

**FIGURE 11.1** Sexual reproduction is a prominent feature of the living world. These three puppies from a litter of Siberian huskies show the classical outcome of sexual reproduction — the production of offspring that differ from each other and from their two parents. Note the different coloured face marking — black, chocolate and fawn. In this chapter, we will explore aspects of sexual reproduction, including the process of meiosis that is responsible for creating the genetic variation in offspring produced through sexual reproduction by the same parents.

**KEY KNOWLEDGE**

The contents of this chapter are designed to enable students to:

- recognise that genetic variation exists in offspring resulting from sexual reproduction
- gain knowledge of the process of meiosis that generates haploid gametes
- identify how meiosis produces the genetic variability in offspring of the same parents.



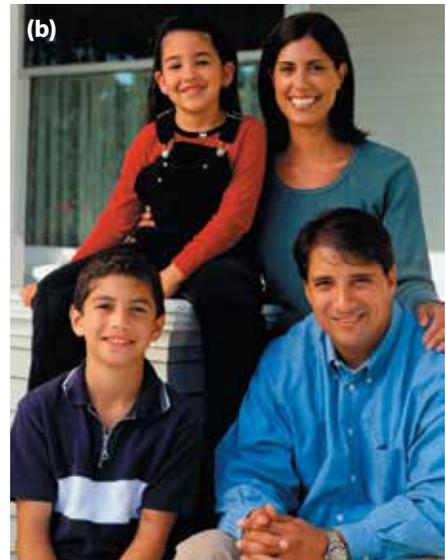
## Changes in family size

A ship called *Bee* arrived in the port of Geelong on 18 April 1857 after a 4-month journey from England. Among the 459 passengers, mainly assisted migrants, was a young married couple, James and Sarah Minter.

Earlier in England, in May 1852, James, then 22, and Sarah, then 17, married. At first they lived in the south Yorkshire town of Barnsley where James worked as a handloom linen weaver. Their first child was born in June 1853 but died from pneumonia about a year later. Within a month of the death of the first baby, Sarah was again pregnant. Their second child was born in May 1855 but died 9 months later in March 1856. Five months later, Sarah was again pregnant and during that pregnancy, she and her husband emigrated to Australia.

Soon after arriving on the *Bee* at the port of Geelong, Sarah gave birth to her third child in May 1857. The couple then moved to Ballarat where their fourth child was born in April 1859. Their fifth and sixth children were born near Maldon in April 1861 and in April 1863, but the sixth baby died aged 10 months. The family — the couple and three surviving children — then moved to Sandhurst (now Bendigo) where they lived at first in a tent on land off Sheepwash Road and later in a house at the same location. Their next five children (seventh to eleventh) were born in Sandhurst with birth dates as follows: January 1865, May 1867, April 1869, April 1871 and February 1873. Apart from the eleventh baby, which was stillborn, these babies survived beyond infancy. James and Sarah's twelfth baby, Emma, was born on 24 April 1874 at Sandhurst. Two days after the birth of this baby, Sarah, aged 40, died from childbirth (puerperal) fever. She was buried at White Hills Cemetery in Bendigo on 26 April 1874. Seven days later, baby Emma died and was buried in the same plot.

In terms of family size, intervals between births and infant mortality, this story of settlers living in country regions of Australia at that time is not unusual. An example of the change in average family size is shown in figure 11.2 with formal photographs for (a) a nineteenth-century family and (b) a twenty-first-century family.



**FIGURE 11.2** Changes in average family sizes. Formal family portraits taken (a) in the mid to late 1800s and (b) around 2005. The late nineteenth-century portrait shows two parents and their 11 surviving children. Contrast this with the twenty-first-century portrait that shows two parents with their two children.

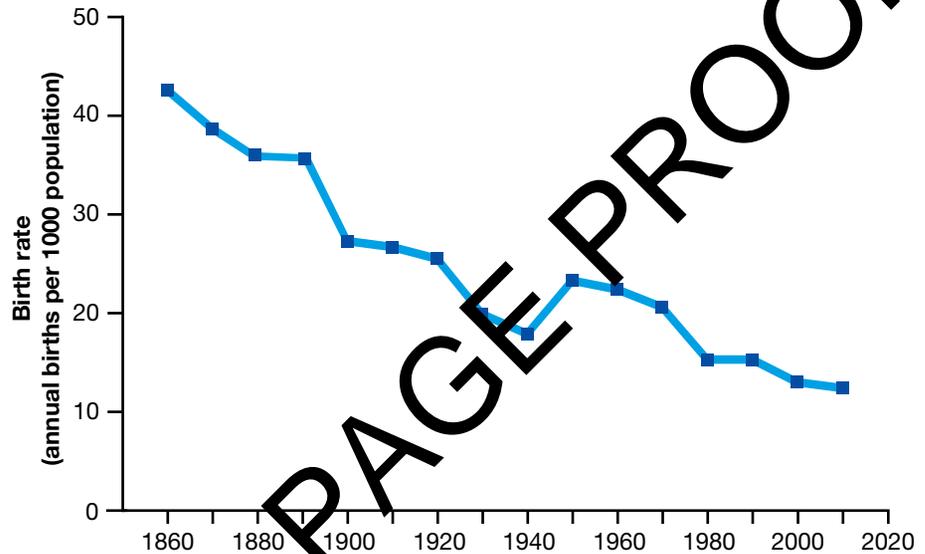
The interval between successive births for Sarah Minter was usually about 24 months. The shortest interval was 14 months between the stillbirth (eleventh) and the twelfth baby, Emma. This occurred because breastfeeding did not take place after the stillbirth. Breastfeeding prevents a woman from becoming pregnant by changing her hormone production to hormones concerned with

### ODD FACT

One study has shown that if women breastfeed their babies five times per day for a total of at least 65 minutes, their ovarian activity is suppressed so that they are infertile.

the production and release of milk and suppressing those hormones concerned with ovulation. If no breastfeeding occurs, or after a breastfed baby is weaned, hormone production changes to that for a normal ovarian cycle and fertility is restored.

In the period from 1860 into the twentieth century and then into the twenty-first century, a decline in the average family size has occurred in Australia. Figure 11.3 shows crude birth rates, expressed as the annual number of births per 1000 population, for that period. These birth rates signal that family sizes were much larger in 1860 than in 2000.



**FIGURE 11.3** Trends in the crude birth rate (annual births per 1000 population) in Australia for given years in the period 1860–2010 (using data from ABS Cat. 3105.65/01 Table 42). What factors have contributed to the overall decline in birth rates?

### ODD FACT

In 2011 in Australia, the median age for women at their first marriage was 28 years, while that for men was 29.7 years. In 2010, the median age of women giving birth to their first baby was 28 years.

Likewise, the decline in average household size from 1911 to 2011 also signals a reduction in average family size. In 1911, the average household size was 4.3 persons; in 1961, the average household size had declined to 3.6, and in 2011 it was 2.6. (Source: [www.aifs.gov.au/institute/info/charts/households/index.html#havsiz](http://www.aifs.gov.au/institute/info/charts/households/index.html#havsiz).)

Factors contributing to the decrease in birth rate include the approval in 1961 of the oral contraceptive pill for use in Australia, and the later average age of marrying and starting families. The oral contraceptive pill was not the first contraceptive. The diaphragm was introduced into Australia in the 1920s. Earlier contraceptive practices identified in the 1904 report of the *Royal Commission into the Decline in Birth Rate in New South Wales* were the use of douches, sponges, condoms, pessaries and withdrawal.

Human reproduction, as for that of familiar animals and plants around us, involves the genetic contribution of two parents to each of their offspring. This is the process of sexual reproduction.

### ODD FACT

In Australia in the mid-eighteenth century, the infant mortality rate was 125 deaths per 1000 births. In 2014, the rate was 4.4 deaths per 1000 live births.

## Sexual reproduction

One of the characteristics of all living organisms is their ability to reproduce according to genetic instructions within the organisms themselves. In chapter 10, we explored the world of asexual reproduction, as seen in prokaryotes and some eukaryotes. Now, let us explore aspects of the world of sexual reproduction, with a focus on animals, in particular mammals.

