新灯塔国际教育

# AS 物理逆袭宝典

A-Level Physics • AS Level

Pearson Edexcel IAL Physics • Units 1-2

学生用书 Student Book

新灯塔国际教育

# 目录

写在前面 1

**1 Mechanics（力学） 2**

**2 Materials（材料） 17**

**3 Waves and Particle Nature of Light（波与光的粒子性） 33**

**4 Electric Circuits（电学与电路） 49**

# 写在前面

课堂上，常看到这样的情形：学生能听懂概念，方法也清楚，但一到自己动笔，就总在计算、单位换算和作图分析上出错。物理量纲、矢量分解、读图取斜率——这些基础步骤本应扎实，却常常成为失分的主要原因。问题往往不在“会不会想”，而在基本功还不够稳。

这本《AS 物理逆袭宝典》正是为这类同学准备的。全书紧扣 AS Level 物理考纲，把每章最核心的知识点拆解开，一步步练扎实。每章安排了三个层次：**Basic Drill（入门综合）**帮你建立手感；**Practice（综合练习）**巩固核心技能；**Advanced Practice（培优）**供有余力的同学进一步思考。目标很明确——把基础算对、算稳，为后面的学习铺好路。

基础暂时薄弱，不代表学不好 A Level。把基本功打扎实，后面的路会宽得多。

# 1 Mechanics（力学）

*Kinematics, dynamics, momentum, moments, work, energy, and power.*

## Rules 规则

- Use the equations of uniformly accelerated motion (匀加速直线运动方程): $v = u + at$, $s = ut + \frac{1}{2}at^2$, $v^2 = u^2 + 2as$, $s = \frac{u+v}{2}t$.
- Resolve vectors into perpendicular components (向量分解) using trigonometry, and find resultants (合力) using Pythagoras and tangent.
- Apply Newton's second law (牛顿第二定律) $\Sigma F = ma$ to systems with constant mass, and use $W = mg$ for weight (重力).
- The principle of conservation of momentum (动量守恒定律) states that total momentum before an interaction equals total momentum after, provided no external forces act.
- The principle of moments (力矩原理) states that for a body in equilibrium, the sum of clockwise moments equals the sum of anticlockwise moments about any point.
- Apply the principle of conservation of energy (能量守恒定律) using work done $\Delta W = F\Delta s$, kinetic energy $E_k = \frac{1}{2}mv^2$, and gravitational potential energy $\Delta E_{grav} = mg\Delta h$.

## Worked Examples 例题

**Example 1.1**

A ball is thrown horizontally at 15 m s$^{-1}$ from a height of 45 m. Calculate its horizontal range.

**Solution**

Vertical motion: $s = 45$ m, $u = 0$, $a = 9.81$ m s$^{-2}$. Using $s = ut + \frac{1}{2}at^2$, $45 = 0 + \frac{1}{2}(9.81)t^2 \Rightarrow t = \sqrt{\frac{90}{9.81}} = 3.03$ s. Horizontal motion: $x = ut = 15 \times 3.03 = 45.4$ m.

**Example 1.2**

A uniform beam of length 3.0 m and weight 200 N is pivoted at 1.0 m from one end. A weight $W$ is placed at this end to balance the beam. Calculate $W$.

**Solution**

The centre of gravity is at 1.5 m, which is 0.5 m from the pivot. Taking moments about the pivot: clockwise moment = anticlockwise moment. $200 \times 0.5 = W \times 1.0 \Rightarrow W = 100$ N.

**Example 1.3**

A 1200 kg car travelling at 20 m $s^{-1}$ collides with a stationary 800 kg car. They stick together. Calculate their velocity after impact.

**Solution**

Total momentum before = Total momentum after. $1200 \times 20 + 0 = (1200 + 800)v \Rightarrow 24000 = 2000v \Rightarrow v = 12$ m $s^{-1}$.

## 考点总览 Key Points

- ☐ 我掌握标量 (scalar) 与矢量 (vector) 的区别，能进行矢量的正交分解及共面矢量合成。
- ☐ 我能熟练运用匀加速直线运动公式求解一维运动问题（如 $s = ut + \frac{1}{2}at^2$ 与 $v^2 = u^2 + 2as$）。
- ☐ 我会绘制并解读 $s-t$、$v-t$ 和 $a-t$ 图像，并利用图像斜率与面积求解相应物理量。
- ☐ 我理解抛体运动 (projectile motion) 在水平与竖直方向运动的独立性，并能结合重力加速度进行计算。
- ☐ 我熟悉测定自由落体加速度 (acceleration of a freely-falling object) 的实验原理与数据处理方法。
- ☐ 我能规范绘制隔离受力图 (free-body force diagram)，并运用牛顿第一、第二定律分析物体受力与运动（$\sum F = ma$ 及 $W = mg$）。
- ☐ 我理解牛顿第三定律 (Newton's third law) 的含义，并掌握相互作用力对 (pairs of forces) 的性质与特征。
- ☐ 我掌握动量定义式 $p = mv$，并能将一维动量守恒定律 (conservation of linear momentum) 与牛顿定律结合应用。
- ☐ 我会计算力矩 (moment $= Fx$)，并结合重心 (centre of gravity) 概念运用力矩平衡原理分析刚体平衡。
- ☐ 我能准确计算功（$\Delta W = F\Delta s$）、动能（$E_k = \frac{1}{2}mv^2$）及重力势能（$\Delta E_{\text{grav}} = mg\Delta h$）。
- ☐ 我掌握能量守恒定律 (conservation of energy)，能综合分析做功与机械能相互转化的过程。
- ☐ 我会运用功率 (power) 及效率 (efficiency) 公式进行能量传递与做功快慢的综合计算。

## Basic Drill（入门综合）· 50

1. An aircraft touches down on a runway at a speed of 70 m $s^{-1}$ and decelerates uniformly at 3.5 m $s^{-2}$ until it comes to a complete stop. Calculate the time taken for the aircraft to come to rest.

2. State whether work done is a scalar or a vector quantity, and give its SI base units.

3. An object moves along a straight line. Its velocity increases uniformly from 4.0 m $s^{-1}$ to 12.0 m $s^{-1}$ over a time interval of 6.0 s. Calculate the displacement of the object during this time.

4. A helicopter climbs with a constant velocity of 48 m $s^{-1}$ at an angle of 30° above the horizontal. Calculate the vertical component of its velocity.

5. A driver applies a couple to a steering wheel. The couple consists of two parallel and opposite forces, each of magnitude 15 N, separated by a perpendicular distance of 0.30 m. Calculate the torque of the couple.

6. A ball is projected horizontally from the edge of a vertical cliff with a speed of 15 m $s^{-1}$. The ball takes 2.0 s to reach the ground. Assuming negligible air resistance, calculate the horizontal distance travelled by the ball.

7. Calculate the weight of a 65 kg space probe on the surface of Mars, where the gravitational field strength is 3.7 N $kg^{-1}$.

8. A resultant force of 180 N acts on a cart of mass 40 kg. Calculate the acceleration of the cart.

9. A book rests on a horizontal table. The table exerts an upward normal contact force on the book. State the Newton's third law pair force to this upward contact force.

10. Calculate the linear momentum of a cricket ball of mass 0.16 kg moving at a velocity of 25 m $s^{-1}$.

11. A trolley of mass 2.0 kg travelling at 3.0 m $s^{-1}$ collides with and sticks to a stationary trolley of mass 1.0 kg. Calculate the common speed of the trolleys immediately after the collision.

12. A mechanic applies a force of 25 N perpendicularly to the end of a spanner of length 0.24 m. Calculate the moment of the force about the pivot.

13. A uniform metre ruler is pivoted at its centre of gravity. A mass with a weight of 2.0 N is placed at a distance of 0.30 m to the left of the pivot. Calculate the weight of the object that must be placed 0.20 m to the right of the pivot to maintain equilibrium.

14. A crate is pulled across a smooth horizontal floor by a rope. The tension in the rope is 50 N at an angle of 60° to the horizontal. Calculate the work done by the tension when the crate moves a horizontal distance of 8.0 m.

15. Calculate the kinetic energy of a runner of mass 70 kg moving at a constant speed of 8.0 m $s^{-1}$.

16. A box of mass 15 kg is lifted vertically through a height of 4.0 m near the Earth's surface. Calculate the increase in gravitational potential energy of the box.

17. An apple falls from rest from a branch 5.0 m above the ground. Assuming negligible air resistance, calculate the speed of the apple immediately before hitting the ground.

18. An electric motor transfers 1.8 kJ of useful energy in a time of 12 s. Calculate the useful power output of the motor.

19. An electric crane uses 4.0 kJ of electrical energy to raise a load, transferring 2.6 kJ to the gravitational potential energy of the load. Calculate the efficiency of the crane.

20. A train decelerates uniformly from an initial speed of 24 m $s^{-1}$ to rest over a straight distance of 180 m. Calculate the magnitude of the deceleration of the train.

21. State the physical quantity represented by the area under an acceleration-time graph.

22. In an experiment to determine the acceleration of free fall $g$, a small metal sphere is released from rest and falls through a vertical distance of 0.800 m in a time of 0.404 s. Calculate the experimental value of $g$.

23. Define the term centre of gravity.

24. An object of mass 5.0 kg is suspended in equilibrium by two vertical strings. The tension in one string is 20.0 N. Calculate the tension in the second string.

25. A car travels along a straight, horizontal road at a constant speed of 22 m $s^{-1}$ against a total resistive force of 650 N. Calculate the power developed by the engine of the car.

26. A car accelerates uniformly from rest to a velocity of 18 m $s^{-1}$ in a time of 6.0 s. Calculate the acceleration of the car.

27. The velocity-time graph shows the motion of an object that travels at a constant velocity of 14 m $s^{-1}$ for 5.0 s and then decelerates uniformly to rest at $t$ = 8.0 s. Calculate the total displacement of the object.

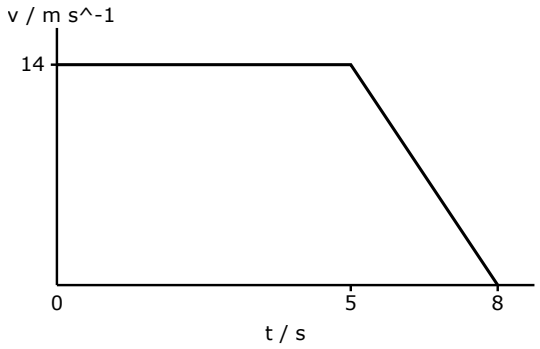


*Fig. 27. Velocity-time graph for the moving object.*

28. A swimmer heads due east across a river at a speed of 1.5 m $s^{-1}$ relative to the water. The river flows due north at a speed of 0.80 m $s^{-1}$. Calculate the magnitude of the resultant velocity of the swimmer.

29. A block of weight 45 N rests on a plane inclined at 30° to the horizontal. Calculate the component of the weight acting parallel to the inclined plane.

30. A metal sphere is projected horizontally with a velocity of 4.0 m $s^{-1}$ from the edge of a bench of height 1.2 m. Air resistance is negligible. Calculate the time taken for the sphere to reach the ground.

31. A resultant horizontal force of 360 N acts on a sledge of mass 80 kg. Calculate the acceleration of the sledge.

32. An astronaut has a mass of 75 kg. The gravitational field strength on the surface of the Moon is 1.6 N $kg^{-1}$. Calculate the weight of the astronaut on the Moon.

33. A box of weight 15 N rests on a horizontal table. State the magnitude, direction and the body on which the Newton's third law pair force to the weight of the box acts.

34. Calculate the magnitude of the linear momentum of an athlete of mass 85 kg running with a velocity of 6.0 m $s^{-1}$.

35. Two skaters, P and Q, of masses 50 kg and 75 kg respectively, are initially stationary on a frictionless ice rink. They push against each other and separate. Skater P moves away at a speed of 3.0 m $s^{-1}$. Calculate the speed of skater Q.

36. A uniform metre rule is pivoted at the 50 cm mark. A mass of 0.20 kg is suspended at the 20 cm mark. Calculate the mass that must be suspended at the 75 cm mark to keep the rule balanced horizontally.

37. A crate is pulled along a flat horizontal surface by a force of 50 N acting at an angle of 35° above the horizontal. Calculate the work done by this force when the crate moves a distance of 8.0 m.

38. A ball of mass 0.50 kg has a kinetic energy of 64 J. Calculate the speed of the ball.

39. A crane lifts a load of mass 450 kg vertically upwards through a height of 12 m. Calculate the increase in gravitational potential energy of the load.

40. A toy car of mass 0.25 kg is released from rest at the top of a frictionless curved track of vertical height 1.8 m. Calculate the speed of the toy car at the bottom of the track.

41. An electric pump lifts 150 kg of water through a vertical height of 6.0 m in a time of 20 s. Calculate the useful power output of the pump.

42. An electric motor receives an electrical power input of 850 W and produces a useful mechanical power output of 595 W. Calculate the efficiency of the electric motor as a percentage.

43. In an experiment to determine the acceleration of free fall $g$, a steel ball is dropped from rest through a vertical distance of 0.800 m. An electronic timer measures the time taken to fall as 0.404 s. Calculate the experimental value of $g$.

44. A displacement-time graph for a cyclist moving in a straight line is a straight line passing through (0 s, 0 m) and (8.0 s, 64 m). (a) State the physical quantity represented by the gradient of the graph. (b) Calculate its value.

45. An object starts from rest and undergoes an acceleration that increases uniformly from 0 to 4.0 m $s^{-2}$ over a time interval of 6.0 s. Calculate the velocity of the object at $t = 6.0$ s.

46. A particle is held in equilibrium under the action of three coplanar forces. Two of the forces are 12 N acting due east and 5.0 N acting due north. Calculate the magnitude of the third force.

47. Define the term centre of gravity of an extended body.

48. State whether each of the following physical quantities is a scalar or a vector: (a) linear momentum, (b) kinetic energy.

49. A ball of mass 0.45 kg moving with an initial velocity of 16 m $s^{-1}$ is caught and brought to rest in a time of 0.15 s. Calculate the magnitude of the average force exerted on the ball.

50. A car of mass 1200 kg travelling at a speed of 20 m $s^{-1}$ is brought to rest by a constant braking force of 4800 N. Calculate the braking distance of the car.

## Practice（综合练习）· 25

1. (a) State one difference between a scalar quantity and a vector quantity. (b) From the following list, identify one scalar quantity and one vector quantity: acceleration, kinetic energy, mass, momentum.

2. A ship is towed in a straight line by two tugboats. Tugboat A pulls with a force of $4.5 \times 10^4$ N at an angle of 30° to the forward direction. Tugboat B pulls with a force $F$ at an angle of 20° to the forward direction on the opposite side. The resultant force on the ship is entirely in the forward direction. Calculate the magnitude of force $F$.

