MDCAT Biology Unit 10: Inheritance, study guide with practice MCQs

What MDCAT asks

This unit covers Mendel's two laws and the crosses built on them, the patterns that go beyond simple dominance (incomplete dominance, codominance, multiple alleles, polygenic inheritance, epistasis and the Rh factor), and sex determination, X-linked inheritance and the chromosomal syndromes produced by non-disjunction. Its three subtopics carry equal weight and together account for about 4 of the 81 Biology questions, so expect three to five questions, most of them ratio or probability problems that must be solved in under a minute without a calculator. The free Mega Lecture quiz already holds 46 practice questions on this unit (14, 15 and 17 per subtopic).

B10.1 Mendelian inheritance

B10.1.1 Explain the laws of segregation and independent assortment

Get the vocabulary exact before anything else. A **gene** is a length of DNA that controls one character and occupies a fixed position (locus) on a chromosome. Its alternative forms are **alleles**. A diploid cell carries two alleles of every gene, one on each homologous chromosome. If the two are the same the organism is **homozygous** (TT or tt); if different, **heterozygous** (Tt). The allele set is the **genotype**; the visible character is the **phenotype**. A **dominant** allele is expressed in the heterozygote; a **recessive** allele is expressed only when homozygous. The parental generation is P, their offspring F_1, and the offspring of $F_1 \times F_1$ are F_2.

Mendel worked on the garden pea, *Pisum sativum*, which was a good choice because it has several clear-cut contrasting characters (he used seven, such as tall or dwarf stem and round or wrinkled seed), it normally self-pollinates so pure-breeding lines are easy to keep, and it can be cross-pollinated by hand. He counted thousands of offspring and worked with ratios, which is why his conclusions held.

Law of segregation. The two alleles of a gene separate (segregate) from each other during gamete formation, so each gamete receives only one allele of each gene. Fertilisation restores the pair. The physical basis is the separation of homologous chromosomes at anaphase I of meiosis: the two alleles sit on the two homologues, so they must part company.

Law of independent assortment. When two or more genes are followed together, the alleles of one gene are distributed to the gametes independently of the alleles of the other gene. A plant that is RrYy therefore makes four kinds of gamete, RY, Ry, rY and ry, in equal numbers. The physical basis is the random orientation of each bivalent on the spindle at metaphase I: how one pair of homologues lines up has no effect on how another pair lines up. The law holds only for genes on different chromosomes (or far apart on the same chromosome). Genes close together on one chromosome are **linked** and tend to travel together, which is the main exception to the law.

The parallel between Mendel's factors and chromosome behaviour in meiosis was pointed out by Sutton and Boveri (the chromosomal theory of inheritance, 1902), long after Mendel's own paper of 1866.

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B10.1.2 Solve monohybrid, dihybrid and test cross problems

A **monohybrid cross** follows one gene. Pure tall (TT) × pure dwarf (tt) gives an F_1 that is all Tt and all tall. Selfing the F_1 (Tt × Tt) gives the F_2 genotypes 1 TT : 2 Tt : 1 tt and the phenotypes 3 tall : 1 dwarf. Draw a two-by-two Punnett square if you are unsure; with practice you should see 3 : 1 instantly.

A **test cross** is used to find the genotype of an organism showing the dominant phenotype. It is crossed with a homozygous recessive partner, whose gametes all carry the recessive allele and so cannot hide anything. If all the offspring show the dominant phenotype the unknown is homozygous (TT); if about half are recessive it is heterozygous (Tt). A **back cross** is any cross of an offspring with one of its parents or an organism of the parental genotype; a test cross is the special back cross to the recessive parent.

A **dihybrid cross** follows two genes at once. RRYY (round, yellow) × rryy (wrinkled, green) gives an F_1 that is all RrYy, round and yellow. RrYy × RrYy gives a 16-square Punnett square with 9 genotypes and 4 phenotypes in the ratio 9 round yellow : 3 round green : 3 wrinkled yellow : 1 wrinkled green. The genotypic ratio is 1 : 2 : 1 : 2 : 4 : 2 : 1 : 2 : 1, with RrYy (the double heterozygote) the commonest at 4/16. The dihybrid test cross RrYy × rryy gives the four phenotypes in equal numbers, 1 : 1 : 1 : 1, which is simply the gamete ratio of the heterozygous parent made visible.