**study on**

Unit 2

**Gamete production**

AOS 1

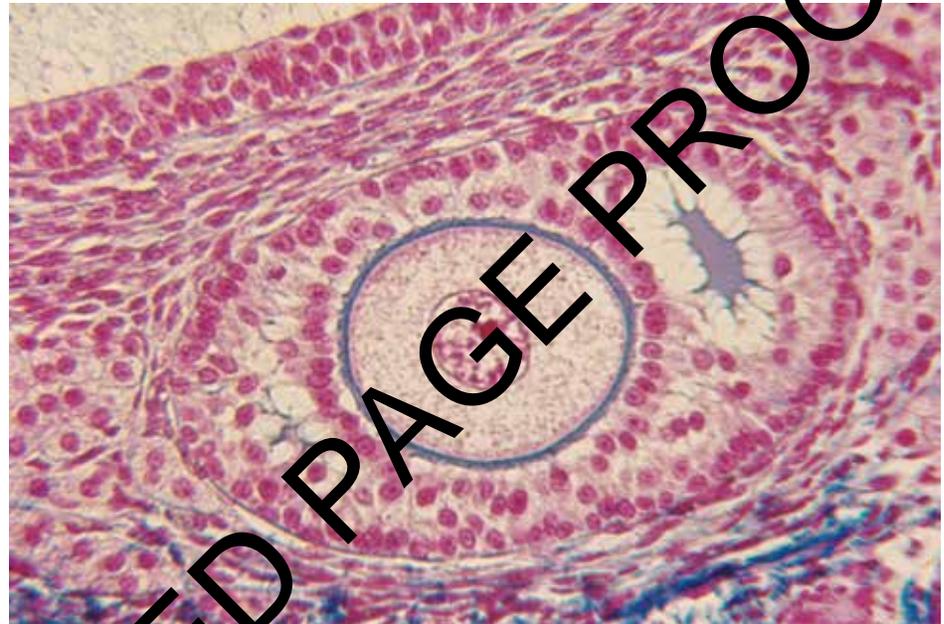
Concept summary and practice questions

Topic 3

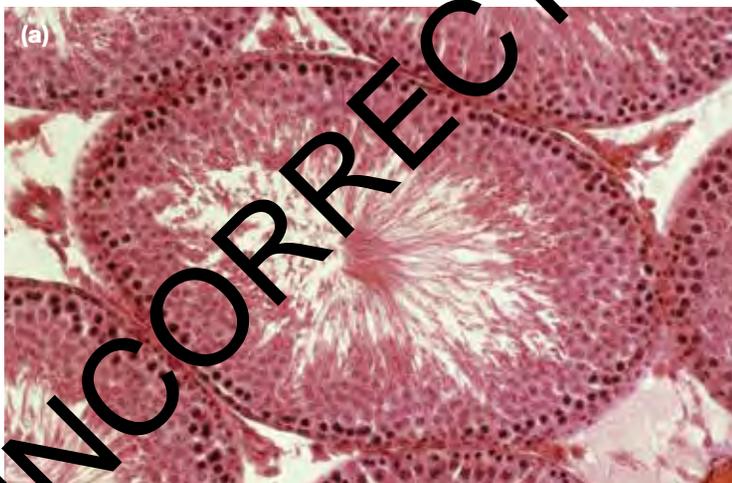
Concept 1

## Two parental contributions

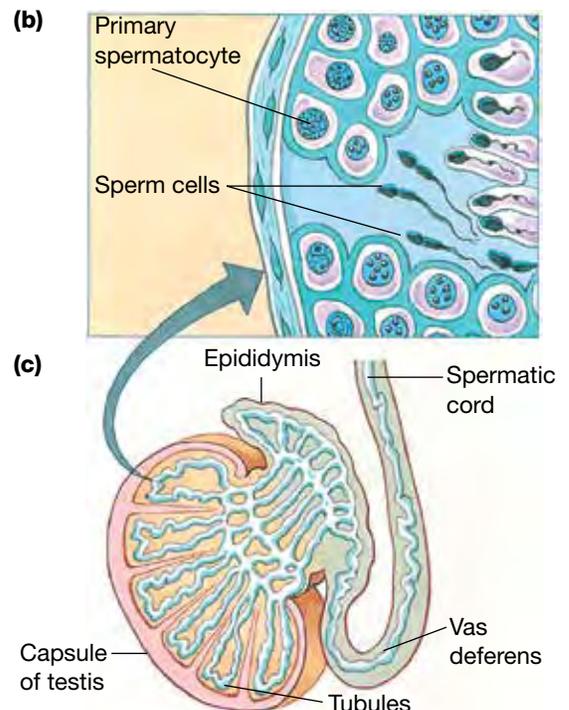
**Sexual reproduction** involves genetic contributions, in the form of **gametes**, from two parental sources to their offspring. In animals, gametes are the **eggs** produced by female parents and the **sperm** produced by male parents. Gametes are produced in specialised reproductive organs, known as **gonads**. In females, the gonads are the **ovaries** (see figure 11.4) and in males, the gonads are the **testes** (see figure 11.5). The cells in the gonads that give rise to the gametes are termed **germ cells**.



**FIGURE 11.4** Photomicrograph of a section through a human ovary, showing a prominent egg cell (oocyte) enclosed within a follicle (with a blue border). The empty structure to the right of the egg-containing follicle is a follicle that has previously discharged its egg. It now forms a structure known as a corpus luteum (*corpus* = body; *luteum* = yellow).



**FIGURE 11.5 (a)** Photomicrograph of a section through a mammalian testis. The mature sperm are located most centrally inside the tubules of the testis. **(b)** Diagram of a longitudinal section through a mammalian testis showing the folded tubules in which sperm are formed **(c)** Diagram of a cross-section through a tubule showing the primary spermatocytes that undergo reduction division (meiosis) to form sperm



## ODD FACT

In general, hermaphrodites cross-fertilise. However, isolated virgin individual organisms of some species can self-fertilise.



**FIGURE 11.6** Some animals can change their sex during their lifetime. They are called sequential hermaphrodites.

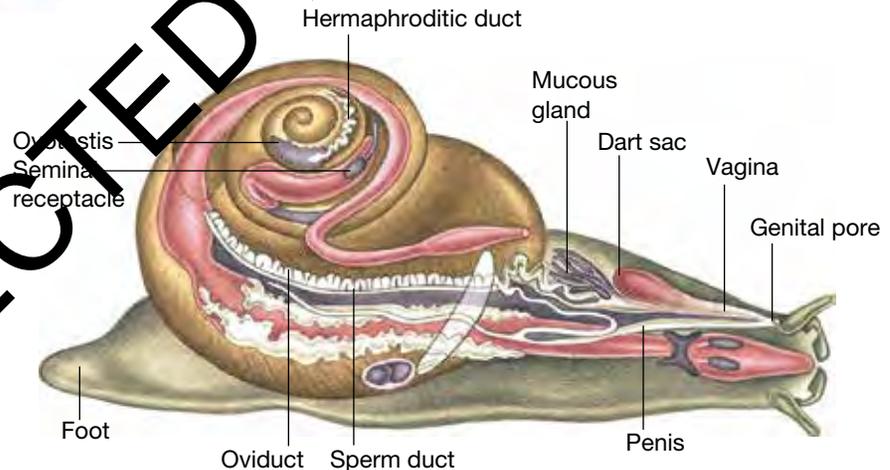
Typically, in people and in familiar animals, such as domestic pets and farm animals, two different sexes — females and males — produce the different gametes, with males producing sperm and females producing eggs. However, this is not the case in many other kinds of animal (see pp. 454–6) and it is rarely the case in flowering plants.

## Just which sex are you?

In some animal species, a single organism has both egg-producing and sperm-producing organs. These organisms are termed **hermaphrodites** (see figure 11.6) and include the garden snail (*Helix aspersa*) (see figure 11.7) and the common earthworm (*Lumbricus terrestris*).

The common earthworm has about 100 body segments, with ovaries in segment 13 and testes in segments 10 and 11 (counting from the head). Sperm released through pores in segment 15 are exchanged between a mating pair of earthworms. They store the sperm in sacs in segments 9 and 10 prior to using them to fertilise their eggs, which are then released through pores in segment 14.

When both sperm-producing and egg-producing organs are present in one organism, such as occurs in snails and earthworms, this is called **simultaneous (synchronous) hermaphroditism**. In contrast, some fish species found around coral reefs change sex and are known as **sequential hermaphrodites**. These fish start life as one sex and can transform to the other sex under certain conditions. Examples of sequential hermaphrodite organisms include various species of anemonefish (*Amphiprion* spp.) that live in groups of several males with one dominant female. If the dominant female fish dies or is removed, one large male fish then changes to become a functioning female.



**FIGURE 11.7** Internal anatomy of the garden snail. Note the presence of an organ labelled 'ovotestis' that produces both eggs and sperm.

## Chromosome number stays constant

**Chromosomes** are the carriers of genetic information. Each eukaryotic species has a characteristic number of chromosomes in its body or **somatic cells**. This number is called the **diploid number** and is denoted by the symbol  $2n$ . For the human species, the number of chromosomes in somatic cells is 46, so, for a person, we can write:  $2n = 46$ . Each other species has its own characteristic diploid number. The chromosomes in a diploid cell exist as matching or **homologous** pairs. So, in a diploid cell ( $2n = 12$ ), there are 6 matching or homologous pairs of chromosomes.

Chromosomes are examined in more detail in chapter 14.

**study on**

Unit 2

AOS 1

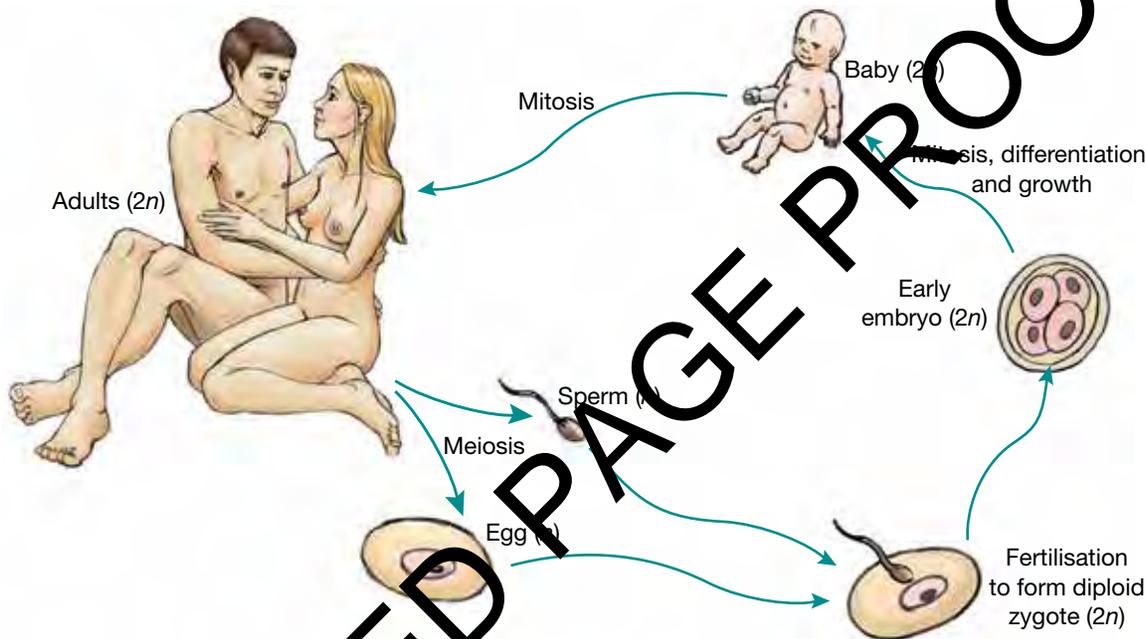
Topic 3

Concept 2

**Meiosis 1**

Concept summary and practice questions

In sexual reproduction, each parent makes an essentially equal genetic contribution to each of its offspring in the form of a gamete, that is, an egg and a sperm. If, in the case of people, these gametes each contained 46 chromosomes, this would mean that an offspring would have a total of  $46 + 46 = 92$  chromosomes. Over successive generations, this chromosome number would increase further. However, this doubling of the number of chromosomes does *not* occur across generations. **Each generation of human beings has a constant 46 chromosomes in their somatic cells.** In consequence, this means that each normal human gamete must have just 23 chromosomes, so that an offspring receives  $23 + 23 = 46$  chromosomes in total from its parents (see figure 11.8).



