Topic 2. DNA AND INHERITANCE

SL: 21 hours
HL: 37 hours

Contents

Objectives from the Biology Guide 2025, published by the IB

A 1.2 Nucleic Acids

Unity and diversity—Molecules

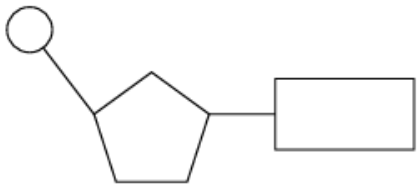
Standard level and higher level: 3 hours

Additional higher level: 2 hours

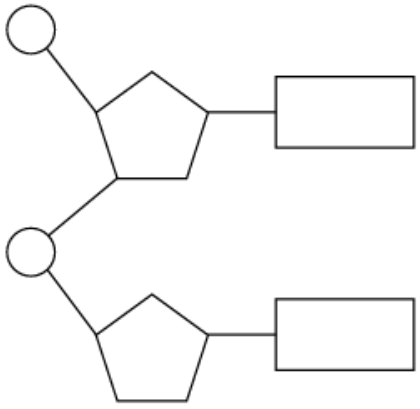
SL and HL

A1.2.1—DNA as the genetic material of all living organisms
Some viruses use RNA as their genetic material but viruses are not considered to be living.

A1.2.2—Components of a nucleotide
In diagrams of nucleotides use circles, pentagons and rectangles to represent relative positions of phosphates, pentose sugars and bases.



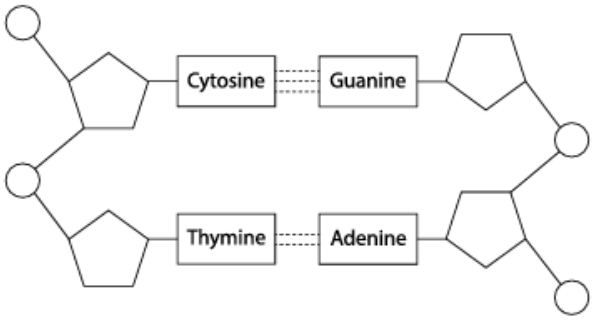
A1.2.3—Sugar–phosphate bonding and the sugar–phosphate "backbone" of DNA and RNA
Sugar–phosphate bonding makes a continuous chain of covalently bonded atoms in each strand of DNA or RNA nucleotides, which forms a strong "backbone" in the molecule.



A1.2.4—Bases in each nucleic acid that form the basis of a code
Students should know the names of the nitrogenous bases.

A1.2.5—RNA as a polymer formed by condensation of nucleotide monomers
Students should be able to draw and recognize diagrams of the structure of single nucleotides and RNA polymers.

A1.2.6—DNA as a double helix made of two antiparallel strands of nucleotides with two strands linked by hydrogen bonding between complementary base pairs
In diagrams of DNA structure, students should draw the two strands antiparallel, but are not required to draw the helical shape. Students should show adenine (A) paired with thymine (T), and guanine (G) paired with cytosine (C). Students are not required to memorize the relative lengths of the purine and pyrimidine bases, or the numbers of hydrogen bonds.



A1.2.7—Differences between DNA and RNA
Include the number of strands present, the types of nitrogenous bases and the type of pentose sugar. Students should be able to sketch the difference between ribose and deoxyribose. Students should be familiar with examples of nucleic acids.

A1.2.8—Role of complementary base pairing in allowing genetic information to be replicated and expressed
Students should understand that complementarity is based on hydrogen bonding.

A1.2.9—Diversity of possible DNA base sequences and the limitless capacity of DNA for storing information
Explain that diversity by any length of DNA molecule and any base sequence is possible. Emphasize the enormous capacity of DNA for storing data with great economy.

A1.2.10—Conservation of the genetic code across all life forms as evidence of universal common ancestry
Students are not required to memorize any specific examples.

Additional higher level

A1.2.11—Directionality of RNA and DNA
Include 5' to 3' linkages in the sugar–phosphate backbone and their significance for replication, transcription and translation.

