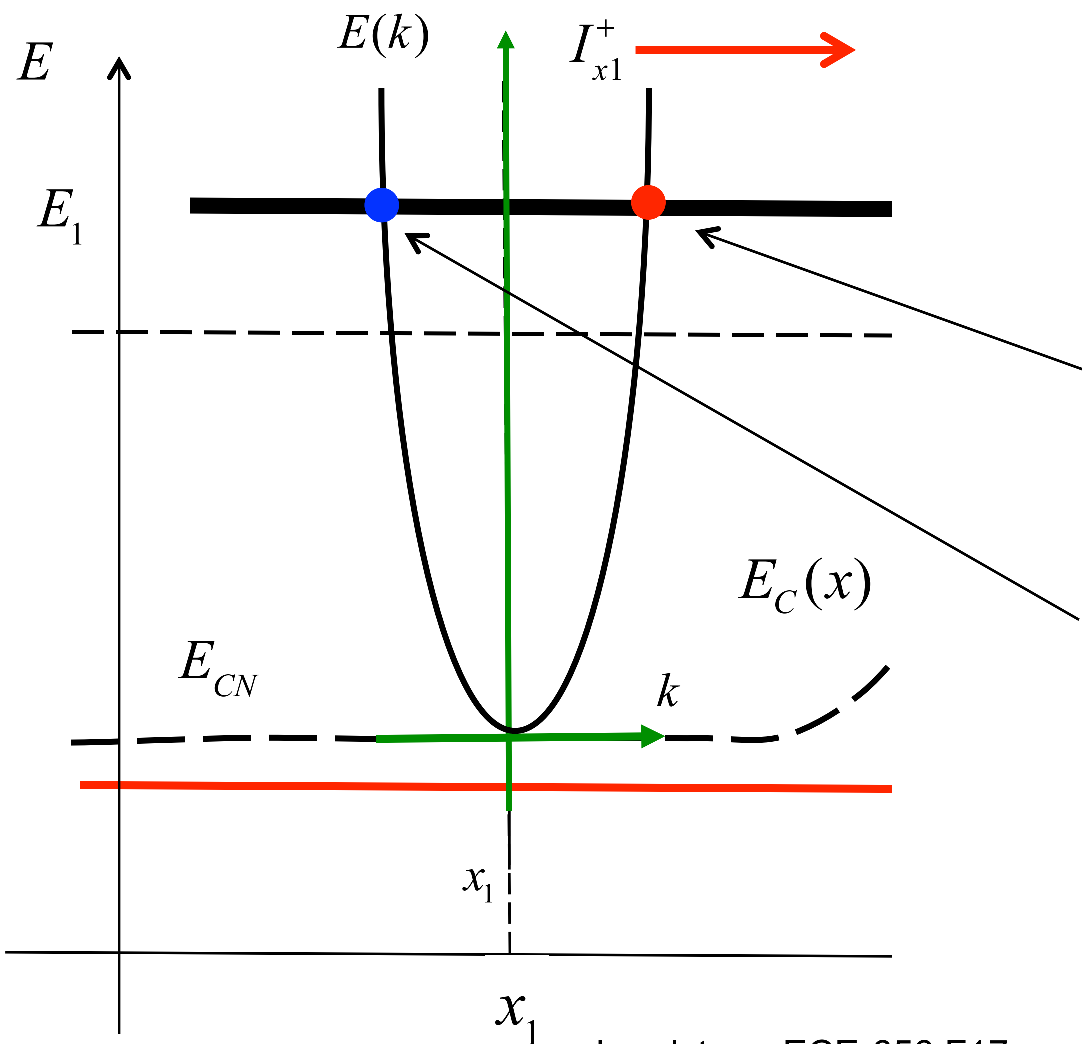



Current is zero at each location, but the magnitude of the forward and reverse currents **varies with position**.

# Another way of looking at this



# Current at x = $x_1$




Probability that this state is occupied is $f_0(E_1)$.