**FIGURE 11.8** The life cycle of the human species. In sexual reproduction, offspring result from the fusion of two parental contributions (one egg and one sperm). Note, that apart from the gametes that are haploid ( $n = 23$ ), the life cycle is otherwise diploid ( $2n = 46$ ).



**FIGURE 11.9** An egg cell with sperm cells adhering. Only one sperm will succeed in fertilising the egg. Both egg and sperm carry a haploid set of chromosomes.

So, while all normal somatic cells of people have 46 chromosomes, their gametes (either eggs or sperm) have just 23 chromosomes. This is called the **haploid number** and is denoted by the symbol,  $n$ . So, for people,  $n = 23$ . It is reasonable to conclude, then, that the process of gamete formation in a person involves a **reduction division** in which a starting cell with 46 chromosomes gives rise to gametes, either egg or sperm, that have only 23 chromosomes. This reduction division is a process called **meiosis**. The **fertilisation** of an egg by a sperm restores the diploid number (see figure 11.9).

We will see in the following section that meiosis is a non-conservative division in which the chromosome number is halved and, as we will see later, the genetic information on the chromosomes is juggled.

A key feature of sexual reproduction is that offspring produced through this mode of reproduction differ genetically from each other and also differ from their parents. In contrast, as we saw in chapter 10, asexual reproduction involves a cellular process called mitosis that is conservative, so it faithfully reproduces an exact copy of the genetic information of the single parent cell in the two daughter cells.

## KEY IDEAS

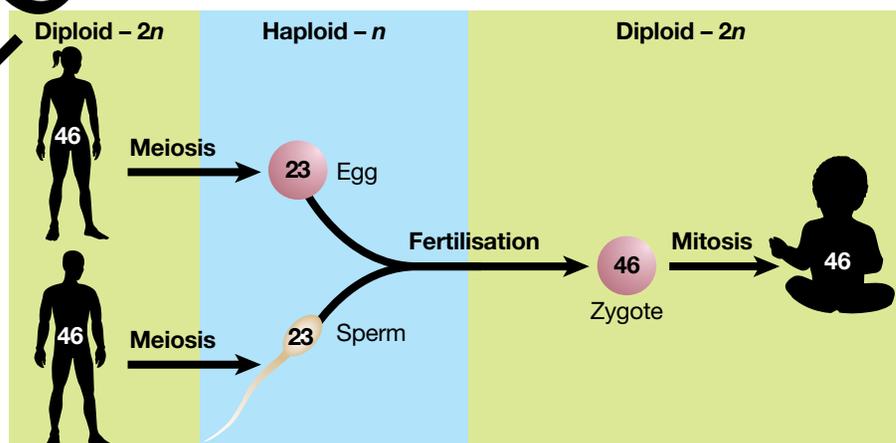
- In animals, offspring resulting from sexual reproduction receive two genetic contributions, one via an egg and the other via a sperm.
- Somatic (body) cells possess a diploid number of chromosomes.
- Mature gametes contain the haploid number of chromosomes.
- Eggs and sperm are gametes that are produced in the ovary and testis respectively.
- The chromosome number is restored to diploid when an egg is fertilised by a sperm.
- Meiosis is the process that produces haploid gametes from diploid germ cells.

## QUICK CHECK

- 1 What is the diploid number of the human species?
- 2 Identify whether each of the following statements is true or false.
  - a The diploid number refers to the number of chromosomes in somatic cells.
  - b A hermaphrodite has both egg-producing and sperm-producing organs.
  - c Meiosis is a conservative process of nuclear division.
  - d Offspring produced by sexual reproduction are genetically different from each other.
- 3 What is the name of each of the following?
  - a A male gamete
  - b The female reproductive organ
  - c The product of fusion of an egg and a sperm

## Meiosis: the halving and mixing machine

Meiosis is the process that produces gametes with the haploid number of chromosomes, that is, half the number present in somatic cells. After fertilisation, when the nucleus of a sperm fuses with that of an egg, the diploid number of chromosomes is restored (see figure 11.10).

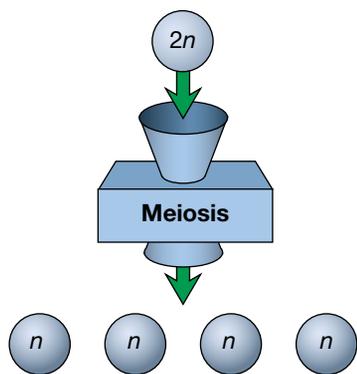


**FIGURE 11.10** Diploid animals produce haploid gametes that fuse at fertilisation to produce a diploid zygote.

First let us consider meiosis from the point of view of input and output only. What are some of the observations that have been made?

The *first observation* is that, if a cell containing  $2n$  chromosomes undergoes meiosis, four cells are produced each containing  $n$ , or half the number of chromosomes present in the original cell (see figure 11.11).

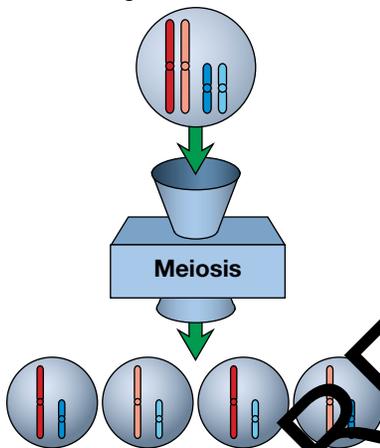
**Input:** 1 cell with  $2n$  chromosomes



**Output:** 4 cells, each with  $n$  chromosomes

**FIGURE 11.11** Meiosis halves the chromosome number. The four cells produced indicate that two cell divisions have occurred.

**Input:** 1 cell with 2 pairs of homologous chromosomes



**Output:** 4 cells with one member only of each pair of homologues

**FIGURE 11.12** The halving is precise—one member of each pair of chromosomes appears in the cell products.

This halving applies for all organisms in which meiosis occurs. Somatic cells of the brushtail possum (*Trichosurus vulpecula*) contain 20 chromosomes. Since meiosis results in halving the number of chromosomes, the gametes of this animal would contain 10 chromosomes.

The diploid number of *Eucalyptus* species is 22. Gametes produced by a *Eucalyptus* tree would contain half this number: 11 chromosomes.

The diploid number of the human species is 46. So, human gametes each contain 23 chromosomes.

The *second observation* is that each gamete produced by meiosis contains only one member of each pair of chromosomes (see figure 11.12).

From this observation we can conclude that the halving of the number of chromosomes is very precise. The members of each pair of chromosomes separate or disjoin into different gametes. In addition, the separation of the members of each pair of homologous (matching) chromosomes is independent of the separation of the members of another pair. This means that it is equally likely that, in another gamete, the long red chromosome would be present with the short blue chromosome.

The *third observation* is that during meiosis, exchanges of segments between matching chromosomes occur. This results in the creation of some new genetic combinations that differ from those in the starting cell (see figure 11.13). This process of exchange between matching chromosomes is called **crossing over**.

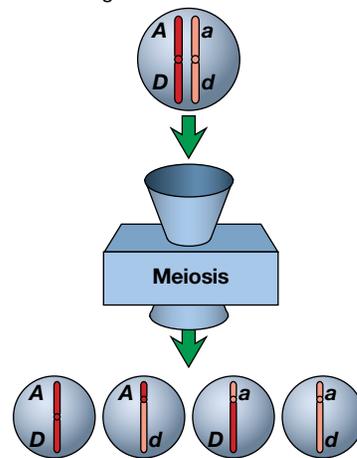
In summary, the key outcomes of meiosis are as follows:

- Meiosis halves the chromosome number, reducing it from diploid to haploid; as a result, each gamete contains just one member of each matching pair of chromosomes.
- Meiosis produces random combinations of the members of the different matching chromosome pairs. As a result, in a large number of gametes, any member of one matching pair of chromosomes can be found with any member of another matching pair.

Meiosis involves exchanges of part of one chromosome with the corresponding part of its matching partner, a process termed crossing over. As a result, meiosis produces gametes containing chromosomes with new genetic combinations that differ from each other and from those in the precursor cell.

Figure 11.14 shows various stages of meiosis, how this process halves the number of chromosomes and how crossing over changes the particular genetic information that the chromosomes carry. Cell 1 in this figure shows the diploid cell that will undergo meiosis. This cell will first pass through an **interphase** stage during which the DNA of its chromosomes is replicated and checkpoints are passed. Cell 3 shows a cell during **prophase 1** of meiosis. Its chromosomes are visibly double stranded, with each chromosome consisting of two sister chromatids joined at their centromeres. During this stage, the matching chromosomes pair (**synapse**) and crossing over occurs, with a mutual exchange of segments between matching chromosomes. By the end of prophase 1, the nuclear envelope has broken down.

