ABSTRACT
Molecular biology topics tend to be abstract and hard to visualize, and consequently pupils form many misconceptions about genetics and molecular biology. We describe how to make a hands-on educational set that provides visual and tactile modeling of DNA replication, transcription, polymerase chain reaction (PCR), and random mutations so that students can examine these processes in detail. The set is inexpensive and easy to make, has been used successfully, and allows for modification to fit individual teachers’ needs.

Key Words: DNA; model; mutation; PCR; replication; transcription.

Introduction
Nucleic acids are crucial components of every living organism on Earth. They contain information about how to build and maintain our bodies and how to transmit our genes to the next generations. The flow of information among nucleic acids, proteins, and other biologically important molecules is called the central dogma of molecular biology.

Many methods are based on knowledge of the molecular mechanisms of transcription and replication of nucleic acids. One of the most famous is the polymerase chain reaction (PCR), which is based on the mechanisms of DNA replication. PCR, invented by Kary B. Mullis (Saiki et al., 1985), began a revolution in molecular biology. It requires DNA template, free deoxyribonucleotides (dNTPs), primers (short oligonucleotides that define the amplified sequence), and thermostable DNA polymerase (Garibyan & Avashia, 2013). During the reaction, three temperature steps are repeated (cycling, usually 25–30 times): denaturation (95°C; DNA strands are separated), annealing (55–65°C; primers bind to the target sequences), and polymerization (about 72°C; polymerase adds nucleotides to the primer). The target sequence is multiplied exponentially (Garibyan & Avashia, 2013).

Hands-on and minds-on activities have been proven to effectively increase student interest and performance (Franke & Bogner, 2011). Molecular biology topics tend to be abstract and hard to visualize, and consequently pupils form many misconceptions about genetics and molecular biology. We believe that students’ understanding can be greatly improved through hands-on experience, so we created an educational set that demonstrates two key concepts in genetics that are often misunderstood: complementarity (Fossey & Hancock, 2005) and the fact that mutations are random (Bahar et al., 1999; Duncan et al., 2009). When covering this topic, Kalinowski et al. (2013) recommend that teachers “emphasize that mutations randomly change DNA sequences.” Lewis and Kattmann (2004) suggest using an example of a single mutation causing sickle cell anemia to demonstrate the gene–trait relationship; they found that some “students believed that chromosomes and/or genetic information is shared out but not copied” (see also Wood-Robinson et al., 2000). Using our set can serve as a starting point for discussion about the accuracy of DNA replication, transcription, and translation. Students themselves will demonstrate that mutations occur randomly. Understanding this concept is necessary for demonstrating the role of genetic variation in evolution.

Activities in the set directly refer to Disciplinary Core Ideas in the Next Generation Science Standards, showing that “inheritable genetic variations may result from . . . viable errors occurring during replication. . . . Although DNA replication is tightly regulated and remarkably accurate, errors do occur and result in mutations, which are also a source of genetic variation” (3-LS3, Heredity: Inheritance and Variation of Traits). This easy-to-make set can
significantly enrich science lessons in a wide range of schools, providing original insights on the molecular processes in cells as well as introducing a very important molecular biology method, PCR.

○ The Set

The set is made from inexpensive materials, including plastic beads (Pyssla, IKEA, catalog no. 501.285.72), binding wire (0.5–1.0 mm in diameter), a pencil eraser (e.g., MAPED, Technic), a plastic Petri dish (10 cm), a paper box (200 × 170 × 55 mm or bigger), and plastic bottles (~120 mL) or small zipper-sealed plastic bags (Figure 1).

The set can be used for various purposes. First, it helps the students to practically grasp the concept of base pairing and the double-strand structure of DNA (strands are antiparallel and complementary). Second, it can be used to demonstrate differences between replication and transcription. Third, it provides the insight into the problem of random origin of mutations. Finally, it can serve as a tool for advanced students to demonstrate the PCR technique. That is why we recommend using the kit in the high school, but also in higher-level education.

The Supplemental Material (available with the online version of this article) includes five videos that will guide you through the process of making and working with the set, as well as detailed written instructions for both teachers and students.

○ Highlights & Shortcomings of the Set

Highlights:
- Open-source teaching tool
- Inexpensive and easy to manufacture
- DIY videos available
- Hands-on activity
- Simulation of basic features of strand synthesis in nucleic acid biology:
  ➢ complementary base pairing
  ➢ antiparallelness of DNA strands

Figure 1. Components of the set: (1) double-stranded DNA template; (2) two RNA primers for replication; (3) three RNA primers for transcription; (4) seven pairs of primers for PCR; (5) free dNTPs in a bottle; (6) free NTPs in a bottle; (7) Petri dish; (8) rubber “stoppers”; (9) manual for students; and (10) key for the quick evaluation of results.
> semi-conservativeness of DNA replication
> synthesis in 5' to 3' direction
> distinguishing between NTPs and dNTPs for distinct processes
• “Challenging” replication mode – showing the random origin of mutations and providing the possibility of discussing mutations and the proofreading activity of DNA polymerase
• Read model of PCR method
• Quick evaluation of results

Shortcomings:
• Short template molecule
• Fixed RNA primers for DNA replication (it is not possible to replace this part)
• Oriented mainly toward base pairing and how a template strand is used to specify the construction and sequence of a complementary RNA or DNA strand
• Hydrogen bonding is not possible in the set (template molecule does not stick together and consists of two separate strands)
• NTP and dNTPs are distinguished only by the bottle selection (colors of beads represent nitrogen base only)

○ Conclusion

Nowadays, there are many educational sets – from inexpensive and simple (Malacinski & Zell, 1996) to complex and sophisticated (Davenport et al., 2017) – that can improve the teaching of molecular biology. Advantages of our set include its low price, the ease of making it yourself following the video instructions, and its time-effectiveness for use in the classroom (in replication and transcription mode, the work takes about 10 minutes; in PCR mode, about 20–30 minutes). We successfully tested this activity with middle school, high school, and university students. Notably, the middle school students reported that they better understood the mechanisms of base pairing and synthesis of nucleic acid strands after using the set.

While working with the set (mostly in PCR mode), some students invented several alternative strategies for quickly accomplishing the task without rigorously following the instructions. This was relatively easily revealed, because in these cases the number of copies of specific length did not match the “theoretical” one (very often, students forgot to use original template strands in every PCR cycle).

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LADISLAV MERTA (ladislav.merta@natur.cuni.cz) is a PhD student in the Department of Cell Biology, Faculty of Science, Charles University, Prague, Czech Republic. VANDA JANŠTOVÁ (vanda.janstova@natur.cuni.cz) is an Assistant Professor in the Department of Teaching and Didactics of Biology, Faculty of Science, Charles University, Prague, Czech Republic.