7.6 The Modern Theory of Evolution

Evolutionary biology has made tremendous advances since Darwin. The science of genetics has allowed scientists to uncover the mechanism of heredity and the actual source of biological variation. The fossil record is now extensive, and our ability to interpret fossil data has been greatly enhanced by remarkable advances in the science of geology. These and other advances in science have not only confirmed Darwin's theory, but have greatly enhanced our understanding of the fundamental biology of all living things. Among these advances are our ability to accurately date the age of Earth, our discovery of the source of variation within species, and new sources of evidence in support of evolution.

The Age of Earth

Investigation 7.6.1

A Walk through Time (page 315)
Consider what you have learned about Earth's history. At the end of this chapter, you will investigate the timing of major events in the history of Earth and humans using a physical time-scale model.

Until well into the nineteenth century, many people, including some scientists, believed that Earth was less than 10 000 years old, and that the mountains, coastlines, and rivers had not changed significantly during that time. People believed that in a few thousand years, processes like erosion had not had enough time to significantly alter the physical surface of Earth. This belief was extended to living organisms. People believed that species never changed, and that species that were present then had always been present. These widely held beliefs began to change early in the twentieth century when the emerging sciences of paleontology and geology started to cast serious doubt on the belief in a young Earth.

Today there is a wide scientific consensus that Earth is extremely old. Modern geology, physics, and astronomy provide compelling evidence that Earth and our solar system are more than 4.5 billion years old, and that the universe is approximately 13 billion years old. Evidence for these values comes from many different sources, all of which are in close agreement. The evidence is largely a product of recent advances in technology and understanding.

radioisotope an atom with an unstable nucleus that is capable of undergoing radioactive decay

half-life the time required for half the quantity of a radioactive substance to undergo decay; the half-life is a constant for any given isotope

Radiometric Dating

Paleontologists are able to use radioisotopes to obtain precise estimates of the ages of rocks. **Radioisotopes** are atoms that undergo radioactive decay—a process in which the nucleus of an atom changes and releases a subatomic particle. The nuclei of these atoms are unstable and release subatomic particles changing from one form, the parent isotope, into another, the daughter isotope. For example, most carbon atoms have six protons and six neutrons and are not radioactive. However, a small fraction of carbon atoms are radioactive. They have a nucleus containing six protons and eight neutrons. When these radioactive carbon 14 (^{14}C) isotopes undergo decay, they release a high-energy particle, and one of the protons changes to a neutron. The daughter isotopes are nitrogen atoms (^{14}N), each containing seven protons and seven neutrons.

The complicated technique of radiometric dating is based on the ratio of parent to daughter isotopes in rock formations. Radioisotopes undergo decay in a very precise way. The length of time that it takes for half of any amount of a particular radioisotope to decay is a constant. This value, called the **half-life**, is the time it takes for exactly 50 % of a parent isotope to decay into a daughter isotope (**Figure 1**). It then takes an additional half-life for the remaining amount to be reduced by half again, and so on.

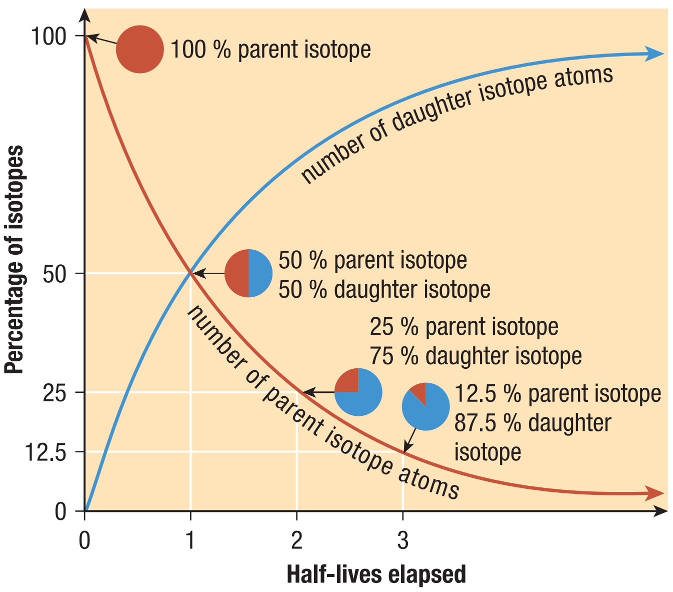

Figure 1 During each half-life of radioactive decay, 50 % of a parent isotope decays into a daughter isotope. The result is a quantitative, predictable relationship between the ratio of parent-to-daughter isotopes and elapsed time.