Three shortcuts save minutes in the test.

- **Number of gamete types** = 2^n, where n is the number of heterozygous gene pairs. AaBbCc makes 8 kinds of gamete; AABbCc makes 4; AAbbcc makes 1.
- **Product rule.** For independent genes, work out each gene separately and multiply. The chance of an aabb offspring from AaBb × AaBb is 1/4 × 1/4 = 1/16. The chance of A_bb (dominant for A, recessive for b) is 3/4 × 1/4 = 3/16.
- **Sum rule.** If a question asks for "either this or that", add the separate probabilities, provided the outcomes cannot happen together.

The fork-line (branching) method does the same job as a big Punnett square: write the ratio for the first gene, then split each class by the ratio for the second gene, and multiply along each branch.

Cross	Genotypic ratio	Phenotypic ratio	Boxes in Punnett square
Tt × Tt (monohybrid F_1 selfed)	1 : 2 : 1	3 : 1	4
Tt × tt (monohybrid test cross)	1 : 1	1 : 1	2
TT × tt	all Tt	all dominant	1
RrYy × RrYy (dihybrid F_1 selfed)	1 : 2 : 1 : 2 : 4 : 2 : 1 : 2 : 1 (9 genotypes)	9 : 3 : 3 : 1	16
RrYy × rryy (dihybrid test cross)	1 : 1 : 1 : 1	1 : 1 : 1 : 1	4
AaBbCc × AaBbCc (trihybrid)	27 genotypes	27 : 9 : 9 : 9 : 3 : 3 : 3 : 1	64

> **MDCAT trap: the hidden carriers.** In Tt × Tt the F_2 has three tall plants for every dwarf, but of

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those tall plants one is TT and two are Tt. So if a question says "a tall F_2 plant is chosen at random", the chance that it is heterozygous is 2/3, not 1/2 and not 3/4, because the dwarf (tt) plants have already been excluded from the choice. The same logic applies to human pedigrees: a healthy child of two carrier parents has a 2/3 chance of being a carrier. Two related slips: a 3 : 1 ratio is an expectation for large numbers, so 28 tall : 12 dwarf from forty seeds still fits Tt × Tt; and a test cross must use a homozygous recessive partner, so crossing the unknown with a heterozygote is not a test cross: it gives either all dominant offspring or a 3 : 1 ratio, which is harder to read because the partner's own dominant allele can hide a recessive one.

Worked example. Two independently assorting genes: A/a and B/b. In the cross AaBb × Aabb, what fraction of the offspring (i) are aabb and (ii) show the dominant A phenotype together with the recessive b phenotype?

Step 1, gene A on its own: Aa × Aa gives 3/4 dominant and 1/4 aa.

Step 2, gene B on its own: Bb × bb is a test cross, giving 1/2 Bb and 1/2 bb.

Step 3, multiply. (i) aabb = 1/4 × 1/2 = 1/8. (ii) A_bb = 3/4 × 1/2 = 3/8.

Check: the four phenotype classes are 3/8 A_B_, 3/8 A_bb, 1/8 aaB_, 1/8 aabb, which add to 1. The ratio 3 : 3 : 1 : 1 is the answer whenever a double heterozygote is crossed with a plant heterozygous for one gene and recessive for the other.

B10.2 Beyond simple dominance

B10.2.1 Explain incomplete dominance, codominance and multiple alleles (ABO blood groups)

Mendel's peas happened to show complete dominance, in which the heterozygote looks exactly like the dominant homozygote. Many genes do not behave this way.

Incomplete dominance. The heterozygote has a phenotype between the two homozygotes. In the four o'clock plant, *Mirabilis jalapa*, and in snapdragon, red (RR) × white (WW) gives all pink (RW) F_1. Pink × pink gives 1 red : 2 pink : 1 white. Because every genotype has its own phenotype, the phenotypic ratio equals the genotypic ratio, 1 : 2 : 1, and the 3 : 1 ratio never appears. Neither allele is dominant, so the symbols are usually two capital letters.

Codominance. Both alleles are expressed fully and separately in the heterozygote; there is no blending. Human MN blood groups are the classic case: L^ML^M people have M antigen, L^NL^N have N antigen, and L^ML^N have both (group MN). Roan cattle, with a mixture of red and white hairs, and blood group AB are further examples. Heterozygote × heterozygote again gives 1 : 2 : 1.

