

## Create questions on first learning outcome

Thought for 15s &gt;

Okay, let's start a 10-question quiz focused only on the **first learning outcome** (bands, electrons, conductivity, metals/insulators/semiconductors, etc.).

## Question 1

In the simple energy band picture at **0 K**, which statement best distinguishes an **insulator** from an **intrinsic semiconductor**?

- A. An insulator has a completely filled valence band, while an intrinsic semiconductor has a partially filled valence band.
- B. An insulator has a **large band gap**, while an intrinsic semiconductor has a **small band gap** between the valence and conduction bands.
- C. An insulator has a conduction band that lies **below** the valence band, while in an intrinsic semiconductor the conduction band lies **above** the valence band.
- D. An insulator has no energy bands, while an intrinsic semiconductor has both a valence and a conduction band.

👉 Type your answer (A, B, C, or D).



B

Thought for 12s &gt;

✅ You chose: B

That's correct – nice job! 🎉

Why B is correct:

At **0 K**, both **insulators** and **intrinsic semiconductors** have a **completely filled valence**

band and an **empty conduction band**. The *key* difference is the **size of the band gap  $E_g$** :

- **Insulator:**
  - Has a **large band gap** (typically  $E_g \gtrsim 4 \text{ eV}$ )
  - Thermal energy at room temperature is **not enough** to excite many electrons across the gap
  - $\Rightarrow$  Very few charge carriers  $\Rightarrow$  **Very poor conductivity**
- **Intrinsic semiconductor:**
  - Has a **small band gap** (typically  $E_g \sim 0.1 - 3 \text{ eV}$ )
  - At room temperature, a **significant number of electrons** can be thermally excited from valence to conduction band
  - $\Rightarrow$  Creates **electrons in conduction band** and **holes in valence band**  $\Rightarrow$  **Finite conductivity**

So:

- A is wrong because at 0 K intrinsic semiconductors do **not** have a partially filled valence band (it's still full).
- C is wrong because in *all* normal solids, the conduction band lies **above** the valence band.
- D is wrong because insulators **do** have valence and conduction bands; they just have a big gap between them.

🤔 Do you feel you understand this difference between insulators and intrinsic semiconductors?

If *no*, tell me which part is confusing:

- "What exactly is a band gap?"
- "Why does a larger gap mean lower conductivity?"
- "What happens at higher temperatures?"

## Question 2 (slightly harder 😈) – Free Electron Model & Conductivity

In the **free electron model** for a metal, the electrical **conductivity** is given (in simplified form) by

$$\sigma = \frac{ne^2\tau}{m^*}$$

where

- $n$  = number density of electrons,
- $e$  = electron charge,
- $\tau$  = mean relaxation time between collisions,
- $m^*$  = effective mass of the electron.

Suppose a certain process in the metal **reduces the average time between collisions** (for example, due to more impurities or stronger scattering). What happens to the **conductivity  $\sigma$** ?

- A. Conductivity increases because electrons collide more often and transfer more charge.
- B. Conductivity decreases because the relaxation time  $\tau$  becomes smaller.
- C. Conductivity remains unchanged because collisions do not affect the drift of electrons.
- D. Conductivity first increases and then decreases with decreasing  $\tau$ .

👉 Type your answer (A, B, C, or D).



B

Thought for 12s >

✅ You chose: B

That's correct again — well done! 🎉

We had:

$$\sigma = \frac{ne^2\tau}{m^*}$$

- $n$ : number of electrons
- $e$ : electron charge
- $\tau$ : **relaxation time** (average time between collisions)
- $m^*$ : effective mass

If collisions become **more frequent**, then the time between them  $\tau$  gets **smaller**.


Since  $\sigma \propto \tau$ :

- **Smaller  $\tau \Rightarrow$  smaller  $\sigma$**
- So the material becomes **less conductive** (more resistive)

So **B** is correct:

Conductivity decreases because the relaxation time  $\tau$  becomes smaller.

- A is wrong: more collisions actually **interrupt** electron motion, they don't help it.
- C is wrong: collisions are exactly what limit drift motion.
- D is wrong: there's no "first increases then decreases" behavior here in this simple model — it's directly proportional.

