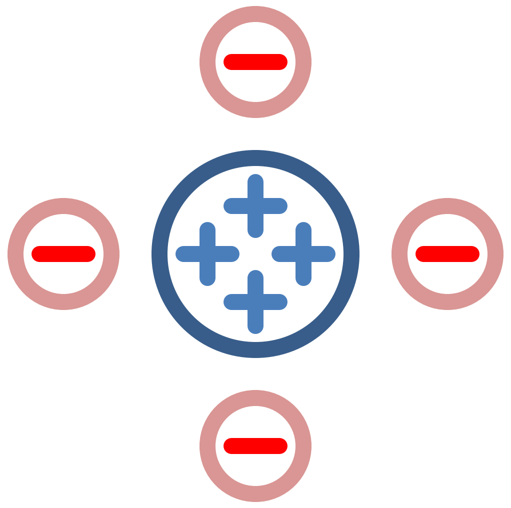
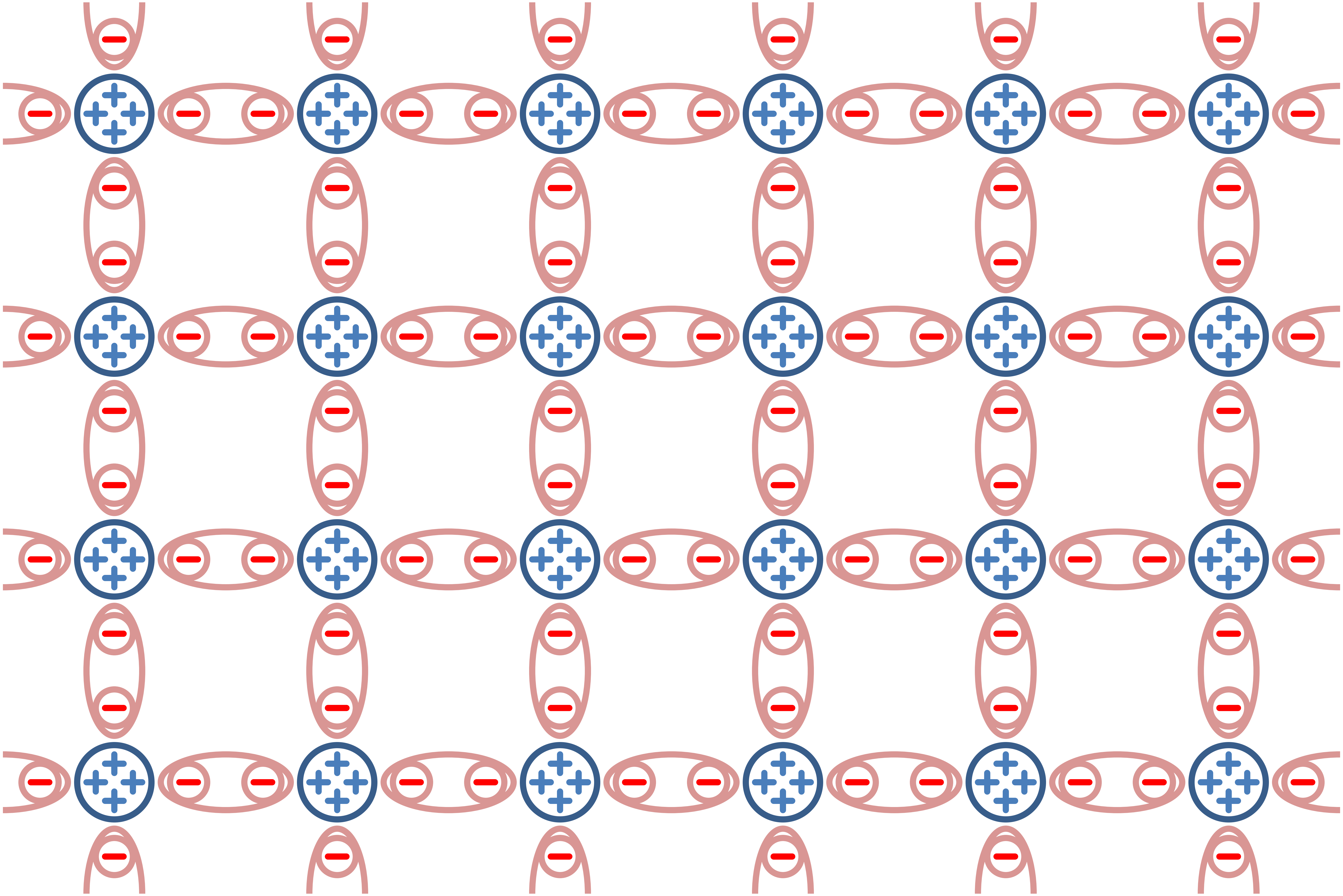


Silicon: 14 electrons

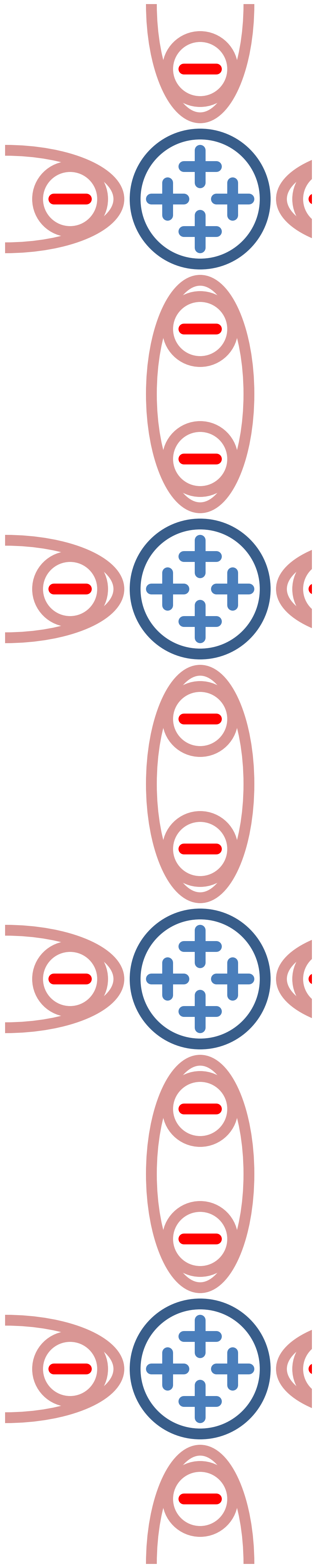
4 in outer shell

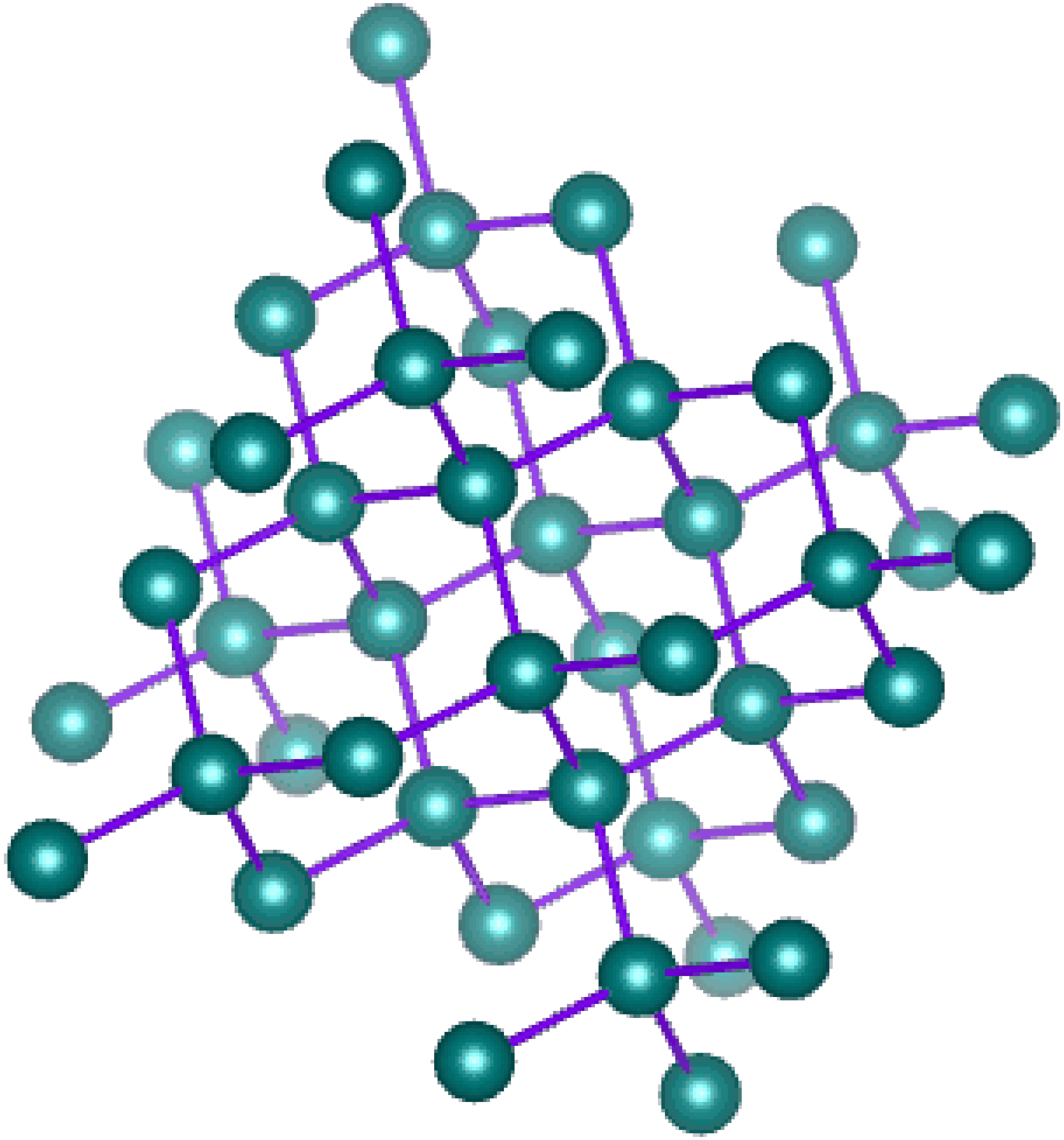
Silicon at T=0K; Covalent bonds Poor conductor