**Input:** 1 cell with 1 pair of homologous chromosomes with 2 linked genes

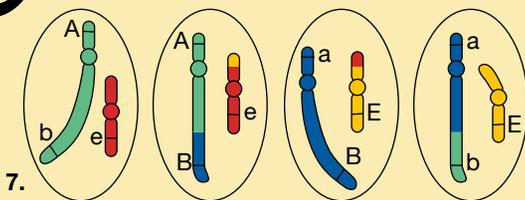
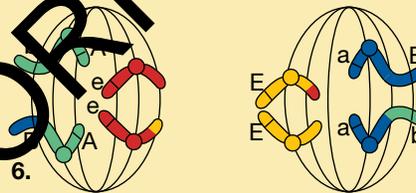
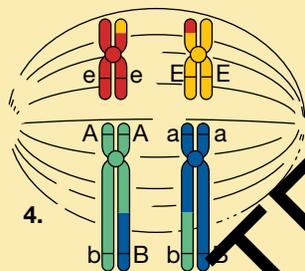
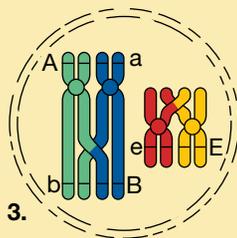
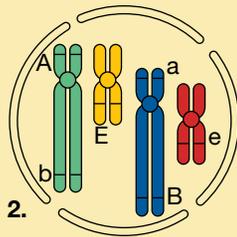
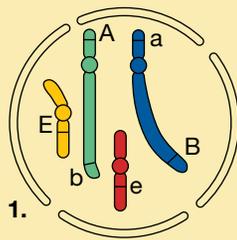


**Output:** 4 cells, some with 'splicing' of homologous chromosomes to create some new gene combinations

**FIGURE 11.13** During meiosis, exchanges of segments between matching chromosomes can occur in a process known as crossing over.

**Stages shown are:**

- 1 Cell before meiosis
- 2 Cell at end of interphase
- 3 Cell at prophase 1
- 4 Metaphase 1 moving into anaphase 1
- 5 Telophase 1 moving into prophase 2
- 6 Anaphase 2
- 7 Telophase 2



1. Starting point: cell with two pairs of single-stranded homologous chromosomes ( $2n = 4$ ).

2. By the end of interphase, the chromosomes have replicated and now appear double-stranded.

3. The homologous chromosomes align and pair closely or synapse. One or more exchanges or crossovers occur between a matching segment of one chromosome with a strand in its paired homologue. Crossing over produces new combinations of genetic instructions. The chromosomes then line up across the equator of the cell. Different arrangements are possible.

4. The homologous chromosomes separate (disjoin) from each other when their centromeres are pulled to opposite poles. The disjunction of each homologous pair is independent of any others. (For example, if the 'red' chromosome goes to the left-hand side, this in no way influences which of the longer chromosomes will go to the right-hand side.)

5. The resulting two products each have two double-stranded chromosomes, one long and one short.

6. The strands of each replicated chromosome then disjoin so that the single-stranded chromosomes move in opposite directions. The separation of the single-stranded copies of each chromosome is independent of that of other chromosomes.

7. End point: typically, four cells result from meiosis with each end product containing the haploid number of chromosomes. Having started from one cell ( $2n = 4$ ), the process has produced four cells, each with  $n = 2$ . Note the variation between end products resulting from crossing over and independent disjunction of homologous pairs.

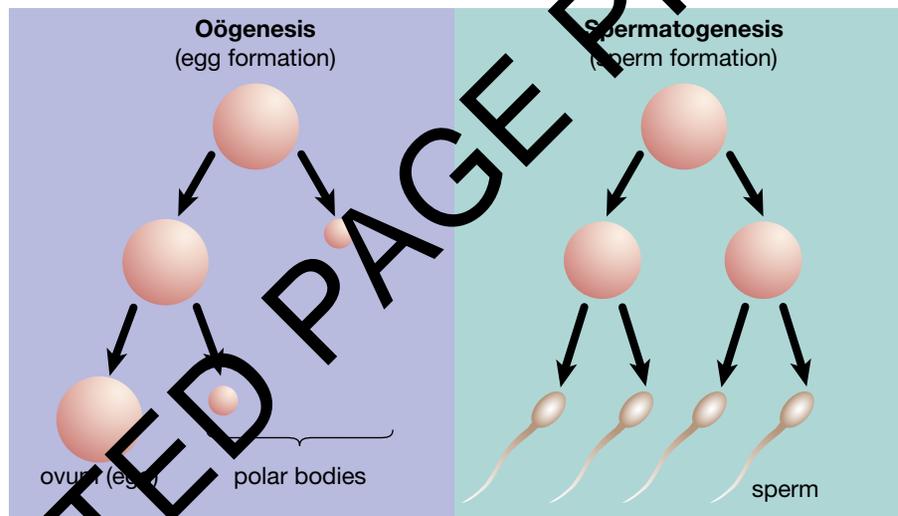
**FIGURE 11.14** Stages in the process of meiosis, from the starting diploid cell ( $2n = 4$ ) to the final haploid gametes ( $n = 2$ )

Just as in mitosis, the microtubules of the spindle are responsible for the arrangement and the movement of the chromosomes during the **metaphase** and **anaphase** stages of meiosis.

Note that two cells present at **telophase** 1 of meiosis are not genetically identical to each other. The two events in meiosis that create the genetic diversity of gametes are:

- crossing over, that is the mutual exchange of chromosomal segments between members of homologous pairs of chromosomes during prophase 1 of meiosis
- independent assortment of nonmatching (**nonhomologous**) chromosomes at anaphase.

The division of a diploid germ cell by meiosis typically produces four cells that are haploid and are genetically varied. In male mammals, the products of meiosis of one diploid germ cell in the testis are four functional sperm. In female mammals, however, the meiotic division of one diploid germ cell in the ovary produces just one functional egg. The other products are small polar bodies (see figure 11.15).



**FIGURE 11.15** The formation of eggs and sperm by meiosis. Note that only one egg is formed but four sperm are produced from each starting cell.

## Meiosis: source of variability in offspring

The biological significance of meiosis is that it produces genetic variability among the offspring produced by sexual reproduction involving gametes from two parents. No two offspring are the same!

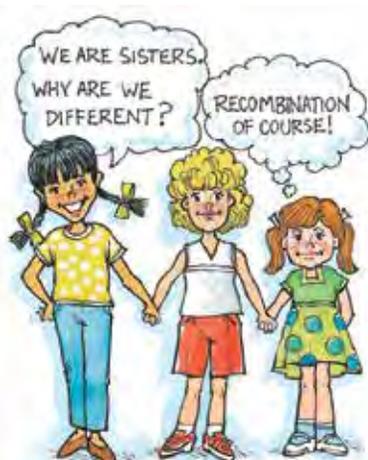
A litter of pups may consist of an odd mixture of colours and patterns (see figure 11.16 and refer to figure 11.1). A litter of piglets shows the variation that is generated by meiosis (see figure 11.17). Siblings (brothers and sisters) in a human family can show differences in hair colour, eye colour, blood types and other traits. Inherited differences between offspring can be traced back to the process of meiosis and to the genetic variation that it produces in gametes.



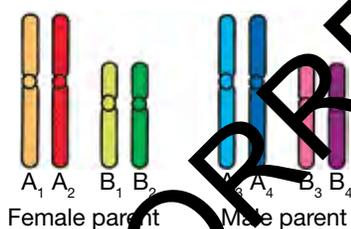
**FIGURE 11.16** Pups from two parents show variation in colour and pattern.



**FIGURE 11.17** This litter of piglets shows genetic variation in coat colour that is the result of meiosis. These piglets differ genetically from each other and from their two parents because they are products of sexual reproduction.



**FIGURE 11.18**



**FIGURE 11.19** Matching chromosomes in an organism. The matching pairs are colour coded.

**study on**

Unit 2

AOS 1

Topic 3

Concept 3

**Meiosis II**

Concept summary and practice questions

Table 11.1 shows a brief summary of some similarities and differences between the processes of mitosis and meiosis in animals.

**TABLE 11.1** Similarities and differences between mitosis and meiosis in animals

Feature	Meiosis	Mitosis
location	occurs only in germ cells of either ovary or testis	occurs in body cells
function	production of gametes, eggs and sperm	growth, by an increase in cell number, and repair
DNA replication in interphase	yes	yes
number of divisions	two	one
pairing of matching chromosomes (synapsis)	yes	no
crossing over occurs	yes	no
end result	four haploid gametes, none being identical to each other	two daughter cells, identical to each other and to the single parent cell

**Recombination produces variation**

Gametes carry unique genetic combinations because of:

1. crossing over between homologous (matching) chromosomes
2. independent disjoining (separation) of nonmatching chromosomes during meiosis.

