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"The Complementary Structure of Deoxyribonucleic Acid" – Adapting the Crick and Watson Paper for Science Education

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Abstract

It has been 70 years since the molecular structure of DNA has been decoded, which can be described as one of the most important scientific achievements of the last century. In 1953, Watson and Crick reported their double helix model in Nature*, after Pauling and Corey had proposed a flawed three-stranded model. Later they gave a detailed description of the building of the model in a following article. Using this article in science education offers a wide range of valuable learning opportunities. In addition to the actual content of the highly interdisciplinary research, it allows students to learn about scientific model building and the use of models in research, as well as the development of scientific knowledge and nature of science. It can also be used as an example for a discussion on social influences on science, ethical considerations in science and good scientific practice. Due to the complexity of the original article, we propose to adapt the text so that it is also understandable for students. In this contribution, we report on our adaptation and the adaptation process, which is based on the concept of adapted scientific literature and suggest measures to unlock its potential for educational settings.*

Keywords: *adapted scientific literature, adapted primary literature, scientific literature, reading, DNA, historical case*

1 Introduction

As previously reported [1], we propose the use of authentic scientific literature such as research papers in form of Adapted Scientific Literature (ASL) in science education to foster an understanding of the scientific processes. Based on the concept of Adapted Primary Literature by Yarden et al. [2], ASL is a new type of text that uses scientific articles as a basis and simplifies their content to make them accessible to students [1]. We argue that reading ASL has the potential to help students understand pivotal features of science, including the social practices of the scientific community, due to central structural and rhetorical features such as the IMRaD structure (Introduction, Methods, Results and Discussion), references to other publications, or the use of rhetorical figures that indicate uncertainty [1, 3]. While we have focused so far on scientific literature about contemporary cases [4, 5], we now want to explore a different approach by determining the potential of ASL in historical contexts.

The usage and benefits of historical contexts to foster an understanding of nature of science (NOS) is well described in literature, e.g. by Matthews [6] or Allchin and coworkers [7]. Benefits arise from the possibilities to discuss cultural, biographical, and economic contexts of research problems and the complexity of scientific practices. Since the outcome of the historical case is known, the whole scientific process as well as the product itself can be analyzed from different perspectives. The possible contexts are very diverse and range from ancient times, e.g. the discovery of Archimedes' principle, to (pre-)modern science, like decoding the DNA.

A significant topic in science education is the field of genetics, in particular the structure and function of DNA. The development of our modern understanding of this polymer is shaped by astonishing stories of flawed hypotheses, social, cultural, and political influences as well as personal relationships between the acting scientists. Therefore, it is not surprising that using this context has already been used in educational frameworks. For instance, Wieder [8] describes how he used the context for a theater play in class, followed by an activity to construct own DNA structure models, while Dai et al. [9] focused on changing students understanding of NOS by exposing them with historical narratives regarding the role of X-ray crystallographer Rosalind Franklin. Focusing more on experimental instructions, Thompson et al. [10] describe two optical experiments for undergraduates, which recreate the X-ray diffraction patterns obtained from Rosalind Franklin and Raymond Gosling, while Crouse

[11] proposes a way for undergraduate students to mathematically verify the model of Crick and Watson by a X-ray diffraction analysis.
As described above, we want to use authentic scientific literature for fostering an understanding of the features of science, especially the social aspects of the scientific community. After briefly describing the historical development of the research on DNA (section 2), we will describe our approach of adapting the Crick and Watson paper [12] (section 3) and conclude with possible learning opportunities for science education using the created adaptation (section 4).

2 Historical development

Unraveling the structure of DNA did not happen overnight. The journey started in 1869, where Friedrich Miescher analyzed the chemical constitution of pus cells and described a nitrogen- and phosphorus-rich substance from the cell nucleus, which he named "Nucleïn". The nuclein was still contaminated with protein residues, but in 1889, Richard Altmann was able to seperate the nucleic acid from the proteins [13]. Several contributions from Albrecht Kossel described the purine and pyrimidine bases guanin (1883, isolated already in 1844), adenine (1885), thymine (1893) and cytosine (1894) [13, 14]. In 1900, with the help of Kossel, Alberto Ascoli isolated uracil from yeast [14], which replaces thymine in the RNA. Phoebus Levene identified a base, carbohydrate and phosphoric acid unit in the nucleic acids extracted from yeast (i.e., RNA, in 1909) and from the thymus (i.e., DNA, in 1929). He was also able to show that the components were linked together and form a repeating unit, which he named nucleotide [15]. Furthermore, Levene proposed that the RNA molecule (and later analogous DNA) is composed of equal amounts of the respective four nucleotides and that the structure repeats itself in a fixed manner, leading to the influential *tetranucleotide hypothesis* (see fig. 1). This hypothesis implies that the DNA or RNA molecule is too simple in its structure to encode complex information and is therefore not suited to describe the complexity of life. As the tetranucleotide hypothesis dominated the field for almost four decades, interest in DNA consequently declined in favor of proteins, as these showed greater complexity and were therefore assumed to carry information [13, 15].