Multiple alleles. A gene may exist in more than two allelic forms in the population, although any one diploid individual still carries only two of them. The ABO blood group gene has three alleles. I^A codes for an enzyme that puts antigen A on the red cell surface, I^B puts antigen B, and i puts neither. I^A and I^B are codominant with each other and both are completely dominant to i. Three alleles give six genotypes but only four phenotypes.

Blood group (phenotype)	Genotypes	Antigen on red cells	Antibody in plasma	Can receive red cells from

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A	I^AI^A, I^Ai	A	anti-B	A, O
B	I^BI^B, I^Bi	B	anti-A	B, O
AB	I^AI^B	A and B	neither	A, B, AB, O (universal recipient)
O	ii	neither	anti-A and anti-B	O only (universal donor)

Transfusion logic: the donor's red cell antigen must not meet the matching antibody in the recipient's plasma. Group O cells carry no antigen, so they can be given to anyone; group AB plasma carries no antibody, so an AB person can accept any group. Blood group problems are solved exactly like monohybrid crosses once the genotypes are written down. Remember that a group A or B person may be homozygous or heterozygous, and the question usually tells you which through a parent or a child of group O (who must be ii, so each parent gave an i).

Multiple alleles also control coat colour in rabbits, where four alleles form a dominance series: full colour C, chinchilla c^{ch}, Himalayan c^h and albino c, each dominant to those after it.

B10.2.2 Explain polygenic inheritance, epistasis and the Rh factor

Polygenic inheritance. Some characters are controlled by several genes at different loci, each contributing a small, additive effect. The result is not a few discrete classes but **continuous variation**, which gives a bell-shaped (normal) curve when plotted. Human skin colour, height, body weight and eye colour are polygenic, and the environment (sunlight, diet) adds further variation. In the usual teaching model skin colour is treated as three gene pairs with additive "dark" alleles: AABBCC (darkest) × aabbcc (lightest) gives an intermediate F_1, and the F_2 shows seven phenotypic classes, from zero to six dark alleles, with the two extremes at 1/64 each and the intermediate class commonest. The more genes involved, the more classes and the smoother the curve.

Epistasis. Here a gene at one locus masks or modifies the expression of a different gene at another locus. The masking gene is epistatic; the masked gene is hypostatic. Because two genes are involved, epistasis shows up as a modified dihybrid ratio in the F_2.

- **Recessive epistasis, 9 : 3 : 4.** Coat colour in Labrador retrievers: gene B gives black pigment (B) or brown (b); gene E allows the pigment to be deposited in the hair. Dogs that are ee are yellow whatever their B alleles. BbEe × BbEe gives 9 black : 3 brown : 4 yellow.
- **Dominant epistasis, 12 : 3 : 1.** Fruit colour in summer squash: a dominant allele W blocks all colour, giving white fruit. Only ww plants show the second gene (yellow Y_ or green yy). WwYy × WwYy gives 12 white : 3 yellow : 1 green.
- **Bombay phenotype in humans.** The ABO antigens are built on a precursor H substance made by gene H. A person who is hh makes no H substance, so neither antigen A nor B can be formed and the blood tests as group O even though the ABO genotype may be I^AI^B. This is why, very rarely, two parents can have a group O child who is not ii.

Pattern	Genes involved	Heterozygote shows	Ratio from het × het	Example
Complete dominance	one	dominant phenotype only	3 : 1	tall and dwarf pea

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Incomplete dominance	one	intermediate phenotype	1 : 2 : 1	pink four o'clock
Codominance	one	both phenotypes, side by side	1 : 2 : 1	blood group AB, MN group
Multiple alleles	one (three or more alleles)	depends on the pair carried	varies	ABO groups, rabbit coat
Polygenic	several, additive	intermediate	continuous, many classes	skin colour, height
Epistasis	two, one masking the other	depends on the masking gene	9 : 3 : 4 or 12 : 3 : 1	Labrador coat, squash fruit

The Rh factor. About 85 per cent of people carry the Rh (D) antigen on their red cells and are Rh-positive; the rest are Rh-negative. The antigen is named after the rhesus monkey in which it was first found. Rh-positive is dominant: DD and Dd are Rh-positive, dd is Rh-negative. Unlike anti-A and anti-B, which are present naturally in the plasma, anti-D antibody is made only after an Rh-negative person has been exposed to Rh-positive blood, by transfusion or by pregnancy.