3. A car travelling at a speed of 24 m $s^{-1}$ along a straight horizontal road brakes uniformly and comes to rest in a time of 6.0 s. Calculate the distance travelled by the car during the braking period.

4. A sprinter accelerates uniformly from rest to a maximum velocity of 10.5 m $s^{-1}$ in a time of 3.0 s. The sprinter then maintains this constant velocity for a further 7.0 s. Calculate the total distance travelled by the sprinter in the 10.0 s interval.

5. A stone is thrown horizontally from the top of a vertical cliff with an initial speed of 15 m $s^{-1}$. The cliff is 45 m above the flat ground below. Calculate the horizontal distance travelled by the stone before it hits the ground. Assume air resistance is negligible.

6. A crate of mass 120 kg is pulled along a rough horizontal floor by a rope. The rope is at an angle of 25° above the horizontal. The tension in the rope is 650 N and the constant frictional force opposing the motion is 280 N. Calculate the horizontal acceleration of the crate.




*Fig. 6. Free-body force diagram of the crate.*

7. A book of weight 15 N rests in equilibrium on a horizontal table. State the Newton's third law pair force to the weight of the book. In your answer, you should specify the magnitude, direction, and the body upon which this force acts.

8. A car of mass 1400 kg is travelling in a straight line at 18 m $s^{-1}$. It collides with a stationary van of mass 2200 kg. Immediately after the collision, the car and the van stick together and move in the same direction. Calculate their common velocity immediately after the collision.

9. A box is pushed a distance of 8.5 m along a horizontal surface by a force of 150 N. The force acts at an angle of 15° below the horizontal. Calculate the work done on the box by this force.

10. An electric motor is used to raise a load of mass 450 kg vertically upwards at a constant speed of 2.5 m $s^{-1}$. The electrical power input to the motor is 14.0 kW. Calculate the efficiency of the motor.

11. A uniform wooden beam AB of length 4.0 m and mass 25 kg rests horizontally on two supports at C and D. Support C is 0.5 m from end A. Support D is 1.0 m from end B. Calculate the upward reaction force at support C.




*Fig. 11. Uniform beam resting on two supports.*

12. A roller coaster car of mass 850 kg starts from rest at a height of 42 m above the ground. It descends along a track to a height of 15 m. The total length of the track between these two heights is 120 m. The average resistive force opposing the motion of the car is 400 N. Calculate the speed of the car when it reaches the 15 m height.

13. A golf ball is struck such that it leaves the ground with an initial velocity of 40 m $s^{-1}$ at an angle of 35° to the horizontal. Assume air resistance is negligible. Calculate the maximum height reached by the golf ball.

14. A picture of weight 45 N is suspended in equilibrium by two symmetrical wires. Each wire makes an angle of 40° to the horizontal. Calculate the tension in each wire.

15. A horizontal jet of water strikes a vertical wall at a speed of 12 m $s^{-1}$ and does not rebound. The mass of water hitting the wall per second is 5.0 kg $s^{-1}$. Calculate the force exerted by the water on the wall.

16. In an experiment to determine the acceleration of free fall $g$, a student drops a steel ball from a measured height $h$ and records the time $t$ taken to fall to the ground. The student plots a graph of $h$ against $t^2$ and draws a line of best fit. The gradient of the line is 4.85 m $s^{-2}$. (a) Determine the experimental value of $g$. (b) Suggest one practical reason why this experimental value is less than 9.81 m $s^{-2}$.

17. Car A is travelling along a straight road at a constant speed of 15 m $s^{-1}$. As it passes a stationary Car B, Car B immediately starts to accelerate at a constant rate of 2.5 m $s^{-2}$ in the same direction. Calculate the time taken for Car B to catch up with Car A.

18. A cyclist and bicycle have a combined mass of 80 kg. The cyclist accelerates from rest to a speed of 12 m $s^{-1}$ in a time of 15 s on a flat, horizontal road. Calculate the average useful power output of the cyclist.

19. A uniform trapdoor of mass 18 kg and length 1.2 m is hinged at one end. It is held open in equilibrium at an angle of 30° to the horizontal by a force $F$ applied at the opposite edge. The force $F$ acts perpendicular to the surface of the trapdoor. Calculate the magnitude of force $F$.

20. A particle of mass $m$ is moving with velocity $v$ and has momentum $p$. Show that the kinetic energy $E_k$ of the particle can be expressed as $E_k = \frac{p^2}{2m}$.

21. An aircraft is flying in a region where the wind is blowing from the East at a speed of 50 m $s^{-1}$. The velocity of the aircraft relative to the air is 240 m $s^{-1}$ due North. (a) Calculate the magnitude of the resultant velocity of the aircraft relative to the ground. (b) Determine the angle between the resultant velocity and due North.

22. A solar panel has a surface area of 2.5 $m^2$. The solar power incident on the panel is 850 W $m^{-2}$. The panel produces a useful electrical power output of 340 W. Calculate the efficiency of the solar panel.

23. A block is sliding down a rough inclined plane at a constant velocity. (a) State the three forces acting on the block. (b) State the resultant of these three forces.

24. The displacement-time graph for a moving object is a curve with a positive gradient that is gradually decreasing. State what this indicates about: (a) the velocity of the object, (b) the acceleration of the object.

25. A shell of mass 4.0 kg is travelling horizontally at a speed of 150 m $s^{-1}$. It explodes into two fragments, X and Y. Fragment X has a mass of 1.5 kg and continues to move in the same horizontal direction at a speed of 280 m $s^{-1}$. Calculate the velocity of fragment Y immediately after the explosion.

## Advanced Practice（培优）· 20

1. A particle is projected from a point $O$ on a horizontal surface with an initial velocity of 24.0 m $s^{-1}$ at an angle of 60° to the horizontal. At time $t$, the particle is at a point $P$, and its velocity vector is at an angle of 30° to the horizontal. Air resistance is negligible.
   Calculate the time $t$.

2. A bullet of mass 12 g is fired horizontally into a stationary wooden block of mass 1.50 kg suspended by two vertical strings. The bullet embeds itself in the block. Immediately after the collision, the block and bullet swing upwards, and their centre of gravity rises by a maximum vertical height of 4.5 cm.
   Calculate the initial speed of the bullet.

3. A uniform rigid beam of length 3.0 m and weight 250 N is hinged at one end to a vertical wall. The beam is held horizontal by a cable attached to the other end. The cable makes an angle of 40° with the horizontal beam. A load of weight $W$ is placed on the beam at a distance of 2.0 m from the hinge. The tension in the cable is 800 N.
   Calculate the weight $W$.

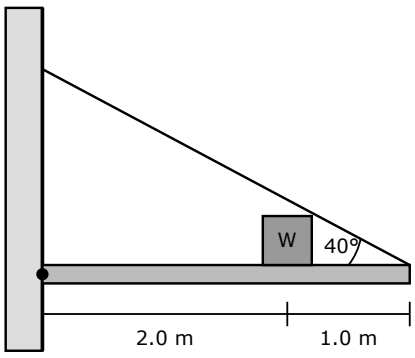


*Fig. 3. A uniform beam supported by a cable and a hinge, carrying a load W.*

4. A train travels between two stations. It starts from rest and accelerates uniformly for 40 s to a speed of 30 m $s^{-1}$. It travels at this constant speed for 120 s, and then decelerates uniformly to rest in 60 s.
   Calculate the average speed of the train for the whole journey.

5. A car of mass 1400 kg is travelling up a straight road inclined at 5.0° to the horizontal. The engine of the car produces a constant useful power output of 45 kW. The total resistive force opposing the motion of the car is constant at 850 N.
   Determine the acceleration of the car at the instant its speed is 18 m $s^{-1}$.

6. A ball A is dropped from rest from a height of 75.0 m. At the same instant, a second ball B is projected vertically upwards from the ground directly below ball A with an initial speed of 25.0 m $s^{-1}$. Air resistance is negligible.
   Calculate the height above the ground at which the two balls collide.

7. Two blocks of masses 3.0 kg and 5.0 kg are connected by a light inextensible string passing over a frictionless pulley. The 3.0 kg block rests on a smooth horizontal table, and the 5.0 kg block hangs vertically. The system is released from rest.
   Calculate the time taken for the 5.0 kg block to fall a distance of 0.80 m.

8. A small object of weight 12 N is suspended by two light strings, A and B. String A makes an angle of 35° to the vertical. String B is horizontal. The object is in equilibrium.
   Calculate the tension in string A.

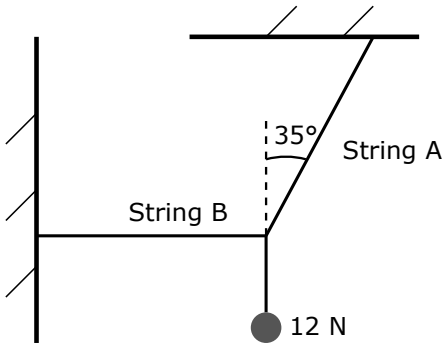


*Fig. 8. An object in equilibrium suspended by two strings.*

9. An electric motor is used to lift a load of mass 550 kg vertically upwards at a constant speed of 0.40 m $s^{-1}$. The motor consumes 180 kJ of energy in 1.0 minute.
   Calculate the efficiency of the motor.

10. A uniform rectangular sign of weight 180 N has dimensions 1.2 m wide and 0.80 m high. It is suspended from a single horizontal pivot at its top left corner. A horizontal force $F$ is applied to the bottom right corner to keep the top edge of the sign perfectly horizontal.
    Calculate the magnitude of force $F$.

11. In an experiment to determine the acceleration of free fall $g$, a steel ball is dropped from rest through a measured height $h$. The time of fall $t$ is recorded. The experiment is repeated for several heights. A graph of $2h$ on the y-axis against $t^2$ on the x-axis is plotted.
    State what the gradient of this graph represents and explain how it is derived from the equations of motion.

12. A skater of mass 65 kg is stationary on a frictionless ice rink. They throw a 2.5 kg medicine ball horizontally. The skater exerts a constant average force of 150 N on the ball for a duration of 0.20 s.
    Calculate the final velocity of the skater.

13. A block of mass 4.0 kg is released from rest at the top of a rough slope of length 5.0 m. The slope is inclined at 30° to the horizontal. The block reaches the bottom of the slope with a speed of 6.0 m $s^{-1}$.
    Calculate the average frictional force acting on the block.

14. An object of mass 80 kg accelerates uniformly from an initial velocity of 10 m $s^{-1}$ to 25 m $s^{-1}$ in a time of 5.0 s.
    Calculate the kinetic energy of the object exactly after it has travelled a distance of 50 m from its starting position.

15. Three coplanar forces act on a point object. Force A is 45 N due North. Force B is 60 N due East. Force C is 30 N acting at an angle of 45° South of West.
    Calculate the magnitude of the resultant force.

16. A water slide terminates at a height of 3.2 m above the surface of a pool. The slide is horizontal at its end. A person of mass 65 kg leaves the slide and lands in the pool at a horizontal distance of 4.5 m from the end of the slide.
    Determine the person's kinetic energy exactly 0.50 s after leaving the slide. Assume air resistance is negligible.

17. A book of mass 1.2 kg rests on a horizontal table. The table rests on the Earth.
Identify the Newton's third law pair force to the weight of the book, stating its magnitude, direction, and the object upon which it acts.

18. A drone of mass 1.4 kg accelerates vertically upwards from rest. The rotors provide a constant upward thrust of 22.0 N. Air resistance is negligible.
Calculate the useful power output of the drone's rotors at the instant it has reached a height of 15.0 m.

19. A non-uniform flagpole of length 4.0 m and mass 15 kg is placed horizontally on two supports. Support A is at one end, and Support B is 1.0 m from the other end. The reaction force at Support A is 65 N.
Calculate the distance of the centre of gravity of the flagpole from the end with Support A.

20. A toy car of mass 0.20 kg is moving at 4.0 m $s^{-1}$ towards a stationary toy truck of mass 0.60 kg. They collide and stick together.
Calculate the percentage of the initial kinetic energy that is dissipated during the collision.

# 2 Materials（材料）

*Properties of materials including density, fluid upthrust, viscous drag, Hooke's law, stress, strain, Young modulus, and elastic strain energy.*

## Rules 规则

- Density is the mass per unit volume of a substance: $\rho = \frac{m}{V}$ (密度).
- Archimedes' principle states that the upthrust on an object in a fluid equals the weight of the fluid displaced: $U = \rho_{\text{fluid}} V g$ (浮力).
- Stokes' Law gives the viscous drag on a small spherical object moving at low speed in laminar flow: $F = 6\pi\eta r v$, where $\eta$ is the temperature-dependent viscosity (斯托克斯定律与黏度).
- Hooke's Law states that the applied force is directly proportional to the extension: $\Delta F = k\Delta x$, where $k$ is the stiffness (胡克定律).
- Stress is the force applied per unit cross-sectional area: $\sigma = \frac{F}{A}$ (应力).
- Strain is the fractional change in length: $\epsilon = \frac{\Delta x}{L}$ (应变).
- The Young modulus is the ratio of stress to strain in the linear elastic region: $E = \frac{\sigma}{\epsilon}$ (杨氏模量).
- Elastic strain energy is the energy stored in a deformed material, equal to the area under the force-extension graph. For linear deformation: $\Delta E_{\text{el}} = \frac{1}{2} F \Delta x$ (弹性应变能).

## Worked Examples 例题

**Example 2.1**

A solid metal cylinder of mass 0.45 kg has a radius of 0.020 m and a length of 0.10 m. Calculate the density of the metal.

**Solution**

Volume of the cylinder $V = \pi r^2 L = \pi(0.020)^2(0.10) = 1.26 \times 10^{-4}$ m$^3$. Density $\rho = \frac{m}{V} = \frac{0.45}{1.26\times10^{-4}} = 3580$ kg m$^{-3}$.

**Example 2.2**

A small steel ball of radius 2.0 mm falls at a constant terminal velocity of 0.050 m $s^{-1}$ through a liquid. The viscosity of the liquid is 0.85 Pa s. Calculate the viscous drag force acting on the ball.

**Solution**

Using Stokes' Law: $F = 6\pi\eta r v = 6\pi(0.85)(0.0020)(0.050) = 1.6 \times 10^{-3}$ N.

**Example 2.3**

A wire of original length 2.0 m and cross-sectional area $1.5 \times 10^{-6}$ $m^2$ is stretched by 4.0 mm under a load of 90 N. Calculate the Young modulus of the material.