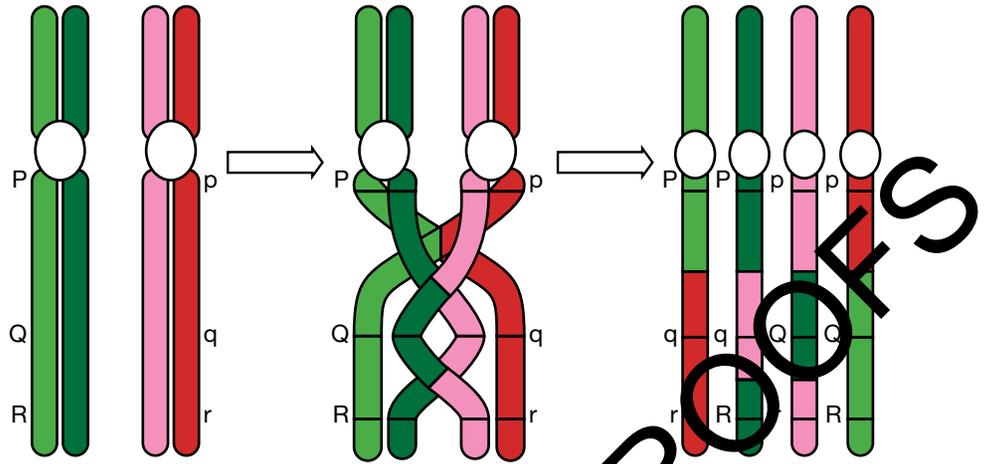
This re-assortment of genetic material from both crossing over and disjoining that produces new genetic combinations is known as **recombination** and is a major cause of variation in offspring of the same parents (see figure 11.18).

We can get some idea of the variation produced by sexual reproduction if we consider organisms with just two pairs of chromosomes ( $2n = 4$ ) (see figure 11.19). Ignoring crossing over, the female parent can produce gametes with four different combinations of chromosomes:  $A_1B_1$  and  $A_1B_2$  and  $A_2B_1$  and  $A_2B_2$ . Likewise, the male parent can produce four combinations:  $A_3B_3$ ,  $A_3B_4$ ,  $A_4B_3$  and  $A_4B_4$ . Consequently, the chance that two offspring receive the same chromosomal combinations from their two parents is  $\frac{1}{4} \times \frac{1}{4} = \frac{1}{16}$ . The probability that two offspring receive different chromosomal combinations from their parents is  $\frac{15}{16}$ .

Table 11.2 shows how the variation in sexually reproducing species increases with increasing numbers of chromosomes, even without the added impact of crossing over. Notice that as the number of chromosomes increases the chance that two offspring will receive the same complement of chromosomes from their parents becomes infinitesimal. For organisms with a diploid number of 20 ( $2n = 20$ ) that chance decreases to just one in more than one million. Given that the diploid number in the human species is 46, the chance that offspring from the same parent will receive the same chromosomes from their parents is less than one in about 70 million. So, unless you have an identical twin, the process of meiosis has made you a genetically unique individual.

If we were to take crossing over into consideration, the chance of two offspring inheriting the same chromosomes from their parents becomes impossibly small even with a small number of chromosomes. Figure 11.20 shows how crossing over further recombines the homologous chromosomes transmitted by the parents. The chromosomes at the left-hand side show the two chromosomes as passed on by a person's female parent and male parent. Note that crossing over recombines the homologous chromosomes so that the output cells or gametes will carry a different combination of genetic information from the input germ cell.

**FIGURE 11.20** Diagram showing one pair of homologous replicated chromosomes (left) at the interphase of meiosis. Note the genetic information that they carry. On the right it can be seen how this genetic information is recombined as a result of the exchange of segments when crossing over occurs during prophase 1 of meiosis.



The process of meiosis also generates a similar genetic diversity in all other eukaryotic organisms that reproduce sexually. Meiosis is the major contributor to genetic biodiversity in populations on planet Earth.

**TABLE 11.2** Probabilities of two offspring receiving identical or dissimilar chromosomal combinations from parents. What happens as  $2n$  increases? (If crossing over is included, the chances of identical combinations are much, much lower.)

Diploid number of chromosomes	Chance of receiving identical chromosomal combinations	Chance of receiving different chromosomal combinations
$2n = 4$	1/16	15/16
6	1/64	63/64
8	1/256	255/256
10	1/1024	1023/1024

**study on**

- Unit 2 **Nondisjunction in meiosis**
- AOS 1 Concept summary and practice questions
- Topic 3
- Concept 4

**When meiosis goes wrong**

Occasionally, a pair of chromosomes fails to disjoin or separate at anaphase so that either two copies of a chromosome, rather than the usual one, are present in a gamete or a copy of one chromosome is missing. This event is termed **nondisjunction**, and it is an unpredictable error. Nondisjunction can occur at either step 4 or 6 of meiosis (refer to figure 11.14). This issue will be further discussed in chapter 14.

**Advantages and disadvantages of sexual reproduction**

The advantage of sexual reproduction comes from the genetic diversity that it creates in offspring. In contrast to a population generated by asexual reproduction that is composed of genetically identical organisms, a population of organisms produced by sexual reproduction contains a remarkable level of genetic diversity. The presence of this variation within its gene pool means that such a population is better equipped to survive in changing, unstable environmental conditions, to cope with an outbreak of a new viral or bacterial disease, or to survive a natural disaster.

Disadvantages of sexual reproduction (relative to asexual reproduction) include the commitment of energy required to find, attract and secure a mate — a process that for some species may involve elaborate courtship displays, or contests between males for mating rights. However, the sexual mode of reproduction dominates the world of eukaryotic organisms, indicating that its advantages outweigh its combined disadvantages. In the next section, we will explore some of these energy costs of sexual reproduction.

**study on**

- Unit 2 **Biological advantages of sexual reproduction**
- AOS 1 Concept summary and practice questions
- Topic 3
- Concept 5

## KEY IDEAS

- Meiosis is the process that produces haploid gametes from a diploid germ cell.
- Genetic variation in gametes results from crossing over and from independent assortment of nonmatching chromosomes.
- Crossing over and independent assortment contribute to the recombination of genetic information in gametes.
- The major advantage of sexual reproduction arises from the genetic diversity that it produces in populations of sexually reproducing organisms.
- Nondisjunction errors can occur during meiosis.
- Apart from persons with an identical twin, every human individual is genetically unique.

## QUICK CHECK

- 4 Identify whether each of the following statements is true or false.
  - a Meiosis in one organism would be expected to generate four different kinds of gamete.
  - b Crossing over is a major contributor to the recombination of genetic information in gametes.
  - c The major advantage of sexual reproduction is the genetic diversity that it creates.
  - d DNA replication does not occur in meiosis.
  - e In meiosis, independent assortment of nonmatching (nonhomologous) chromosomes occurs twice.
- 5 The mating of two animals with a diploid number of  $2n = 20$  produces a litter of 10 offspring. Is it reasonable to assume that at least two of these offspring will be genetically identical? Briefly explain.

## Getting gametes together

### ODD FACT

Tapeworms that live in the gut of an animal are hermaphrodites that self-fertilise.

### ODD FACT

Mass release of gametes by coral polyps (or spawning) on the Great Barrier Reef occurs every year after the full moon in October and November. For coral polyps on the Ningaloo Reef off the Western Australian coast, this mass spawning occurs after the full moon in March.

In sexual reproduction, two parental contributions (egg and sperm/pollen) fuse to produce a zygote that then develops into an animal or a plant. Even in the case of hermaphrodite animals, the gametes typically come from two separate animals, rather than self-fertilisation occurring.

Some animals release their gametes into the external environment so that fertilisation occurs outside the body of females. This situation is termed **external fertilisation**. This has the energy cost of producing large numbers of gametes in order to increase the chance of fertilisation.

In other species of animal, males deliver sperm directly into the reproductive tract of females so that fertilisation of eggs occurs inside the body of females. This situation is termed **internal fertilisation**. This process has the energy cost of finding, attracting and securing a female mate.

### External fertilisation in animals

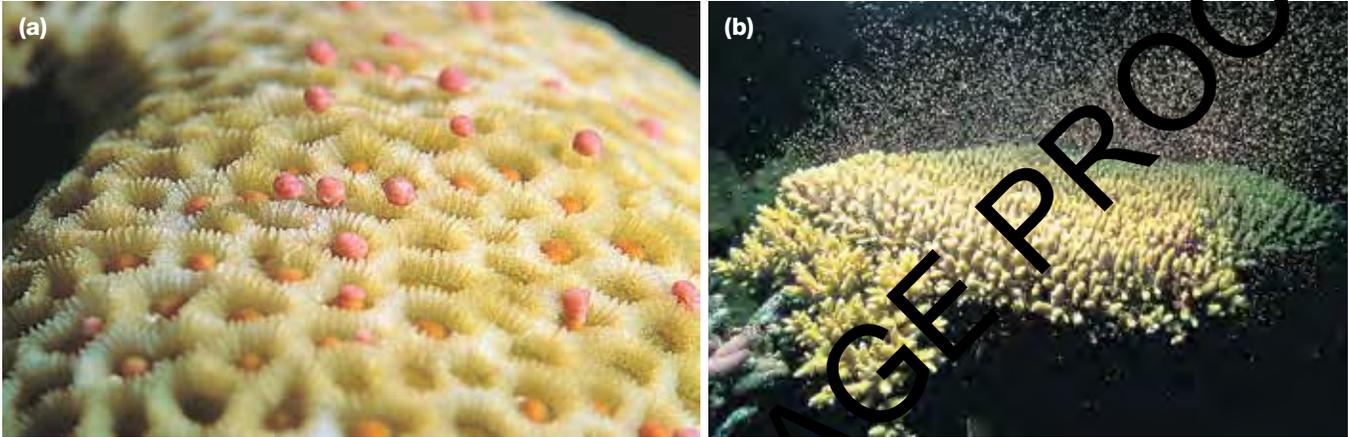
When animals use external fertilisation, they produce very large numbers of gametes. These large numbers increase the chance of fertilisation but also mean much gamete wastage. Aquatic species that live in large bodies of water and depend on external fertilisation produce very large numbers of gametes. Oysters, for example, each produce about 500 million eggs in a single season.

Because sperm need a watery environment to swim to an egg, external fertilisation is limited to animals that either live in aquatic environments or reproduce in a watery environment. External fertilisation occurs in aquatic invertebrates such as coral polyps, bony fish and amphibians (frogs and toads).