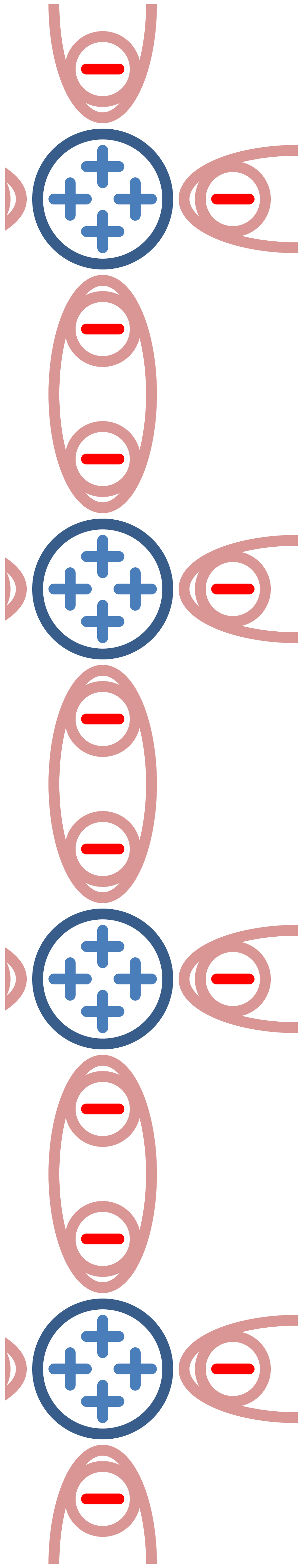


Silicon at T=0K; Covalent bonds

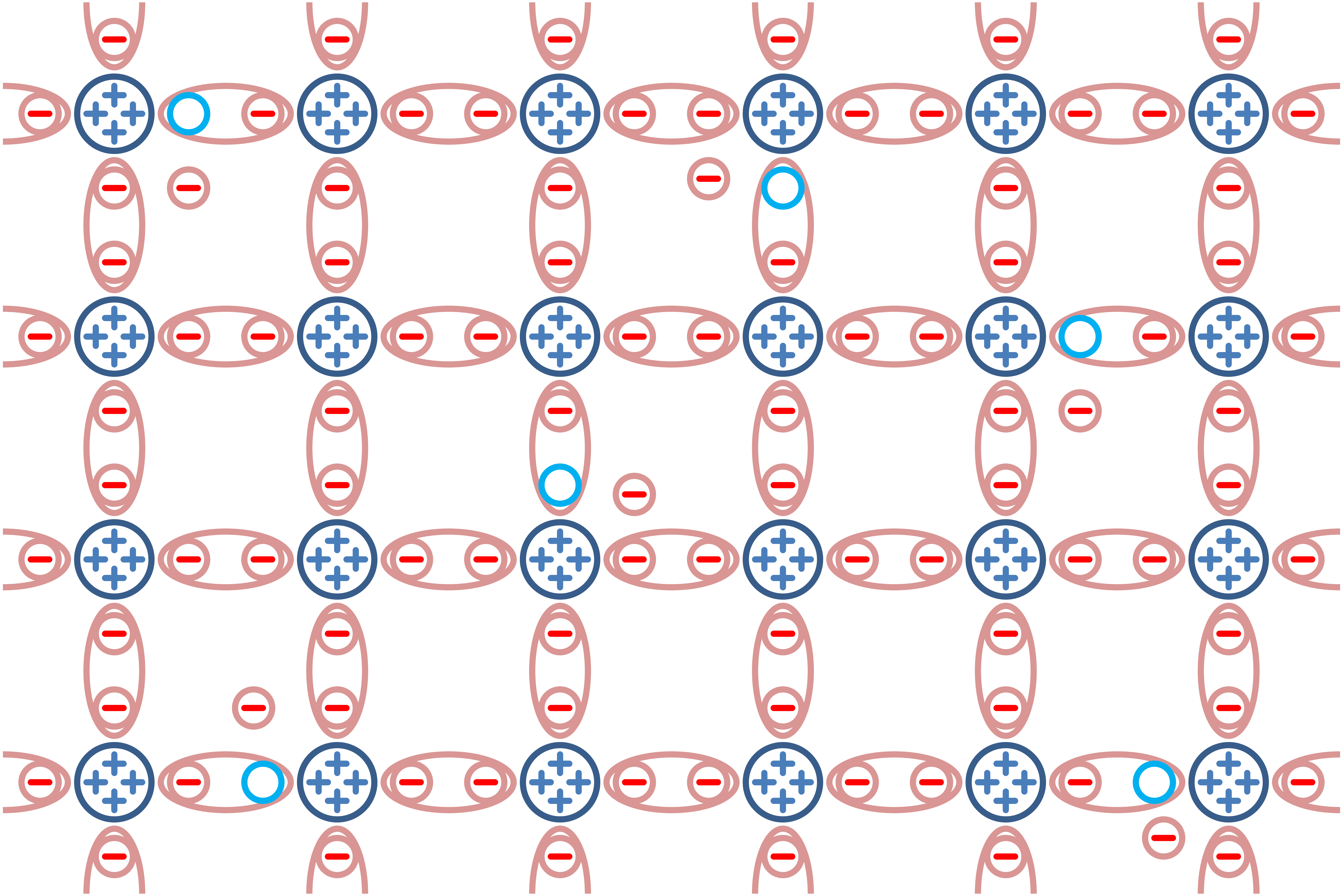
Poor conductor







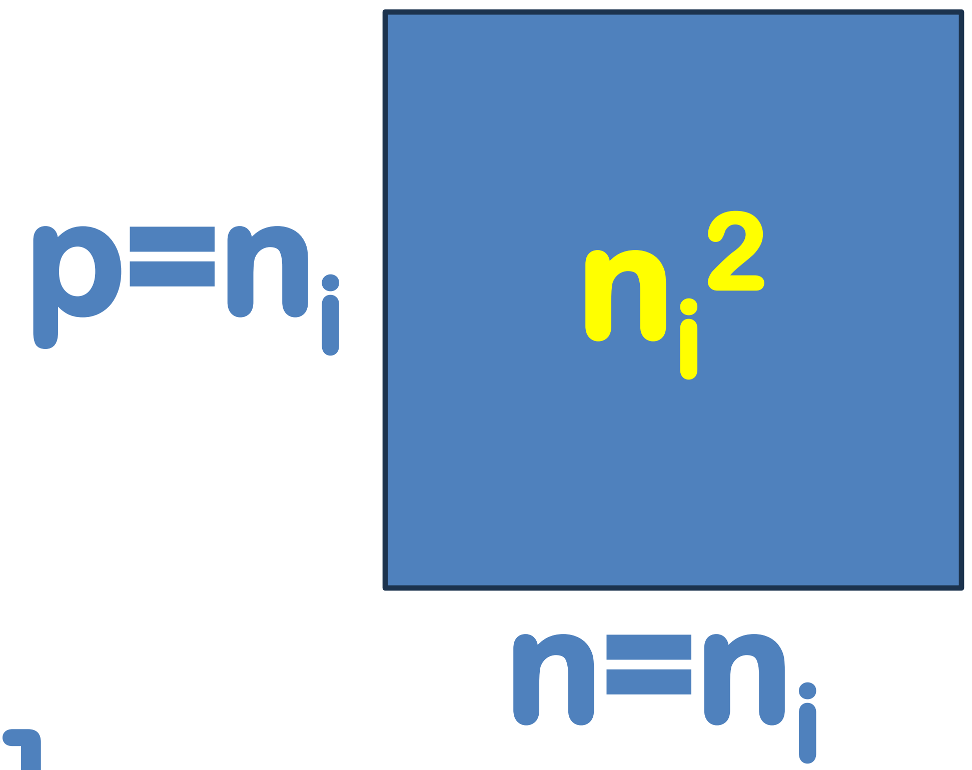
Silicon at T>0K; free electrons (f.e.) and holes



Silicon at T>0K; Better Conductor

Charge Carriers: free electrons and holes

n: number of f.e. per unit volume (cm^3)
p: number of holes per unit volume



Intrinsic (pure silicon)

$n=p=n_i$
$n_i=BT^{3/2}e^{-Eg/2kT}$ $B=7.3x10^{15}[cm^{-3}K^{-3/2}]$
$E_g=1.12[eV]$, $k=8.62x10^{-5}[eV/K]$

Commonly refer to the product

$pn=n_i^2$

Area (n_i^2) is set by temperature.
# of charge carriers is set by the perimeter.
Square is the worst shape to maximize perimeter (p+n).

Silicon at T>0K; Better Conductor

What is the concentration of charge carriers (p and n) for intrinsic silicon at 27 degree C.

Silicon at T>0K; Better Conductor

- What is the concentration of charge carriers (p and n) for intrinsic silicon at 27 degree C.
  - 27C = 300K
  - $p=n=n_i=BT^{3/2}e^{-Eg/2kT}$

  - $B=7.3x10^{15}[cm^{-3}K^{-3/2}]$
  - $E_g=1.12[eV]$ Electron Volt 1eV = $1.6x10^{-19}$ J
  - $k=8.62x10^{-5}[eV/K]$

  - $p=n=7.3x10^{15}\ (300^{3/2})\ e^{-1.12/(2*8.62e-5*300)}$
    $=1.5x10^{10}$ carriers/cm^3

  - There are $5x10^{22}$ atoms/cm^3 for silicon, so only 1 out of every $5x10^{12}$ is ionized.

Current:

Free Electrons and Holes Moving.

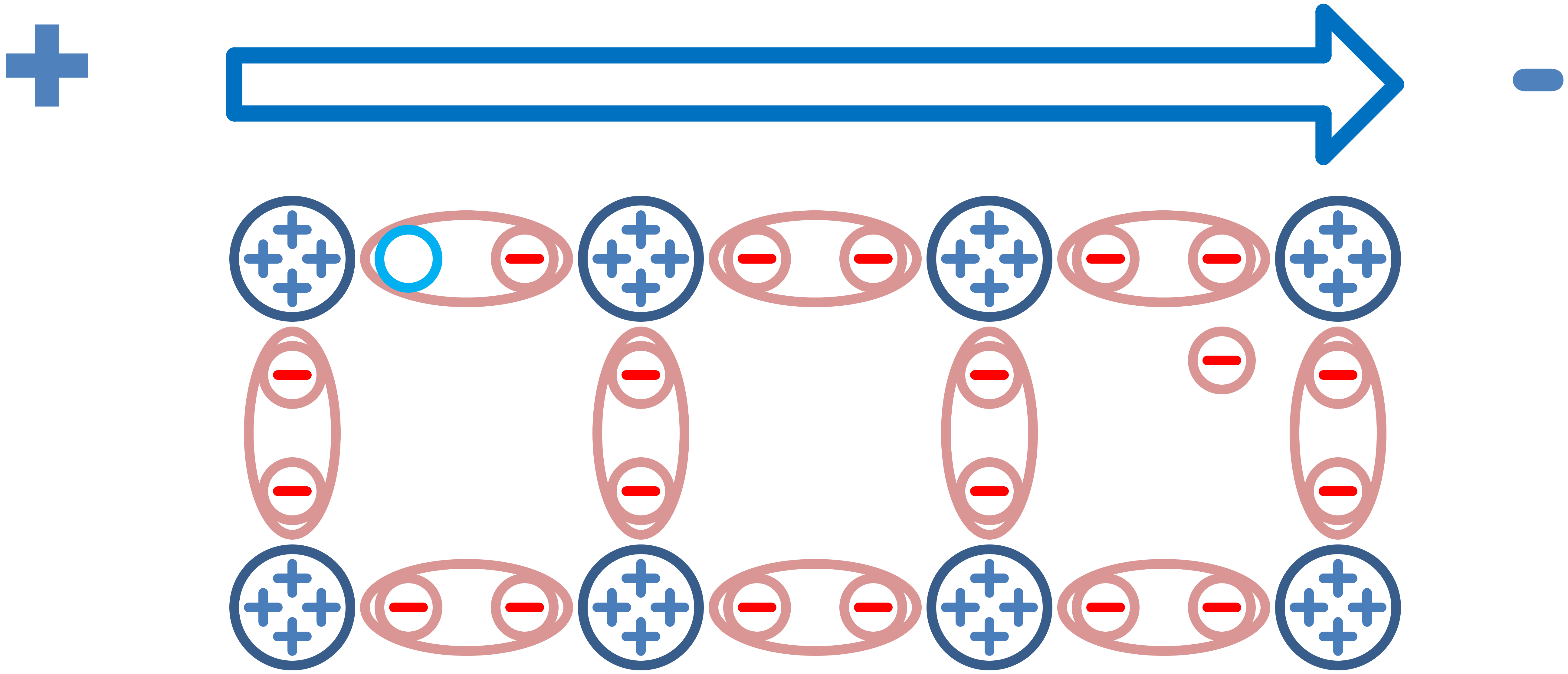
How do they move? (2 Types)

Currents:

Free Electrons and Holes Moving.