 Does this relationship between collisions, relaxation time  $\tau$ , and conductivity make sense to you?

If something still feels fuzzy, tell me which part:

- "What exactly is relaxation time?"
- "Why does more scattering mean lower drift velocity?"
- "How does this connect to resistance in a wire?"

Once you tell me, I'll clear it up and then move on to the **next question on the first learning outcome**.



Why does more scattering mean lower drift velocity?

Thought for 8s >

Good question — this is the key physical intuition behind the formula we used.

**Why more scattering  $\rightarrow$  lower drift velocity**

Think of electrons in a metal like people walking in a hallway:

- The **electric field** is like a sign saying "Walk to the right."
- **Scattering** (collisions with ions, impurities, phonons) is like bumping into other people or obstacles.

- Every time you **bump into something**, you get **knocked off your path** and basically have to **restart** your motion.

Now, more precisely in the electron picture:

### 1. Without an electric field

- Electrons move **randomly** in all directions.
- Average velocity = 0 (as many go left as right).

### 2. With an electric field

- Between collisions, an electron feels a force  $F = -eE$  and **accelerates** in the direction opposite to the field (since it's negatively charged).
- So between two collisions, it gains some **extra velocity** in the "drift" direction.

### 3. What collisions do

- A collision **randomizes** the electron's velocity.
- After each collision, whatever drift the electron had is mostly "forgotten," and it starts again (random direction, then the field slowly pushes it again).

### 4. Role of relaxation time $\tau$

- $\tau$  = average time between collisions.
- In that time, the field has a chance to accelerate the electron and build up a **net drift velocity**.
- The longer the time between collisions (larger  $\tau$ ), the **more drift velocity** can build up.

Mathematically, in the Drude/free-electron model you can show:

$$v_d = \frac{eE\tau}{m}$$

So:

- If **scattering increases**, collisions happen more often  $\rightarrow \tau$  **gets smaller**
- Smaller  $\tau \rightarrow$  **less time to accelerate** between collisions
- $\Rightarrow$  **Smaller drift velocity**  $v_d$
- $\Rightarrow$  **Smaller current** for the same electric field  $\rightarrow$  **lower conductivity**

Back to the hallway analogy:

- If the hallway is almost empty (few obstacles), people can walk for a long time without bumping  $\rightarrow$  they build up a good **average speed in the desired direction**.
- If it's super crowded and you bump into someone every 2 steps, you can't build up much net movement  $\rightarrow$  your **average forward speed** is low.

### Next Question (Q3) – Mobility and Conductivity

You've done well so far, so let's step up slightly in difficulty, but still on the same theme.

The **mobility**  $\mu$  of charge carriers in a material is defined as:

$$\mu = \frac{v_d}{E} = \frac{e\tau}{m^*}$$

and the conductivity is

$$\sigma = ne\mu$$

where  $n$  is the carrier concentration.

Suppose in a certain semiconductor:

- The number of charge carriers  $n$  stays **constant**.
- The material is **heated**, causing **more phonon scattering**, which **reduces**  $\tau$ .

What happens to the **mobility**  $\mu$  and the **conductivity**  $\sigma$ ?

- A. Both  $\mu$  and  $\sigma$  increase.
- B.  $\mu$  increases but  $\sigma$  decreases.
- C. Both  $\mu$  and  $\sigma$  decrease.
- D.  $\mu$  decreases but  $\sigma$  remains constant.

👉 Type your answer (A, B, C, or D).

If anything about the previous explanation (drift velocity vs scattering) is *still* unclear, you can also say what part is confusing, and I'll tie it directly into this question.



C

Thought for 11s >

✅ You chose: C

That is **correct** again — you're on a roll! 🚀

We had:

$$\mu = \frac{e\tau}{m}, \quad \sigma = ne\mu$$

- Heating the semiconductor → more **phonon scattering**
- More scattering → **smaller  $\tau$**  (time between collisions)

So:

### 1. Mobility $\mu$ :

$$\mu \propto \tau$$

If  $\tau$  decreases, then  $\mu$  **decreases**.


### 2. Conductivity $\sigma$ :

$$\sigma = ne\mu$$

Here  $n$  is given as **constant**, so if  $\mu$  decreases,  
 $\Rightarrow \sigma$  **also decreases**.