The Modern Synthesis

Darwin's theory of evolution by natural selection could account for how species evolve but could not explain the actual source of variation. Today the knowledge and understanding gained from genetics and other fields of biology have been combined with Darwin's theory to form the **modern evolutionary synthesis**. This comprehensive theory now forms the basis for all work in evolutionary biology.

modern evolutionary synthesis the modern theory of evolution that takes into account all branches of biology

Darwin defined evolution as changes in the inherited traits of a species over time. Today, biologists define evolution as changes in the gene pool of a species over time. A **gene pool** consists of all the alleles of all individuals that are currently present in a particular species or population. Individuals vary in their traits because they inherit different combinations of alleles. Natural selection acts to favour some genetic combinations over others.

gene pool the complete set of all alleles contained within a species or population

Mutations: The Source of Variation

All species exhibit genetic variation. Different individuals have different combinations of the many alleles that are already present in the population. Sexual reproduction recombines, or shuffles, these alleles and produces an almost unlimited number of combinations. New or altered traits arise when new alleles and genes are produced by mutation and acted upon by natural selection. A genetic mutation is a change in DNA. The bases that make up DNA may be switched or lost, and/or new bases may be inserted (**Figure 2**).

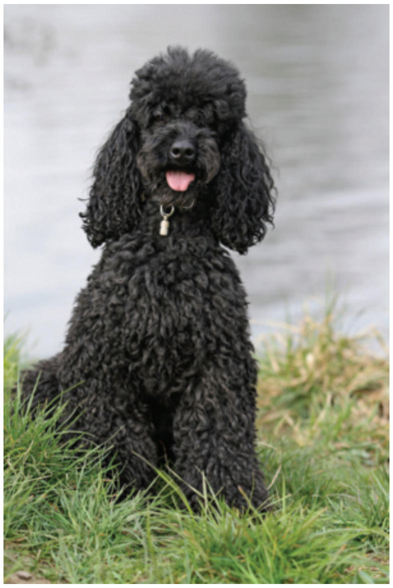

Figure 2 Perhaps hundreds of generations ago, a dog was born with a single base mutation in a gene coding for a hair protein. The mutation resulted in very curly hair—a trait that was selected for by breeders and is now common in a number of breeds, including poodles and many terriers.

Mutation events can also result in an individual having duplicate copies of genes. Duplication events are usually the result of mismatches during crossover in meiosis. A misalignment of the chromosomes during crossover causes an unequal exchange—transferring a portion of one chromosome to another (**Figure 3**). The transferred portion of the chromosome is likely to contain many genes.

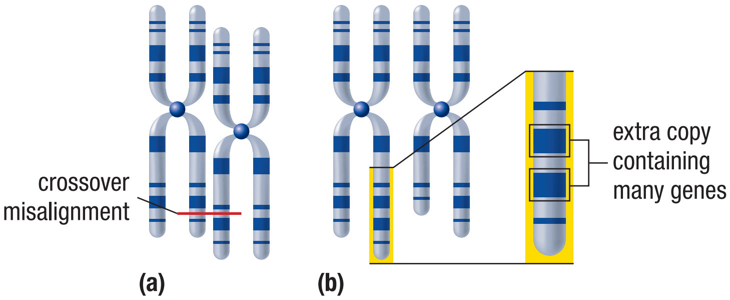

Figure 3 (a) Crossover errors can result in (b) one sister chromatid having a duplicated portion of a chromosome and the other chromatid missing a portion of the chromosome.

Gametes that receive a chromosome that is missing a section will have a low chance of survival, while gametes that receive a chromosome with duplicated genes are often viable. In fact, extra copies of genes can be beneficial. For example, scientists recently studied the gene responsible for the production of amylase, the digestive enzyme that breaks down starch. The study compared people of Japanese descent, whose traditional diet is high in starch, with Amazon rainforest dwellers, whose diet is typically low in starch. The people of Japanese descent had multiple copies of the amylase gene, enabling their cells to produce more of the digestive enzyme.