Haemolytic disease of the newborn (erythroblastosis foetalis). An Rh-negative mother (dd) carrying an Rh-positive foetus (Dd, the D allele from the father) is normally unaffected during the first such pregnancy, because the two circulations do not mix. At delivery some foetal red cells enter her blood and she becomes sensitised, making anti-D antibody. In a later Rh-positive pregnancy her anti-D antibody (IgG) crosses the placenta and destroys the foetal red cells, causing anaemia, jaundice and, in severe cases, death before or soon after birth. The condition is prevented by injecting the mother with anti-D antibody (anti-Rh globulin) within about 72 hours of each Rh-positive delivery, which clears the foetal cells before her immune system responds. An Rh-positive mother never develops the disease, whatever the father's group.

MDCAT trap: dominance is not epistasis. Dominance describes the relationship between two alleles of the **same** gene, at one locus. Epistasis describes an interaction between **different** genes at different loci. So "a dominant allele masks a recessive allele" is dominance, while "the ee genotype hides whatever B gene the dog carries" is epistasis, and a question that calls epistasis "a form of dominance" is wrong. The quick test: count the genes. One gene, with ratios of 3 : 1 or 1 : 2 : 1, means dominance (complete, incomplete or co-). Two genes, with 16-box ratios such as 9 : 3 : 4 or 12 : 3 : 1, mean epistasis. A second confusion worth killing: in incomplete dominance the heterozygote is a blend (pink), in codominance both parental phenotypes appear unblended (AB has both antigens; roan has both red and white hairs). Both give 1 : 2 : 1, so the ratio alone cannot tell them apart; the phenotype of the heterozygote can.

Worked example. A woman is blood group O and Rh-negative. Her husband is group AB and Rh-positive, and his mother was Rh-negative. What is the probability that their first child is group B and Rh-positive, and is that child at risk of haemolytic disease of the newborn?

Step 1, genotypes. Woman: ii dd. Husband: I^AI^B for ABO; for Rh he is positive but must have received d from his Rh-negative mother, so he is Dd.

Step 2, ABO alone: I^AI^B × ii gives 1/2 group A (I^Ai) and 1/2 group B (I^Bi).

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Step 3, Rh alone: Dd × dd gives 1/2 Rh-positive (Dd) and 1/2 Rh-negative (dd).

Step 4, multiply: group B and Rh-positive = 1/2 × 1/2 = 1/4.

Risk: the mother is Rh-negative and the child Rh-positive, which is the risky combination, but this is her first pregnancy, so the child is almost certainly unaffected. The mother becomes sensitised at delivery unless she receives anti-D, and a later Rh-positive child would be at risk.

B10.3 Sex linkage and chromosomes

B10.3.1 Explain sex determination and X-linked inheritance (haemophilia, colour blindness)

A human body cell has 46 chromosomes: 22 pairs of **autosomes**, identical in the two sexes, and one pair of **sex chromosomes**, XX in the female and XY in the male. The X is large and carries many genes; the Y is small and carries few, the most important being the testis-determining factor (SRY gene), which switches the embryo towards male development. Every egg carries one X. Meiosis in the male gives half the sperm an X and half a Y, so the male is the **heterogametic** sex and the sperm decides the sex of the child: X sperm + egg gives XX (girl), Y sperm + egg gives XY (boy), each with probability 1/2 at every birth. In humans it is the presence of a Y chromosome, not the number of X chromosomes, that makes a male, which is why XXY is male and XO is female.

Other sex-determining systems are set as recall questions.

- **XX-XY**: humans, other mammals, *Drosophila* and many plants. Male heterogametic.
- **XX-XO**: grasshoppers and some other insects. The male has a single X and no Y (XO); half the sperm carry an X and half carry no sex chromosome.
- **ZW-ZZ**: birds, butterflies and moths, some fish and reptiles. The female is ZW and heterogametic, so the egg decides the sex; the male is ZZ.
- **Haplodiploidy**: honey bees and other hymenopterans. Fertilised (diploid) eggs become females, unfertilised (haploid) eggs become males (drones).
- In some reptiles such as turtles and crocodiles the temperature of egg incubation, not a chromosome, decides the sex.