How do they move? (2 Types)

1) Apply and electric field (Voltage)



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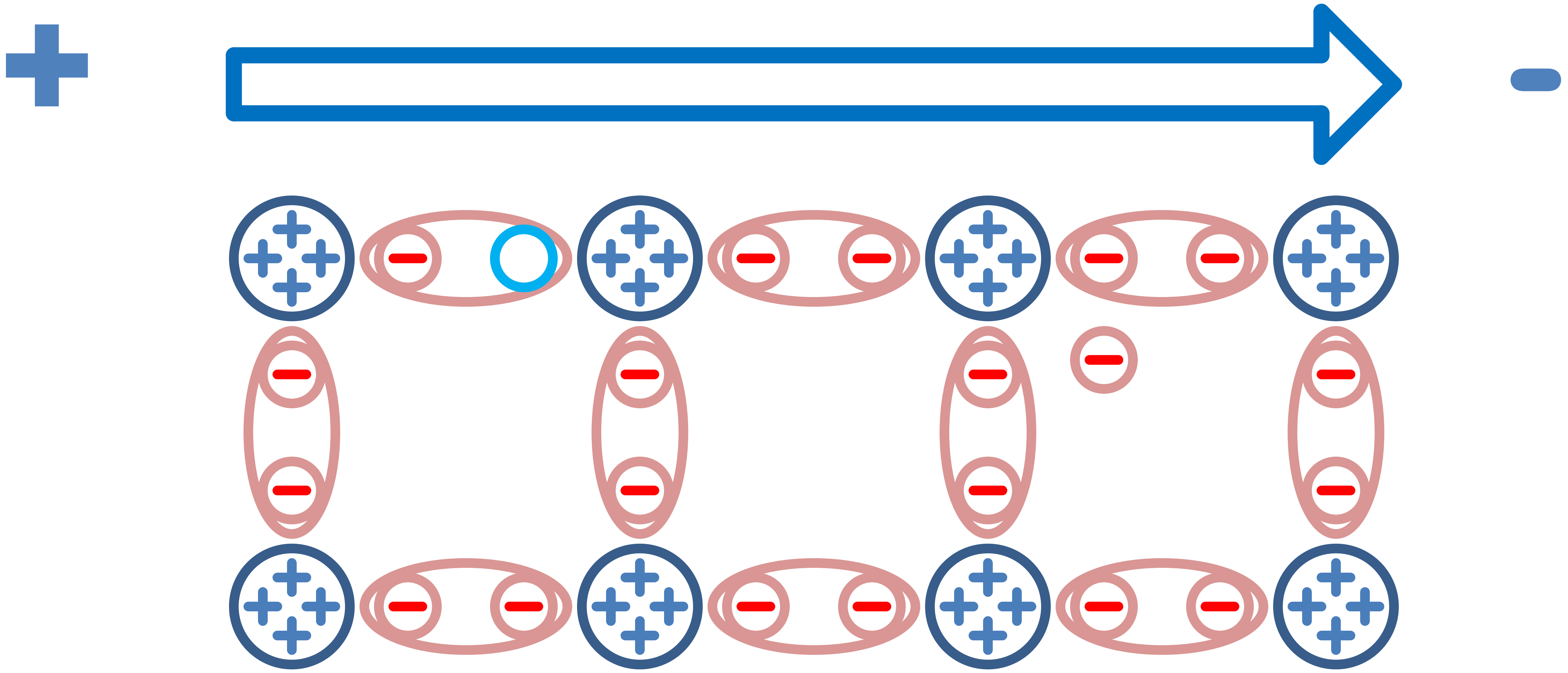

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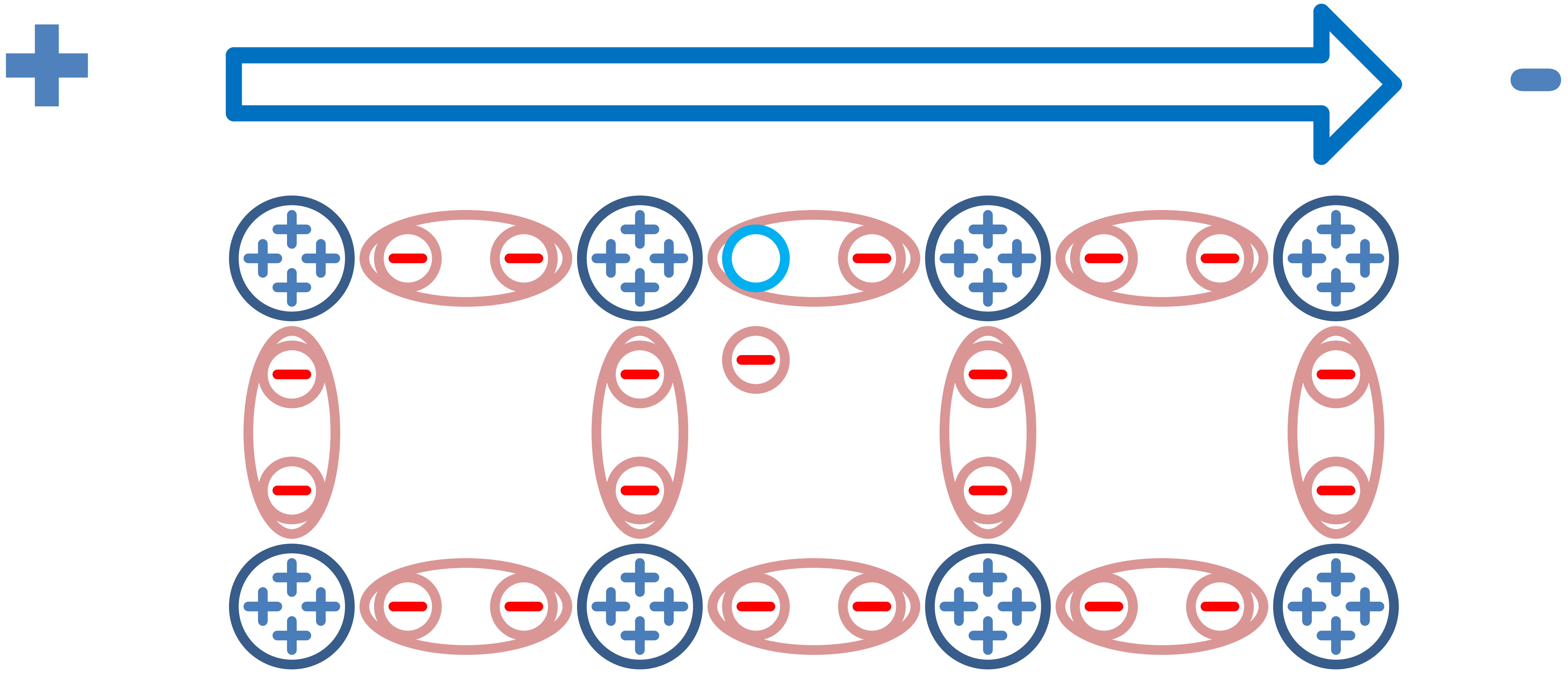

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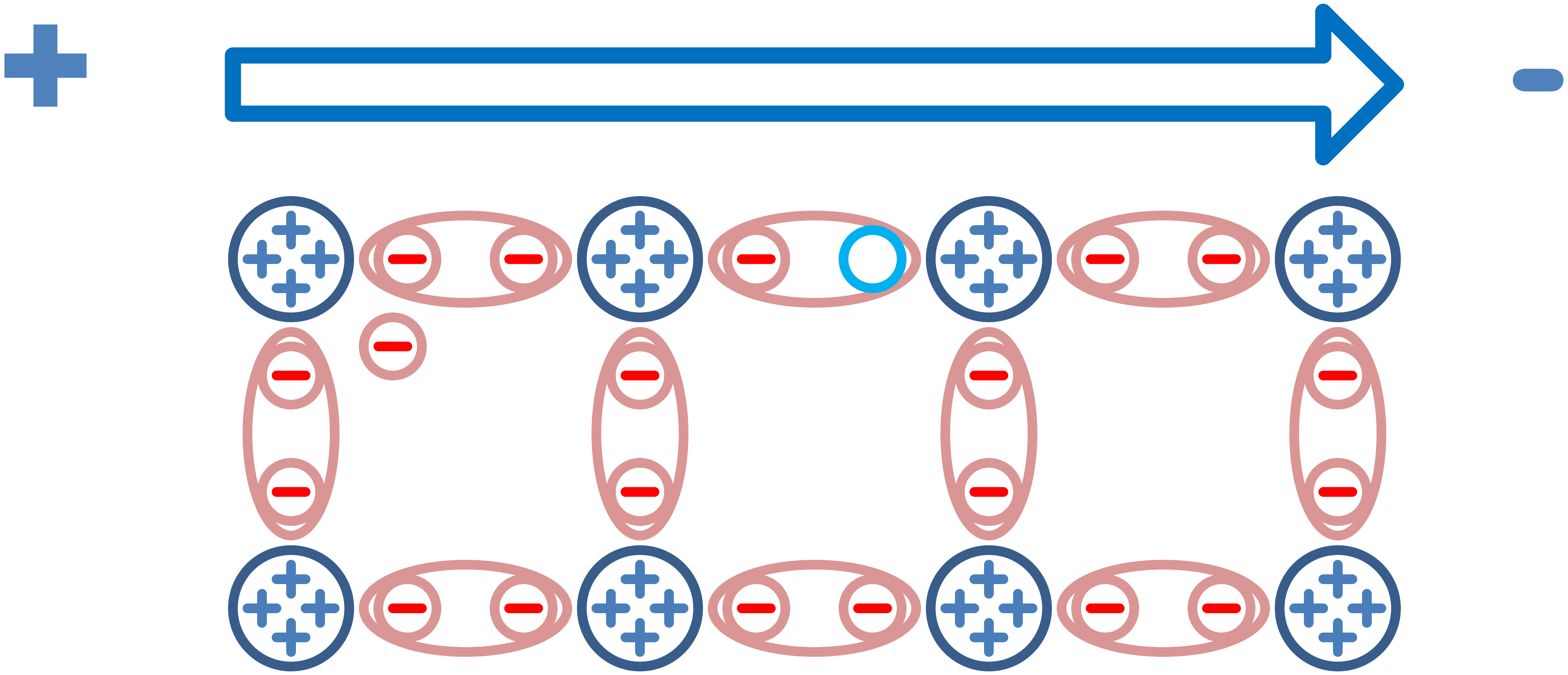


Drift Current: Current due to an e-field.