**Solution**

Stress $\sigma = \frac{F}{A} = \frac{90}{1.5\times10^{-6}} = 6.0 \times 10^7$ Pa. Strain $\epsilon = \frac{\Delta x}{L} = \frac{0.0040}{2.0} = 2.0 \times 10^{-3}$. Young modulus $E = \frac{\sigma}{\epsilon} = \frac{6.0\times10^7}{2.0\times10^{-3}} = 3.0 \times 10^{10}$ Pa.

## 考点总览 Key Points

- ☐ 我掌握密度 (density) 的定义并能熟练运用公式计算（$\rho = \frac{m}{V}$）
- ☐ 我理解浮力 (upthrust) 等于排开流体重量的原理并能进行受力分析
- ☐ 我掌握斯托克斯定律 (Stokes' Law) 公式（$F = 6\pi\eta r v$），并理解其层流 (laminar flow) 适用条件及粘度 (viscosity) 与温度的关系
- ☐ 我熟悉用落球法 (falling-ball method) 测定液体粘度的核心实验流程与误差分析（CP2）
- ☐ 我能运用胡克定律 (Hooke's law) 解决形变问题并理解刚度 (stiffness)（$\Delta F = k\Delta x$）
- ☐ 我掌握拉伸与压缩应力 (stress) 及应变 (strain) 的定义与计算（$\sigma = \frac{F}{A}$, $\varepsilon = \frac{\Delta x}{x}$）
- ☐ 我能绘制并解释力-伸长量图，辨析比例极限 (limit of proportionality)、弹性极限 (elastic limit)、屈服点 (yield point) 及弹性与塑性形变
- ☐ 我能分析应力-应变图并理解断裂应力 (breaking stress) 的物理意义
- ☐ 我熟悉测定材料杨氏模量 (Young modulus) 的实验步骤与数据图象处理（CP3）
- ☐ 我会通过图线下覆面积或公式计算线性和非线性形变中的弹性应变能 (elastic strain energy)（$\Delta E_{el} = \frac{1}{2}F\Delta x$）

## Basic Drill（入门综合）· 50

1. A solid rectangular block of copper has dimensions 0.050 m × 0.040 m × 0.020 m and a mass of 0.358 kg. Calculate the density of copper.

2. A vertical spring with an unstretched length of 12.0 cm extends to a total length of 15.5 cm when a load of 4.2 N is suspended from it. Assuming the spring obeys Hooke's law, calculate the stiffness $k$ of the spring.

3. A solid cylinder of volume $2.5 \times 10^{-4}$ m$^3$ is completely submerged in water of density $1.0 \times 10^3$ kg m$^{-3}$. Calculate the upthrust acting on the cylinder.

4. State what is meant by elastic deformation.

5. A steel wire of circular cross-section with a diameter of 0.80 mm is subjected to a tensile force of 150 N. Calculate the tensile stress in the wire.

6. A nylon thread of original length 1.80 m extends by 4.5 mm when stretched by a force. Calculate the tensile strain in the thread.

7. A small spherical bead of radius 1.5 mm falls through glycerol of viscosity 1.2 Pa s at a steady speed of 0.040 m s$^{-1}$. Calculate the viscous drag force acting on the bead.

8. Two identical springs, each of stiffness 120 N m$^{-1}$, are connected in series. Calculate the total extension produced when a load of 6.0 N is suspended from the combination.

9. A spring obeys Hooke's law. A tensile force of 18 N produces an extension of 0.060 m. Calculate the elastic strain energy stored in the spring.

10. Determine the base units of the Young modulus in the SI system.

11. A metal wire of original length 2.4 m and cross-sectional area $3.0 \times 10^{-7}$ m$^2$ extends by 1.6 mm when a tensile load of 40 N is applied. Assuming the wire behaves elastically, calculate the Young modulus of the metal.

12. The diagram shows a force-extension graph for a metal wire stretched to its breaking point. State which labelled point corresponds to the limit of proportionality.

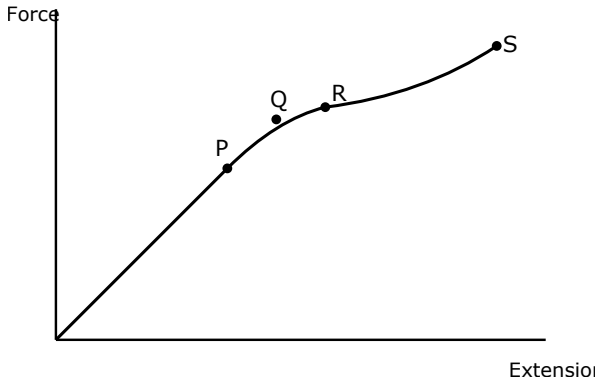


*Fig. 12. Force-extension graph for a metal wire.*

13. State the effect of an increase in temperature on the viscosity of a liquid.

14. A helical spring has a stiffness constant $k = 450$ N m$^{-1}$. Calculate the elastic strain energy stored in the spring when it is compressed by 0.040 m.

15. In a falling-ball method experiment used to determine the viscosity of motor oil, state why the ball must reach terminal velocity before passing the timing markers.

16. A steel cable has a cross-sectional area of $1.2 \times 10^{-4}$ m$^2$. The cable breaks when the applied tensile load reaches $4.8 \times 10^4$ N. Calculate the breaking stress of the steel.

17. A hollow brass sphere has an external volume of $5.0 \times 10^{-5}$ m$^3$ and a mass of 0.255 kg. The density of brass is $8.5 \times 10^3$ kg m$^{-3}$. Calculate the volume of the internal cavity.

18. A rubber band is stretched and then allowed to contract. During the cycle, the area under the loading force-extension curve is 0.85 J and the area under the unloading curve is 0.60 J. Calculate the energy dissipated as thermal energy during this cycle.

19. A small ball bearing of weight 0.052 N falls vertically at terminal velocity through a viscous oil. The upthrust on the ball bearing is 0.016 N. Determine the magnitude of the viscous drag force acting on the ball bearing.

20. Define plastic deformation.

21. A tensile force of 6.0 N produces an extension of 1.5 cm in a wire that obeys Hooke's law. Calculate the extension produced when the force is increased to 14.0 N.

22. In an experiment to determine the Young modulus of a metal wire, name the measuring instrument used to measure the diameter of the wire and state one procedure to ensure a reliable value.

23. A wooden block of mass 0.48 kg floats in equilibrium in water of density $1.0 \times 10^3$ kg $m^{-3}$. Calculate the volume of water displaced by the block.

24. State the physical quantity represented by the gradient of the straight-line section of a stress-strain graph.

25. State what is meant by the yield point of a material.

26. A solid brass sphere has a radius of 1.5 cm. The density of brass is $8.4 \times 10^3$ kg $m^{-3}$. Calculate the mass of the sphere.

27. A small sphere of radius $1.2 \times 10^{-3}$ m moves through glycerol at a steady speed of 0.050 m $s^{-1}$. The viscosity of glycerol is 1.4 Pa s. Calculate the viscous drag force acting on the sphere.

28. A metal block of volume $2.5 \times 10^{-4}$ $m^3$ is completely immersed in water of density $1.0 \times 10^3$ kg $m^{-3}$. Calculate the upthrust exerted by the water on the block.

29. A tensile force of 18 N produces an extension of 4.5 cm in a spring that obeys Hooke's law. Calculate the stiffness of the spring.

30. A wire of circular cross-section has a diameter of 0.80 mm. A tensile load of 150 N is applied to the wire. Calculate the tensile stress in the wire.

31. A steel cable of original length 2.50 m extends by 3.5 mm under tension. Calculate the tensile strain in the cable.

32. A metal rod is subjected to a tensile stress of $1.8 \times 10^8$ Pa, resulting in a tensile strain of $9.0 \times 10^{-4}$. Calculate the Young modulus of the metal.

33. A spring with a stiffness of 250 N $m^{-1}$ is stretched by 0.060 m within its limit of proportionality. Calculate the elastic strain energy stored in the spring.

34. State what is meant by the limit of proportionality of a material.

35. The force-extension graph for a stretched wire is shown. When the tensile force is 24 N, the extension is 0.080 m. Calculate the elastic strain energy stored in the wire at this extension.

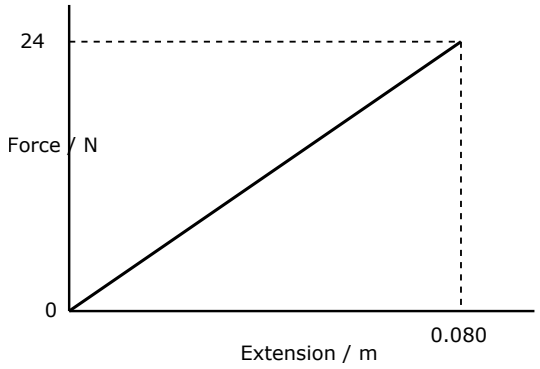


*Fig. 35. Force-extension graph for the stretched wire*

36. Two springs with stiffnesses $k_1 = 120$ N $m^{-1}$ and $k_2 = 240$ N $m^{-1}$ are connected in series. Calculate the effective stiffness of the combined spring system.

37. In an experiment to determine the Young modulus of a metal wire, state the purpose of using an unloaded reference wire suspended alongside the test wire from the same support.

38. Sphere A of radius $r$ and sphere B of radius $2r$ fall at the same speed through a viscous fluid under laminar flow. Determine the ratio of the viscous drag force on sphere B to that on sphere A.

39. A uniform metal rod of length 1.5 m and cross-sectional area $4.0 \times 10^{-6}$ $m^2$ is made of a metal with a Young modulus of $1.2 \times 10^{11}$ Pa. Calculate the stiffness of the rod.

40. In a falling-ball experiment to determine liquid viscosity, explain how the terminal velocity of the ball is determined.

41. Define the term breaking stress.

42. A metal wire is stretched elastically. The tensile stress in the wire is $1.6 \times 10^8$ Pa and the resulting tensile strain is $8.0 \times 10^{-4}$. Calculate the elastic strain energy stored per unit volume of the wire.

43. A copper wire of length 1.8 m and cross-sectional area $1.2 \times 10^{-6}$ $m^2$ has a Young modulus of $1.1 \times 10^{11}$ Pa. Calculate the extension of the wire when subjected to a tensile force of 66 N.

44. A tensile force applied to a metal wire increases linearly from 0 to 80 N, producing an extension of 2.0 mm within the elastic limit. Calculate the work done in stretching the wire.

45. A compression spring has a stiffness of $4.5 \times 10^5$ N $m^{-1}$. Calculate the compressive force needed to compress the spring by 12 mm.

46. A submerged object displaces $1.8 \times 10^3$ $m^3$ of seawater of density 1030 kg $m^{-3}$. Calculate the magnitude of the upthrust acting on the object.

47. In an experiment to determine the Young modulus of a metal wire, state the most suitable instrument for measuring the diameter of the wire accurately.

48. A small sphere of weight $4.8 \times 10^{-4}$ N falls vertically at terminal velocity through an oil. The upthrust on the sphere is $1.2 \times 10^{-4}$ N. The radius of the sphere is $1.5 \times 10^{-3}$ m and the viscosity of the oil is 0.25 Pa s. Calculate the terminal velocity of the sphere.

49. A steel cable must support a maximum tensile force of $2.4 \times 10^4$ N. The maximum allowable tensile stress in the cable is $3.0 \times 10^8$ Pa. Calculate the minimum cross-sectional area of the cable.

50. A solid block of density 750 kg $m^{-3}$ floats in equilibrium in a liquid of density 1200 kg $m^{-3}$. Calculate the percentage of the block's volume that is submerged.

## Practice（综合练习）· 25

1. A solid metal cylinder has a radius of 0.015 m and a length of 0.080 m. The mass of the cylinder is 0.45 kg. Calculate the density of the metal.

2. A solid cube of side length 0.20 m is completely submerged in a liquid of density 1200 kg $m^{-3}$. Calculate the upthrust acting on the cube.

3. A small steel ball of radius $2.0 \times 10^{-3}$ m falls through a liquid at a constant speed of 0.050 m $s^{-1}$. The viscosity of the liquid is 0.85 Pa s. Calculate the viscous drag force acting on the ball.

4. Stokes' law can be used to calculate the viscous drag force on a moving object. State three conditions that must be met for the Stokes' law equation to apply.

5. A cylindrical bone sample of length 6.50 cm and average cross-sectional area $3.20 \times 10^{-4}$ $m^2$ is subjected to a compressive force of 850 N. The Young modulus of the bone is $1.50 \times 10^{10}$ Pa. (a) Calculate the compressive stress in the bone sample. (b) Calculate the reduction in length of the sample.

6. A wire has a circular cross-section of diameter $1.2 \times 10^{-3}$ m. A tensile force of 85 N is applied to the wire. Calculate the tensile stress in the wire. Give your answer to 2 significant figures.

7. A metal wire of original length 2.50 m is stretched by a force. The new length of the wire is 2.54 m. Calculate the tensile strain of the wire.

8. A material has a Young modulus of $1.2 \times 10^{11}$ Pa. A sample of this material has a length of 3.0 m and a cross-sectional area of $4.0 \times 10^{-6}$ $m^2$. Calculate the force required to produce an extension of $1.5 \times 10^{-3}$ m.

9. A steel spring obeys Hooke's law. When subjected to a tensile force of 24.0 N, its extension is 1.50 cm. The applied force is then increased from 24.0 N to 40.0 N. (a) Determine the stiffness of the spring. (b) Calculate the additional elastic strain energy stored in the spring as the force is increased from 24.0 N to 40.0 N.

10. A student investigates the extension of a polymer thread of original length 0.85 m and cross-sectional area $4.0 \times 10^{-7}$ m$^2$. The extension $\Delta x$ for different applied tensile forces $F$ is recorded below: $F = 2.0$ N, $\Delta x = 1.5$ mm $F = 4.0$ N, $\Delta x = 3.0$ mm $F = 6.0$ N, $\Delta x = 4.5$ mm $F = 8.0$ N, $\Delta x = 6.5$ mm $F = 10.0$ N, $\Delta x = 9.0$ mm (a) State the lowest recorded force at which the limit of proportionality has clearly been exceeded. (b) Calculate the Young modulus of the polymer using the data from the linear region.

11. A stress-strain graph for a material shows a maximum stress value of $4.5 \times 10^8$ Pa before the material fractures. State the term used for this maximum stress value.

12. On a force-extension graph for a metal wire, there is a point beyond the elastic limit where a large extension occurs for a very small or no increase in force. State the name of this point.

13. A student uses a falling-ball method to determine the viscosity of glycerol. Explain why it is important to record the temperature of the glycerol during this experiment.