Gene duplication is an important type of mutation because it is a source of new genes. The extra copy of the gene is free to mutate and may gain a new function. Many genes code for vitally important proteins. If a mutation in a gene results in a new protein that can no longer perform a vital function, the organism may die—even if the new protein is beneficial in some other way. However, the same mutation occurring in an extra copy of the gene might result in the creation of a new and potentially beneficial protein. The duplication and mutation of gene copies can result in entire "families" of closely related genes. For example, four human genes—three involved in colour vision and one for night vision—are all thought to have been produced from a single ancestral gene.

The Effects of Mutations

As you learned in Section 7.1, mutations can be neutral, beneficial, or harmful. Most mutations are neutral because they occur in non-coding portions of DNA and therefore produce no visible change in an individual. The environment does not favour or select against individuals with neutral mutations.

Beneficial mutations, which give the individual an advantage, are selected for by the environment. For example, mutations that have allowed some plants to produce colourful flowers and attract pollinators have been beneficial to those species, and these new genes have become widespread.

Harmful mutations may make an organism less able to resist disease or avoid predators, or less efficient at obtaining food. Individuals with harmful mutations are less successful at reproducing, and therefore harmful mutations tend to disappear.

MUTATION RATES

When chromosomes, consisting of strings of DNA bases, are replicated, the error rate is typically less than one mutation in a million bases. Duplications, inversions, deletions, and other mutations are also relatively uncommon events. However, organisms have genomes consisting of millions and often billions of DNA bases. In addition, populations often consist of millions of individuals.

Individual mutation rates are very difficult to estimate, but recent studies suggest that species with large genomes are likely to have mutation rates averaging more than one per individual. The same studies suggest that humans, with genomes consisting of billions of bases, may average 20 or more mutations per individual. Even if these are almost always neutral, the numbers are staggering. The human population—approaching 7 billion people—is carrying well over 100 billion genetic mutations. A similar high incidence of mutation occurs in all species with large populations. **Table 1** summarizes key relationships between mutations and evolution.

LEARNING **TIP**

Consider the Numbers
Natural populations are often extremely large. A small section of forest can be home to millions of blackflies, while a soccer field is home to millions of grass plants. Even if the mutation rates for individuals are relatively low, the number of mutations within a population is very large.

Table 1 Mutation and Evolution

Factor	Influence on evolution
beneficial mutations	relatively rare but are favoured by natural selection and tend to accumulate in populations over time
harmful mutations	more common than beneficial mutations but are selected against and therefore have no influence on populations
duplication mutations	often neutral and so do not immediately benefit the individual, but provide a source of new genetic material with the potential to evolve into new genes
mutation rates	relatively low for individuals but can be numerous in populations overall

Homologous Genes and Pseudogenes

In Section 7.5 you observed that closely related species share many homologous features. All mammals, for example, have similar numbers and arrangements of bones because they have inherited this pattern from a common ancestor. Similarly, closely related species inherit homologous genes. These genes, inherited from a common ancestor, mutate and evolve over time. The degree of similarity between homologous genes provides good evidence for the degree of relatedness between species. The more closely related two species are, the more similar we would expect their homologous genes to be. **Figure 4** compares very small portions of a DNA sequence from a number of species.

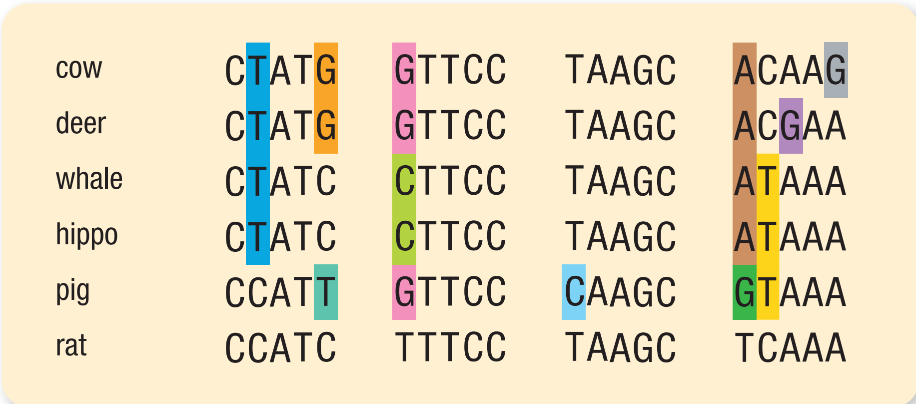

Figure 4 The letters represent the sequence of bases on the DNA of these species. All sequences code for a short portion of a homologous gene. The more closely related the species, the greater the similarity. Coloured letters highlight the differences from those of the rat sequence—the least closely related mammal. Each colour represents a different inherited mutational change.