Force: Electric field (left to right)
Property: Charge

Equations:
velocity (cm/s) = mobility × Force (E=V/cm)
$v_{p\text{-drift}} = \mu_p E$ μ_p=480 cm^2/Vs (for silicon) depends on Temp
$v_{n\text{-drift}} = -\mu_n E$ μ_n=1350 cm^2/Vs (for silicon)

Current (A) = Area (cm^2) × ($\#/cm^3$) × v (cm/s) × charge (q)
A = (#q)/s (left to right: same direction as E-field)
$I_p = A \cdot q \cdot p \cdot v_{p\text{-drift}} = A \cdot q \cdot p \cdot \mu_p \cdot E$
$I_n = -A \cdot q \cdot n \cdot v_{n\text{-drift}} = A \cdot q \cdot n \cdot \mu_n \cdot E$

Current Density = Current / Area = Conductivity × Force
$J_p = q \cdot p \cdot \mu_p \cdot E$ $J_n = q \cdot n \cdot \mu_n \cdot E$
$J = J_p + J_n = q(p \cdot \mu_p + n \cdot \mu_n)E = \sigma \cdot E$

Conductivity and resistivity
$\sigma = q(p \cdot \mu_p + n \cdot \mu_n)$ $\rho = 1/\sigma = 1/q(p \cdot \mu_p + n \cdot \mu_n)$

Drift Current: Current due to an e-field.

Force: Electric field (left to right)

Property: Charge

Conductivity and resistivity

$\sigma = q(p \cdot \mu_p + n \cdot \mu_n)$ $\rho = 1/\sigma = 1/q(p \cdot \mu_p + n \cdot \mu_n)$

What is the resistivity of intrinsic silicon at room temp (T=300K)?

Drift Current: Current due to an e-field.

Force: Electric field (left to right)
Property: Charge

Conductivity and resistivity

$\sigma = q(p \cdot \mu_p + n \cdot \mu_n)$ $\rho = 1/\sigma = 1/q(p \cdot \mu_p + n \cdot \mu_n)$

What is the resistivity of intrinsic silicon at room temp (T=300K)?

$\rho = 1/\sigma = 1/q(p \cdot \mu_p + n \cdot \mu_n)$

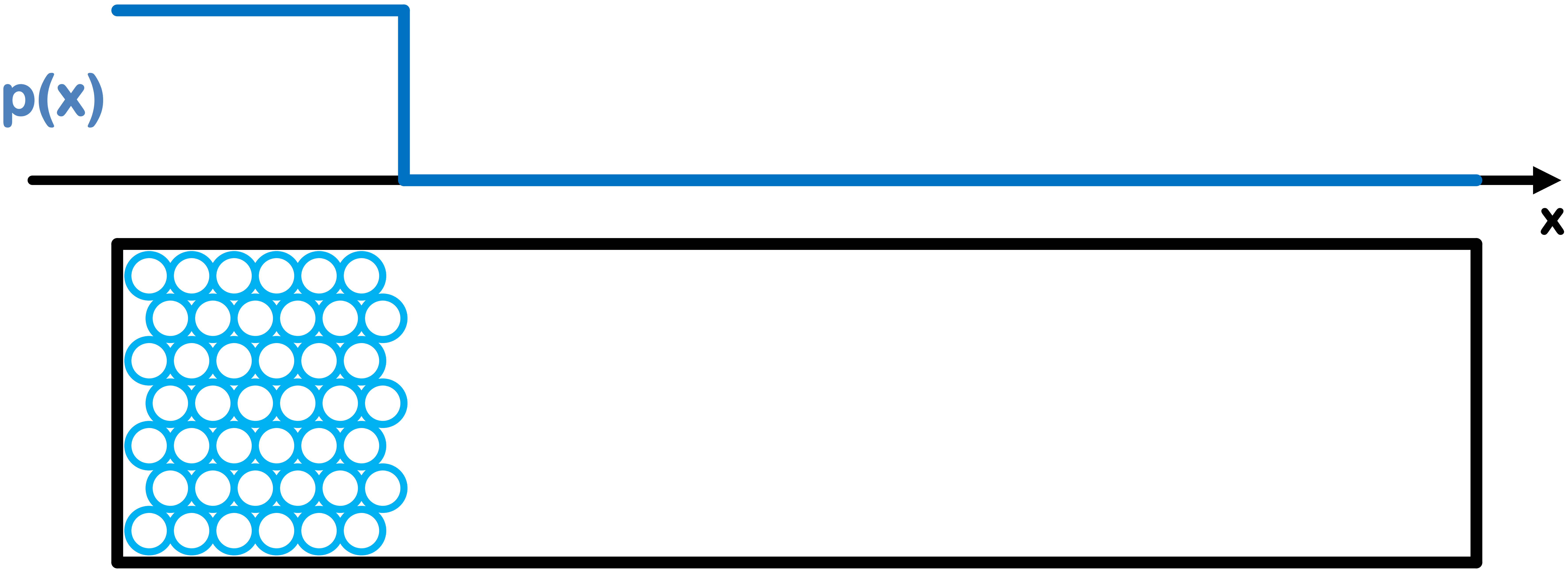
$\rho = 1/(1.6e\text{-}19)(1.5e10 * 480 + 1.5e10 * 1350) = 2.28 \times 10^5\ \Omega\ \text{cm}$

Currents:

Free Electrons and Holes Moving.

How do they move? (2 Types)

2) Concentration Gradient, p'(x)



Currents:

Free Electrons and Holes Moving.

How do they move? (2 ways)

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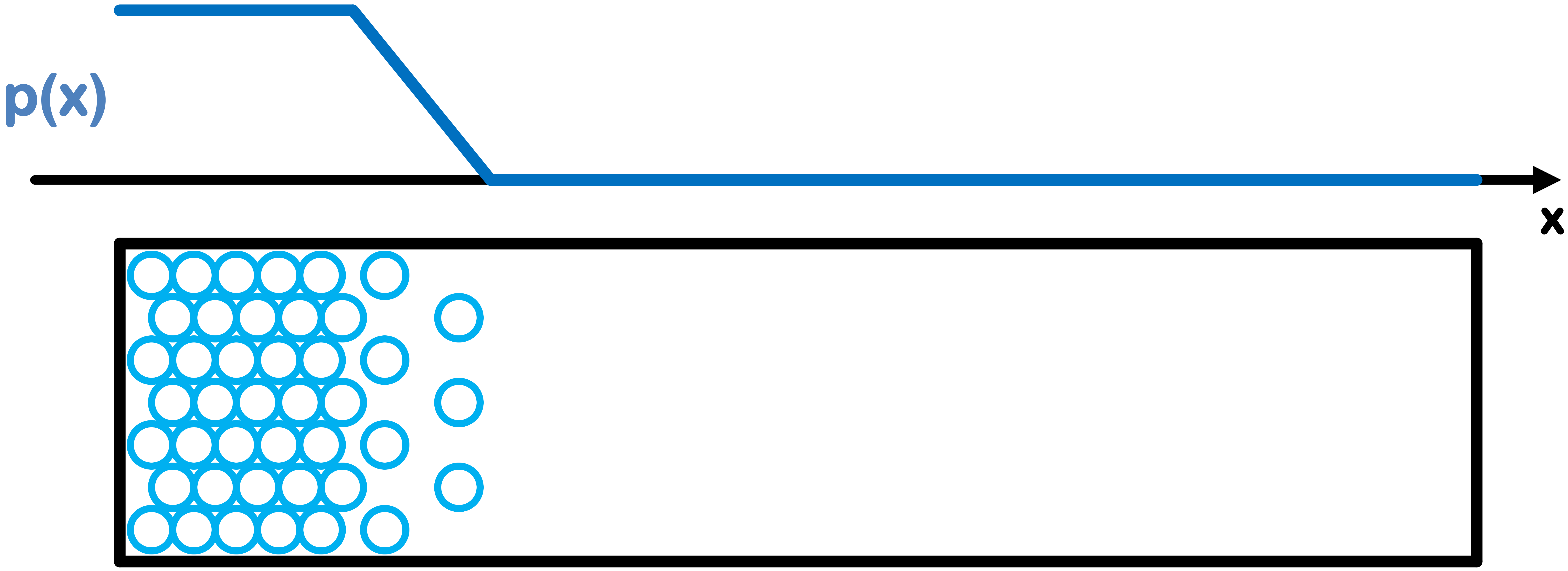

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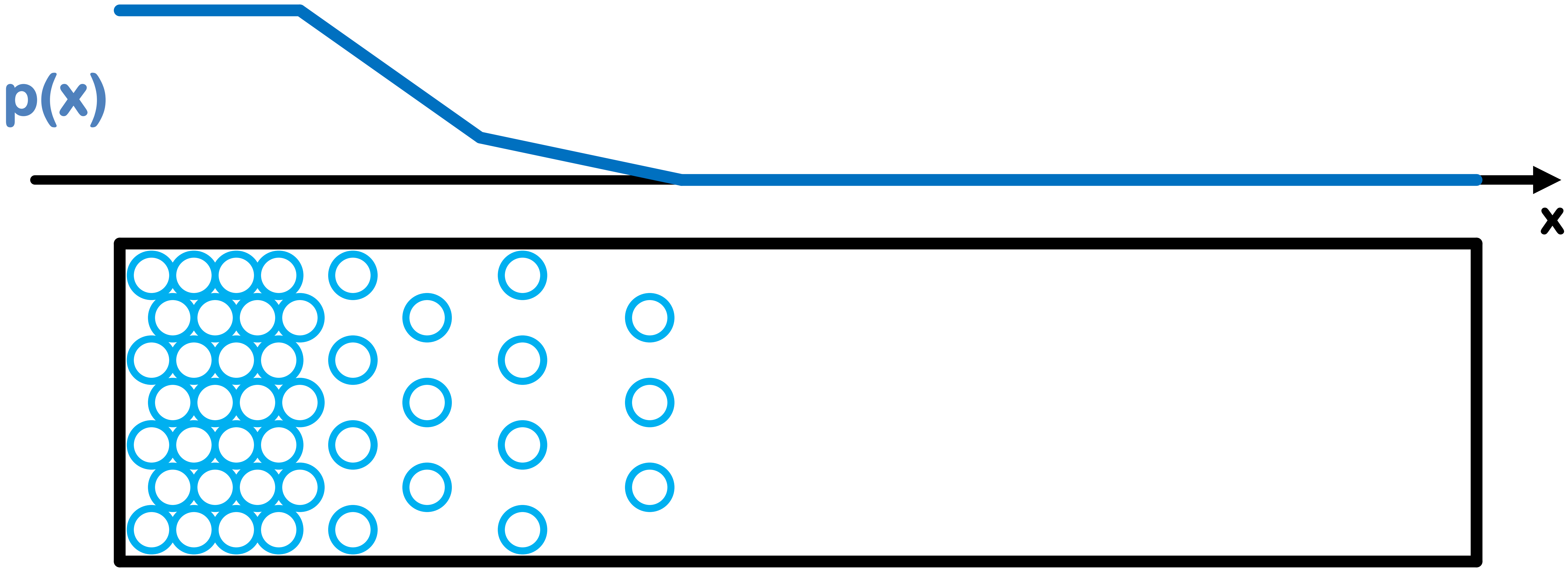

Currents:

Free Electrons and Holes Moving.