A1.2.12—Purine-to-pyrimidine bonding as a component of DNA helix stability
Adenine–thymine (A–T) and cytosine–guanine (C–G) pairs have equal length, so the DNA helix has the same three-dimensional structure, regardless of the base sequence.

A1.2.13—Structure of a nucleosome
Limit to a DNA molecule wrapped around a core of eight histone proteins held together by an additional histone protein attached to linker DNA. **Application of skills:** Students are required to use molecular visualization software to study the association between the proteins and DNA within a nucleosome.

A1.2.14—Evidence from the Hershey–Chase experiment for DNA as the genetic material
Students should understand how the results of the experiment support the conclusion that DNA is the genetic material. **NOS:** Students should appreciate that technological developments can open up new possibilities for experiments. When radioisotopes were made available to scientists as research tools, the Hershey–Chase experiment became possible.

A1.2.15—Chargaff's data on the relative amounts of pyrimidine and purine bases across diverse life forms
NOS: Students should understand how the "problem of induction" is addressed by the "certainty of falsification". In this case, Chargaff's data falsified the tetranucleotide hypothesis that there was a repeating sequence of the four bases in DNA.

D 1.2 Protein Synthesis

Standard level and higher level: 3 hours

Additional higher level: 3 hours

D1.2.1—Transcription as the synthesis of RNA using a DNA template
Students should understand the roles of RNA polymerase in this process.

D1.2.2—Role of hydrogen bonding and complementary base pairing in transcription
Include the pairing of adenine (A) on the DNA template strand with uracil (U) on the RNA strand.

D1.2.3—Stability of DNA templates
Single DNA strands can be used as a template for transcribing a base sequence, without the DNA base sequence changing. In somatic cells that do not divide, such sequences must be conserved throughout the life of a cell.

D1.2.4—Transcription as a process required for the expression of genes
Limit to understanding that not all genes in a cell are expressed at any given time and that transcription, being the first stage of gene expression, is a key stage at which expression of a gene can be switched on and off.

D1.2.5—Translation as the synthesis of polypeptides from mRNA
The base sequence of mRNA is translated into the amino acid sequence of a polypeptide.

D1.2.6—Roles of mRNA, ribosomes and tRNA in translation
Students should know that mRNA binds to the small subunit of the ribosome and that two tRNAs can bind simultaneously to the large subunit.

D1.2.7—Complementary base pairing between tRNA and mRNA
Include the terms “codon” and “anticodon”.

D1.2.8—Features of the genetic code
Students should understand the reasons for a triplet code. Students should use and understand the terms “degeneracy” and “universality”.

D1.2.9—Using the genetic code expressed as a table of mRNA codons
Students should be able to deduce the sequence of amino acids coded by an mRNA strand.

D1.2.10—Stepwise movement of the ribosome along mRNA and linkage of amino acids by peptide bonding to the growing polypeptide chain
Focus on elongation of the polypeptide, rather than on initiation and termination.

D1.2.11—Mutations that change protein structure
Include an example of a point mutation affecting protein structure.

B2.2.2—Advantage of the separation of the nucleus and cytoplasm into separate compartments
Limit to separation of the activities of gene transcription and translation—post-transcriptional modification of mRNA can happen before the mRNA meets ribosomes in the cytoplasm. In prokaryotes this is not possible—mRNA may immediately meet ribosomes.

Additional higher level

D1.2.12—Directionality of transcription and translation
Students should understand what is meant by 5' to 3' transcription and 5' to 3' translation.

D1.2.13—Initiation of transcription at the promoter
Consider transcription factors that bind to the promoter as an example. However, students are not required to name the transcription factors.

D1.2.14—Non-coding sequences in DNA do not code for polypeptides
Limit examples to regulators of gene expression, introns, telomeres and genes for rRNAs and tRNAs in eukaryotes.

D1.2.15—Post-transcriptional modification in eukaryotic cells
Include removal of introns and splicing together of exons to form mature mRNA and also the addition of 5' caps and 3' polyA tails to stabilize mRNA transcripts.