14. A student performs an experiment to determine the Young modulus of a copper wire. State the measurements the student must take to determine the cross-sectional area of the wire.

15. A wooden block of volume 0.012 m$^3$ floats in water of density 1000 kg m$^{-3}$ with 75% of its volume submerged. Calculate the weight of the wooden block.

16. A spring is stretched beyond its elastic limit. Describe the difference between elastic deformation and plastic deformation in terms of the shape of the spring when the force is removed.

17. Liquid A has a density of 800 kg $m^{-3}$ and liquid B has a density of 1100 kg $m^{-3}$. A student mixes 0.020 $m^3$ of liquid A with 0.030 $m^3$ of liquid B. Assuming the total volume is conserved, calculate the density of the mixture.

18. The force-extension graph for a spring is shown in the figure. Calculate the elastic strain energy stored in the spring when it is extended by 0.14 m.

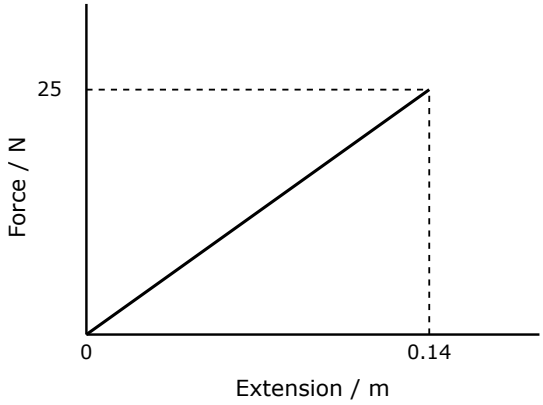


*Fig. 18. Force-extension graph for a spring*

19. Wire X and Wire Y are made of the same material. Wire X has twice the length and twice the diameter of Wire Y. A force $F$ is applied to Wire Y, producing an extension $e$. Calculate the extension produced in Wire X when the same force $F$ is applied. Express your answer in terms of $e$.

20. A spring of length 0.40 m has a stiffness of 50 N $m^{-1}$. The spring is cut in half to form two springs, each of length 0.20 m. State and explain the stiffness of one of these shorter springs.

21. In a falling-ball experiment, a small sphere of radius $1.5 \times 10^{-3}$ m and density 7800 kg $m^{-3}$ falls at a constant terminal velocity of 0.042 m $s^{-1}$ through a liquid of density 950 kg $m^{-3}$. Calculate the viscosity of the liquid.

22. The force-extension graph for a material is a curve. The area under the curve is estimated by counting squares on the graph paper. Each small square represents a force of 0.50 N and an extension of 0.0020 m. The area under the curve is estimated to be 145 small squares. Estimate the elastic strain energy stored in the material.

23. In a falling-ball experiment to determine the viscosity of a liquid, a student measures the terminal velocity of a small steel sphere. State the measurements the student must take to determine this terminal velocity.

24. A compressive force is applied to a concrete pillar of original height 4.000 m. The pillar compresses by 1.2 mm. Calculate the percentage compressive strain in the pillar.

25. A nylon rope has a breaking stress of $7.5 \times 10^7$ Pa and a diameter of 8.0 mm. Calculate the maximum tensile force the rope can withstand before breaking.

## Advanced Practice（培优）· 20

1. A solid metal cylinder of mass 2.4 kg and density 7800 kg $m^{-3}$ is suspended from a vertical spring of stiffness 150 N $m^{-1}$. The cylinder is then fully submerged in a liquid of density 1200 kg $m^{-3}$. (a) Calculate the volume of the cylinder. (b) Calculate the upthrust acting on the cylinder. (c) Determine the change in the extension of the spring when the cylinder is submerged.

2. A glass sphere of radius 2.5 mm and density 2500 kg $m^{-3}$ falls at a constant terminal velocity in oil of density 920 kg $m^{-3}$. The viscosity of the oil is 0.085 Pa s. (a) State the three forces acting on the sphere. (b) Calculate the weight of the sphere. (c) Calculate the terminal velocity of the sphere.

3. A wire consists of a 2.0 m length of steel joined end-to-end to a 1.5 m length of brass. Both wires have a diameter of 0.80 mm. The composite wire is suspended vertically and a load of 45 N is applied to the lower end. Young modulus of steel = $2.1 \times 10^{11}$ Pa Young modulus of brass = $1.0 \times 10^{11}$ Pa (a) Calculate the stress in the steel wire. (b) Calculate the total extension of the composite wire.

4. A force-extension graph for a ductile metal wire is shown. (a) Determine the stiffness of the wire in the linear region. (b) Estimate the elastic strain energy stored in the wire when the extension is 8.0 mm. (c) Explain the difference between elastic deformation and plastic deformation.

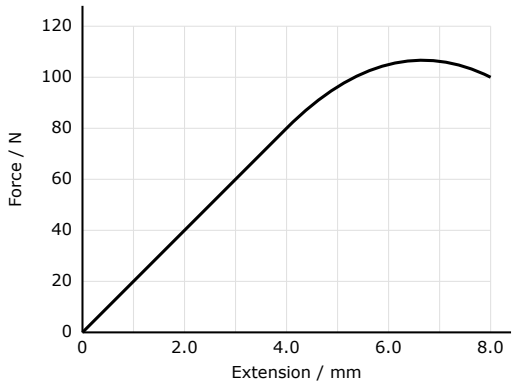


*Fig. 4. Force-extension graph for a ductile metal wire*

5. In an experiment to determine the viscosity of a liquid, a student measures the terminal velocity $v$ of steel spheres of different radii $r$ falling through the liquid. (a) Use Stokes' law and the principle of upthrust to show that $v$ is proportional to $r^2$. (b) The student repeats the experiment with the liquid at a higher temperature. Explain how the terminal velocity for a given sphere will change.

6. A rectangular wooden block of length 0.40 m, width 0.30 m and height 0.20 m floats in water of density 1000 kg $m^{-3}$. The density of the wood is 650 kg $m^{-3}$. (a) Calculate the mass of the block. (b) Determine the depth of the block that is submerged below the surface of the water.

7. A rigid horizontal bar of negligible weight is supported by two vertical wires, A and B. Wire A is made of steel and has a length of 1.5 m and a diameter of 0.50 mm. Wire B is made of copper and has a length of 1.0 m and a diameter of 0.80 mm. A load of 150 N is applied to the bar such that it remains horizontal, meaning both wires experience the same extension $\Delta x$.
The Young modulus of steel is $2.0 \times 10^{11}$ Pa and the Young modulus of copper is $1.3 \times 10^{11}$ Pa.
(a) Show that the ratio of the tension in wire A to the tension in wire B is approximately 0.4.
(b) Calculate the extension $\Delta x$ of the wires. (c) Calculate the total elastic strain energy stored in the two wires.

8. A student performs falling-ball experiments using small, identical spherical beads of radius 2.0 mm and density $\rho_s$. When dropped into liquid 1, the bead reaches a terminal velocity of 0.050 m $s^{-1}$. Liquid 1 has a density of 800 kg $m^{-3}$ and a viscosity of 0.40 Pa s.
(a) Use Stokes' law to calculate the density $\rho_s$ of the bead. (b) The student then drops an identical bead into liquid 2, which has a density of 1200 kg $m^{-3}$ and a viscosity of 0.60 Pa s. Calculate the terminal velocity of the bead in liquid 2. (c) State one condition about the flow of the liquid that must be met for Stokes' law to apply.

9. A solid concrete block of volume 0.50 $m^3$ and density 2400 kg $m^{-3}$ is completely submerged in seawater of density 1030 kg $m^{-3}$. The block is suspended by a vertical steel cable of length 25.0 m and diameter 1.20 cm. The Young modulus of steel is $2.0 \times 10^{11}$ Pa. The block is being lifted vertically upwards at a constant velocity. Viscous drag on the block is negligible. (a) Calculate the tension in the cable. (b) Calculate the elastic strain energy stored in the cable while the block is completely submerged. (c) The block is eventually lifted completely out of the water. Calculate the additional extension of the cable compared to when it was fully submerged.

10. A stress-strain graph for two materials, X and Y, is shown. (a) Deduce which material has the greater Young modulus. (b) State what is meant by the breaking stress of a material. (c) Material X has a linear region up to a strain of 0.020 and a stress of 200 MPa. Calculate the elastic strain energy per unit volume stored in X at its elastic limit.

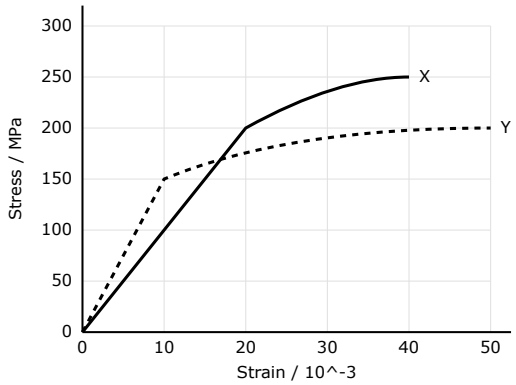


*Fig. 10. Stress-strain graph for materials X and Y*

11. A student determines the Young modulus of a metal wire. The wire has an original length of 2.50 m and a diameter of 0.45 mm. A load of 30.0 N produces an extension of 1.8 mm. (a) Calculate the Young modulus of the metal. (b) The diameter is measured using a micrometer with a resolution of 0.01 mm. Calculate the percentage uncertainty in the cross-sectional area. (c) Suggest why the wire should be as long as possible.

12. A spherical air bubble of radius 1.5 mm rises at a constant velocity through a liquid of density 1100 kg $m^{-3}$ and viscosity 0.25 Pa s. The density of the air is negligible. (a) State the equation linking the forces acting on the bubble. (b) Calculate the upthrust on the bubble. (c) Determine the terminal velocity of the bubble.

13. A rubber band is stretched and then unloaded. The force-extension graph forms a hysteresis loop. (a) State what the area enclosed by the loading and unloading curves represents. (b) Explain, in terms of the graph, why the rubber band becomes warm. (c) State whether the deformation of the rubber band is elastic or plastic.

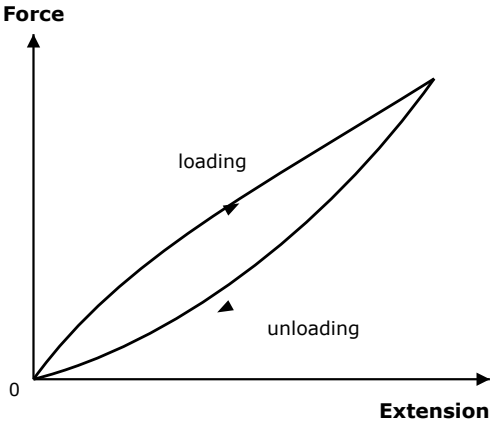


*Fig. 13. Force-extension graph showing the hysteresis loop for a rubber band during loading and unloading.*

14. An alloy is made by mixing volume $V_1$ of metal 1 (density $\rho_1$) and volume $V_2$ of metal 2 (density $\rho_2$). (a) Show that the density of the alloy $\rho$ is given by $\rho = \frac{\rho_1 V_1 + \rho_2 V_2}{V_1 + V_2}$. (b) 60% of the volume of an alloy is copper (density 8900 kg $m^{-3}$) and 40% is zinc (density 7100 kg $m^{-3}$). Calculate the density of the alloy. (c) A uniform wire made of this alloy has a mass of 15 g, a length of 2.0 m and a Young modulus of $1.1 \times 10^{11}$ Pa. Calculate the extension produced by a 50 N load.

15. A small solid sphere A of radius 1.0 mm and density 8000 kg $m^{-3}$ falls at a constant terminal velocity through a liquid of density 1200 kg $m^{-3}$ and viscosity 0.50 Pa s. (a) Calculate the viscous drag force acting on sphere A. (b) Calculate the terminal velocity of sphere A. (c) A second solid sphere B of radius 2.0 mm is dropped into the same liquid. It is observed to reach the exact same terminal velocity as sphere A. Determine the density of sphere B.

16. A short concrete pillar is reinforced with 4 vertical steel rods. The cross-sectional area of the concrete is 0.080 $m^2$ and the total cross-sectional area of the steel rods is 0.0020 $m^2$. A compressive load of $4.5 \times 10^5$ N is applied to the top of the pillar. The concrete and steel compress by the same amount. Young modulus of concrete = $2.0 \times 10^{10}$ Pa Young modulus of steel = $2.0 \times 10^{11}$ Pa (a) Show that the ratio of the compressive stress in the steel to the compressive stress in the concrete is 10. (b) Calculate the force supported by the concrete. (c) Calculate the compressive strain in the pillar.

17. A heavy steel ball is dropped into a tall cylinder of glycerol. (a) Describe how the velocity of the ball changes as it falls from rest. (b) The experiment is repeated with the glycerol at a higher temperature. Explain how the new terminal velocity compares to the original terminal velocity. (c) Explain why Stokes' law may not apply if the steel ball falls at a very high speed.

18. A mass $M$ is suspended from a rigid support by two identical springs in parallel. The stiffness of each spring is $k$. The elastic strain energy stored in the system is $E_1$. The same mass $M$ is then suspended from the same support by the two springs in series. The elastic strain energy stored in the system is $E_2$. (a) State the equivalent stiffness of the parallel combination and the series combination in terms of $k$. (b) Show that the ratio $E_2/E_1$ is 4.

19. A copper wire is subjected to an increasing tensile force. (a) Define the elastic limit of a material. (b) Define the yield point. (c) A wire of original length 1.200 m is stretched beyond its elastic limit. When the load is removed, its new length is 1.205 m. Calculate the permanent plastic strain.

20. A solid metal block of mass 5.0 kg and density 8000 kg $m^{-3}$ rests on the bottom of a tank of water (density 1000 kg $m^{-3}$). A string is attached to the block and pulled vertically upwards with a tension $T$. (a) Calculate the upthrust acting on the block. (b) Calculate the minimum tension $T$ required to lift the block off the bottom of the tank. (c) The block is lifted at a constant low velocity. Explain why the tension required is greater than the value calculated in (b).