How do they move? (2 ways)

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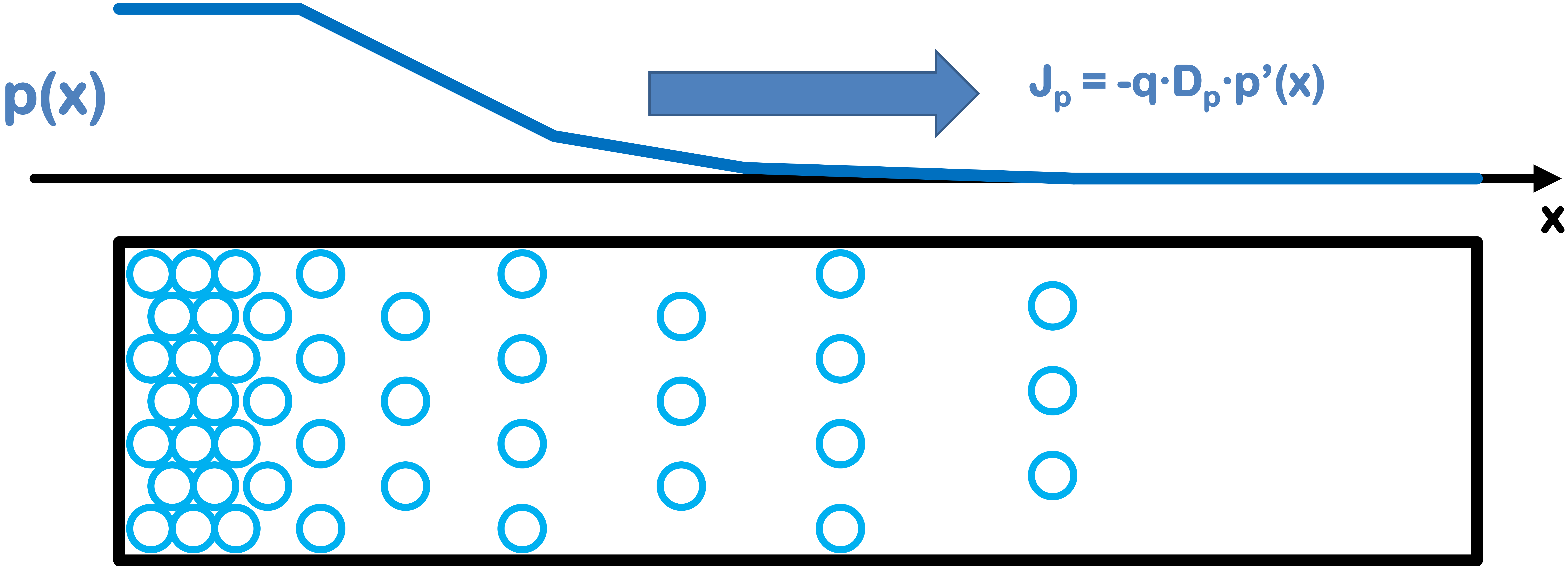


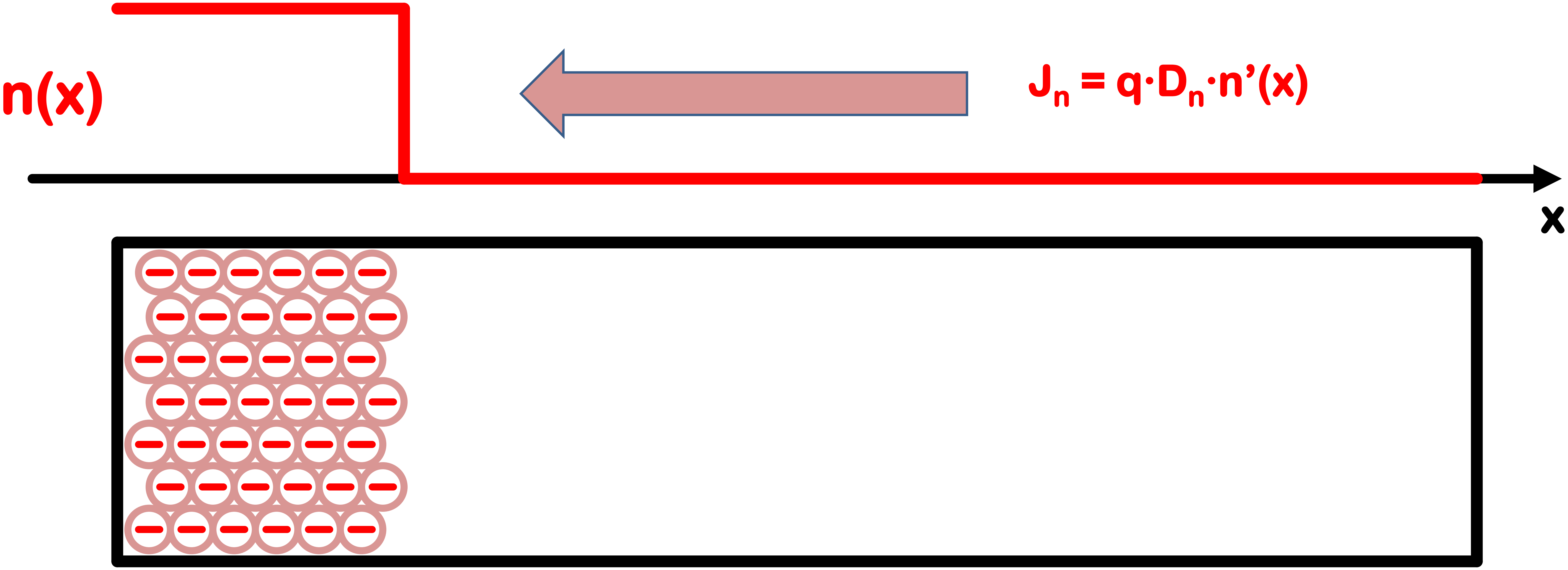
$J_p = -q \cdot D_p \cdot p'(x)$

Currents:

Free Electrons and Holes Moving.

How do they move? (2 ways)

2) Concentration Gradient, n'(x)



$J_n = q \cdot D_n \cdot n'(x)$

Diffusion Current: Current due to an mass, heat, and con. grad.

Force: Heat

Property: Mass and Concentration Gradient

Current Density = Current / Area = Conductivity × Force

$J_p = -q \cdot D_p \cdot p'(x)$ $D_p = 12 cm^2/s$ (for silicon)

$J_n = q \cdot D_n \cdot n'(x)$ $D_n = 35 cm^2/s$ (for silicon)

Remember, Current = Current Density × Area

$I_p = -A \cdot q \cdot D_p \cdot p'(x)$

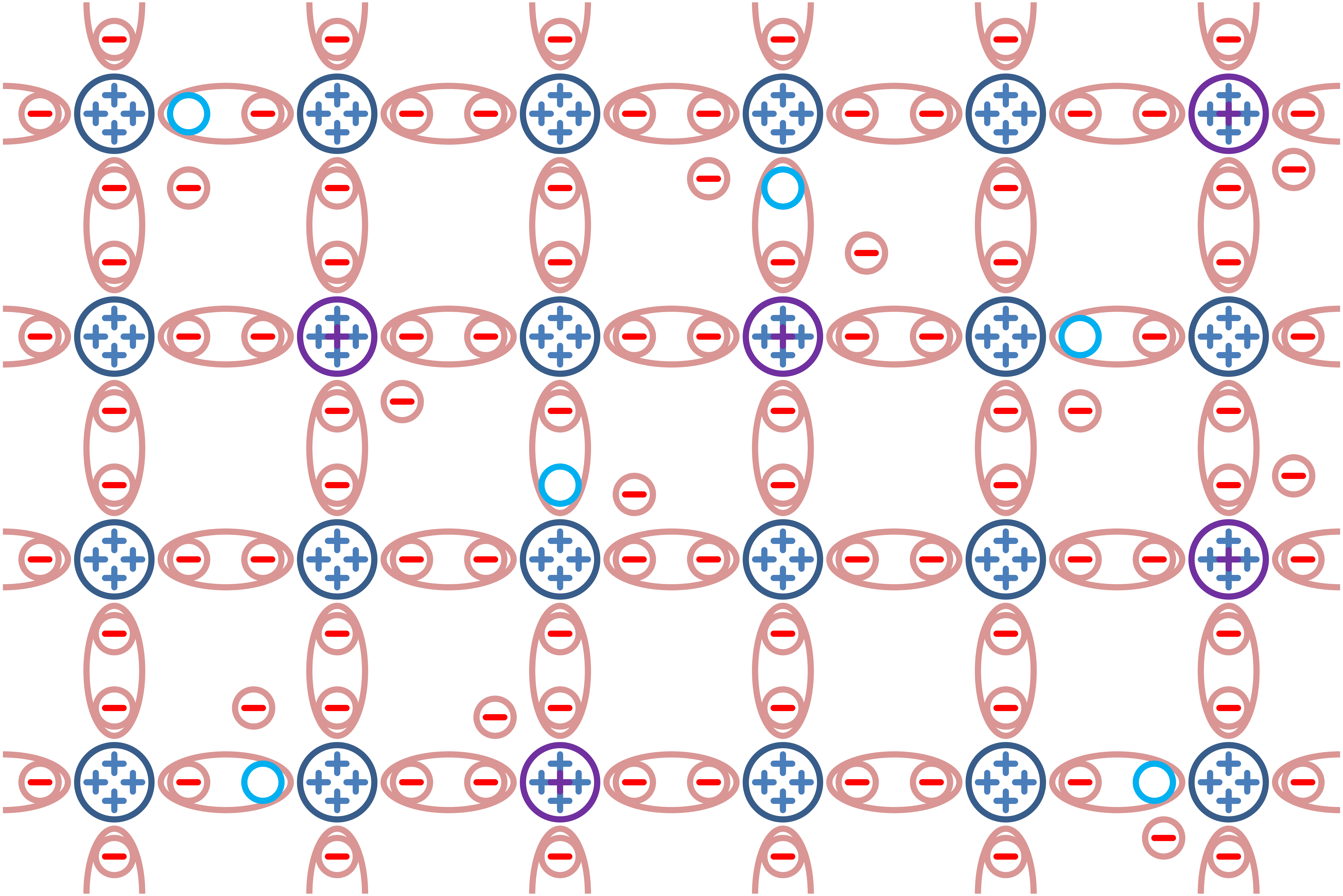
$I_n = A \cdot q \cdot D_n \cdot n'(x)$

$D_n/\mu_n = D_p/\mu_p = V_T$

The problem with pure (intrinsic) silicon is that p and n are small resulting in a poor conductor.

How can we increase the number of f.e. or holes?