D1.2.16—Alternative splicing of exons to produce variants of a protein from a single gene
Students are only expected to understand that splicing together different combinations of exons allows one gene to code for different polypeptides. Specific examples are not required.

D1.2.17—Initiation of translation
Include attachment of the small ribosome subunit to the 5' terminal of mRNA, movement to the start codon, the initiator tRNA and another tRNA, and attachment of the large subunit. Students should understand the roles of the three binding sites for tRNA on the ribosome (A, P and E) during elongation.

D1.2.18—Modification of polypeptides into their functional state
Students should appreciate that many polypeptides must be modified before they can function. The examples chosen should include the two-stage modification of pre-proinsulin to insulin.

D1.2.19—Recycling of amino acids by proteasomes
Limit to the understanding that sustaining a functional proteome requires constant protein breakdown and synthesis.

D 2.2 Gene Expression

Additional higher level: 3 hours

D2.2.1—Gene expression as the mechanism by which information in genes has effects on the phenotype
Students should appreciate that the most common stages in this process are transcription, translation and the function of a protein product, such as an enzyme.

D2.2.2—Regulation of transcription by proteins that bind to specific base sequences in DNA

Include the role of promoters, enhancers and transcription factors.

D2.2.3—Control of the degradation of mRNA as a means of regulating translation
In human cells, mRNA may persist for time periods from minutes up to days, before being broken down by nucleases.

D2.2.4—Epigenesis as the development of patterns of differentiation in the cells of a multicellular organism
Emphasize that DNA base sequences are not altered by epigenetic changes, so phenotype but not genotype is altered.

D2.2.5—Differences between the genome, transcriptome and proteome of individual cells
No cell expresses all of its genes. The pattern of gene expression in a cell determines how it differentiates.

D2.2.6—Methylation of the promoter and histones in nucleosomes as examples of epigenetic tags
Methylation of cytosine in the DNA of a promoter represses transcription and therefore expression of the gene downstream. Methylation of amino acids in histones can cause transcription to be repressed or activated. Students are not required to know details of how this is achieved.

D2.2.7—Epigenetic inheritance through heritable changes to gene expression
Limit to the possibility of phenotypic changes in a cell or organism being passed on to daughter cells or offspring without changes in the nucleotide sequence of DNA. This can happen if epigenetic tags, such as DNA methylation or histone modification, remain in place during mitosis or meiosis.

D2.2.8—Examples of environmental effects on gene expression in cells and organisms
Include alteration of methyl tags on DNA in response to air pollution as an example.

D2.2.9—Consequences of removal of most but not all epigenetic tags from the ovum and sperm
Students can show this by outlining the epigenetic origins of phenotypic differences in tigons and ligers (lion–tiger hybrids).

D2.2.10—Monozygotic twin studies
Limit to investigating the effects of the environment on gene expression.

D2.2.11—External factors impacting the pattern of gene expression
Limit to one example of a hormone and one example of a biochemical such as lactose or tryptophan in bacteria.

D 1.3 Mutation and Gene Editing

Standard level and higher level: 3 hours

Additional higher level: 2 hours

D1.3.1—Gene mutations as structural changes to genes at the molecular level
Distinguish between substitutions, insertions and deletions.

D1.3.2—Consequences of base substitutions
Students should understand that single-nucleotide polymorphisms (SNPs) are the result of base substitution mutations and that because of the degeneracy of the genetic code they may or may not change a single amino acid in a polypeptide.

D1.3.3—Consequences of insertions and deletions
Include the likelihood of polypeptides ceasing to function, either through frameshift changes or through major insertions or deletions. Specific examples are not required.

D1.3.4—Causes of gene mutation
Students should understand that gene mutation can be caused by mutagens and by errors in DNA replication or repair. Include examples of chemical mutagens and mutagenic forms of radiation.