Species also have **pseudogenes**—genes that have undergone mutations and no longer serve a useful purpose. Like vestigial anatomical features, a pseudogene is the remaining part of a gene that once served a useful purpose. For example, dolphins, like all mammals, breathe through their noses, but, unlike most mammals, have no need for a sense of smell in the air (**Figure 5(a)**). Dolphins are thought to have evolved from land mammals. Most land mammals have an excellent sense of smell. Mammals have approximately 1000 functioning olfactory receptor (*OR*) genes that code for the receptors that detect airborne chemicals. Dolphins have these same 1000 genes, but only about 200 of them are functional. The remaining 800 or so are pseudogenes. Biologists suspect that after dolphins evolved an aquatic lifestyle, their *OR* genes were of no value. Any mutations that made the genes dysfunctional would have been neutral and not selected for or against. Over millions of years most of the dolphins' *OR* genes have become pseudogenes.

Pseudogenes, like vestigial features, are found in virtually all species. For example, the stomach of the duck-billed platypus has no chemical digestive function, yet the platypus has three defective genes that code for the production of digestive enzymes normally produced by the stomach. This provides evidence that platypuses evolved from an ancestor with a stomach that released digestive enzymes coded for by properly functioning genes (**Figure 5(b)**).

The human genome contains thousands of pseudogenes. Among the most interesting is a dysfunctional copy of a GULO gene. The gene is necessary for the production of vitamin C. Humans and most other primates, bats, guinea pigs, and some birds are all known to have defective GULO genes. Mutations that cause the GULO gene to be defective are not harmful in these species because their normal diet provides adequate amounts of the vitamin.

pseudogene a vestigial gene that no longer codes for a functioning protein

(a)

(b)

Figure 5 (a) Dolphins have many pseudogenes that once coded for a keen sense of smell. (b) The platypus has pseudogenes for the production of stomach enzymes—useful in ancestors that had a functioning stomach.

Research This

Puijila, the Young Seal

Skills: Researching, Observing, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK A4, A5.1

Canada has been home to many remarkable fossil finds. One of the most recent is that of *Puijila darwini*—a missing link between prehistoric land mammals and modern seals (**Figure 6**). *Puijila* was discovered in Canada's High Arctic by a team led by Natalia Rybczynski, a paleontologist with the Canadian Museum of Nature in Ottawa. Dr. Rybczynski's efforts and success highlight the challenges and rewards of scientific discovery. In this activity you will have the opportunity to research this important fossil discovery and see how paleontologists put pieces of evidence together.

(a)

(b)

Figure 6 (a) The *Puijila* fossil and (b) the Haughton crater, Devon Island, Nunavut.

1. Use the Internet and other sources to learn the details of the *Puijila* fossil discovery. Research the details of Rybczynski's fieldwork, including the particular challenges associated with working in the Arctic.
2. Research the scientific publication of the discovery.

A. Why was this particular fossil find so important? Why was this missing link of interest? A

B. What anatomical features of *Puijila* indicate that it was semi-aquatic? T/I A

C. New fossil species are given new names. How did Rybczynski's team decide on a suitable name? A

D. Describe the formation of the Haughton crater. Why it is a good location for finding fossils? T/I A

E. Describe the events leading up to the discovery of the initial fossil and the later discovery of the skull fragment. T/I

F. In which science journal was this discovery reported? There are thousands of different journals. What makes this one special? T/I A

G. Report your findings to the class. Consider putting on a short skit to re-enact the fossil discovery. C

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Modern Paleontology

WEB LINK

Fossil Discovery

To learn more about how fossils are discovered, extracted, and preserved,

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The last 100 years have witnessed many important fossil discoveries that have enhanced and enriched our understanding of evolution. These include fossils of early human ancestors and primitive whales in Pakistan. In recent decades, paleontologists have unearthed spectacular fossils of feathered dinosaurs in China and have even been able to determine the colour of some the feathers. Some new fossils of dinosaurs and other organisms have been found in Canada.