X-linked (sex-linked) inheritance. Genes on the X chromosome have no partner on the Y. A male is therefore **hemizygous** for X-linked genes: he carries one allele, and whatever it is, it shows. A female has two alleles and needs two recessive copies to be affected; with one recessive copy she is a healthy **carrier**. The rules that follow are the ones MDCAT tests.

- A father passes his X to every daughter and his Y to every son. A son's X always comes from his mother. An X-linked trait therefore never passes from father to son.
- X-linked recessive traits are far commoner in males than in females, because a male needs only one recessive allele.
- The usual route is criss-cross: an affected man gives the allele to his daughters (all carriers), who pass it to half their sons (affected). The trait skips a generation and reappears in grandsons.
- An affected daughter must have an affected father and a mother who is at least a carrier.

Haemophilia is an X-linked recessive failure of blood clotting. Haemophilia A, the commoner form, is a lack of clotting factor VIII; haemophilia B (Christmas disease) is a lack of factor IX. Minor injuries bleed

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for a long time and bleeding into joints is a feature. The condition spread through the royal families of Europe from Queen Victoria, a carrier. **Red-green colour blindness** is X-linked recessive and much commoner: it affects roughly 8 per cent of men but well under 1 per cent of women, because a woman must inherit the allele from both parents. Duchenne muscular dystrophy is a third X-linked recessive disorder worth knowing. A few traits are carried on the Y chromosome (Y-linked or holandric), passing from father to all sons and never to daughters; hairy ears (hypertrichosis of the pinna) is the example usually quoted.

Cross (colour blindness, c recessive)	Daughters	Sons
Carrier mother X^CX^c × normal father X^CY	1/2 normal, 1/2 carrier; none affected	1/2 normal, 1/2 colour blind
Normal mother X^CX^C × colour-blind father X^cY	all carriers	all normal
Carrier mother X^CX^c × colour-blind father X^cY	1/2 carrier, 1/2 colour blind	1/2 normal, 1/2 colour blind
Colour-blind mother X^cX^c × normal father X^CY	all carriers	all colour blind

B10.3.2 Describe chromosomal abnormalities (Down, Turner and Klinefelter syndromes) and non-disjunction

Non-disjunction is the failure of a pair of chromosomes to separate during meiosis. If homologous chromosomes fail to separate at anaphase I, or sister chromatids fail to separate at anaphase II, one gamete receives both copies (n + 1) and another receives none (n – 1). Fertilisation of such a gamete by a normal one produces a zygote with 2n + 1 chromosomes (**trisomy**, 47 in humans) or 2n – 1 (**monosomy**, 45). A change in the number of individual chromosomes is called **aneuploidy**, as opposed to polyploidy, in which whole sets are added. Non-disjunction can occur in either parent, but the risk of a trisomic child rises steeply with the mother's age, probably because her oocytes have been held in prophase I since before her birth. Loss of an entire autosome is lethal; the only monosomy compatible with life in humans is the loss of one sex chromosome.

Syndrome	Chromosomes	Cause	Sex and fertility	Main features
Down syndrome	47, trisomy 21 (47, XX, +21 or 47, XY, +21)	non-disjunction of chromosome 21, usually in the mother; risk rises with maternal age	either sex; males usually infertile, females have reduced fertility	characteristic facial features (flat face, slanting eyes, epicanthic fold), short stature, low muscle tone, learning disability, heart defects common
Turner syndrome	45, XO (one X only)	non-disjunction of sex chromosomes in either parent; one gamete lacked a sex chromosome	female, sterile; ovaries do not develop	short stature, webbed neck, broad chest, no puberty without hormone treatment; intelligence usually normal

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Klinefelter syndrome	47, XXY	non-disjunction of sex chromosomes; egg XX + sperm Y, or egg X + sperm XY	male, sterile; small testes	tall, long limbs, some breast development, little facial hair, mild learning difficulty in some

Two further aneuploidies appear occasionally. XYY males (47, XYY) are tall and usually fertile and normal; XXX females (47, XXX, "metafemale" or triple X) are usually fertile and near normal. Both show that extra sex chromosomes are tolerated far better than extra autosomes, partly because surplus X chromosomes are inactivated in the body cells (the Barr body seen in the nucleus of a normal female is her inactivated second X).