Doped Silicon: With Phosphorus (15)



N-type Silicon:

Doped with **Phosporus (Donor)**

Excess of free electrons (negative)

- $n_n=N_D$ Donor Concentration
- $n_n>>p_n$
- $p_n n_n=n_i^2$
- $p_n=n_i^2/N_D$

$p=n_i^2/N_D$

n_i^2

$n=N_D$

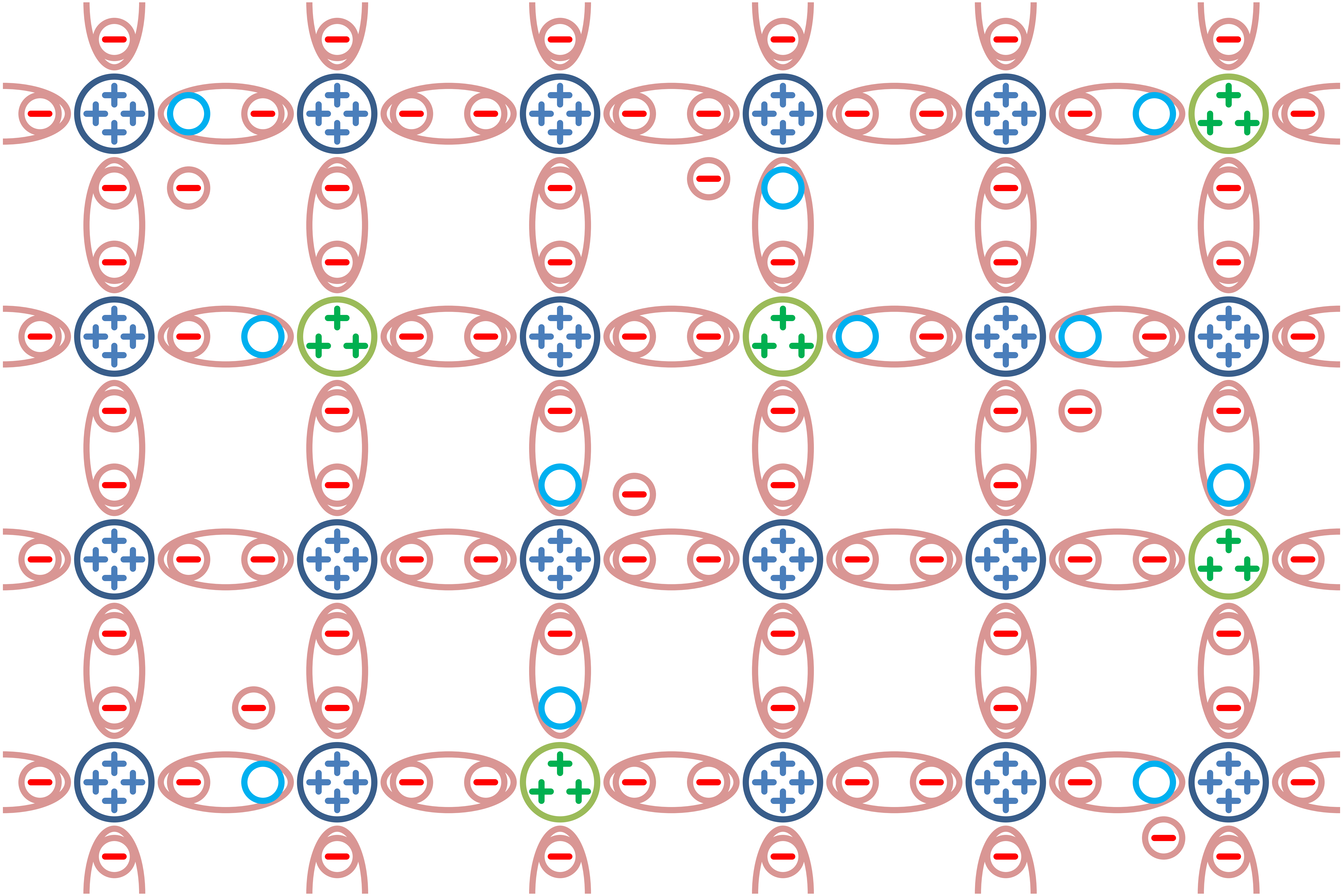
Charge Carriers

- free electrons: majority carriers
- holes: minority carriers

If f.e. are removed to equalize holes and f.e.

- The region becomes depleted (poor cond.)
- The region becomes positively charged

Doped Silicon: With Boron (5)



P-type Silicon:

Doped with **Boron (Acceptor)**

Excess of holes (positive)

$p_p = N_A$ Donor Concentration

$p_p >> n_p$

$p_p n_p = n_i^2$

$n_p = n_i^2 / N_A$

Charge Carriers

holes:	majority carriers
free electrons:	minority carriers

If holes are filled to equalize holes and f.e.

The region becomes depleted (poor cond.)

The region becomes negatively charged

Review (Silicon):

- Silicon lattice (intrinsic, covalent bonds).
  - 0K – no charge carriers.
  - >0K – free electrons (negative), holes (positive).
    - n: concentration of free electrons.
    - p: concentration of holes.
      - $p=n=n_i$ which is a function of Temperature.

- Current (two types)
  - Drift – charge moving due to electric field.
  - Diffusion – charge moving due to heat and concentration gradient.

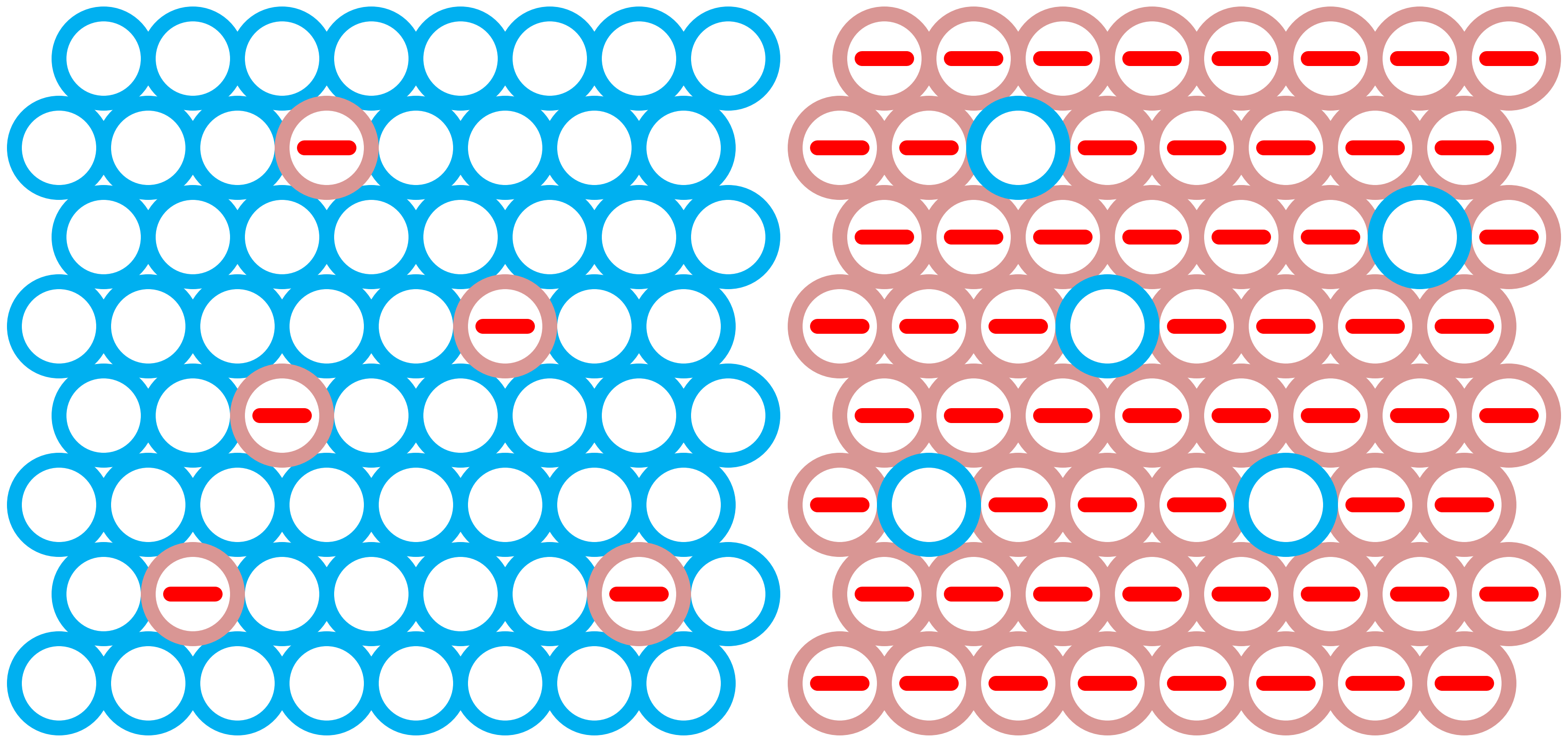
- Intrinsic silicon even at room temperature does not have a sufficient amount of charge carriers to be a good conductor

Review (Doped Silicon):

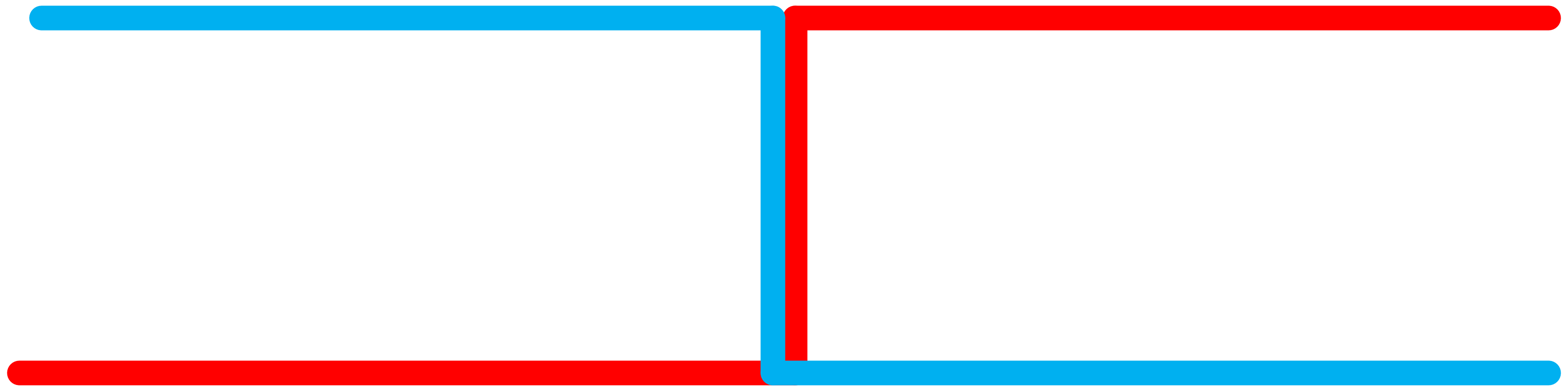
- N-Type: use Phosphorus to add extra electrons.
  - Majority carriers: f.e. – $n_n=N_D$
  - Minority carriers: holes – $p_n=n_i^2/N_D$
  - Depleted
    - Remove f.e. to equalize n and p.
    - Results in a positive charge.

- P-Type: use Boron to add extra holes.
  - Majority carriers: holes – $p_p=N_A$
  - Minority carriers: f.e. – $n_p=n_i^2/N_A$
  - Depleted
    - Add f.e. to fill holes and equalize n and p.
    - Results in a negative charge.