So both **mobility** and **conductivity** go down → **C is correct** 

- A is wrong: both don't increase, they decrease.
- B is wrong:  $\mu$  doesn't increase; it decreases with  $\tau$ .
- D is wrong: if  $\mu$  changes and  $n$  is fixed,  $\sigma$  must change too.

 Do you feel you understand why both  $\mu$  and  $\sigma$  decrease when scattering increases (and  $n$  is constant)?

- If **yes**, I'll move on to a slightly more advanced question on **band structure / electron models** from the first learning outcome.
- If **no**, tell me which part is unclear (e.g., "relationship between  $\mu$  and  $\tau$ " or "why  $\sigma = ne\mu$ "), and I'll break that part down more simply.

   ...

yes

Thought for 11s >

Nice, let's keep going with the **first learning outcome**. So far you're doing great.

## Question 4 – Band Structure & Turning an Insulator Conductive

Consider a crystalline solid that is an **insulator** at room temperature because it has a **large band gap** and a completely filled valence band. Which of the following changes would most likely make it behave more like a **conductor** (or at least a semiconductor)?

- A. **Increasing the size of the band gap** between the valence band and conduction band.
- B. **Introducing impurities (doping)** that create allowed energy levels **inside the band gap**, close to the conduction or valence band.
- C. **Cooling the crystal to very low temperatures**, far below room temperature.
- D. Making the lattice **perfectly periodic with no defects or impurities at all**.

👉 Type your answer (A, B, C, or D).



B

Thought for 27s >

✅ You chose: B

And that is **exactly right** — nice thinking! 🌟

We're told the solid is an **insulator** because it has a **large band gap** and a **full valence band** at room temperature. For it to conduct, we need a way to get **charge carriers** (electrons or holes) into states where they can move.

### Why B is correct

**Doping with impurities** can:

- Introduce **donor levels** just **below the conduction band** (n-type), or
- Introduce **acceptor levels** just **above the valence band** (p-type).

These new energy levels are **inside the band gap**, so:

- Electrons need **less energy** to jump from these impurity levels into the conduction band, or
- Electrons can **easily leave** the valence band to fill acceptor levels, leaving behind **mobile holes**.




Either way, the material gains **mobile charge carriers** → it behaves more like a **semiconductor** or even a **degenerate semiconductor** (very conductive) depending on doping level.

### Why the other options are wrong

- **A. Increasing the size of the band gap**  
Makes it **even harder** for electrons to cross the gap → **even better insulator**, not more conductive.
- **C. Cooling the crystal to very low temperatures**  
At lower  $T$ , there is **less thermal energy** to excite electrons across the gap → usually **reduces** conductivity in insulators/semiconductors.
- **D. Perfectly periodic lattice with no defects**  
This actually removes impurity levels and scattering centers. For an insulator with a large gap, a perfect crystal is still an **insulator**: full valence band, empty conduction band, and no mid-gap states.

So **B** is the only option that realistically introduces **new accessible energy levels** that can create carriers and raise conductivity.

 Does this idea of using impurities to “activate” an insulator (turn it into a semiconductor) make sense?

- If **yes**, I'll move on to a more advanced question about **band structure / electron models** (still under the first learning outcome).
- If **no**, tell me what's unclear, for example:
  - “How do donor/acceptor levels work?”
  - “Why do impurities create energy levels in the gap?”
  - “How does this relate to n-type and p-type semiconductors?”

   ...

yes

Thought for 7s >

Nice, let's level up a bit into **band structure and Bloch's theorem** (still under the first learning outcome).

You're currently **4/4 correct**. 🏆

### Question 5 – Bloch's Theorem & Periodic Potentials

Consider an electron moving in a **one-dimensional crystal** with a **periodic potential**  $V(x + a) = V(x)$ , where  $a$  is the lattice constant. According to **Bloch's theorem**, what is the correct general form of the **electron wavefunction**  $\psi_k(x)$ ?