# 3 Waves and Particle Nature of Light（波与光的粒子性）

*Properties of waves, superposition, standing waves, refraction, diffraction, and the quantum nature of light including the photoelectric effect and atomic spectra.*

## Rules 规则

- The wave equation relates speed, frequency, and wavelength: $v = f\lambda$ (波速公式).
- The speed of a transverse wave on a string depends on tension and mass per unit length: $v = \sqrt{\frac{T}{\mu}}$ (弦上横波波速).
- Intensity is the power transferred per unit area: $I = \frac{P}{A}$ (波的强度).
- Snell's law of refraction and critical angle: $n_1 \sin\theta_1 = n_2 \sin\theta_2$ and $\sin C = \frac{1}{n}$ (折射定律与临界角).
- For a diffraction grating, the maxima occur at angles given by $n\lambda = d\sin\theta$, where $d$ is the slit spacing (衍射光栅公式).
- The photoelectric effect equation relates photon energy to the work function and maximum kinetic energy of emitted electrons: $hf = \Phi + \frac{1}{2}mv_{\max}^2$ (光电效应方程).
- The de Broglie wavelength of a particle is inversely proportional to its momentum: $\lambda = \frac{h}{p}$ (德布罗意波长).

## Worked Examples 例题

**Example 3.1**

A string has a mass per unit length of $4.5 \times 10^{-3}$ kg m$^{-1}$ and is kept under a tension of 25 N. Calculate the speed of the transverse wave on the string.

**Solution**

Using the equation for the speed of a transverse wave on a string: $v = \sqrt{\frac{T}{\mu}}$ Substitute the given values: $v = \sqrt{\frac{25}{4.5\times10^{-3}}}$ $v = \sqrt{5556} = 74.5$ m s$^{-1}$

**Example 3.2**

Light travels from a glass block of refractive index 1.52 into air (refractive index 1.00). Calculate the critical angle for the glass-air interface.

**Solution**

The critical angle $C$ occurs when the angle of refraction is 90°. Using Snell's law or the critical angle formula: $\sin C = \frac{n_2}{n_1}$ $\sin C = \frac{1.00}{1.52} = 0.658$ $C = \sin^{-1}(0.658) = 41.1°$

**Example 3.3**

Ultraviolet light of wavelength 250 nm is incident on a metal surface with a work function of 4.1 eV. Calculate the maximum kinetic energy of the emitted photoelectrons in eV.

**Solution**

First, calculate the energy of the incident photons in joules: $E = \frac{hc}{\lambda} = \frac{6.63\times10^{-34}\times3.0\times10^{8}}{250\times10^{-9}} = 7.96\times 10^{-19}$ J Convert this energy to electronvolts (eV): $E = \frac{7.96\times10^{-19}}{1.60\times10^{-19}} = 4.97$ eV Use the photoelectric equation to find the maximum kinetic energy: $E = \Phi + K_{\max}$ $K_{\max} = 4.97 - 4.1 = 0.87$ eV

**Example 3.4**

A laser beam of wavelength 633 nm is directed normally at a diffraction grating with 300 lines $\text{mm}^{-1}$. Calculate the angle of the second-order maximum.

**Solution**

First, find the slit spacing $d$ in metres: $d = \frac{1}{300\times10^{3}}$ m $= 3.33 \times 10^{-6}$ m Use the diffraction grating equation for the second order ($n = 2$): $n\lambda = d\sin\theta$ $2 \times 633 \times 10^{-9} = 3.33 \times 10^{-6} \times \sin\theta$ $\sin\theta = \frac{1.266\times10^{-6}}{3.33\times10^{-6}} = 0.380$ $\theta = \sin^{-1}(0.380) = 22.3°$

## 考点总览 Key Points

- ☐ 我掌握横波 (transverse wave) 与纵波 (longitudinal wave) 的振动态和图像特征，并熟练运用 $v = f\lambda$。
- ☐ 我熟悉利用双踪示波器 (oscilloscope)、信号发生器和麦克风测定空气中声速的实验方法 (CP4)。
- ☐ 我理解波阵面 (wavefront)、相干 (coherence) 与叠加原理 (superposition)，能计算相位差与光程差。
- ☐ 我掌握驻波 (stationary wave) 与波节波腹的成因，并能结合 $v = \sqrt{T/\mu}$ 探究弦振动规律 (CP5)。
- ☐ 我能计算辐射强度 $I = P/A$，并用折射定律 $n_1 \sin\theta_1 = n_2 \sin\theta_2$ 及 $\sin C = 1/n$ 分析全反射。
- ☐ 我理解平面偏振 (plane polarisation) 现象，以及脉冲回波技术 (pulse-echo) 的定位原理与分辨率限制。
- ☐ 我熟悉用惠更斯原理解释衍射 (diffraction)，并能利用光栅方程 $n\lambda = d\sin\theta$ 测定光波长 (CP6)。
- ☐ 我掌握电子衍射证实粒子波动性的物理依据，并能熟练运用德布罗意公式 $\lambda = h/p$。
- ☐ 我理解光子模型 (photon model)，能熟练转换电子伏特 (eV) 并用 $E = hf$ 计算光子能量。
- ☐ 我能用光电效应解释光的粒子性，并运用方程 $hf = \phi + \frac{1}{2}mv_{\max}^2$ 求解极限频率与逸出功。
- ☐ 我掌握原子线状光谱 (line spectra) 与分立能级跃迁的关系，能计算吸收或辐射光子的频率。

## Basic Drill（入门综合）· 50

1. A sound wave travels through air with a frequency of 680 Hz and a wavelength of 0.50 m. Calculate the speed of the sound wave.

2. State whether the air pressure at a compression in a progressive sound wave is higher than, equal to, or lower than the ambient atmospheric pressure.

3. An electromagnetic wave has a period of $4.0 \times 10^{-15}$ s. Calculate the frequency of the wave.

4. A flexible string is held under a tension of 36 N. The mass per unit length of the string is 0.040 kg $\mathrm{m}^{-1}$. Calculate the speed of a transverse wave on this string.

5. A stationary sound wave is set up inside a tube. The distance between two adjacent displacement nodes is 0.25 m. Calculate the wavelength of the stationary wave.

6. A laser beam delivers a constant power of 6.0 mW perpendicularly onto a circular spot of area $3.0 \times 10^{-6}$ m$^2$. Calculate the intensity of the laser radiation at the spot.

7. The speed of light in a vacuum is $3.00 \times 10^8$ m s$^{-1}$ and the speed of light in a transparent polymer is $1.88 \times 10^8$ m s$^{-1}$. Calculate the refractive index of the polymer. Give your answer to 3 significant figures.

8. A block of optical glass has a refractive index of 1.50. Calculate the critical angle for light incident on the glass-air boundary. Give your answer to the nearest degree.

9. State the two conditions required for total internal reflection to occur at a boundary between two optical media.

10. Define what is meant by plane polarisation of a transverse wave.

11. Two coherent waves with a wavelength of 0.40 m arrive at a point in space. The path difference between the two waves at this point is 0.10 m. Calculate the phase difference between the two waves at this point.

12. State what is meant by two coherent wave sources.

13. A light ray in air enters a transparent liquid of refractive index 1.33 at an angle of incidence of 40.0°. Calculate the angle of refraction inside the liquid.

14. An ultrasound probe sends a pulse into body tissue where the speed of sound is 1540 m s$^{-1}$. The echo reflected from a tissue boundary returns to the probe $8.0 \times 10^{-5}$ s after emission. Calculate the depth of the boundary beneath the probe.

15. In ultrasound imaging, pulses of very short duration are emitted. Explain why short pulse durations are necessary to resolve reflections from two closely spaced boundaries.

16. State what happens to the degree of diffraction of a wave as the width of the slit through which it passes is decreased towards the wavelength of the wave.

17. Monochromatic light of wavelength 500 nm is incident normally on a diffraction grating with a line spacing of $2.0 \times 10^{-6}$ m. Calculate the angle of the second-order maximum ($n = 2$).

18. A diffraction grating is ruled with 400 lines $\text{mm}^{-1}$. Calculate the grating spacing $d$ in metres.

19. Calculate the energy of a photon of ultraviolet radiation with a frequency of $1.5 \times 10^{15}$ Hz. ($h = 6.63 \times 10^{-34}$ J s)

20. The work function of a caesium surface is 2.30 eV. Convert this value into joules. ($e = 1.60 \times 10^{-19}$ C)

21. A metal has a work function of $6.88 \times 10^{-19}$ J. Calculate the threshold frequency for this metal. ($h = 6.63 \times 10^{-34}$ J s)

22. Photons of energy 5.20 eV are incident on a clean metal surface with a work function of 3.10 eV. Calculate the maximum kinetic energy of the emitted photoelectrons in eV.

23. An electron of mass $9.11 \times 10^{-31}$ kg travels at a speed of $2.00 \times 10^{6}$ m $\text{s}^{-1}$. Calculate the de Broglie wavelength of the electron. ($h = 6.63 \times 10^{-34}$ J s)

24. An electron in an isolated atom undergoes a transition from an energy level of $-1.50$ eV to an energy level of $-3.40$ eV. Calculate the frequency of the emitted photon. ($h = 6.63 \times 10^{-34}$ J s, 1 eV $= 1.60 \times 10^{-19}$ J)

25. State the experimental phenomenon that provides direct evidence for the wave nature of electrons.

26. A sound wave travels through air at a speed of 340 m $\text{s}^{-1}$. The frequency of the sound wave is 850 Hz. Calculate the wavelength of the sound wave.

27. State the difference between a transverse wave and a longitudinal wave in terms of the direction of particle oscillations relative to the direction of energy transfer.

28. A horizontal string of mass per unit length $4.5 \times 10^{-3}$ kg $\text{m}^{-1}$ is kept under a tension of 72 N. Calculate the speed of a transverse wave travelling along the string.

29. A laser beam with a power of 15 mW is focused onto a circular spot of radius 0.50 mm. Calculate the intensity of the radiation at the spot.

30. Two coherent monochromatic sources emit waves of wavelength 600 nm in phase. At a point P, the path difference between the waves from the two sources is 150 nm. State the phase difference between the waves at P, in radians.

31. A stationary sound wave is set up in a tube. The distance between two consecutive nodes is measured to be 0.18 m. Determine the wavelength of the sound wave.

32. A stretched wire of length 0.80 m is fixed at both ends. The speed of transverse waves on the wire is 240 m $s^{-1}$. Calculate the fundamental frequency (first harmonic) of vibration of the wire.

33. A ray of light in air is incident on a flat glass block at an angle of incidence of 40°. The refractive index of the glass is 1.52. Calculate the angle of refraction inside the glass.

34. A transparent plastic has a refractive index of 1.44. Calculate the critical angle for light travelling from this plastic into air.

35. The speed of light in a vacuum is $3.00 \times 10^8$ m $s^{-1}$. The refractive index of water is 1.33. Calculate the speed of light in water.

36. State what is meant by a plane polarised wave.

37. A diffraction grating has $4.00 \times 10^5$ lines $m^{-1}$. Monochromatic light of wavelength 532 nm is incident normally on the grating. Calculate the angle $\theta$ for the second-order maximum.

38. Light of wavelength 633 nm is directed normally onto a diffraction grating. The first-order diffraction maximum is observed at an angle of 14.7°. Determine the number of lines per millimetre on the grating.

39. An electron has a de Broglie wavelength of $2.50 \times 10^{-10}$ m. Calculate the momentum of the electron. ($h = 6.63 \times 10^{-34}$ J s)

40. An ultrasound probe sends a short pulse into soft tissue. The echo reflected from a boundary is received by the probe $4.0 \times 10^{-5}$ s after emission. The speed of ultrasound in the tissue is 1540 m $s^{-1}$. Calculate the depth of the boundary.

41. State one reason why short pulse durations are used in ultrasound imaging.

42. Calculate the energy, in joules, of a single photon of red light with a frequency of $4.40 \times 10^{14}$ Hz.

43. A photon has an energy of $3.68 \times 10^{-19}$ J. Express this energy in electronvolts (eV).

44. The work function of potassium is 2.30 eV. Calculate the threshold frequency for potassium.

45. The threshold wavelength for zinc is 290 nm. Calculate the work function of zinc in joules.

46. Ultraviolet radiation of photon energy 5.60 eV is incident on a metal surface having a work function of 4.10 eV. Determine the maximum kinetic energy, in eV, of the emitted photoelectrons.

47. The maximum kinetic energy of photoelectrons emitted from a sodium plate is $1.20 \times 10^{-19}$ J. Given that the mass of an electron is $9.11 \times 10^{-31}$ kg, calculate the maximum speed of the emitted electrons.

48. An electron in a mercury atom falls from an energy level of $-1.57$ eV to an energy level of $-5.52$ eV, emitting a photon. Calculate the frequency of the emitted photon.

49. An atom absorbs a photon and transitions from an energy state of $-13.6$ eV to $-3.4$ eV. Calculate the wavelength of the absorbed photon.

50. In a laboratory experiment to determine the speed of sound in air using a 2-beam oscilloscope, a speaker emits sound at a frequency of 1.20 kHz. Moving a microphone a distance of 0.285 m causes the detected wave trace on the oscilloscope to shift by exactly one complete cycle. Calculate the speed of sound in air.

## Practice（综合练习）· 25

1. (a) Define the term amplitude of a wave. (b) A sound wave travelling through water has a speed of 1500 m $s^{-1}$ and a wavelength of 0.060 m. Calculate the frequency of the sound wave.

2. The graph shows the displacement of particles in a transverse wave against distance along the wave at a particular instant. (a) Determine the amplitude and the wavelength of the wave. (b) The wave travels at a speed of 24 cm $s^{-1}$. Calculate the period of the wave.

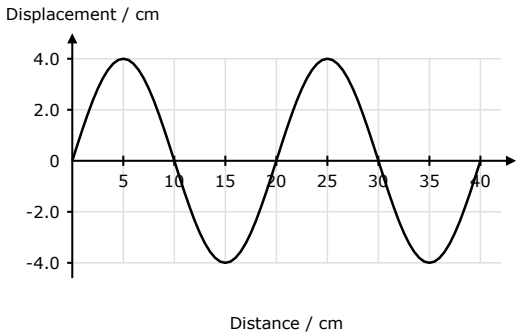


*Fig. 2. Graph showing the displacement of particles against distance along a transverse wave.*

3. A student uses a pulse-echo technique to determine the speed of sound in air. A transmitter emits a short pulse of sound towards a rigid wall. The echo is detected by a microphone placed next to the transmitter. The distance from the transmitter to the wall is 4.50 m. The time interval between emitting the pulse and detecting the echo is 26.5 ms. (a) Describe how the sound wave travels through the air in terms of the displacement of molecules. (b) Calculate the speed of sound in air.

4. A string of length 1.50 m and mass $6.00 \times 10^{-3}$ kg is held under a tension of 40.0 N. A transverse wave travels along the string. Calculate the speed of the transverse wave on the string.

5. A laser emits a beam of light with a continuous power of 4.8 mW. The beam has a circular cross-section with a diameter of 1.6 mm. Calculate the intensity of the light in the beam.