D1.3.5—Randomness in mutation
Students should understand that mutations can occur anywhere in the base sequences of a genome, although some bases have a higher probability of mutating than others. They should also understand that no natural mechanism is known for making a deliberate change to a particular base with the purpose of changing a trait.

D1.3.6—Consequences of mutation in germ cells and somatic cells
Include inheritance of mutated genes in germ cells and cancer in somatic cells.

D1.3.7—Mutation as a source of genetic variation
Students should appreciate that gene mutation is the original source of all genetic variation. Although most mutations are either harmful or neutral for an individual organism, in a species they are in the long term essential for evolution by natural selection.

NOS: Commercial genetic tests can yield information about potential future health and disease risk. One possible impact is that, without expert interpretation, this information could be problematic.

Additional higher level

D1.3.8—Gene knockout as a technique for investigating the function of a gene by changing it to make it inoperative
Students are not required to know details of techniques. Students should appreciate that a library of knockout organisms is available for some species used as models in research.

D1.3.9—Use of the CRISPR sequences and the enzyme Cas9 in gene editing
Students are not required to know the role of the CRISPR–Cas system in prokaryotes. However, students should be familiar with an example of the successful use of this technology. **NOS:** Certain potential uses of CRISPR raise ethical issues that must be addressed before implementation. Students should understand that scientists across the world are subject to different regulatory systems. For this reason, there is an international effort to harmonize regulation of the application of genome editing technologies such as CRISPR.

D1.3.10—Hypotheses to account for conserved or highly conserved sequences in genes
Conserved sequences are identical or similar across a species or a group of species; highly conserved sequences are identical or similar over long periods of evolution. One hypothesis for the mechanism is the functional requirements for the gene products and another hypothesis is slower rates of mutation.

D 1.1 DNA Replication

Standard level and higher level: 2 hours

Additional higher level: 2 hours

D1.1.1—DNA replication as production of exact copies of DNA with identical base sequences
Students should appreciate that DNA replication is required for reproduction and for growth and tissue replacement in multicellular organisms.

D1.1.2—Semi-conservative nature of DNA replication and role of complementary base pairing
Students should understand how these processes allow a high degree of accuracy in copying base sequences.

D1.1.3—Role of helicase and DNA polymerase in DNA replication
Limit to the role of helicase in unwinding and breaking hydrogen bonds between DNA strands and the general role of DNA polymerase.

D1.1.4—Polymerase chain reaction and gel electrophoresis as tools for amplifying and separating DNA
Students should understand the use of primers, temperature changes and *Taq* polymerase in the polymerase chain reaction (PCR) and the basis of separation of DNA fragments in gel electrophoresis.

D1.1.5—Applications of polymerase chain reaction and gel electrophoresis
Students should appreciate the broad range of applications, including DNA profiling for paternity and forensic investigations. **NOS:** Reliability is enhanced by increasing the number of measurements in an experiment or test. In DNA profiling, increasing the number of markers used reduces the probability of a false match.

Additional higher level

D1.1.6—Directionality of DNA polymerases
Students should understand the difference between the 5' and 3' terminals of strands of nucleotides and that DNA polymerases add the 5' of a DNA nucleotide to the 3' end of a strand of nucleotides.

D1.1.7—Differences between replication on the leading strand and the lagging strand
Include the terms “continuous”, “discontinuous” and “Okazaki fragments”. Students should know that replication has to be initiated with RNA primer only once on the leading strand but repeatedly on the lagging strand.

D1.1.8—Functions of DNA primase, DNA polymerase I, DNA polymerase III and DNA ligase in replication
Limit to the prokaryotic system.

D1.1.9—DNA proofreading
Limit to the action of DNA polymerase III in removing any nucleotide from the 3' terminal with a mismatched base, followed by replacement with a correctly matched nucleotide.

B 2.3 Cell Specialization

Standard level and higher level: 2 hours

B2.3.1—Production of unspecialized cells following fertilization and their development into specialized cells by differentiation
Students should understand the impact of gradients on gene expression within an early-stage embryo.