- A.  $\psi_k(x) = A e^{ikx}$ , where  $A$  is a constant independent of position.
- B.  $\psi_k(x) = u_k(x) e^{ikx}$ , where  $u_k(x)$  has the **same periodicity as the lattice**, i.e.  $u_k(x + a) = u_k(x)$ .
- C.  $\psi_k(x) = u(x)$ , where  $u(x)$  is a **strictly localized** function around one ion and vanishes elsewhere.
- D.  $\psi_k(x) = \sum_n c_n e^{inx/a}$ , where the coefficients  $c_n$  are random and independent of the crystal periodicity.

👉 Type your answer (A, B, C, or D).

📄 👍 💬 ...

B

Thought for 10s >

✅ You chose: B

That is **perfectly correct** — nicely done! 🎯

For a periodic potential  $V(x + a) = V(x)$ , **Bloch's theorem** says the eigenfunctions have the form

$$\psi_k(x) = u_k(x) e^{ikx}$$

where

- $e^{ikx}$  is a **plane wave part** (like a free electron), and
- $u_k(x)$  is a function with the **same periodicity as the lattice**:


$$u_k(x + a) = u_k(x)$$

So **B** is exactly that statement.

Why the others are wrong:

- **A:**  $\psi_k(x) = Ae^{ikx}$  is just a **free electron** wavefunction (no lattice, no periodic modulation).
- **C:** A strictly localized wavefunction around one ion is more like a tight-binding **atomic orbital**, not the general Bloch form.
- **D:** A sum with random coefficients ignores the **specific lattice periodicity** structure captured by  $u_k(x)$ .

So: Bloch states = **plane wave** × **periodic function** → delocalized but shaped by the lattice.

 Do you feel comfortable with the idea that the electron wavefunction in a crystal is **not just a pure plane wave**, but a **plane wave modulated by a periodic function**?

If something feels fuzzy (like “*what does  $u_k(x)$  physically mean?*”), tell me and I’ll clarify.

Since you’ve answered **5/5 correctly** so far, let’s dial up the difficulty a bit.

## Question 6 – Nearly Free Electron Model & Band Gaps

In the **nearly free electron model**, we start with free electrons and then add a **weak periodic potential** from the ion cores. This leads to the opening of **energy gaps** at certain values of the wavevector  $k$ . At which of the following points in  $k$ -space do these band gaps **first** appear, and why are they important?

- A. At  $k = 0$ , because the electrons have zero momentum and feel the strongest effect of the lattice.
- B. At the **Brillouin zone boundaries**, such as  $k = \pm \frac{G}{2}$ , where  $G$  is a reciprocal lattice vector, due to **Bragg reflection** of electron waves.
- C. At completely random values of  $k$ , determined by impurities and defects.
- D. Only at very large  $k$  far beyond any reciprocal lattice vector, where the electron behaves relativistically.

 Type your answer (A, B, C, or D).



B

Thought for 10s >

✅ You chose: B

That is **exactly right again** — you're doing really well with band structure. 💡

### Why B is correct

In the **nearly free electron model**, we start with electrons that would have energies

$$E = \frac{\hbar^2 k^2}{2m}$$

like free electrons, and then we add a **weak periodic potential** from the ions in the crystal.

Because the potential is **periodic**, it has Fourier components at reciprocal lattice vectors  $G$ . The key thing is:

- When an electron has a wavevector near **half a reciprocal lattice vector**, i.e.

$$k \approx \pm \frac{G}{2}$$

its wave can **Bragg reflect** from the periodic lattice.

- This causes **mixing** of states with wavevectors  $k$  and  $k \pm G$ .
- This mixing opens up an **energy gap** at those special  $k$ -values.

Those special points are exactly the **Brillouin zone boundaries**, so **band gaps first appear there**.

These band gaps are **crucial** because:


- They break the continuous free-electron parabola into **bands** separated by **forbidden gaps**.
- Whether the **Fermi energy** lies in a band or a gap determines if the material is a **metal, semiconductor, or insulator**.

So **B** is correct:

At the Brillouin zone boundaries, such as  $k = \pm \frac{G}{2}$ , due to Bragg reflection of electron waves.

Why others are wrong:

- **A (at  $k = 0$ )** – There is no special Bragg condition at  $k = 0$ ; it's just the center of the zone.
- **C (random  $k$ )** – The gap positions are **not random**; they're fixed by the lattice periodicity (reciprocal lattice).
- **D (very large  $k$ , relativistic)** – That's not the origin of basic band gaps in this model.