MDCAT trap: father to son is impossible. A son receives his father's Y chromosome, never his X, so an X-linked trait cannot pass directly from father to son. If a pedigree or a question shows a haemophilic father with a haemophilic son, the allele came from the mother, who must be a carrier (or affected); the father's own haemophilia is irrelevant to his sons. The same fact works in reverse: a colour-blind daughter proves that her father is colour blind, because one of her two recessive X chromosomes had to come from him. Two more traps in this subtopic: Turner syndrome is a monosomy (45), not a trisomy, and a Turner girl has only one X yet is female because there is no Y; and the Klinefelter patient is male despite having two X chromosomes, because he has a Y.

Worked example. A colour-blind man marries a woman who is homozygous for normal vision. Their daughter has Turner syndrome and is colour blind. In which parent, and at which stage, did non-disjunction occur?

Step 1, genotypes: father X^cY, mother X^CX^C.

Step 2, the daughter is Turner, so she is $X^?O$ with a single X. She is colour blind, so that single X must carry the recessive allele c.

Step 3, only the father has an X^c, so her X came from him in a normal X sperm. Her other parent must have contributed no sex chromosome at all.

Step 4: the egg therefore lacked an X, which means non-disjunction of the X chromosomes happened in the mother during oogenesis (at meiosis I or meiosis II; the data cannot say which).

Had the daughter instead been X^CO with normal vision, the empty gamete would have been the sperm and the non-disjunction would have been in the father.

Practice MCQs

1. In a cross between two pea plants heterozygous for two independently assorting genes (RrYy × RrYy), what fraction of the offspring show the recessive phenotype for both characters?
   A. 1/4
   B. 1/16
   C. 3/16
   D. 9/16
2. A pea plant with round yellow seeds, genotype RrYy, is test crossed. What fraction of the offspring have round green seeds?

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A. 9/16
B. 3/16
C. 1/2
D. 1/4

3. Two tall pea plants are crossed and produce 60 tall and 20 dwarf offspring. If one tall offspring is chosen at random and self-pollinated, what is the probability that it breeds true for tallness?
   A. 1/3
   B. 1/2
   C. 1/4
   D. 2/3
4. In snapdragon, a cross between a red-flowered and a white-flowered plant gives all pink flowers. If two of these pink plants are crossed, the offspring are expected to be:
   A. 3 pink : 1 white
   B. all pink
   C. 1 red : 2 pink : 1 white
   D. 1 red : 1 white
5. A woman of blood group A whose mother was group O marries a man of blood group B whose father was group O. What is the probability that their child is blood group O?
   A. 0
   B. 1/4
   C. 1/2
   D. 3/4
6. Haemolytic disease of the newborn is most likely to occur when:
   A. an Rh-negative mother carries her second Rh-positive foetus
   B. an Rh-positive mother carries an Rh-negative foetus
   C. an Rh-negative mother carries an Rh-negative foetus
   D. an Rh-positive mother carries her first Rh-positive foetus
7. In Labrador retrievers, allele B gives black pigment and b gives brown, but dogs that are ee are yellow whatever their B alleles. The phenotypic ratio of the offspring of BbEe × BbEe is:
   A. 9 : 3 : 3 : 1
   B. 12 : 3 : 1
   C. 1 : 2 : 1
   D. 9 : 3 : 4
8. A colour-blind woman marries a man with normal colour vision. Which statement about their children is correct?
   A. All the children will be colour blind.
   B. All the daughters will be colour blind and all the sons normal.
   C. All the sons will be colour blind and all the daughters carriers.
   D. Half the sons will be colour blind and half the daughters carriers.
9. A couple who both have normal colour vision have a colour-blind son. What is the probability that their next child will be a colour-blind daughter?
   A. 0
   B. 1/4
   C. 1/8
   D. 1/2

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10. A karyotype shows 47 chromosomes with the sex chromosomes XXY. The individual has:
    A. Turner syndrome
    B. Down syndrome
    C. a normal male karyotype with one extra autosome
    D. Klinefelter syndrome

1. B. rryy needs rr (1/4) and yy (1/4); by the product rule 1/4 × 1/4 = 1/16, the smallest class of the 9 : 3 : 3 : 1 ratio.