6. A ray of light travels from air into a rectangular glass block. The angle of incidence is 48°. The refractive index of the glass is 1.52. (a) Calculate the angle of refraction. (b) Calculate the speed of light in the glass block.

7. The refractive index of a type of optical glass is 1.65. (a) Calculate the critical angle for light travelling from this glass into air. (b) A ray of light inside the glass meets the boundary with air at an angle of incidence of 40°. Deduce whether total internal reflection will occur.

8. Two coherent sources emit waves of wavelength 0.30 m. The waves meet at a point P. The distance from the first source to P is 4.10 m and the distance from the second source to P is 4.85 m. (a) Calculate the path difference of the waves at P. (b) Calculate the phase difference between the waves at P in radians.

9. State what is meant by plane polarisation and explain why sound waves cannot be plane polarised.

10. A medical laser emits ultraviolet radiation of wavelength 300 nm. The laser produces a single pulse of duration 2.0 ms. During this pulse, the beam has a constant power of 1.5 W and is focused onto a circular spot of diameter $2.0 \times 10^{-4}$ m on a patient's tissue. ($h = 6.63 \times 10^{-34}$ J s, $c = 3.00 \times 10^{8}$ m s$^{-1}$) (a) Calculate the intensity of the laser beam at the spot. (b) Calculate the energy, in joules, of a single photon of this radiation. (c) Calculate the total number of photons delivered to the tissue during the pulse.

11. Monochromatic light of wavelength 620 nm is incident normally on a diffraction grating. The first-order maximum is observed at an angle of 18.5°. Determine the number of lines per millimetre of the diffraction grating.

12. Calculate the energy, in electronvolts (eV), of a single photon of electromagnetic radiation with a frequency of $7.50 \times 10^{14}$ Hz.

13. The work function of a metal surface is $3.8 \times 10^{-19}$ J. Electromagnetic radiation of wavelength 320 nm is incident on the surface, causing the emission of photoelectrons. Calculate the maximum kinetic energy of the emitted photoelectrons.

14. The threshold frequency of a metal is $1.15 \times 10^{15}$ Hz. (a) State what is meant by the threshold frequency. (b) Calculate the work function of the metal in electronvolts (eV).

15. An electron is accelerated to a speed of $6.2 \times 10^6$ m s$^{-1}$. Calculate the de Broglie wavelength of this electron. (Mass of an electron = $9.11 \times 10^{-31}$ kg)

16. An electron in a hydrogen atom transitions from an energy level of $-1.51$ eV to an energy level of $-3.40$ eV. (a) Calculate the energy of the emitted photon in Joules. (b) Calculate the frequency of the emitted radiation.

17. An experiment is set up to determine the wavelength of light from a laser using a diffraction grating. Explain how Huygens' construction can be used to describe what happens to the wave when it meets the slits of the grating.

18. An ultrasound probe is used to examine a flaw in a metal block. A short pulse of ultrasound is transmitted into the metal. The echo from the flaw is detected $1.4 \times 10^{-5}$ s later. The speed of ultrasound in the metal is 5900 m s$^{-1}$. (a) Calculate the depth of the flaw. (b) Explain how the duration of the pulses limits the amount of information obtained.

19. A student wants to measure the refractive index of a transparent semicircular block. Describe the measurements the student must take and how they are used to determine the refractive index.

20. Explain how the photoelectric effect provides evidence for the particle nature of electromagnetic radiation, rather than the wave model.

21. The diagram shows a stationary wave formed on a vibrating string. The frequency of the wave is 45 Hz. (a) State the number of antinodes shown on the string. (b) Calculate the speed of the transverse waves on the string.

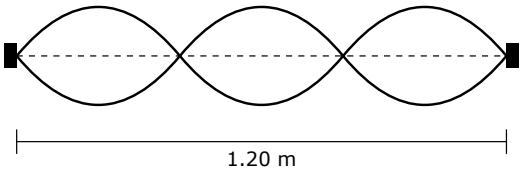


*Fig. 21. A stationary wave on a string of length 1.20 m.*

22. Two light waves from coherent sources meet at a point and destructively interfere. The wavelength of the light is 650 nm. (a) State what is meant by coherent sources. (b) State the minimum path difference between the two waves for complete destructive interference to occur.

23. A star emits electromagnetic radiation uniformly in all directions. At a distance of $1.5 \times 10^{11}$ m from the star, the intensity of the radiation is 1360 W $m^{-2}$. Calculate the total power emitted by the star.

24. A wave travelling in medium 1 meets a boundary with medium 2. The speed of the wave in medium 1 is $v_1$ and the speed in medium 2 is $v_2$. State what happens to the frequency and the wavelength of the wave as it is transmitted into medium 2, given that $v_2 > v_1$.

25. Photons of wavelength 250 nm are incident on a metal plate. Electrons are emitted with a maximum kinetic energy of $1.5 \times 10^{-19}$ J. (a) Calculate the work function of the metal. (b) Calculate the de Broglie wavelength of an electron emitted with the maximum kinetic energy. (Mass of an electron = $9.11 \times 10^{-31}$ kg)

## Advanced Practice（培优）· 20

1. Ultraviolet light of wavelength 240 nm is incident on a clean zinc plate. The work function of zinc is 4.3 eV. (a) Calculate the maximum kinetic energy, in Joules, of the emitted photoelectrons. (b) Calculate the de Broglie wavelength of a photoelectron emitted with this maximum kinetic energy.

2. A string of length 0.85 m is fixed at both ends. The mass of the string is 3.2 g and it is kept under a constant tension of 45 N. (a) Calculate the fundamental frequency of the stationary wave on this string. (b) The tension is now increased until the frequency of the 3rd harmonic matches the original frequency of the 4th harmonic. Calculate the new tension in the string.

3. An optical fibre consists of a glass core with refractive index 1.48 surrounded by a cladding with refractive index 1.41. (a) Calculate the critical angle at the boundary between the core and the cladding. (b) Light enters the flat end of the core from air ($n = 1.00$) at an angle of incidence $\theta_i$. Calculate the maximum value of $\theta_i$ for which total internal reflection will still occur at the core-cladding boundary.

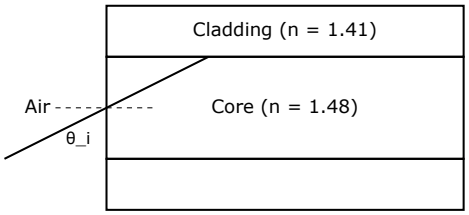


*Fig. 3. Cross-section of the step-index optical fibre.*

4. A laser beam of wavelength 532 nm and power 2.5 mW produces a circular spot of radius 1.2 mm on a diffraction grating. The grating has 500 lines $\text{mm}^{-1}$. (a) Calculate the diffraction angle of the second-order maximum. (b) Calculate the intensity of the laser beam incident on the grating.

5. An ultrasound pulse-echo technique is used in medical imaging. The speed of ultrasound in human tissue is 1540 m $\text{s}^{-1}$. A transducer emits pulses of duration 2.0 $\mu$s. (a) Calculate the minimum distance between two boundaries in the tissue that can be resolved without the reflected pulses overlapping. (b) A reflection from a deep organ returns to the transducer 45 $\mu$s after emission. Calculate the depth of the organ.

6. An atom has simplified energy levels at $-13.6$ eV, $-3.4$ eV, $-1.5$ eV, and $-0.85$ eV. (a) Calculate the highest frequency of radiation that can be emitted by electron transitions between these four energy levels. (b) Calculate the wavelength of the photon emitted when an electron transitions from the $-1.5$ eV level to the $-3.4$ eV level.

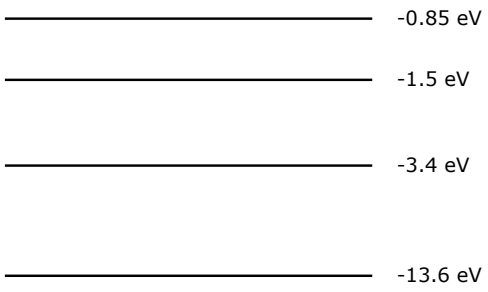


*Fig. 6. Simplified energy level diagram.*

7. In an experiment to determine the speed of sound, a signal generator is connected to a speaker. Two microphones are placed in front of the speaker. When the distance between the microphones is 2.0 cm, the traces on a 2-beam oscilloscope show a phase difference of 0.92 rad. The frequency of the sound is 2.5 kHz. (a) Calculate the wavelength of the sound wave. (b) Calculate the speed of sound in air determined by this experiment.

8. Light is directed at a diffraction grating with a slit spacing of 2.5 $\mu$m. The 3rd order maximum is observed at an angle of 42.0°. (a) Calculate the wavelength of the incident light. (b) Determine the total number of maxima (including the zero order) that can be observed with this grating.

9. Monochromatic light of frequency $1.2 \times 10^{15}$ Hz is incident on metal X, causing the emission of photoelectrons with a maximum speed $v$. The work function of metal X is 2.1 eV. The same light is incident on metal Y, causing the emission of photoelectrons with a maximum speed of $0.5v$. (a) Calculate the maximum kinetic energy, in Joules, of the photoelectrons emitted from metal X. (b) Calculate the work function of metal Y in eV.

10. An electron has a kinetic energy of 4.5 keV. (a) Calculate the momentum of the electron. (b) Show that the de Broglie wavelength of this electron is approximately $1.8 \times 10^{-11}$ m.

11. Two coherent sources emit microwaves of wavelength 2.8 cm in phase. A detector is moved along a line parallel to the sources. At point P, the path difference from the two sources is 7.0 cm. (a) State the phase difference between the two waves arriving at point P. (b) State and explain whether point P is a location of a local maximum or minimum of microwave intensity.

12. A ray of light traveling in air is incident on the flat surface of a rectangular glass block at an angle of 55° to the normal. The refractive index of the glass is 1.52. The block has a thickness of 4.5 cm. (a) Calculate the angle of refraction at the first surface. (b) Calculate the lateral displacement of the ray as it emerges from the opposite parallel face of the block.

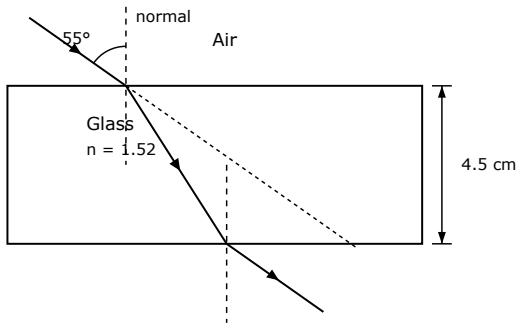


*Fig. 12. A light ray incident at 55° onto a 4.5 cm thick rectangular glass block of refractive index 1.52, showing refraction and emergence.*

13. A light source emits 5.0 W of monochromatic light of wavelength 450 nm uniformly in all directions. (a) Calculate the number of photons emitted by the source per second. (b) Calculate the photon flux (number of photons passing through per second per square metre) at a distance of 2.0 m from the source.

14. A vibrating string has a mass per unit length of $1.5 \times 10^{-3}$ kg m$^{-1}$. When the tension is 25 N, the fundamental frequency is 120 Hz. (a) Calculate the length of the string. (b) A second string made of the same material but with twice the diameter is subjected to the same tension and has the same length. Calculate its fundamental frequency.

15. A laser emits a constant power of 3.60 mW at a frequency of $5.00 \times 10^{14}$ Hz. The laser beam has a circular cross-section of diameter 1.20 mm.
The light enters a transparent glass block of refractive index 1.50, where it is split into two coherent waves. The waves travel through the glass and superpose at a point P. The path length from the splitting point to P is $8.45 \times 10^{-5}$ m for the first wave and $8.67 \times 10^{-5}$ m for the second wave.
($c = 3.00 \times 10^8$ m s$^{-1}$)
(a) Calculate the intensity of the laser beam before it is split. (b) Calculate the wavelength of the light inside the glass block. (c) Calculate the phase difference, in radians, between the two waves when they meet at point P. (d) State and explain the type of interference that occurs at point P. (e) The light inside the block strikes the boundary between the glass and air. Calculate the critical angle for this boundary.

16. A sonar system on a submarine uses a frequency of 2.0 MHz. The speed of sound in seawater is 1500 m s$^{-1}$. (a) Calculate the wavelength of the sonar waves. (b) The system emits pulses consisting of exactly 5 cycles. Calculate the minimum distance from the transducer that an object can be detected without the returning echo overlapping the emitted pulse.

17. The light from a distant star is passed through a diffraction grating with 600 lines mm$^{-1}$. A prominent dark absorption line is observed at an angle of 15.5° in the first-order spectrum. (a) Calculate the wavelength of this absorption line. (b) This absorption corresponds to an electron transitioning to a higher energy level. Calculate the energy difference between these two levels in eV.

18. A right-angled isosceles prism is made of glass with a refractive index of 1.60. A ray of light enters the prism normal to one of the shorter faces and strikes the hypotenuse. (a) Show that the ray will undergo total internal reflection at the hypotenuse. (b) The prism is then immersed in a transparent liquid. The same ray now refracts along the boundary of the hypotenuse. Calculate the refractive index of the liquid.

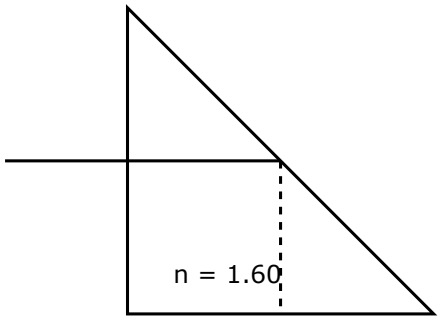


*Fig. 18. Ray entering a right-angled isosceles prism.*

19. A pipe closed at one end has a length of 0.65 m. The speed of sound in the air inside the pipe is 340 m $s^{-1}$. (a) Calculate the fundamental frequency of the stationary longitudinal wave in the pipe. (b) Describe the variation of air pressure at the closed end and at the open end of the pipe when the stationary wave is present.

20. Light of intensity $5.0 \times 10^{-3}$ W $m^{-2}$ and wavelength 250 nm falls on a metal surface of area $1.0 \times 10^{-4}$ $m^2$. (a) Explain how the existence of a threshold frequency in the photoelectric effect provides evidence for the particulate nature of light rather than the wave model. (b) Calculate the maximum number of photoelectrons emitted per second from this surface, assuming every incident photon ejects one electron.