The PN Junction:



n(x),p(x)



Diffusion Current

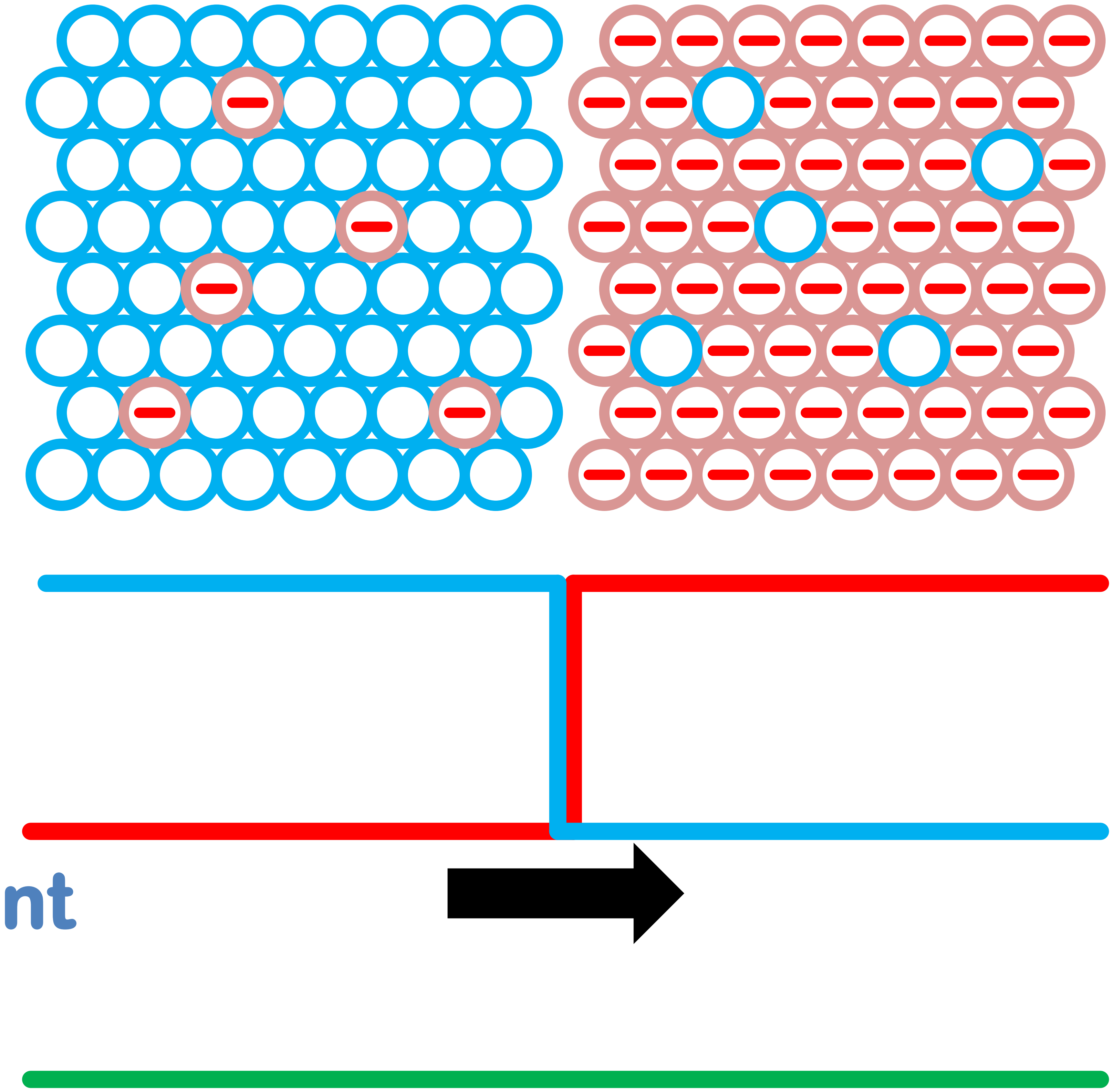
Net Charge

E-field

NONE

Drift Current

The PN Junction:



n(x),p(x)

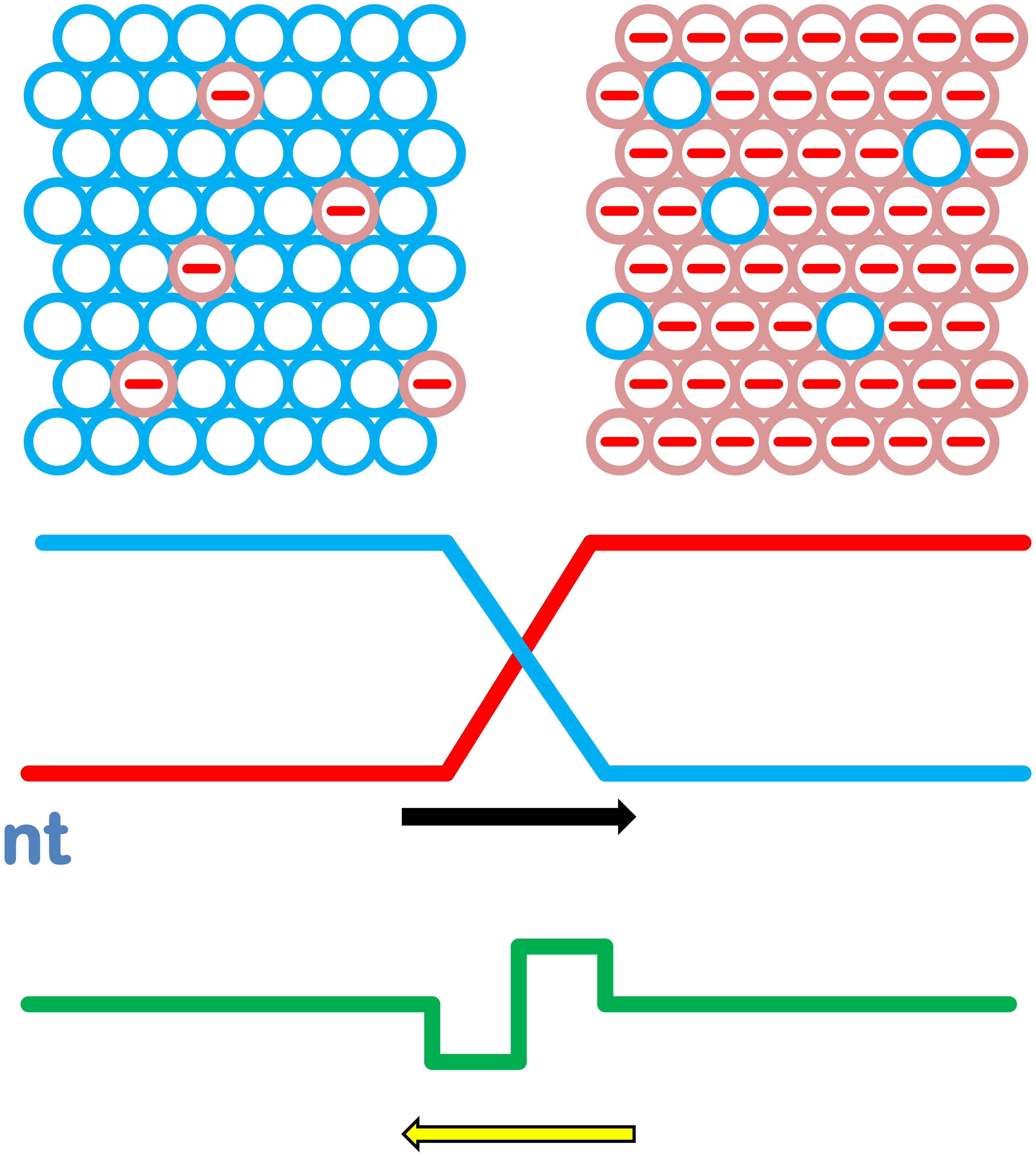
Diffusion Current

Net Charge

E-field

NONE

The PN Junction:



n(x),p(x)

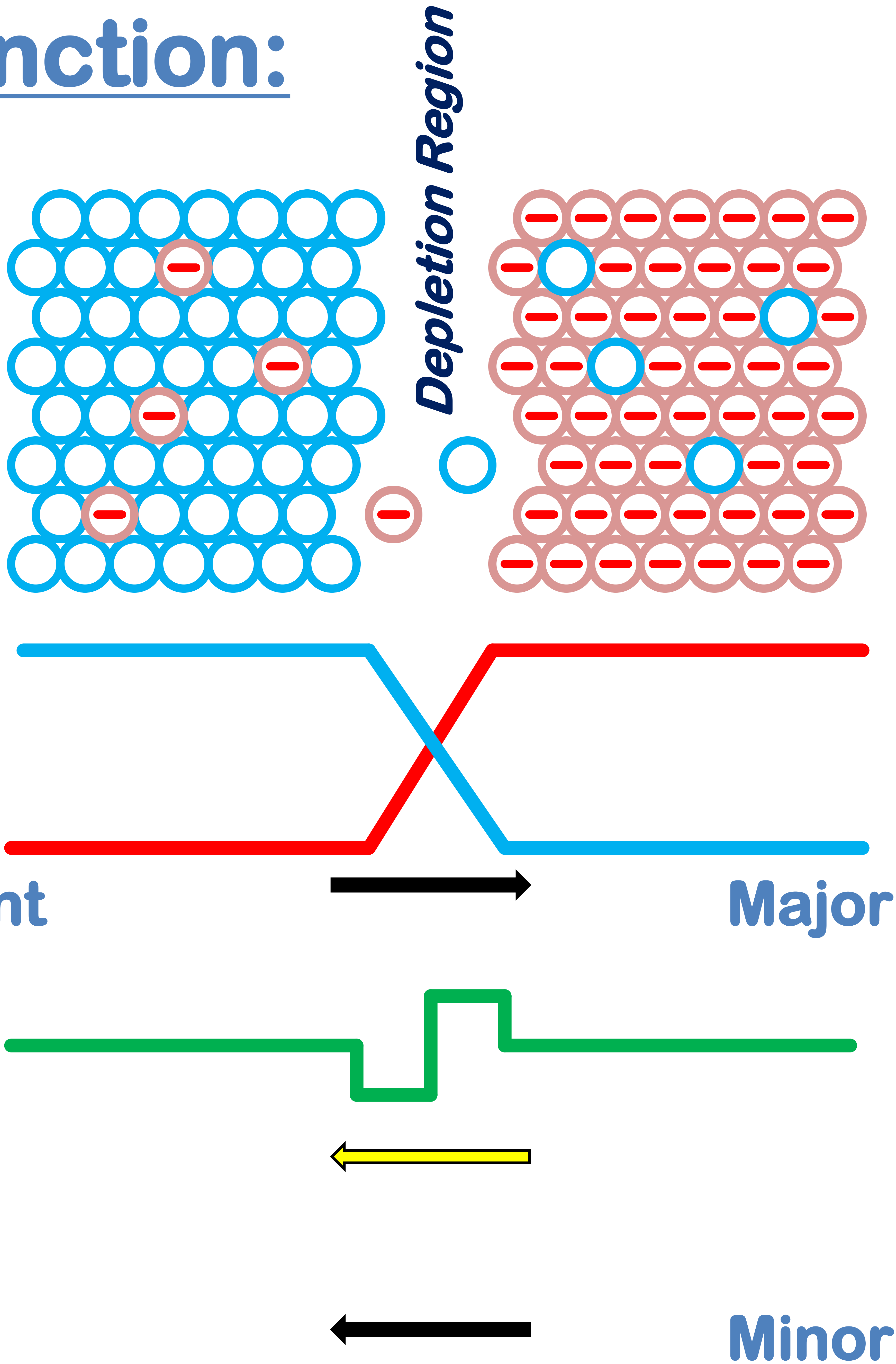
Diffusion Current

Net Charge

E-field

Drift Current

The PN Junction:



n(x),p(x)

Diffusion Current **Majority Carriers**

Net Charge

E-field

Drift Current **Minority Carriers**

The PN Junction:

Diffusion Current (anode to cathode)

- Majority Carriers
- Significantly blocked by the depletion region voltage.
- Dependent on voltage (overcome the depletion region voltage).