2. D. A dihybrid test cross (RrYy × rryy) gives the four phenotypes in equal numbers, so round green (Rryy) is 1/4; 3/16 belongs to the F_2 of a selfed dihybrid, not a test cross.

3. A. The 3 : 1 ratio shows both parents are Tt, so the tall offspring are 1 TT : 2 Tt; only the TT third breed true, giving 1/3.

4. C. Pink is the heterozygote under incomplete dominance, and heterozygote × heterozygote gives 1 : 2 : 1 for phenotype as well as genotype.

5. B. Each parent has a group O parent and so must carry i: she is I^Ai, he is I^Bi; the chance of ii is 1/2 × 1/2 = 1/4 (A, B and AB are each 1/4 as well).

6. A. The mother must be Rh-negative and the foetus Rh-positive, and she is normally sensitised only at the first Rh-positive delivery, so a later Rh-positive foetus is the one at risk; an Rh-positive mother cannot make anti-D.

7. D. This is recessive epistasis: the 9 B_E_ are black, 3 bbE_ brown, and the 3 B_ee plus 1 bbee are all yellow, giving 9 : 3 : 4.

8. C. She is X^cX^c, so every son gets an X^c and is colour blind; every daughter gets X^c from her and the normal X^C from the father, so all daughters are carriers.

9. A. A colour-blind son shows the mother is a carrier (X^CX^c), but the father is X^CY and gives every daughter a normal X, so no daughter can be colour blind; the chance is zero.

10. D. 47, XXY is Klinefelter syndrome, a sterile male, because the Y chromosome makes him male; Turner is 45, XO and Down is trisomy 21 with normal sex chromosomes.

Before the test: 12 facts to recite

1. Segregation: the two alleles of a gene part during gamete formation (anaphase I); independent assortment: alleles of different genes on different chromosomes are distributed independently (random orientation at metaphase I).
2. Monohybrid Tt × Tt: genotypes 1 : 2 : 1, phenotypes 3 : 1; test cross Tt × tt: 1 : 1; all dominant offspring in a test cross means the parent was homozygous.
3. Dihybrid RrYy × RrYy: 9 : 3 : 3 : 1 in 16 boxes, 9 genotypes, double heterozygote 4/16; dihybrid test cross: 1 : 1 : 1 : 1.
4. Gamete types = 2^n for n heterozygous pairs; for independent genes multiply the separate probabilities; among dominant-phenotype offspring of Aa × Aa, 2/3 are carriers.
5. Incomplete dominance: heterozygote intermediate (pink four o'clock), 1 : 2 : 1. Codominance: both alleles fully shown (AB, MN, roan cattle), 1 : 2 : 1.

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6. ABO: three alleles, six genotypes, four groups; I^A and I^B codominant, both dominant to i; O = ii has no antigen (universal donor of red cells); AB has no antibody (universal recipient).
7. AB × O parents give only group A or B children; a group O child proves both parents carry i.
8. Polygenic inheritance: several additive genes, continuous variation, bell-shaped curve (skin colour, height); the three-gene skin model gives seven F_2 classes with 1/64 at each extreme.
9. Epistasis is between different genes, dominance between alleles of one gene; recessive epistasis 9 : 3 : 4 (Labrador coat), dominant epistasis 12 : 3 : 1 (squash fruit).
10. Rh-positive (DD, Dd) is dominant to Rh-negative (dd); haemolytic disease of the newborn needs an Rh-negative mother and an Rh-positive foetus, usually in a second or later such pregnancy, and is prevented by anti-D given after each Rh-positive delivery.
11. Humans: 44 autosomes + XX or XY; the sperm decides the sex; a Y makes a male. Father's X goes to all daughters, never to sons; a son's X is from his mother. Haemophilia A (factor VIII) and red-green colour blindness are X-linked recessive. Grasshoppers XO, birds ZW (female heterogametic).
12. Non-disjunction gives n + 1 and n – 1 gametes, hence trisomy (47) or monosomy (45). Down = trisomy 21, risk rises with maternal age; Turner = 45, XO, sterile female; Klinefelter = 47, XXY, sterile male.

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