B2.3.2—Properties of stem cells
Limit to the capacity of cells to divide endlessly and differentiate along different pathways.

B2.3.3—Location and function of stem cell niches in adult humans
Limit to two example locations and the understanding that the stem cell niche can maintain the cells or promote their proliferation and differentiation. Bone marrow and hair follicles are suitable examples.

B2.3.4—Differences between totipotent, pluripotent and multipotent stem cells
Students should appreciate that cells in early-stage animal embryos are totipotent but soon become pluripotent, whereas stem cells in adult tissue such as bone marrow are multipotent.

B2.3.5—Cell size as an aspect of specialization
Consider the range of cell size in humans including male and female gametes, red and white blood cells, neurons and striated muscle fibres.

B2.3.6—Surface area-to-volume ratios and constraints on cell size
Students should understand the mathematical ratio between volume and surface area and that exchange of materials across a cell surface depends on its area whereas the need for exchange depends on cell volume. **NOS:** Students should recognize that models are simplified versions of complex systems. In this case, surface-area-to-volume relationship can be modelled using cubes of different side lengths. Although the cubes have a simpler shape than real organisms, scale factors operate in the same way.

Additional higher level

B2.3.7—Adaptations to increase surface area-to-volume ratios of cells
Include flattening of cells, microvilli and invagination. Use erythrocytes and proximal convoluted tubule cells in the nephron as examples.

B2.3.8—Adaptations of type I and type II pneumocytes in alveoli
Limit to extreme thinness to reduce distances for diffusion in type I pneumocytes and the presence of many secretory vesicles (lamellar bodies) in the cytoplasm that discharge surfactant to the alveolar lumen in type II pneumocytes. Alveolar epithelium is an example of a tissue where more than one cell type is present, because different adaptations are required for the overall function of the tissue.

B2.3.9—Adaptations of cardiac muscle cells and striated muscle fibres
Include the presence of contractile myofibrils in both muscle types and hypotheses for these differences: branching (branched or unbranched), and length and numbers of nuclei. Also include a discussion of whether a striated muscle fibre is a cell.

B2.3.10—Adaptations of sperm and egg cells
Limit to gametes in humans.

D 2.1 Cell and Nuclear Division

Standard level and higher level: 3 hours

Additional higher level: 1 hour

D2.1.1—Generation of new cells in living organisms by cell division
In all living organisms, a parent cell—often referred to as a mother cell—divides to produce two daughter cells.

D2.1.2—Cytokinesis as splitting of cytoplasm in a parent cell between daughter cells
Students should appreciate that in an animal cell a ring of contractile actin and myosin proteins pinches a cell membrane together to split the cytoplasm, whereas in a plant cell vesicles assemble sections of membrane and cell wall to achieve splitting.

D2.1.3—Equal and unequal cytokinesis
Include the idea that division of cytoplasm is usually, but not in all cases, equal and that both daughter cells must receive at least one mitochondrion and any other organelle that can only be made by dividing a pre-existing structure. Include oogenesis in humans and budding in yeast as examples of unequal cytokinesis.

D2.1.4—Roles of mitosis and meiosis in eukaryotes
Emphasize that nuclear division is needed before cell division to avoid production of anucleate cells. Mitosis maintains the chromosome number and genome of cells, whereas meiosis halves the chromosome number and generates genetic diversity.

D2.1.5—DNA replication as a prerequisite for both mitosis and meiosis
Students should understand that, after replication, each chromosome consists of two elongated DNA molecules (chromatids) held together until anaphase.

D2.1.6—Condensation and movement of chromosomes as shared features of mitosis and meiosis
Include the role of histones in the condensation of DNA by supercoiling and the use of microtubules and microtubule motors to move chromosomes.

D2.1.7—Phases of mitosis
Students should know the names of the phases and how the process as a whole produces two genetically identical daughter cells.

D2.1.8—Identification of phases of mitosis
Application of skills: Students should do this using diagrams as well as with cells viewed with a microscope or in a micrograph.