The distribution of fossils provided Darwin with important evidence for his theory of evolution. He discovered fossil remains of giant prehistoric mammals that were similar in form to present-day armadillos and sloths living in the same region. Such a pattern has now been documented in many locations around the world. Australia, for example, is home to many fossils of primitive kangaroos but has no fossils of mammals typical of other continents.

Until the 1960s, the locations of some fossils were quite puzzling. Particularly surprising was the discovery of fossils of the same species in Africa, India, and Antarctica—but nowhere else on Earth. Today the study of biogeography has been complemented by great advances in the study of **plate tectonics** and continental drift. Plate tectonics describes the movements of Earth's crust and accounts for many large surface features such as mountains, as well as volcano and earthquake activity. **Figure 7** illustrates the arrangement of some of Earth's major land masses approximately 200 million years ago. Species distributions at that time were permanently captured in the fossil record.

plate tectonics the scientific theory that describes the large-scale movements and features of Earth's crust

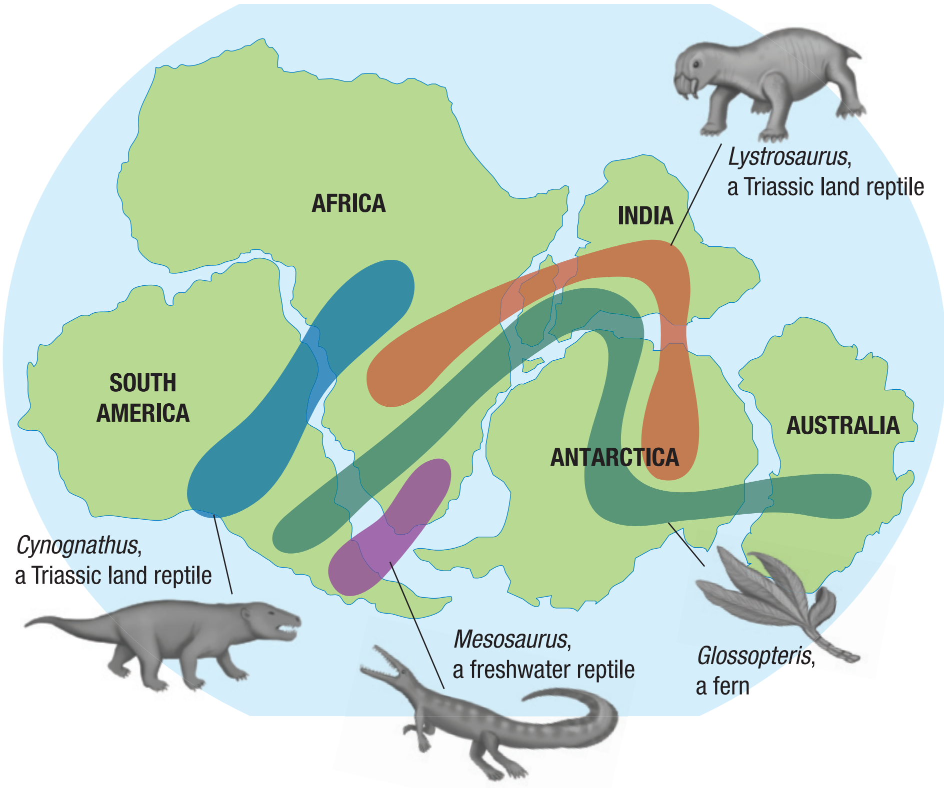

Figure 7 Fossil distributions of these four species match the arrangements of the Earth's land masses at the time the species were alive.