External fertilisation can be a chancy process. Some species that use external fertilisation have developed strategies to increase the chance that eggs and sperm will meet and that fertilisation will occur.

#### All together now

Figure 11.21a shows the release of eggs by a colony of coral polyps, the animals that build coral reefs. All the polyps in one region release their eggs and sperm into the sea in a synchronised manner, creating a 'soup' of gametes (see figure 11.21b). The high concentration of gametes during spawning increases the likelihood of eggs and sperm colliding and fertilisation occurring.



**FIGURE 11.21** (a) Close-up of the release of gametes by a group of colonial animals known as coral polyps (b) Mass spawning of eggs and sperm bundles by coral polyps occurs at the same time (synchronously) each year. What benefit results from this synchrony?

#### ODD FACT

In one Australian frog species, fertilised eggs are swallowed by females and develop in their stomachs. They are regurgitated later as tiny froglets. In another Australian frog species, after fertilisation the eggs are transferred into moist pouches on the hips of the male of the species where embryonic development occurs.

#### Just checking you out

Fish depend on external fertilisation. If a female fish releases her eggs independently of the release of sperm by a male fish of the same species, then the chance of fertilisation of her eggs is extremely low or even nil.

Behaviours such as courtships before spawning can lead to an improved chance of fertilisation. Through a courtship display, a female can recognise that a male is a member of her species and, if she is ready to release her eggs, this occurs in close proximity to a male. In turn, he will release sperm nearby so that the likelihood of fertilisation is increased. Again, courtship has an energy cost.

#### Hang on there

Frogs and toads have external fertilisation. The chance of fertilisation is increased by a behavioural adaptation of males. When a female frog is ready to



lay eggs she goes into a nearby pond or pool. A male tightly clasps her and remains on her back until she releases her eggs (see figure 11.22). As the female releases her eggs, the male is stimulated to release sperm over the eggs, fertilising them. The fertilised eggs then undergo embryonic development and give rise to larvae, known as tadpoles, that later metamorphose to frogs.

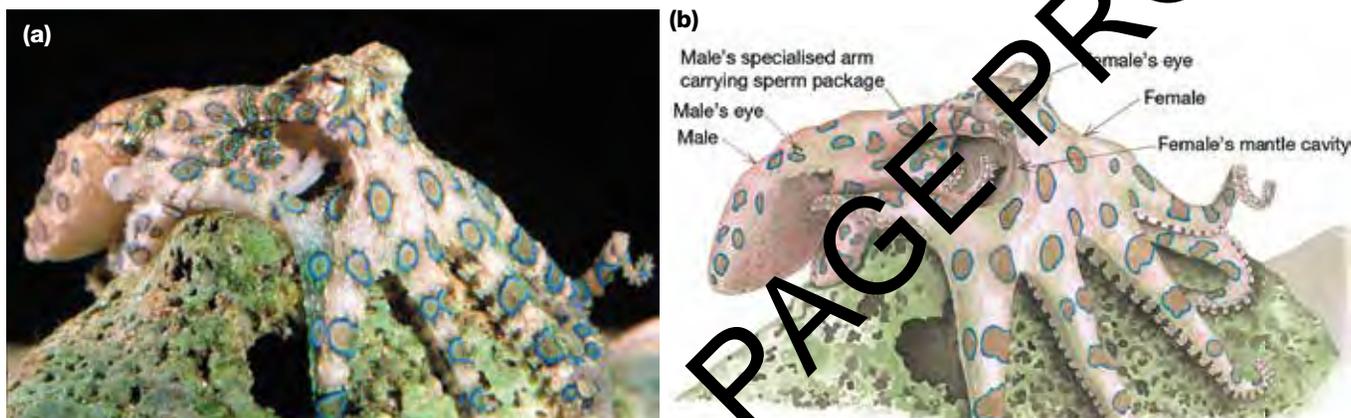
**FIGURE 11.22** Ornate burrowing frogs (*Limnodynastes ornatus*). The male is clasping the female tightly and when the female releases her eggs into the water, the male releases sperm over the eggs. The eggs are suspended on a raft of bubbles.

### Internal fertilisation in animals

The watery environment in which aquatic animals live enables external fertilisation because it provides an environment in which eggs are protected from drying out and in which gametes can move to meet. However, **with internal fertilisation, the chance of gametes meeting is greater** and hence the chance of fertilisation is increased. So, it is not surprising that internal fertilisation occurs in some aquatic organisms.

### Marine animals

Octopuses have internal fertilisation. In the male octopus, one of his eight arms is shorter than the other arms. This arm is specialised for the direct transfer of a parcel of sperm to a female. Figure 11.23 shows a male octopus that has mounted a female and inserted his specialised arm into her mantle cavity where he will deposit a package of sperm.



**FIGURE 11.23** (a) Smaller male blue-ring octopus (*Haplochromis lunulata*) transferring a sperm package into the mantle cavity of a larger female (b) Diagram showing the smaller male blue-ring octopus (at left) inserting his specialised arm carrying a sperm package into the mantle cavity of the larger female octopus (at right)

In sharks, the male of the species has claspers that are appendages of his pectoral fins (see figure 11.24). The male shark inserts his claspers into the vagina of a female and forces his sperm inside her carried by water pressure that he generates.

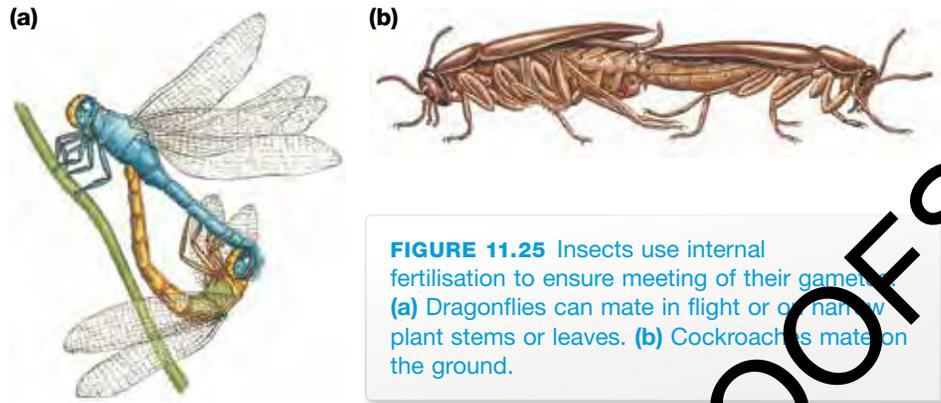
**FIGURE 11.24** Ventral (belly) view of a male shark showing its two claspers. Claspers are a modification of the shark's pelvic fins. During mating, the male shark uses one of his claspers to deposit sperm in the genital duct of a female shark via her cloaca.



### Terrestrial animals

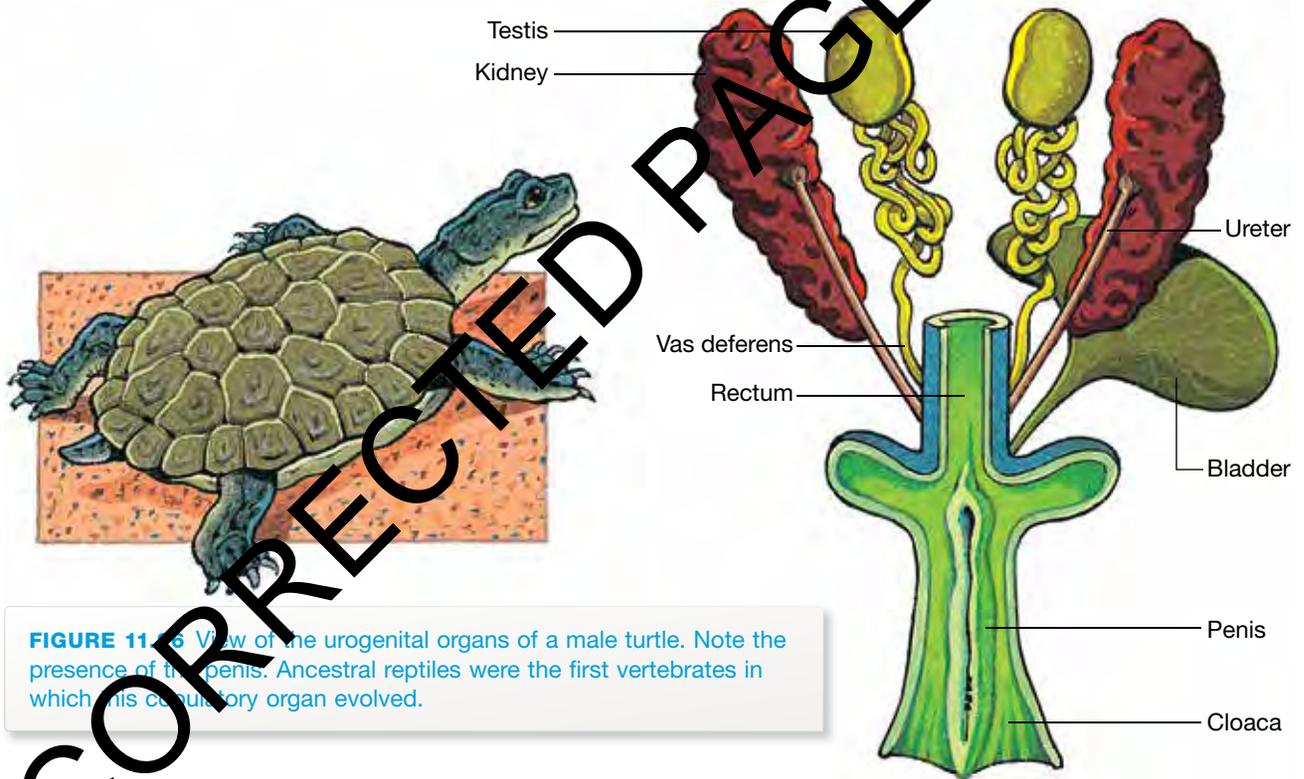
Except for amphibians, such as frogs and toads that return to water to get their gametes together, other terrestrial animals have internal fertilisation. We will briefly explore internal fertilisation in some terrestrial animals.