D2.1.9—Meiosis as a reduction division
Students should understand the terms “diploid” and “haploid” and how the two divisions of meiosis produce four haploid nuclei from one diploid nucleus. They should also understand the need for meiosis in a sexual life cycle. Students should be able to outline the two rounds of segregation in meiosis.

D2.1.10—Down syndrome and non-disjunction
Use Down syndrome as an example of an error in meiosis.

D2.1.11—Meiosis as a source of variation
Students should understand how meiosis generates genetic diversity by random orientation of bivalents and by crossing over.

Additional higher level

D2.1.12—Cell proliferation for growth, cell replacement and tissue repair
Include proliferation for growth within plant meristems and early-stage animal embryos as examples. Include skin as an example of cell proliferation during routine cell replacement and during wound healing. Students are not required to know details of the structure of skin.

D2.1.13—Phases of the cell cycle
Students should understand that cell proliferation is achieved using the cell cycle. Students should understand the sequence of events including G1, S and G2 as the stages of interphase, followed by mitosis and then cytokinesis.

D2.1.14—Cell growth during interphase
Students should appreciate that interphase is a metabolically active period and that growth involves biosynthesis of cell components including proteins and DNA. Numbers of mitochondria and chloroplasts are increased by growth and division of these organelles.

D2.1.15—Control of the cell cycle using cyclins
Limit to the concentration of different cyclins increasing and decreasing during the cell cycle and a threshold level of a specific cyclin required to pass each checkpoint in the cycle. Students are not required to know details of the roles of specific cyclins.

D2.1.16—Consequences of mutations in genes that control the cell cycle
Include mutations in proto-oncogenes that convert them to oncogenes and mutations in tumour suppressor genes, resulting in uncontrolled cell division.

D2.1.17—Differences between tumours in rates of cell division and growth and in the capacity for metastasis and invasion of neighbouring tissue
Include the terms “benign”, “malignant”, “primary tumour” and “secondary tumour”, and distinguish between tumours that do and do not cause cancer. **Application of skills:** Students should observe populations of cells to determine the mitotic index.

D 3.2 Inheritance

Standard level and higher level: 5 hours

Additional higher level: 3 hours

D3.2.1—Production of haploid gametes in parents and their fusion to form a diploid zygote as the means of inheritance
Students should understand that this pattern of inheritance is common to all eukaryotes with a sexual life cycle. They should also understand that a diploid cell has two copies of each autosomal gene.

D3.2.2—Methods for conducting genetic crosses in flowering plants
Use the terms "P generation", "F1 generation", "F2 generation" and "Punnett grid". Students should understand that pollen contains male gametes and that female gametes are located in the ovary, so pollination is needed to carry out a cross. They should also understand that plants such as peas produce both male and female gametes on the same plant, allowing self-pollination and therefore self-fertilization. Mention that genetic crosses are widely used to breed new varieties of crop or ornamental plants.

D3.2.3—Genotype as the combination of alleles inherited by an organism
Students should use and understand the terms "homozygous" and "heterozygous", and appreciate the distinction between genes and alleles.

D3.2.4—Phenotype as the observable traits of an organism resulting from genotype and environmental factors
Students should be able to suggest examples of traits in humans due to genotype only and due to environment only, and also traits due to interaction between genotype and environment.

D3.2.5—Effects of dominant and recessive alleles on phenotype
Students should understand the reasons that both a homozygous-dominant genotype and a heterozygous genotype for a particular trait will produce the same phenotype.

D3.2.6—Phenotypic plasticity as the capacity to develop traits suited to the environment experienced by an organism, by varying patterns of gene expression
Phenotypic plasticity is not due to changes in genotype, and the changes in traits may be reversible during the lifetime of an individual.

D3.2.7—Phenylketonuria as an example of a human disease due to a recessive allele
Phenylketonuria (PKU) is a recessive genetic condition caused by mutation in an autosomal gene that codes for the enzyme needed to convert phenylalanine to tyrosine.

D3.2.8—Single-nucleotide polymorphisms and multiple alleles in gene pools

Students should understand that any number of alleles of a gene can exist in the gene pool but an individual only inherits two.