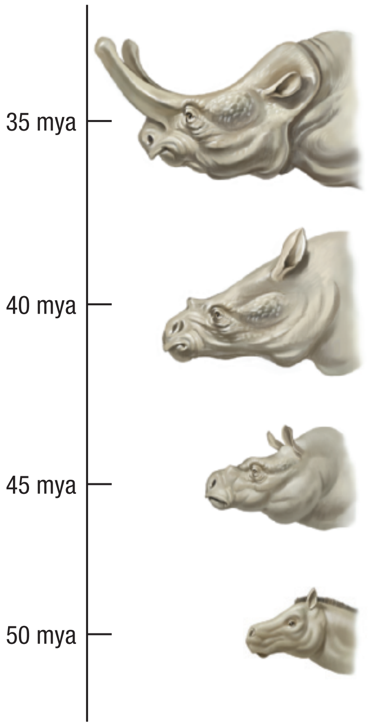

Figure 8 Evolution of an early Eocene mammal as it was thought to have appeared, based on fossil evidence (mya stands for "million years ago").

Fossils also show distinct patterns in time. The oldest fossil deposits contain only simple life forms. More recent fossil deposits contain species that are both more complex and more similar to living species (**Figure 8**). Of the millions of fossils that have been recovered and carefully documented, not a single fossil has been found to contradict this underlying pattern.

Modern evolutionary biology is supported by the most recent advances and discoveries in molecular genetics, geology, and paleontology. This has enabled scientists to understand the source of new variations within species, account for the unusual distribution of some fossils, and confirm predictions of the theory. As you will soon discover, the modern theory of evolution also has the power to explain the evolution of complex adaptations and structures, as well as explain the evolution of entirely new species.

7.6 Summary

- The modern synthesis of evolutionary biology combined Darwin's theory of evolution by natural selection with the science of genetics.
- Genetic mutations provide a continuous supply of new heritable information and variation within a species.
- Beneficial mutations are favoured by natural selection.
- Neutral mutations have no immediate influence on the success of an individual.
- Harmful mutations are selected against—reducing their frequencies within a population.
- Pseudogenes provide compelling evidence for evolution.
- The sciences of plate tectonics and paleontology have greatly enhanced our understanding of evolution.

7.6 Questions

1. How might the daily experiences of people contribute to their belief that Earth and species do not change? A
2. Approximately how old is Earth? What types of scientific evidence were used to arrive at this age? K/U
3. Describe the relationship between the following terms: K/U A
   (a) parent isotope, daughter isotope, half-life
   (b) evolution, gene pool, species
   (c) duplication, crossing over, gene family
4. *E. coli* bacteria are extremely numerous (billions of *E. coli* cells are living inside you!) and reproduce extremely quickly. Geneticists estimate that every part of *E. coli* DNA undergoes a mutation somewhere on Earth every day. What might this suggest about the ability of *E. coli* to evolve? A
5. When geneticists examine genomes they often find "families" of very similar genes close together on the same chromosome. Explain how such families of genes might have arisen. K/U A
6. All dolphin species have hundreds of defective genes that are involved with olfactory function in other mammals. There is no evidence to believe that mutations occur any more frequently in dolphins than in other species. If this is true, why are there not as many of the same defective genes in land mammals? K/U A
7. Modern lemurs are found only on Madagascar Island off the east coast of Africa. However, fossils of ancient lemurs have been found thousands of kilometres away in India, where there are no lemurs. Consult Figure 7 on page 312 and provide a possible explanation for this finding. T/I A
8. Copy the following DNA base sequences into your notebook. They are all short samples taken from what appear to be matching chromosomes in closely related species. Compare the sequence in Species A with that of Species B, and then compare the sequence of Species A with that of Species C. T/I A

   Species A GGTAA AACAG CCTTA AGCGCC . . .

   Species B GGTAA CAACA GCCTT AAGCGC . . .

   Species C GCTAA AACAG CCCCA AGCGGC . . .

   (a) Is there any evidence that one species experienced a single base "insertion" mutation? Explain.
   (b) Which two species are probably more closely related?
9. Humans are one of a small number of mammals that are unable to synthesize vitamin C. Instead, we obtain vitamin C in our diet. Humans have a pseudogene that is homologous to a gene involved in vitamin C synthesis in other mammals. T/I A
   (a) Is the presence of this gene surprising? Why or why not?
   (b) What does it suggest about human evolution?
10. Use the Internet and other sources to research the use of carbon dating. T/I C
    (a) Why is carbon dating useful for dating samples of plant and animal material that are thousands of years old?
    (b) Explain why carbon dating cannot be used for samples that are millions of years old.

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