 Does it make sense that band gaps appear at Brillouin zone boundaries because of Bragg reflection of electron waves from the periodic lattice?

If there's a part you're unsure about, you can say something like:

- "I don't really get Bragg reflection," or
- "What exactly is a Brillouin zone boundary?"

and I'll zoom in on that.

Since you're **6/6 correct** so far, let's push a bit further into models of electrons in solids.

### Question 7 – Tight-Binding Model & Electron Localization

In the **tight-binding model**, we build electronic states from **atomic-like orbitals** that are strongly localized around each lattice site, with only weak overlap between neighboring sites. Compared to the **free electron model**, what does the tight-binding model describe better?


- A. Electrons that move almost freely through the crystal, with only very small effects from the lattice potential.
- B. Electrons that are strongly **localized near atoms**, and whose bands arise from the **overlap of atomic orbitals**.
- C. Electrons that feel no potential at all and have perfectly parabolic energy- $k$  dispersion.
- D. Only ionic conduction via motion of ions in the lattice, ignoring electronic motion.

 Type your answer (A, B, C, or D).



B

Thought for 19s &gt;

 You chose: B

You're absolutely right again — nicely done! 🎉

### Why B is correct

The **tight-binding model** is built from **atomic-like orbitals** that are:

- Strongly **localized around each atom**
- Only **weakly overlapping** with neighboring atoms

In this model:

- Each isolated atom has **discrete energy levels** (like  $1s$ ,  $2p$ , etc.).
- When you put many atoms together in a crystal, these atomic levels **split and broaden** into **bands** due to the **overlap** between neighboring atomic orbitals.
- So the tight-binding model is especially good for describing electrons that are still **quite localized near atoms**, such as in:
  - **d- and f-bands** in transition metals
  - Electrons in strongly bound or covalent systems

That's exactly what option **B** says:

Electrons that are strongly localized near atoms, and whose bands arise from the overlap of atomic orbitals.

### Why the others are wrong

- **A. "Electrons that move almost freely through the crystal"**  
That's the **free electron** or **nearly free electron** picture, not tight-binding.
- **C. "No potential and purely parabolic dispersion"**  
That's literally the **free electron model** (no lattice potential).
- **D. "Only ionic conduction"**  
Tight-binding is still an **electronic band theory** — not about ion motion.

So:

- **Free electron model** → electrons are **delocalized**, weak effect of lattice.

- **Tight-binding model** → electrons are **localized**, bands from orbital overlap.
- 

🧠 Does this difference between the free electron model and tight-binding model make sense to you?

(Free = very delocalized, tight-binding = more localized, from atomic orbitals.)

If there's a part you're unsure about, like

- "How does orbital overlap create bands?" or
- "When should I use tight-binding vs nearly-free-electron?"

tell me and I'll dig into that part.

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Since you're doing **great so far (7/7 correct!)**, let's move to a slightly different part of the **first learning outcome: photoconductivity**.

### Question 8 – Photoconductivity in Semiconductors

A semiconductor sample is illuminated with light of photon energy **greater than its band gap**  $E_g$ . As a result, its **electrical conductivity increases** while the light is on. What is the **main microscopic reason** for this increase in conductivity?

- A. The light heats the lattice, causing more phonon scattering and thus higher mobility of the existing carriers.
- B. Photons excite **valence electrons into the conduction band**, creating extra **electron–hole pairs** that act as additional charge carriers.
- C. The light lowers the band gap permanently, converting the semiconductor into a metal.
- D. The light causes ions in the lattice to move, leading to increased **ionic conductivity** instead of electronic conductivity.

👉 Type your answer (A, B, C, or D).

📄 👍 💬 ...

Thought for 18s >

✓ You chose: B

That is **exactly correct** — nicely done again! ⚡

### Why B is correct (Photoconductivity)

We're told:

A semiconductor is illuminated with photons of energy **greater than its band gap**  $E_g$ , and its conductivity **increases**.