*Insects.* **Internal fertilisation occurs in insects.** Complex genital structures at the end of the abdomen of a male insect enable him to couple with a female and transfer sperm packages into her reproductive tract. Some insects, such as dragonflies, mate on the wing but most insects keep their feet (all 12 in a mating couple) on the ground (see figure 11.25).



**FIGURE 11.25** Insects use internal fertilisation to ensure meeting of their gametes. **(a)** Dragonflies can mate in flight or on narrow plant stems or leaves. **(b)** Cockroaches mate on the ground.

*Reptiles.* Ancestral reptiles were the first vertebrates to evolve a male copulatory organ, the penis (see figure 11.26). The presence of a penis enabled reptiles to transfer sperm directly into the reproductive tract of a female. Apart from sharks, reptiles were the first vertebrates that did not need to release their gametes into water for fertilisation to occur. Internal fertilisation freed the ancestral terrestrial reptiles and their descendants from the need to return to water for reproduction.



**FIGURE 11.26** View of the urogenital organs of a male turtle. Note the presence of the penis. Ancestral reptiles were the first vertebrates in which this copulatory organ evolved.

For internal fertilisation, female animals produce a small number of eggs (or even a single egg) in each reproductive cycle. Less gamete wastage occurs and the chance of fertilisation for a given egg is quite high.

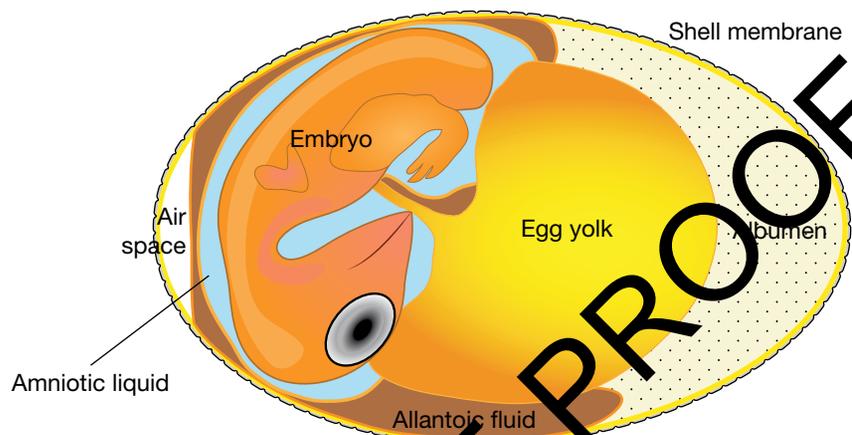
Another important evolutionary change in ancestral reptiles was the appearance of an egg with a protective outer shell, a series of internal membranes and a food supply for the developing embryo. This type of egg is a self-contained aquatic environment in which embryonic development occurs even when the egg is laid on land and is called an amniotic egg (see figure 11.27).

*Birds.* Birds also have internal fertilisation but male birds lack a penis. Instead, sperm transfer takes place through close contact of the urogenital

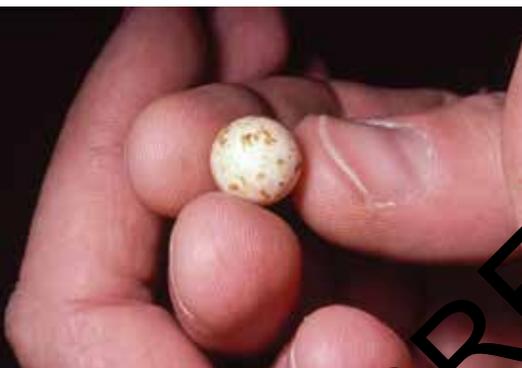


**FIGURE 11.27** Amniotic eggs of reptiles, in this case those of a snake, enable reptiles to reproduce on dry land without the dependence on the presence of free water (as exists for amphibians). Developing reptilian embryos are enclosed in self-contained leathery eggs that are impermeable to water. Having completed development, a snake is hatching from the egg.

openings (cloacae) of male and female birds. Like their reptilian ancestors, birds produce eggs in which their embryos develop (see figure 11.28). The production of a shell amniot occurs as the fertilised egg passes through the genital tract of a female bird to the cloaca from where the egg is laid.



**FIGURE 11.28** Simplified diagram showing a bird developing within an amniotic egg — a self-contained apartment. Note the watertight outer hard eggshell, the yolk and the albumen (egg white) that are sources of nutrients, the fluid within the amnion that prevents the embryo from drying out and the allantois, a sac in which waste products are stored as insoluble uric acid.



**FIGURE 11.29** Platypus egg

*Mammals.* Mammals have internal fertilisation.

- In monotreme mammals, such as the platypus and the echidna, the fertilised egg becomes enclosed within a shell and embryonic development occurs within the shelled egg (see figure 11.29).
- Female marsupials and placental mammals retain the fertilised eggs in their bodies and embryonic development proceeds within the uterus. Young marsupials are born at a very undeveloped stage. Young placental mammals are born at a much more developed stage.

#### KEY IDEAS

- Compared with asexual reproduction, sexual reproduction has a higher energy cost.
- In animals, fertilisation may be internal or external.
- Some species that use external fertilisation have developed strategies to increase the chance of fertilisation occurring.
- With internal fertilisation, there is a greater chance of gametes meeting and fertilisation occurring.
- The emergence of the amniotic egg allowed the first reptiles to colonise dry land.

#### QUICK CHECK

- Briefly explain why external fertilisation is far more common in aquatic animals than in terrestrial animals.
- Identify two energy costs of sexual reproduction that are not present in asexual reproduction.
- Identify one example of each of the following.
  - A marine animal that uses external fertilisation
  - A marine animal that uses internal fertilisation
  - A terrestrial animal that uses external fertilisation.

**Jan West and the test-tube puppies**

Jan West, a Senior Lecturer at Deakin University, tells the story of her test-tube puppies.

There are two breeds of corgi — the Pembroke Welsh corgi made famous by Queen Elizabeth II and the lesser known Cardigan Welsh corgi, which was bred to drive cattle across the hills of Wales. Cardigan Welsh corgis are now an endangered breed in Britain, their country of origin, and numbers are also declining in Australia. The small gene pool available locally makes breeding challenging because genetic diversity must be maintained to ensure healthy dogs.

How can the gene pool be increased? Dogs can be imported from other countries or frozen semen can be imported from suitable stud dogs. Frozen semen has several advantages; it increases the breeding life of males and, as animals do not move between countries, no quarantine is needed.

Meet the female Cardigan corgi Gem, born in England and imported to Australia in early 2010 with the long-term goal of increasing the Cardigan corgi gene pool in Australia. On arrival, Gem spent 30 days at the Spotswood quarantine station in Melbourne.

In 2011, Gem produced a litter of eight puppies conceived using frozen semen. The first step was a series of progesterone tests to identify when ovulation had occurred in Gem. Once this was known, a new technique, called transcervical insemination (TCI), was used by reproductive specialist Dr Stuart Mason to implant thawed semen in Gem's uterus. In TCI, a thin catheter fitted with a tiny camera is inserted into the reproductive tract, passing through the cervix into the uterus where the eggs are located. Semen is placed in the uterus where, within 6 to 12 hours, viable sperm can fertilise the eggs. In Gem's case, a total of eight eggs were fertilised. Previously the procedure to place semen in the uterus involved surgery. The advantage of TCI is that no surgery is required.

Just over a week after fertilisation, mitotic divisions increased the cell numbers, with each embryo consisting of a hollow ball of cells about 2 mm in diameter. Three weeks after fertilisation, the embryos, floating in amniotic fluid, were 7 mm long, and the first signs of eyes and ears were evident. An ultrasound showed sacs of amniotic fluid enclosing the developing puppies and, at this stage, development of the internal organs was complete (see figure 11.30). Five weeks after fertilisation, the first signs of the pups' sex were detected, predicting a

litter of four males and four females. By 6 to 7 weeks, the developing pups reached about 90 mm in length and had whiskers, toes and toenails. The pups then started growing body hair and the shafts of their bones formed.



**FIGURE 11.30** Colour Doppler ultrasound carried out at Monash Veterinary Clinic at week 4 of Gem's pregnancy. The coloured structure is the heart of one of the pups. Colours indicate the direction and speed of blood flow, with red-yellow identifying blood flow towards top of image and blue identifying flow towards bottom of image. The other smudges are caused by movement of Gem, the mother.

Between weeks 8 and 9, the finishing touches were put on the pups' footpads and their coats of various colours: red and white, black and white with brindle points, and brindle and white. Finally, after 61 days (a couple of days shorter than the normal gestation of 63 days because of the transcervical implantation), the puppies were born on 3 December 2011.

At birth, the puppies' eyelids and ear canals were closed (see figure 11.31a). About 12 days later these opened and their pink noses turned black. Puppies have a well-developed sense of smell and a strong 'suck' reflex. Their suckling stimulates the mother's pituitary gland to release oxytocin, the hormone that triggers her mammary glands to release milk. Milk is high in calories and nutrients and the pups doubled their birth weight in their first week. Figure 11.31b shows some of the pups aged 2 months, well on the path of developing into healthy adult Cardigan Welsh corgis.