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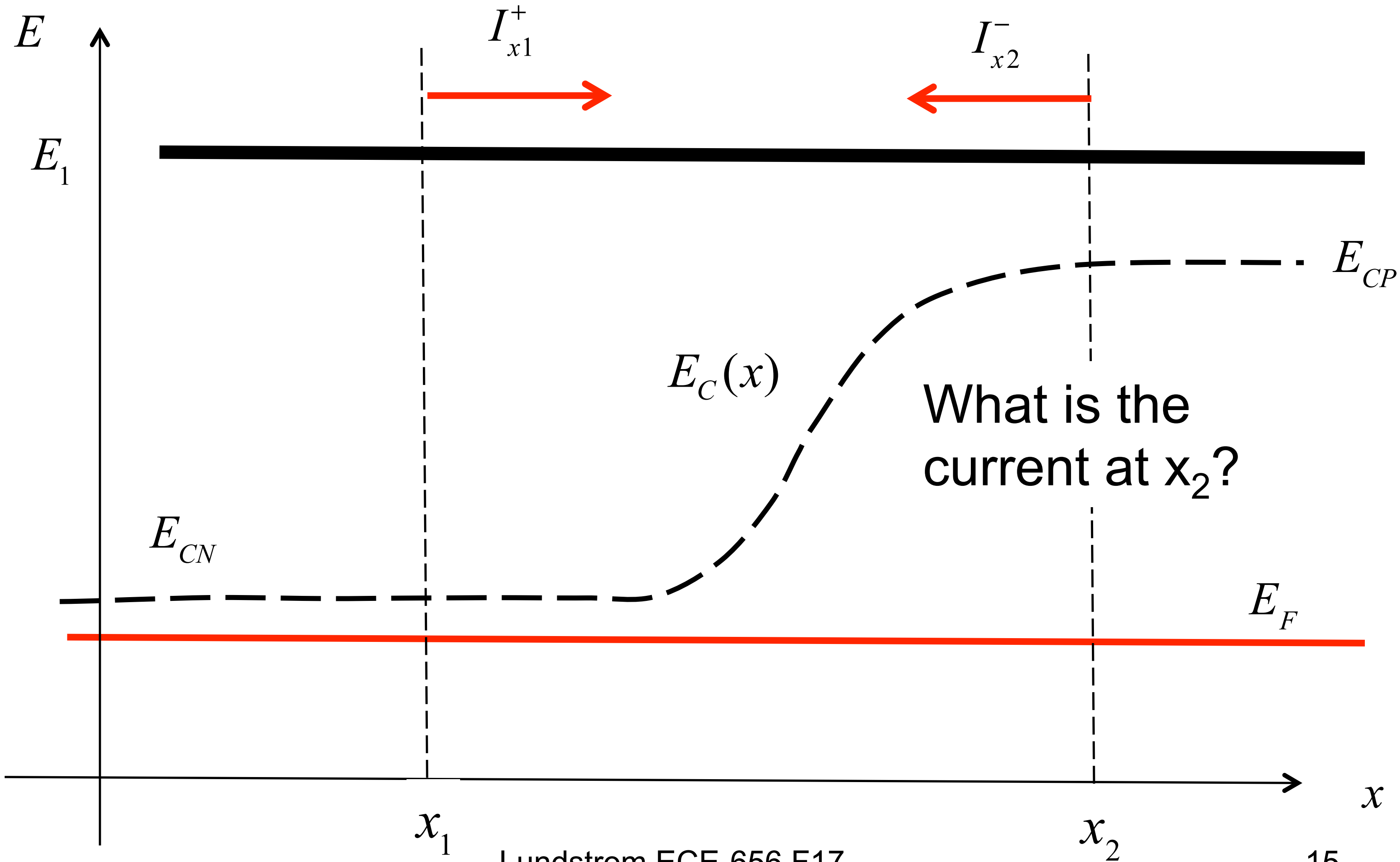
$$I^+_{x1} = I^-_{x1}$$

$$I = I^+_{x1} - I^-_{x1} = 0$$

# Current at x = $x_2$



# Current at x = $x_2$

Probability that this state is occupied is $f_0(E_1)$.