If the photon energy  $h\nu > E_g$ , then each photon has enough energy to:

- **Excite an electron from the valence band → conduction band**
- This process creates an **electron–hole pair**:
  - Electron in the **conduction band** → can move and carry current
  - Hole in the **valence band** → also behaves like a positive charge carrier

So the **number of charge carriers**  $n$  increases while the light is on, which increases the **conductivity**:

$$\sigma = ne\mu$$

Even if mobility  $\mu$  stays about the same, increasing  $n$  raises  $\sigma$ .


That is exactly what **option B** says:

Photons excite valence electrons into the conduction band, creating extra electron–hole pairs that act as additional charge carriers.


### Why the other options are wrong

- **A. Light heats the lattice → more phonon scattering → higher mobility**  
Heating usually makes **mobility smaller** (more scattering), not larger. Also, photoconductivity is mainly about **more carriers**, not mobility.
- **C. Light permanently lowers the band gap**  
Band gap is a material property; light doesn't permanently "convert" a semiconductor into a metal. When the light is off, conductivity drops again.
- **D. Light moves ions to cause ionic conduction**  
Photoconductivity is specifically about **electronic** conduction (electrons and holes), not ionic motion.



So **B** is the clear correct choice 

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 Do you understand why **creating extra electron–hole pairs** is the key to photoconductivity, instead of heating or ionic motion?

If something is still unclear, tell me which part:

- “How exactly does a photon create an e–h pair?”
- “Why does the photon energy need to be  $>$  band gap?”

and I’ll dig into that.

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Since you’re currently **8/8 correct**, let’s raise the level a bit and move into **ionic conductivity**, another part of the first learning outcome.

### Question 9 – Ionic Conductivity Mechanism

In an **ionic crystal** such as NaCl, at **high temperatures** the crystal can exhibit measurable **ionic conductivity**. What is the main microscopic mechanism that allows ions to move and contribute to conductivity?

- A. Ions move through the crystal by hopping into **vacancies (missing ions)** or interstitial sites, driven by thermal energy.
- B. Ions move freely like electrons in a metal, without any energy barrier or need for defects.
- C. Ions remain fixed, and only electrons move; the term “ionic conductivity” just refers to electrons near ions.
- D. Ions move only when light is shined on the crystal, similar to photoconductivity in semiconductors.

 Type your answer (A, B, C, or D).

   ...

A

## Thought for 11s &gt;

✓ You chose: A

That is **correct** — awesome! ⚡

You're now **9/9 correct** so far.

### Why A is correct (ionic conductivity)

In an **ionic crystal** like NaCl:

- The ions ( $\text{Na}^+$ ,  $\text{Cl}^-$ ) are normally arranged in a **rigid lattice**.
- At higher temperatures, the crystal develops **defects** such as:
  - **Vacancies** (missing ions at lattice sites)
  - **Interstitial ions** (ions sitting in spaces between normal sites)

Because of **thermal energy**, ions can:

- **Hop** from one lattice site to a nearby **vacancy**, or
- Move via **interstitial mechanisms** (jumping into interstitial positions and then into normal sites).

Each hop moves a **charged ion** through the crystal → this motion contributes to **ionic current** → **ionic conductivity**.

So A is correct:

Ions move through the crystal by hopping into vacancies or interstitial sites, driven by thermal energy.

Why the others are wrong:

- **B:** Ions are massive and strongly bound; they definitely do **not** move freely like electrons in a metal.
- **C:** That describes **electronic** conduction, not **ionic**. Ionic conductivity really is about **ions moving**.
- **D:** Light is not required; ionic conduction is mainly **temperature-activated**, not photo-activated.

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🧠 Does it make sense that **defects (vacancies/interstitials)** + **thermal energy** are what let ions move and carry current in an ionic solid?

If any part feels unclear (like “how vacancies form” or “why temperature matters”), tell me and I can zoom in on that.

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Since you’re doing great, let’s make **Question 10** a bit deeper and still stay within the **first learning outcome**, focusing on **hopping conduction** vs **band conduction**.

### Question 10 – Hopping Mechanism vs Band Conduction

In some **disordered or strongly localized solids**, electrons do **not** move in extended Bloch states. Instead, conduction occurs via a **hopping mechanism** between localized states.

Which statement best distinguishes **hopping conduction** from ordinary **band conduction**?