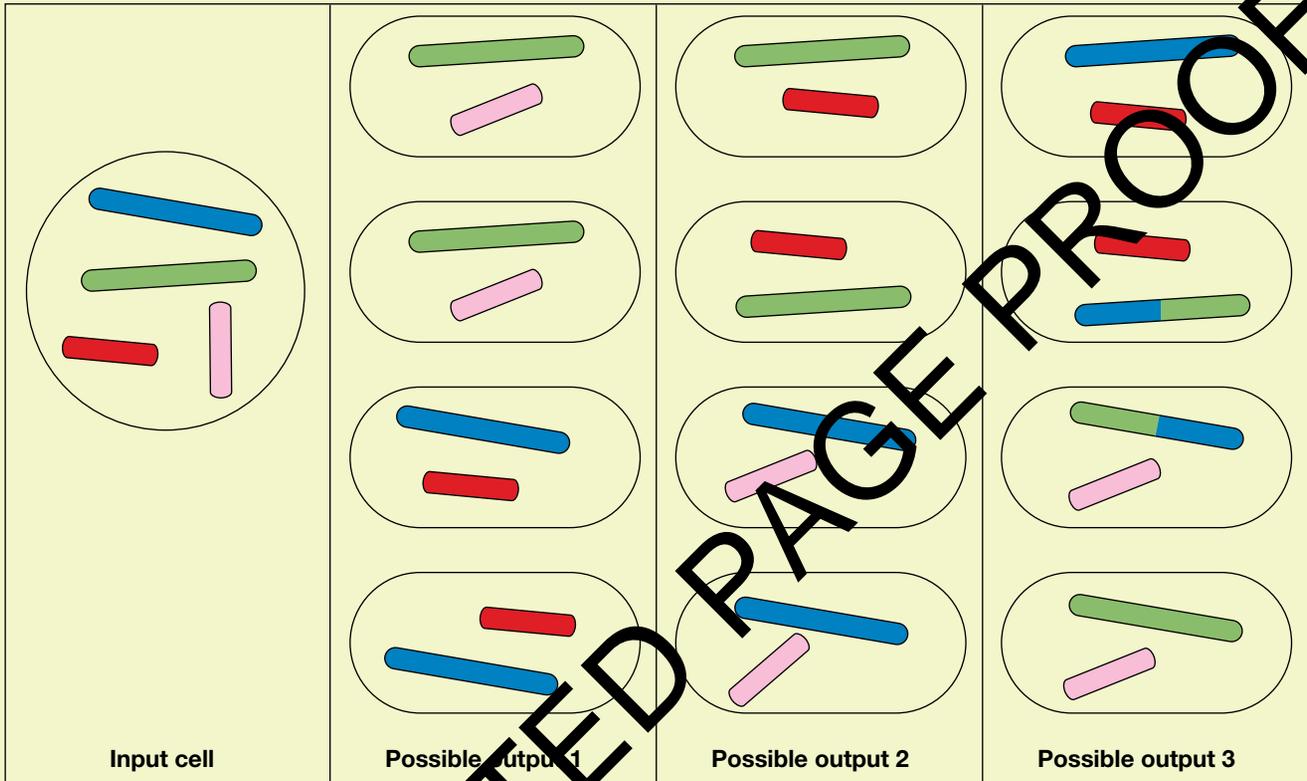


**FIGURE 11.31** (a) Three of Gem's litter of eight pups, one day after birth. Note the pink noses and closed eyes of these pups at this age. (b) Gem and three of her pups, aged 2 months. Note the colour of their noses.

UNCORRECTED PAGE PROOFS

# BIOCHALLENGE

1 Figure 11.32 shows some of the variation in the gametes resulting from meiosis. Just three of many possible sets of gametes from the division by meiosis of one germ cell are shown.

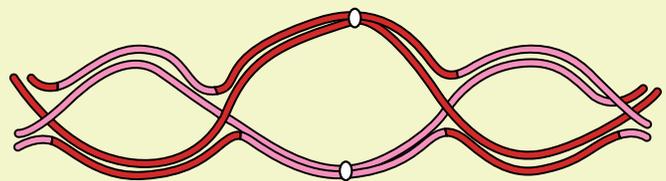


**FIGURE 11.32** Variations in output of meiosis. Notice that, even with the same starting input, the outputs of meiosis can differ each time.

In this diagram, the input germ cell is diploid ( $2n = 4$ ), with two pairs of homologous (matching) chromosomes: one long pair (one blue and one green) and a short pair (one red and one pink).

Your challenge is to replicate this table, starting with the same input cell, but producing three more possible outcomes.

2 Figure 11.33 shows a stage of meiosis.



**FIGURE 11.33**

- Identify what this structure is.
- Where is this happening?
- When does this happen?
- Draw the chromosomes in the four gametes that would result from meiosis.



# Chapter review

## Key words

anaphase  
 chromosome  
 crossing over  
 diploid number  
 egg  
 external fertilisation  
 fertilisation  
 gametes  
 germ cells

gonads  
 haploid number  
 hermaphrodite  
 homologous  
 internal fertilisation  
 interphase  
 meiosis  
 metaphase  
 nondisjunction

nonhomologous  
 ovaries  
 prophase  
 recombination  
 reduction division  
 sequential  
 hermaphrodite  
 sexual reproduction

simultaneous  
 (synchronous)  
 hermaphrodite  
 somatic cell  
 sperm  
 synapse  
 telophase  
 testis

## Questions

- 1 Making connections** → Use at least eight chapter key words to draw a concept map. You may use other words in drawing your map.
- 2 Communicating understanding** → For each of the following questions, identify two correct answers from the choices given.
  - a Which animals have internal fertilisation: crocodiles, frogs, koalas, cats?
  - b Which animals depend on the availability of water for breeding: cane toads, goannas, seagulls?
  - c Which animals produce shelled eggs: platypus, frogs, kangaroos, turtles, toads, penguin?
- 3 Applying your knowledge and understanding** → Figure 11.34 shows various stages during the process of meiosis. Examine the figure.
  - a List the stages in order from the beginning to the end of meiosis.
  - b What is the diploid number of this cell?
- 4 Making valid predictions based on your knowledge** → Plesiosaurs are extinct reptiles that lived in the sea. What prediction, if any, can be made about their manner of reproduction?

- 5 Applying your knowledge** → Consider the following statements about internal fertilisation and identify them as true or false.
  - a Internal fertilisation occurs in all terrestrial animals.
  - b Internal fertilisation occurs in all marine animals.
  - c Internal fertilisation does not occur in hermaphrodite animals.
- 6 Applying your knowledge** → Identify the structure that assists sperm transfer to the female in internal fertilisation in the following species.
  - a Tortoises
  - b Sharks
  - c Dogs
  - d Octopuses
- 7 Communicating understanding** → Refer to figure 11.14 on page 449 that shows the stages of meiosis.
  - a How many nuclear divisions occur during meiosis?
  - b A student commented: 'One of the divisions in meiosis is just like mitosis!'  
 Indicate whether you agree or disagree with this student, giving a brief reason for your choice.

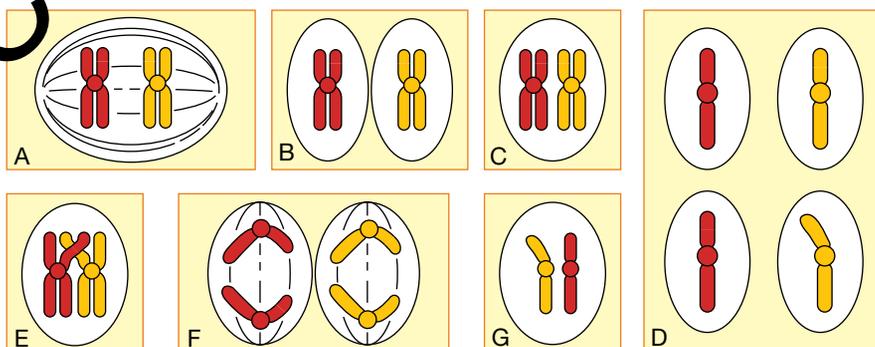


FIGURE 11.34

- 8 Applying your understanding three** → A particular organism produces normal sperm with three chromosomes.
- What is the haploid number of this organism?
  - What is the diploid number of this organism?
  - How many matching pairs of chromosomes would be expected to be present in a somatic cell of this organism?
  - How many matching pairs of chromosomes would be expected in an egg cell of this organism.
  - Sketch a possible image of the chromosomes in a somatic cell of this organism.
  - Without including crossing over, and using your diagram from part (e) above, identify how many different kinds of gametes (in terms of different chromosome combinations) this organism could produce.
  - Would this number increase or decrease if you included crossing over? Briefly explain.
- 9 Applying your knowledge and understanding** → Horses (*Equus caballus*) have a diploid number of 64, while the diploid number in the closely related donkeys (*Equus asinus*) is 62. Mules (see figure 11.35) are the sterile offspring of the mating of a male donkey (jack) with a female horse (mare).



**FIGURE 11.35** A mule

- How many chromosomes would be expected to be present in each of the following?
  - A normal egg of a horse
  - A normal sperm of a donkey
  - A somatic cell of a mule
 As indicated above, mules are sterile and cannot reproduce.
- In light of your knowledge of meiosis, suggest a possible reason for the inability of mules to produce functional gametes.

- 10 Communicating understanding** → If two brothers obtain half their genes from their mother and half from their father, why are they not identical?
- 11 Applying your knowledge** → External fertilisation in a marine environment frees a sexually reproducing organism from having to find, court and secure a potential mate.
- What is the energy downside to this type of external fertilisation?
  - List four different ways in which gametes can be made to meet.
- 12 Applying your knowledge and understanding** → For each of the following stages of meiosis, identify the amount of DNA in one cell. Assume that the amount of DNA in the diploid germ cell before it starts to undergo meiosis is  $4x$ .
- Metaphase 1 of meiosis
  - Telophase 1 of meiosis
  - Prophase 1 of meiosis
  - Telophase 2 of meiosis