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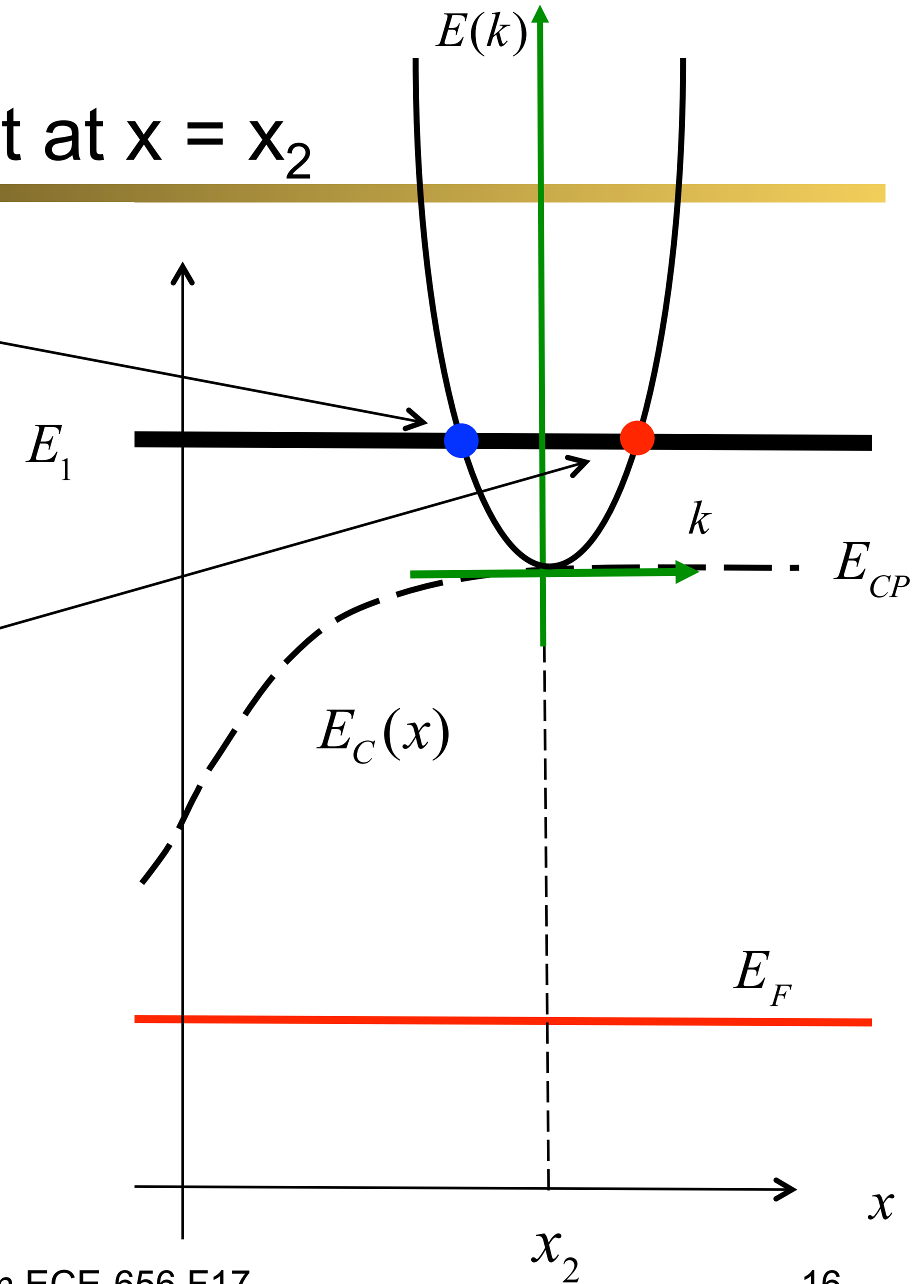
$$I_{x2}^{+} = I_{x2}^{-}$$

$$I = I_{x2}^{+} - I_{x2}^{-} = 0$$

But:

$$I_{x2}^{+} < I_{x1}^{+} = 0$$



# Summary

$$I_1^+\left(x\right) \propto \left(E_1 - E_C\left(x\right)\right) f_o\left(E_1\right) = I_1^-\left(x\right)$$

The forward (and reverse) currents are position-dependent, but the two are equal at any given location, so the current is zero at any given location.

In the first try, we were comparing the forward current at one location with the reverse current at another location.