# 4 Electric Circuits（电学与电路）

*Fundamentals of electric current, resistance, DC circuits, potential dividers, and electromotive force.*

## Rules 规则

- Electric current is the rate of flow of charge: $I = \frac{\Delta Q}{\Delta t}$ (电流).
- Potential difference is defined as work done per unit charge: $V = \frac{W}{Q}$ (电势差).
- Resistance is defined as $R = \frac{V}{I}$, and the resistivity of a material is $\rho = \frac{RA}{l}$ (电阻与电阻率).
- Electrical power can be calculated using $P = VI = I^2R = \frac{V^2}{R}$ (电功率).
- For a cell with electromotive force $E$ and internal resistance $r$, the terminal potential difference is $V = E - Ir$ (电动势与内阻).
- In a potential divider, the voltage across $R_1$ is $V_1 = V_{\text{in}} \frac{R_1}{R_1+R_2}$ (分压器).

## Worked Examples 例题

**Example 4.1**

A metal wire has a length of 3.0 m, a cross-sectional area of $2.5 \times 10^{-7}$ m$^2$, and a resistance of 0.45 Ω. Calculate the resistivity of the metal.

**Solution**

Using the formula for resistivity $\rho = \frac{RA}{l}$: $\rho = \frac{0.45 \times 2.5 \times 10^{-7}}{3.0}$ $\rho = 3.75 \times 10^{-8}$ Ω m Final answer: $3.8 \times 10^{-8}$ Ω m

**Example 4.2**

A battery of e.m.f. 12.0 V and internal resistance 1.5 Ω is connected to a 6.5 Ω resistor. Calculate the terminal potential difference across the battery.

**Solution**

First, calculate the total current in the circuit: $I = \frac{E}{R+r} = \frac{12.0}{6.5+1.5} = \frac{12.0}{8.0} = 1.5$ A Next, calculate the terminal potential difference $V$: $V = E - Ir = 12.0 - (1.5 \times 1.5) = 12.0 - 2.25 = 9.75$ V Final answer: 9.8 V

**Example 4.3**

A potential divider consists of a 10 kΩ resistor in series with a light-dependent resistor (LDR) and a 5.0 V supply. In the dark, the LDR has a resistance of 40 kΩ. Calculate the potential difference across the LDR in the dark.

**Solution**

Using the potential divider equation: $V_{\text{LDR}} = V_{\text{in}} \times \frac{R_{\text{LDR}}}{R_{\text{total}}}$ $V_{\text{LDR}} = 5.0 \times \frac{40}{10+40} = 5.0 \times \frac{40}{50} = 4.0$ V
Final answer: 4.0 V

## 考点总览 Key Points

- ☐ 我掌握电流 (current)、电势差 (potential difference) 与电阻定义，能熟练运用欧姆定律 (Ohm's law) 及公式 $I = \frac{\Delta Q}{\Delta t}$ 与 $V = \frac{W}{Q}$。
- ☐ 我理解电荷守恒与能量守恒在电路中的体现，能推导并计算串联 (series) 与并联 (parallel) 电阻的等效阻值。
- ☐ 我能熟练推导并运用电功率 (power) 与电功公式进行计算（如 $P = VI$、$P = I^2R$ 及 $W = VIt$）。
- ☐ 我会绘制、识别并解释欧姆导体、灯丝灯泡 (filament bulb)、热敏电阻与二极管 (diode) 的 $I$-$V$ 特性图像。
- ☐ 我掌握电阻率 (resistivity) 公式 $R = \frac{\rho l}{A}$，并能运用微观电流公式 $I = nqvA$ 解释不同材料导电性能的巨大差异。
- ☐ 我熟悉测定金属材料电阻率的实验原理与操作步骤（CP7）。
- ☐ 我能基于晶格振动和自由电子浓度的微观模型，解释金属导体、NTC 热敏电阻及光敏电阻 (LDR) 阻值随温度或光照的变化。
- ☐ 我理解电势沿均匀导线的分布规律，能分析并计算含可变电阻的分压电路 (potential divider)。
- ☐ 我掌握电动势 (e.m.f.)、内阻 (internal resistance) 与路端电压的区别，并能熟练应用公式 $E = V + Ir$。
- ☐ 我熟悉测定电源电动势与内阻的实验操作及图像分析方法（CP8）。

## Basic Drill（入门综合）· 50

1. A constant electric current of 2.5 A flows through an electric component for 4.0 minutes. Calculate the total electric charge that passes through the component.

2. A current of 0.48 A flows through a metal wire for 15 s. Calculate the number of conduction electrons passing through a cross-section of the wire during this time.

3. Define the electromotive force (e.m.f.) of an electrical source.

4. A total charge of 35 C passes through a potential difference of 12 V. Calculate the electrical energy transferred.

5. State Ohm's law.

6. A fixed resistor of resistance 47 Ω is connected across a potential difference of 9.4 V. Calculate the current in the resistor.

7. A copper wire has a length of 2.4 m and a cross-sectional area of $1.5 \times 10^{-7}$ $m^2$. The resistivity of copper is $1.7 \times 10^{-8}$ Ω m. Calculate the resistance of the wire.

8. A cell of electromotive force (e.m.f.) 4.5 V and internal resistance 1.2 Ω is connected to an external circuit. The current in the circuit is 0.50 A. Calculate the lost volts (potential difference across the internal resistance) of the cell.

9. At a circuit junction, two currents of 1.8 A and 2.4 A flow into the junction through two separate wires. Determine the current flowing out of the junction through a third wire.

10. Three resistors with resistances of 12 Ω, 18 Ω, and 30 Ω are connected in series. Calculate the total resistance of the combination.

11. Two resistors of resistances 20 Ω and 30 Ω are connected in parallel. Calculate the equivalent resistance of this parallel combination.

12. A heating element has a resistance of 15 Ω and carries a steady current of 4.0 A. Calculate the electrical power dissipated in the heating element.

13. An electric heater connected to a 230 V supply draws a current of 8.0 A. Calculate the electrical energy supplied to the heater in 20 minutes.

14. A potential divider circuit consists of a 4.0 kΩ resistor and an 8.0 kΩ resistor connected in series to a 12 V supply of negligible internal resistance. Calculate the output potential difference $V_{\text{out}}$ across the 8.0 kΩ resistor.

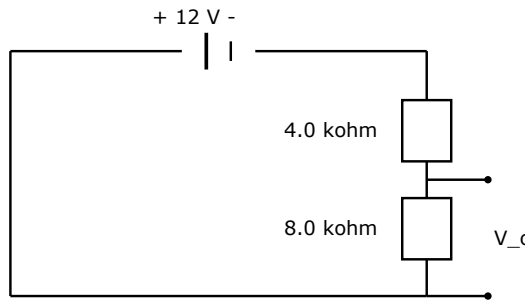


*Fig. 14. Potential divider circuit with two resistors in series.*

15. Explain why the resistance of a metal filament lamp increases as the potential difference across it increases.

16. State and explain the effect of increasing temperature on the resistance of a negative temperature coefficient (NTC) thermistor.

17. Explain why the electrical resistance of a light-dependent resistor (LDR) decreases when the intensity of light incident on it increases.

18. A cell has an electromotive force (e.m.f.) of 1.50 V and an internal resistance of 0.40 Ω. It is connected to an external resistor of resistance 5.60 Ω. Calculate the terminal potential difference across the cell.

19. A uniform resistance wire of length 1.00 m is connected across a 3.00 V d.c. power supply of negligible internal resistance. Calculate the potential difference across a 35 cm length of the wire.

20. A forward-biased silicon diode has a constant potential drop of 0.70 V across it. The diode is connected in series with a 220 Ω resistor and a 5.00 V d.c. supply of negligible internal resistance. Calculate the current in the circuit.

21. A combination of three resistors consists of a 12 Ω resistor in parallel with a 6.0 Ω resistor, and this entire parallel combination is connected in series with a 4.0 Ω resistor. Calculate the total equivalent resistance between terminals A and B.

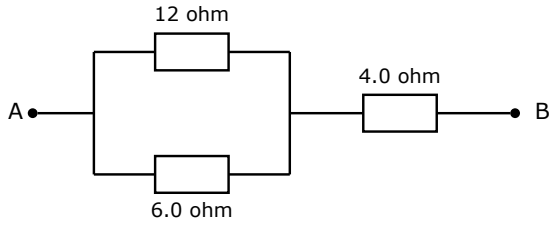


*Fig. 21. Resistor network with a parallel pair in series with a third resistor.*

22. Define potential difference between two points in an electric circuit in terms of energy transferred.

23. A high-resistance voltmeter connected across the terminals of a battery reads 9.0 V on open circuit. When a 15 Ω resistor is connected across the battery, the voltmeter reading falls to 7.5 V. Calculate the internal resistance of the battery.

24. Two cylindrical copper wires, P and Q, have equal lengths. The diameter of wire P is twice the diameter of wire Q. Calculate the numerical ratio $\frac{R_{\mathrm{P}}}{R_{\mathrm{Q}}}$ of their electrical resistances.

25. An electric kettle has a power rating of 2.2 kW when operated from a 230 V mains supply. Calculate the resistance of its heating element.

26. A steady current of 0.48 A exists in a copper wire. Calculate the number of electrons passing a cross-section of the wire in 5.0 minutes.

27. A charge of 35 C moves through an electrical component, transferring 420 J of electrical energy. Calculate the potential difference across the component.

28. State Ohm's law in words.

29. Three wires meet at a junction. Wire 1 carries a current of 2.4 A towards the junction and Wire 2 carries a current of 1.1 A towards the junction. Determine the magnitude and direction of the current in Wire 3.

30. State the fundamental conservation law from which Kirchhoff's second law (the loop rule) is derived.

31. Three identical resistors, each of resistance 18 Ω, are connected in parallel. Determine the equivalent resistance of this combination.

32. The circuit diagram shows three identical resistors, each of resistance 6.0 Ω, connected to a 12 V power supply of negligible internal resistance. Determine the total electrical power dissipated in the circuit.

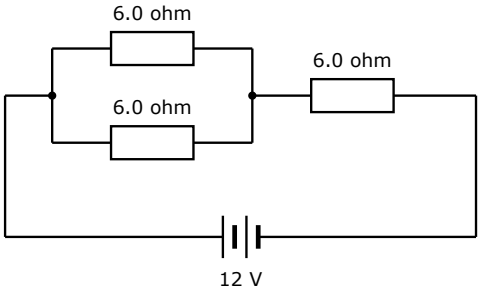


*Fig. 32. Circuit diagram with two parallel 6.0 ohm resistors connected in series with a third 6.0 ohm resistor and a 12 V power supply.*

33. An electric heating element operates at a potential difference of 240 V and has a resistance of 48 Ω. Calculate the power output of the heater.

34. A 60 W lamp is switched on for 2.0 hours. Calculate the total electrical energy transferred by the lamp in joules.

35. Explain why the resistance of a filament lamp increases as the current through it increases.

36. State the typical value of the threshold potential difference required for a silicon semiconductor diode to conduct significantly in forward bias.

37. A heating wire has a resistance of 25 Ω and a cross-sectional area of $2.0 \times 10^{-7}$ $\text{m}^2$. The resistivity of the metal is $1.0 \times 10^{-6}$ Ω m. Calculate the length of the wire.

38. A cylindrical metal wire of original resistance $R$ is stretched uniformly until its length is doubled while its volume remains unchanged. Determine the new resistance of the wire in terms of $R$.

39. In an experiment to determine the resistivity of a metal wire, a student plots a graph of resistance $R$ against wire length $l$. The gradient of the best-fit line is 4.5 Ω $\text{m}^{-1}$. The diameter of the wire is 0.40 mm. Calculate the resistivity of the metal.

40. A copper wire carries a current of 2.0 A. The cross-sectional area of the wire is $1.0 \times 10^{-6}$ m$^2$ and the number density of conduction electrons in copper is $8.5 \times 10^{28}$ m$^{-3}$. Calculate the mean drift velocity of the electrons.

41. State which variable in the equation $I = nqvA$ is primarily responsible for the large difference in electrical resistivity between good conductors and insulators.

42. A uniform potentiometer wire of length 2.0 m has a constant potential difference of 4.0 V maintained across its ends. Determine the length of wire across which the potential difference is 1.4 V.

43. A potential divider circuit connected across a 10 V supply consists of a fixed resistor of 1.5 kΩ in series with a variable resistor $R_{\text{v}}$. Determine the required resistance of $R_{\text{v}}$ so that the potential difference across it is 4.0 V.

44. A potential divider consists of a negative temperature coefficient (NTC) thermistor and a fixed resistor connected in series across a constant supply voltage. The output voltage is taken across the fixed resistor. State and explain how the output voltage changes when the temperature of the thermistor rises.

45. A potential divider contains a light-dependent resistor (LDR) and a 10 kΩ fixed resistor connected in series across a 9.0 V supply. In bright illumination, the resistance of the LDR drops to 2.0 kΩ. Calculate the output potential difference across the LDR under this illumination.

46. A battery of e.m.f. 12.0 V supplies a current of 2.5 A to an external circuit. The terminal potential difference across the battery is 11.0 V. Calculate the internal resistance of the battery.

47. A dry cell has an e.m.f. of 1.5 V and an internal resistance of 0.25 Ω. Calculate the maximum current that flows if the cell terminals are short-circuited by a wire of negligible resistance.

48. In an experiment to determine the e.m.f. $\mathcal{E}$ and internal resistance $r$ of a battery, a graph of terminal potential difference $V$ on the $y$-axis against current $I$ on the $x$-axis is plotted. State what physical quantities are represented by: (a) the $y$-intercept, and (b) the magnitude of the gradient.

49. State what happens to the electrical resistance of a negative temperature coefficient (NTC) thermistor when a large current causes its temperature to rise.

50. State the effect on the number density $n$ of conduction electrons in a light-dependent resistor (LDR) when the intensity of light incident on it increases.

## Practice（综合练习）· 25

1. A smartphone battery delivers a steady current of 1.5 A for 10 minutes. Calculate (a) the total charge that flows from the battery, and (b) the number of electrons that pass a point in the circuit during this time.

2. A power supply does 72 J of work to move 4.5 C of charge through a component. (a) State the definition of potential difference. (b) Calculate the potential difference across the component.

3. A silver wire has a cross-sectional area of $2.5 \times 10^{-6}$ m$^2$ and carries a current of 3.2 A. The charge carrier density of silver is $5.9 \times 10^{28}$ m$^{-3}$. Calculate the drift velocity of the free electrons in the wire.

4. A uniform nichrome wire has a length of 2.5 m and a cross-sectional area of $1.4 \times 10^{-7}$ m$^2$. The resistance of the wire is 19 Ω. Calculate the resistivity of nichrome.

5. A battery of electromotive force (e.m.f.) $E$ and internal resistance $r$ is connected in series with a variable resistor. When the variable resistor is set to 3.0 Ω, the current in the circuit is 1.2 A. When the variable resistor is set to 7.0 Ω, the current in the circuit decreases to 0.60 A. Calculate (a) the internal resistance $r$, and (b) the e.m.f. $E$ of the battery.