Drift Current (cathode to anode)

- Minority Carriers
- Not dependent on e-field, but rather the small number of available charge carrier.
- Significantly reduced by small number of minority carriers.
- Relatively constant.

Diffusion and Drift Currents are in opposite directions.

$$i_D = i_{Diffusion} - i_{Drift}$$

The PN Junction:

Diffusion Current

- Majority Carriers
- Significantly blocked by the depletion region voltage.
- Dependent on voltage (overcome the depletion region voltage).

Drift Current

- Minority Carriers
- Not dependent on e-field, but rather the small number.
- Significantly reduced by small number of minority carriers.
- Relatively constant.

Forward Biased PN Junction.

- v_D is from P to N, opposite that of the depletion region voltage.
- Diffusion current increases.
- The solution to a diffusion equation is an exponential.

$$i_{diffusion} = K\exp(v_D/nV_T)$$

The PN Junction:

Diffusion Current

- Majority Carriers
- Significantly blocked by the depletion region voltage.
- Dependent on voltage (overcome the depletion region voltage).

Drift Current

- Minority Carriers
- Not dependent on e-field, but rather the small number.
- Significantly reduced by small number of minority carriers.
- Relatively constant.

Reversed Biased PN Junction.

- v_D is from N to P, enhances that of the depletion region voltage.
- Diffusion current is pushed to near zero.
- Drift current is constant.

$$i_{drift} = I_S$$

The PN Junction:

Diffusion Current
- Majority Carriers
- Significantly blocked by the depletion region voltage.
- Dependent on voltage (overcome the depletion region voltage).

Drift Current
- Minority Carriers
- Not dependent on e-field, but rather the small number.
- Significantly reduced by small number of minority carriers.
- Relatively constant.

Diffusion and Drift Currents are in opposite directions.

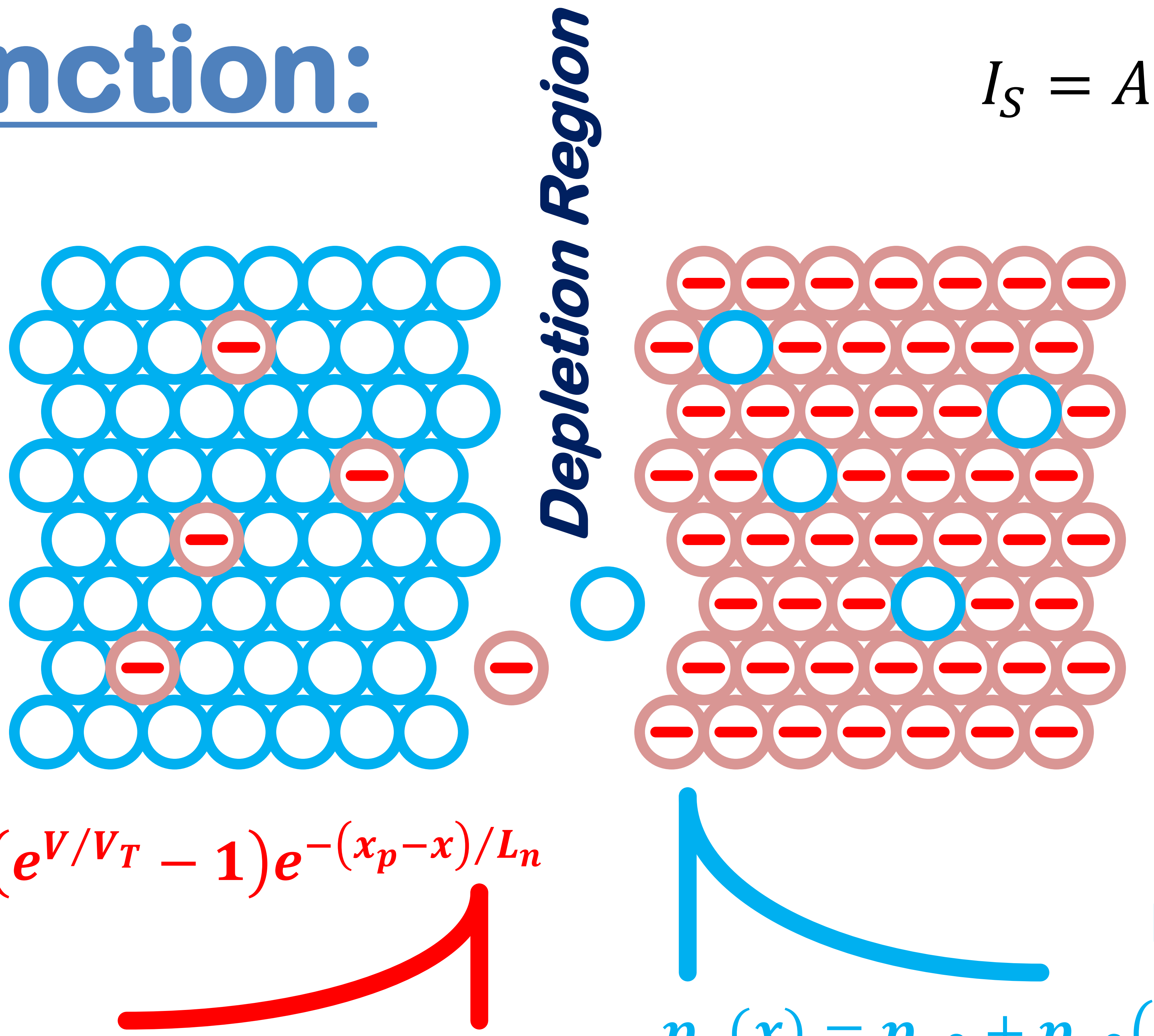
$$i_D = K\exp(v_D/nV_T) - I_S$$

Passive device $i_D(0) = 0$, so $K = I_S$.

$$i_D = I_S(\exp(v_D/nV_T) - 1)$$

The PN Junction:

$$I_S = Aqn_i^2\left(\frac{D_p}{L_pN_D}+\frac{D_n}{L_nN_A}\right)$$



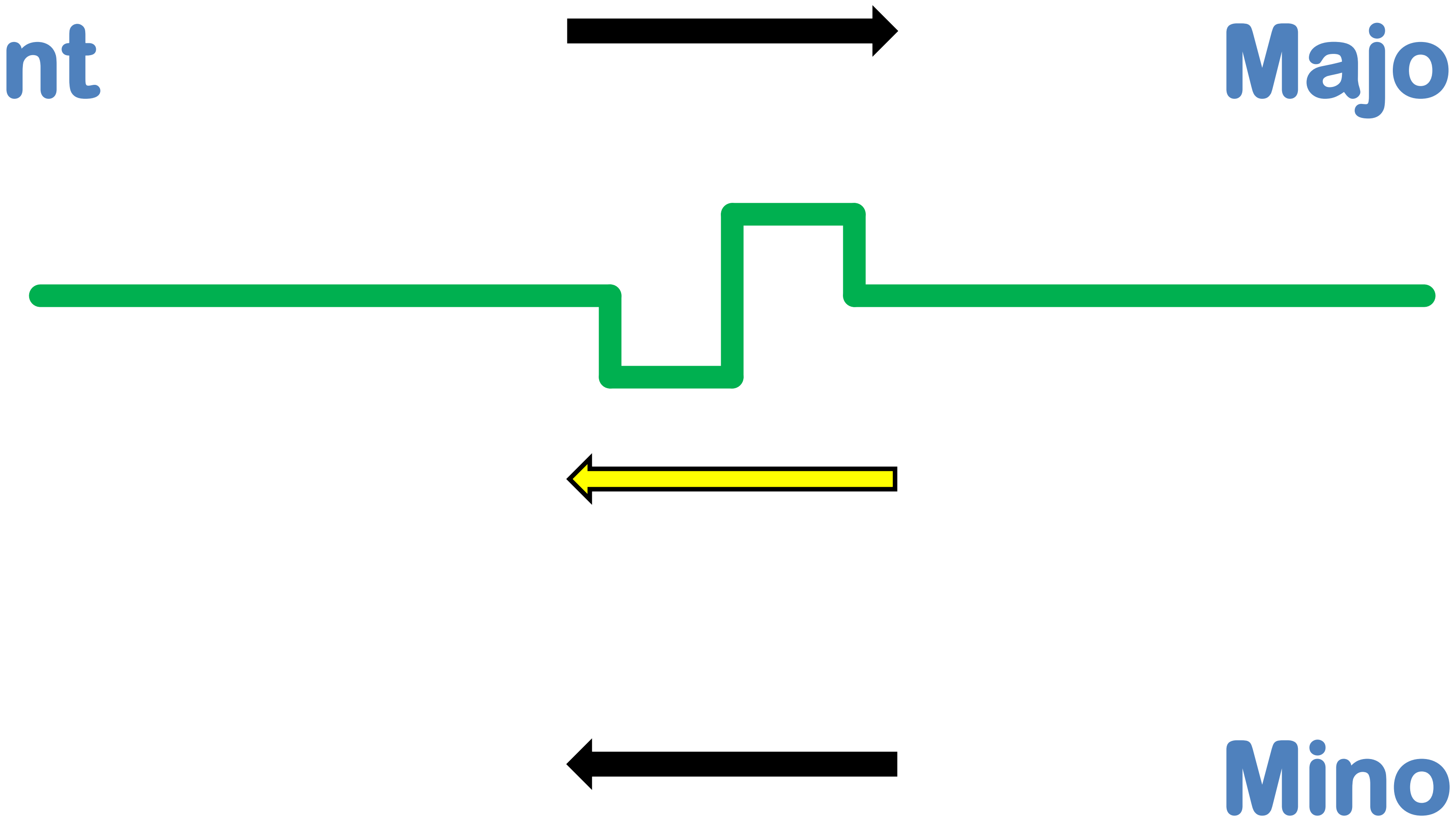
I_n = A·q·D_n·n_p'(x)

$$n_p(x) = n_{p0} + n_{p0}\left(e^{V/V_T}-1\right)e^{-(x_p-x)/L_n}$$

n_p(x),p_n(x)

I_p = -A·q·D_p·p_n'(x)

$$p_n(x) = p_{n0} + p_{n0}\left(e^{V/V_T}-1\right)e^{-(x-x_n)/L_p}$$



Diffusion Current **Majority Carriers**

Net Charge

E-field

Drift Current **Minority Carriers**

The PN Junction:

Diffusion Current

- Majority Carriers
- Significantly blocked by the depletion region voltage.
- Dependent on voltage (overcome the depletion region voltage).

Drift Current

- Minority Carriers
- Not dependent on e-field, but rather the small number.
- Significantly reduced by small number of minority carriers.
- Relatively constant.

PN Junction in Breakdown.

- v_D is from N to P and is very large.
- v_D is sufficiently large (negative) to break covalent bonds (Zener).

- Rush of free electrons.

- Electrons collide with other bonds freeing those electrons
  (Avalanche).