D3.2.9—ABO blood groups as an example of multiple alleles
Use I^A, I^B and i to denote the alleles.

D3.2.10—Incomplete dominance and codominance
Students should understand the differences between these patterns of inheritance at the phenotypic level. In codominance, heterozygotes have a dual phenotype. Include the AB blood type (I^AI^B) as an example. In incomplete dominance, heterozygotes have an intermediate phenotype. Include four o'clock flower or marvel of Peru (*Mirabilis jalapa*) as an example. *Note: When students are referring to organisms in an examination, either the common name or the scientific name is acceptable.*

D3.2.11—Sex determination in humans and inheritance of genes on sex chromosomes
Students should understand that the sex chromosome in sperm determines whether a zygote develops certain male-typical or female-typical physical characteristics and that far more genes are carried by the X chromosome than the Y chromosome.

D3.2.12—Haemophilia as an example of a sex-linked genetic disorder
Show alleles carried on X chromosomes as superscript letters on an uppercase X.

D3.2.13—Pedigree charts to deduce patterns of inheritance of genetic disorders
Students should understand the genetic basis for the prohibition of marriage between close relatives in many societies. **NOS:** Scientists draw general conclusions by inductive reasoning when they base a theory on observations of some but not all cases. A pattern of inheritance may be deduced from parts of a pedigree chart and this theory may then allow genotypes of specific individuals in the pedigree to be deduced. Students should be able to distinguish between inductive and deductive reasoning.

D3.2.14—Continuous variation due to polygenic inheritance and/or environmental factors
Use skin colour in humans as an example. **Application of skills:** Students should understand the distinction between continuous variables such as skin colour and discrete variables such as ABO blood group. They should also be able to apply measures of central tendency such as mean, median and mode.

D3.2.15—Box-and-whisker plots to represent data for a continuous variable such as student height
Application of skills: Students should use a box-and-whisker plot to display six aspects of data: outliers, minimum, first quartile, median, third quartile and maximum. A data point is categorized as an outlier if it is more than 1.5 × IQR (interquartile range) above the third quartile or below the first quartile.

Additional higher level

D3.2.16—Segregation and independent assortment of unlinked genes in meiosis
Students should understand the link between the movements of chromosomes in meiosis and the outcome of dihybrid crosses involving pairs of unlinked genes.

D3.2.17—Punnett grids for predicting genotypic and phenotypic ratios in dihybrid crosses involving pairs of unlinked autosomal genes
Students should understand how the 9:3:3:1 and 1:1:1:1 ratios are derived. **NOS:** 9:3:3:1 and 1:1:1:1 ratios for dihybrid crosses are based on what has been called Mendel's second law. This law only applies if genes are on different chromosomes or are far apart enough on one chromosome for recombination rates to reach 50%. Students should recognize that there are exceptions to all biological "laws" under certain conditions.

D3.2.18—Loci of human genes and their polypeptide products
Application of skills: Students should explore genes and their polypeptide products in databases. They should find pairs of genes with loci on different chromosomes and also in close proximity on the same chromosome.

D3.2.19—Autosomal gene linkage
In crosses involving linkage, the symbols used to denote alleles should be shown alongside vertical lines representing homologous chromosomes. Students should understand the reason that alleles of linked genes can fail to assort independently.

D3.2.20—Recombinants in crosses involving two linked or unlinked genes
Students should understand how to determine the outcomes of crosses between an individual heterozygous for both genes and an individual homozygous recessive for both genes. Identify recombinants in gametes, in genotypes of offspring and in phenotypes of offspring.

D3.2.21—Use of a chi-squared test on data from dihybrid crosses
Students should understand the concept of statistical significance, the $p = 0.05$ level, null/alternative hypothesis and the idea of observed versus expected results. **NOS:** Students should recognize that statistical testing often involves using a sample to represent a population. In this case the sample is the F2 generation. In many experiments the sample is the replicated or repeated measurements.