

Create questions on first learning outcome

Thought for 15s >

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 >

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  $E_g \gtrsim 4$  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  $E_g \sim 0.1 - 3$  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  $\sigma$** ?

- Conductivity increases because electrons collide more often and transfer more charge.
- Conductivity decreases because the relaxation time  $\tau$  becomes smaller.
- Conductivity remains unchanged because collisions do not affect the drift of electrons.
- 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.

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🧠 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**  $\times$  **periodic function**  $\rightarrow$  delocalized but shaped by the lattice.

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 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.

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## 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).

□ Like Dislike ...

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.

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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 >

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).

   ...

B

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  $\hbar\nu > E_g$ , 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**:

$$\sigma = n e \mu$$

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 >

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).

— Condensed Matter Physics Diagnostic Assessor 5.1 Thinking ↘ ↑ ...

- 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 

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## 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?