6. A circuit contains three resistors of resistances 12 Ω, 24 Ω, and 8.0 Ω. The 12 Ω and 24 Ω resistors are connected in parallel. This parallel combination is connected in series with the 8.0 Ω resistor. Calculate the total resistance of this combination.

7. An electric heating element operates at a potential difference of 230 V and dissipates 1.5 kW of power. Calculate (a) the resistance of the heating element, and (b) the electrical energy transferred in 30 minutes.

8. Sketch and explain the shape of the current-potential difference ($I-V$) graph for a filament lamp.

9. A circuit consists of a silicon diode connected in series with a fixed resistor of resistance $R$ and a 5.0 V d.c. power supply of negligible internal resistance. The diode is forward-biased and has a constant potential difference of 0.70 V across it. The electrical power dissipated by the resistor is 86 mW. Calculate (a) the potential difference across the resistor, (b) the current in the circuit, and (c) the value of $R$.

10. The graph shows how the terminal potential difference $V$ of a battery varies with the current $I$ drawn from it. Use the graph to determine (a) the electromotive force (e.m.f.) of the battery, and (b) its internal resistance.

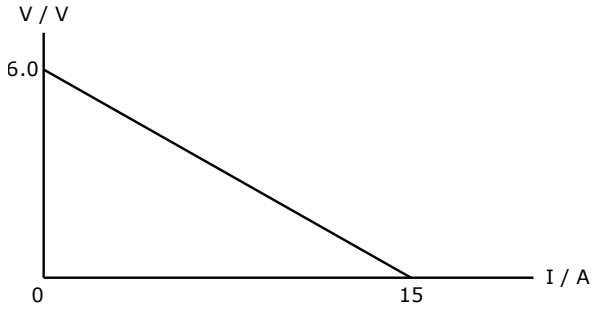


*Fig. 10. Graph of terminal potential difference V against current I.*

11. A potential divider circuit is shown in the figure. It consists of a 5.0 V power supply of negligible internal resistance connected in series with a 4.0 kΩ resistor and a 6.0 kΩ resistor. Calculate the potential difference across the 6.0 kΩ resistor.

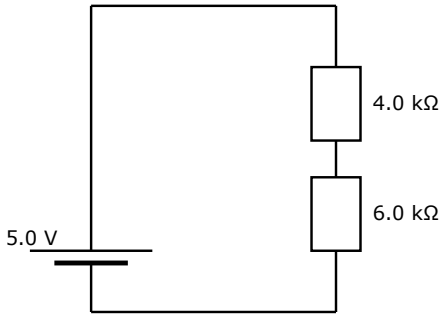


*Fig. 11. Potential divider circuit with a 5.0 V supply and two resistors.*

12. A 9.0 V battery of negligible internal resistance is connected in series with a 2.2 kΩ fixed resistor and a light-dependent resistor (LDR). In bright sunlight, the LDR has a resistance of 800 Ω. Calculate the potential difference across the LDR when it is in bright sunlight.

13. Explain, in terms of the number of conduction electrons and lattice vibrations, why the resistance of a negative temperature coefficient (NTC) thermistor decreases as its temperature increases.

14. State the principle of charge conservation and explain how it applies to the distribution of electric current at a junction in a circuit.

15. State the principle of energy conservation and explain how it applies to the distribution of potential differences in a closed loop of an electric circuit.

16. A uniform resistance wire $XY$ has a length of 100 cm and a resistance of 4.5 Ω. It is connected in series with a 3.0 V cell of negligible internal resistance and a fixed resistor of 1.5 Ω. A voltmeter is connected between point $X$ and a sliding contact $Z$ on the wire. The distance $XZ$ is 40 cm. Calculate the reading on the voltmeter.

17. In an experiment to determine the resistivity of constantan, a student measures the diameter of a constantan wire using a micrometer. The readings are 0.34 mm, 0.35 mm, and 0.33 mm. The wire has a length of 0.85 m and a resistance of 4.6 Ω. Calculate the resistivity of the constantan wire.

18. A battery of e.m.f. 12.0 V and internal resistance 0.50 Ω is connected to a variable resistor $R$. The variable resistor is adjusted to a value of 3.5 Ω. Calculate the power dissipated in the internal resistance of the battery.

19. A cell of e.m.f. 6.0 V and internal resistance 1.2 Ω is connected to two 4.0 Ω resistors that are in parallel with each other. Calculate the current through the cell.

20. Use the equation $I = nqvA$ to explain why an insulator has a much greater electrical resistivity than a metal.

21. A 12 V power supply of negligible internal resistance is connected to a 5.0 kΩ fixed resistor and a variable resistor in series. The variable resistor can be adjusted from 0 to 10 kΩ. Determine the maximum possible potential difference across the variable resistor.

22. Derive the formula for the combined resistance $R$ of two resistors $R_1$ and $R_2$ connected in series, using the principles of conservation of energy and conservation of charge.

23. A filament lamp has a normal operating rating of 12 V, 24 W. It is connected to a 6.0 V power supply of negligible internal resistance. (a) Calculate the resistance of the lamp when operating at its normal rating. (b) State whether the power dissipated by the lamp at 6.0 V is greater than, equal to, or less than 6.0 W. (c) Explain your answer to (b) in terms of lattice vibrations and conduction electrons.

24. Explain how an increase in illumination affects the resistance of a light-dependent resistor (LDR) in terms of the number of conduction electrons.

25. A circuit contains a 12.0 V battery of negligible internal resistance connected to a 2.0 Ω resistor in series with a parallel combination of a 3.0 Ω and a 6.0 Ω resistor, as shown in the figure. Calculate the current in the 6.0 Ω resistor.

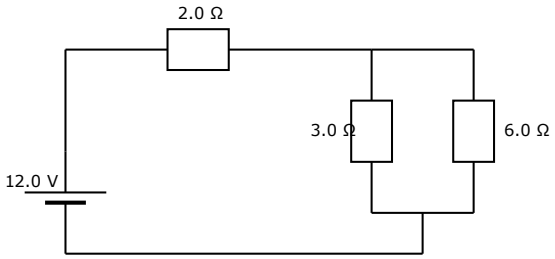


*Fig. 25. Circuit diagram with a 12.0 V battery, a 2.0 ohm resistor in series, and 3.0 ohm and 6.0 ohm resistors in parallel.*

## Advanced Practice（培优）· 20

1. (a) State the principles of conservation of charge and conservation of energy as applied to a parallel electrical circuit. (b) Hence, derive the equation for the equivalent resistance $R$ of three resistors $R_1$, $R_2$, and $R_3$ connected in parallel.

2. A copper wire of length 2.5 m and diameter 1.2 mm carries a current of 4.5 A. The resistivity of copper is $1.7 \times 10^{-8}$ Ω m and its free electron density is $8.5 \times 10^{28}$ $m^{-3}$. Calculate (a) the potential difference across the wire, and (b) the mean drift velocity of the free electrons.

3. A cell of e.m.f. 12.0 V and internal resistance 0.50 Ω is connected in series with a cell of e.m.f. 9.0 V and internal resistance 1.5 Ω, such that their e.m.f.s oppose each other. This combination is connected across a load resistor of 4.0 Ω. Calculate (a) the current in the circuit, and (b) the terminal potential difference of the 9.0 V cell.

4. A non-ohmic component has a current $I$ related to the potential difference $V$ across it by the equation $I = kV^2$, where $k = 0.020$ A $V^{-2}$. It is connected in series with a resistor of resistance $R$ and a cell of e.m.f. 9.0 V and negligible internal resistance. The current in the circuit is 0.50 A. Determine the value of $R$.

5. A potential divider consists of a fixed resistor of 4.7 kΩ and a light-dependent resistor (LDR) connected in series across a 5.0 V supply of negligible internal resistance. The output voltage is taken across the LDR. In dark conditions, the LDR has a resistance of 25 kΩ. In bright sunlight, its resistance drops to 450 Ω. Calculate the change in the output voltage between dark and bright conditions.

6. A battery of electromotive force (e.m.f.) 12.0 V and internal resistance 1.2 Ω is connected to a parallel combination of a fixed resistor of 6.0 Ω and a variable resistor $R$. (a) The variable resistor $R$ is adjusted until the electrical power dissipated in the internal resistance of the battery is 4.8 W. Calculate the value of $R$. (b) Calculate the power dissipated in the 6.0 Ω fixed resistor under this condition. (c) The resistance of the variable resistor $R$ is now decreased. State and explain the effect this has on the terminal potential difference of the battery.

7. A uniform resistance wire $AB$ has length 1.00 m and resistance 5.0 Ω. It is connected in series with a cell of e.m.f. 2.0 V and internal resistance 1.0 Ω. A second cell of e.m.f. $E$ and negligible internal resistance is connected via a galvanometer to the wire, as shown in the figure. The galvanometer shows zero deflection when the sliding contact is at a distance of 65 cm from $A$. Calculate the e.m.f. $E$.

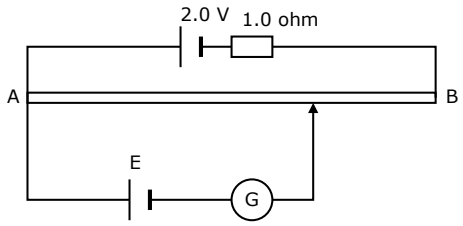


*Fig. 7. A potentiometer circuit used to determine an unknown e.m.f. E.*

8. A heating element is designed to operate at 230 V and dissipate 1.2 kW. It is accidentally connected to a 110 V supply. (a) Assuming the resistance of the element remains constant, calculate the new power dissipated. (b) Explain why, in reality, the power dissipated at 110 V would be slightly different from your calculated value.

9. A battery supplies a constant current of 3.2 A to a circuit for 45 minutes. During this time, $1.0 \times 10^5$ J of energy is transferred by the battery to the circuit. Calculate (a) the e.m.f. of the battery, and (b) the total number of electrons that pass through the battery.

10. A student determines the e.m.f. $E$ and internal resistance $r$ of a cell by varying the external resistance and measuring the terminal potential difference $V$ and current $I$. The student plots a graph of $V$ against $I$, as shown in the figure. (a) Determine the e.m.f. and internal resistance of the cell. (b) Calculate the maximum power that this cell can deliver to an external resistor.

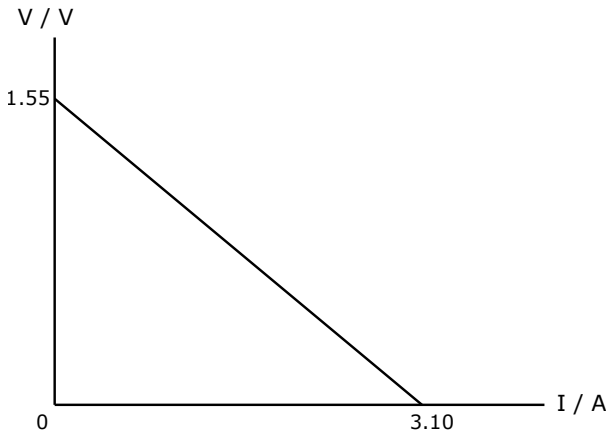


*Fig. 10. Graph of terminal potential difference V against current I.*

11. Wire X has length 0.40 m, diameter $d$, and resistivity $\rho$. Wire Y has length 0.60 m, diameter $2d$, and resistivity $3\rho$. The two wires are connected in series. Determine the ratio of the potential difference across wire X to the potential difference across wire Y.

12. A variable resistor $R_v$ is connected in series with a fixed resistor of 2.2 kΩ across a 12.0 V supply of negligible internal resistance. The resistance of $R_v$ can be varied from 0 to 10.0 kΩ. Calculate the minimum and maximum possible potential differences across the fixed resistor.

13. A light-emitting diode (LED) begins to conduct and emit light when the potential difference across it reaches 1.8 V. It is connected in series with a resistor $R$ and a 5.0 V cell of negligible internal resistance. The normal operating current of the LED is 15 mA. Calculate (a) the required value of $R$, and (b) the total energy supplied by the cell in 2.0 hours of continuous operation.

14. The resistivity of a typical insulator is approximately $10^{20}$ times greater than that of a typical metal. Using the equation $I = nqvA$, explain this extremely large difference in resistivities.

15. Two identical filament bulbs, each rated 12 V, 24 W, are connected first in series and then in parallel across a 12 V supply of negligible internal resistance. Assuming the resistance of the bulbs remains constant, calculate the total power dissipated by the circuit in both cases.

16. A cell of e.m.f. 6.0 V and internal resistance 1.5 Ω is connected to a potential divider circuit consisting of a 3.0 Ω resistor and a 4.5 Ω resistor in series. Calculate the potential difference across the 4.5 Ω resistor.

17. A circuit consists of a 10 V supply of negligible internal resistance connected to three parallel branches, as shown in the figure. Branch 1 has a 20 Ω resistor. Branch 2 has a 30 Ω resistor in series with a 10 Ω resistor. Branch 3 has a 50 Ω resistor. Calculate (a) the total current drawn from the supply, and (b) determine what fraction of this total current flows through Branch 2.

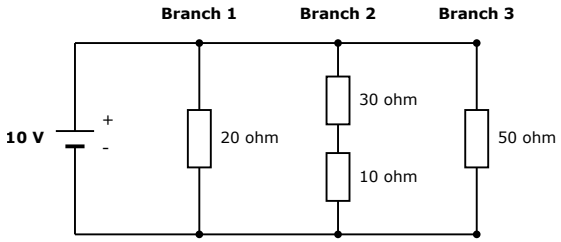


*Fig. 17. A 10 V DC supply connected across three parallel resistor branches.*

18. A rechargeable battery has an e.m.f. of 4.2 V and an internal resistance of 0.15 Ω. It is being charged by a battery charger that supplies a constant current of 2.0 A. Calculate (a) the terminal potential difference of the battery during charging, and (b) the rate at which electrical energy is converted into chemical energy.

19. In an experiment to determine the resistivity of a metal, a student measures the resistance of a wire of length 0.850 m to be 2.4 Ω. The diameter of the wire is measured at several points using a micrometer screw gauge, giving a mean value of 0.46 mm. (a) Calculate the resistivity of the metal. (b) State two precautions the student should take to ensure the diameter measurement is accurate.

20. A potential divider circuit is formed by a negative temperature coefficient (NTC) thermistor and a light-dependent resistor (LDR) connected in series across a 9.0 V supply of negligible internal resistance. The output voltage is measured across the LDR. Explain how the output voltage changes if the temperature of the thermistor increases while the light intensity on the LDR remains constant.