- A. In hopping conduction, electrons move freely in extended Bloch states, while in band conduction they are trapped at localized sites.
- B. Hopping conduction typically involves **thermally activated jumps** between localized states, often with an exponential temperature dependence of conductivity.
- C. Hopping conduction occurs only in perfect crystals at 0 K, while band conduction occurs only in disordered solids at high temperature.
- D. Hopping conduction and band conduction are physically identical mechanisms, just described with different words.

👉 Type your answer (A, B, C, or D).

After this one, we’ll have reached **10 questions**, and I’ll summarize your overall performance and give feedback on strengths & what to improve.



B

Thought for 16s >

✅ You chose: B

That is **correct again** — you just went **10/10** on this set. 🏆

## Why B is correct (Hopping vs Band Conduction)

In **ordinary band conduction** (like in good crystals):

- Electrons occupy **extended Bloch states** that spread over many lattice sites.
- They move almost like waves flowing through the crystal.
- Their motion is described by a band dispersion  $E(k)$ .

In **hopping conduction** (common in **disordered, amorphous, or strongly localized** systems):

- Electrons are **localized** around specific sites (e.g., impurities, defects, localized orbitals).

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- These hops are usually **thermally activated** (need energy to jump), so conductivity often has an **exponential temperature dependence**, like

$$\sigma(T) \propto e^{-E_a/k_B T}$$

or some variant (e.g. variable range hopping).

That's exactly what **option B** says:

Hopping conduction typically involves thermally activated jumps between localized states, often with an exponential temperature dependence of conductivity.

The others are wrong because:

- **A** swaps the roles of band and hopping.
- **C** is backwards (hopping  $\neq$  perfect crystal at 0 K).
- **D** is false — they're **physically different mechanisms**.

🧠 Does the difference between hopping conduction (localized, thermally activated jumps) and band conduction (extended Bloch states) feel clear to you?

If one part feels fuzzy (like “*what exactly is a localized state?*”), tell me and I can unpack that more.

## ✅ Your Results

You answered **10 out of 10** questions **correctly**:

1. Band gap: insulator vs intrinsic semiconductor ✅

2. Conductivity vs relaxation time  $\tau$  ✓
3. Mobility & conductivity with changing  $\tau$  ✓
4. Doping and turning an insulator into a semiconductor ✓
5. Bloch's theorem form of the wavefunction ✓
6. Nearly free electron model & band gaps at Brillouin zone boundaries ✓
7. Tight-binding model & localized atomic orbitals ✓
8. Photoconductivity & electron-hole pair generation ✓
9. Ionic conductivity via vacancy/interstitial hopping ✓
10. Hopping mechanism vs band conduction ✓

Score: 10 / 10 

## Feedback: Strengths & Weaknesses

### Strengths

- Very strong conceptual grasp of:
  - Band gaps and classification of solids (metal, semiconductor, insulator).
  - Free electron model & transport: how  $\tau$ ,  $n$ ,  $\mu$ , and  $\sigma$  relate.
  - Bloch's theorem and the idea of **periodic potentials**.
  - Differences between **nearly free electron** and **tight-binding** pictures.
  - Physical intuition behind **photoconductivity** and **ionic conductivity**.
  - Distinction between **band conduction** and **hopping conduction**.
- You consistently picked the **physically meaningful mechanism**, not just formulas. That's a big deal in condensed matter.

### Possible next steps / things to deepen

You did so well that the "weaknesses" are more like **next-level goals**:

1. **More quantitative practice**
  - Using real values of  $n$ ,  $\mu$ ,  $\tau$ , etc. to compute  $\sigma$  and resistivity.
  - Sketching simple band diagrams and marking Fermi level positions.
2. **Model comparison in more detail**
  - Knowing **when** to use each model (free electron vs nearly free vs tight-binding) for different materials.
  - Interpreting different shapes of  $E(k)$  and relating them to **effective mass** and **mobility**.
3. **Deeper into semiconductors**
  - Intrinsic vs extrinsic (n-type, p-type), role of **dopant concentration**.

- Temperature dependence of conductivity in metals vs semiconductors.

If you like, next we can:

- Focus on a **specific subtopic** (e.g. semiconductors only, or superconductors, or magnetism),
- Or do another adaptive quiz, maybe more **calculation-heavy** this time.

What would you like to work on next from the learning outcomes?