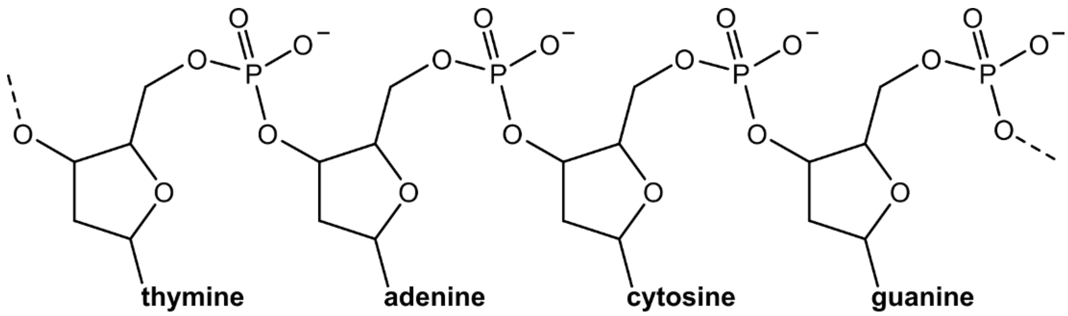

Fig. 1. Repeating tetranucleotide monomer unit of the DNA according to the *tetranucleotide hypothesis* by Levene [15].

This changed in the late 1940s and early 1950s, where Erwin Chargaff and coworkers published their observations on the exact amounts of the nucleotides and their relative proportions to each other, now known as the Chargaff's rules [13]. Contrary to the tetranucleotide hypothesis, only the ratios between adenine and thymine as well as between guanine and cytosine are nearly one, while the other ratios can differ among different species. Meanwhile, in 1937, William Astbury produced the first X-ray diffraction patterns indicating a spiral structure of DNA [16], while Oswald Avery, Colin MacLeod and Maclyn McCarty were able to show that DNA was responsible for changes in bacterial organisms in the experiments carried out by Frederick Griffith earlier, strongly suggesting that the DNA helix is the carrier of genetic information. This was further supported by experiments from Alfred Hershey and Martha Chase on bacteriophages in 1952 [13].
After establishing that hereditary information was encoded by DNA, the scientific community focused on investigating the exact three-dimensional conformation of the molecule as well as how the DNA stores information [13]. With the help of a new X-ray diffraction image of high hydrated DNA from Rosalind Franklin and Raymond Gosling [18], Francis Crick and James Watson were able to build a correct model of the DNA molecule in 1953 [19], showing a specific paring of nucleotides, which suggests a biological role for the replication mechanism. Earlier the same year, Linus Pauling and Robert Corey proposed a flawed three-stranded model with bases outside and the chains inside (see

fig. 2) [20]. One year later, Crick and Watson explained their modeling in an extended article entitled "The complementary structure of deoxyribonucleic acid" [12], which is the template for the adaptation process described in the following section.

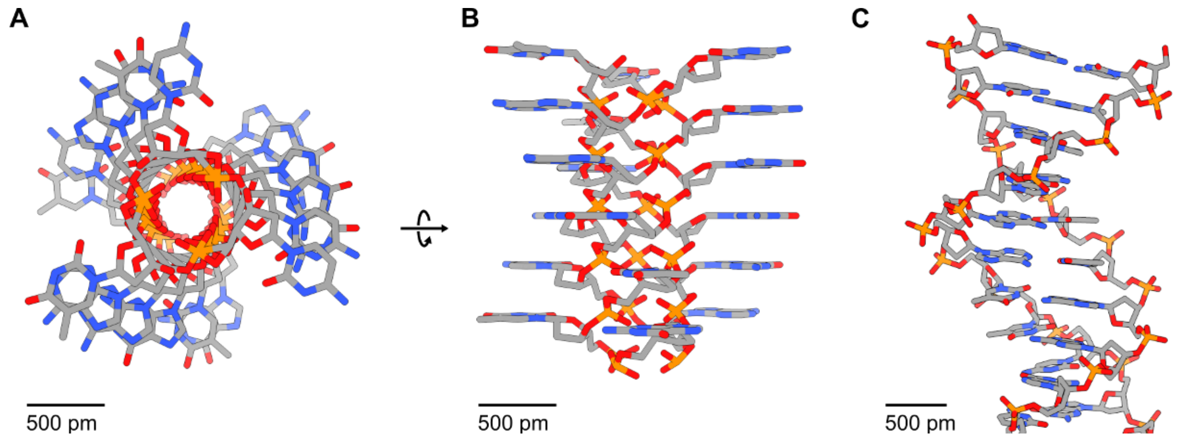

Fig. 2. Three-stranded DNA model from Pauling and Corey [20]. Fig. A and B show a computer-generated model of their calculations (PDB file by Lu [21]). For comparison, Fig. C shows a model of the B-DNA based on X-ray diffraction data (PDB: 1BNA; [22]). This image is made with ChimeraX [23], coloration by chemical elements (gray = carbon, red = oxygen, blue = nitrogen, orange = phosphorous), and reprinted from [3].

3 Adapting the Crick and Watson paper

The potential of adapted scientific literature for science education is described in numerous publications [3]. Many authors observe improved inquiry skills [24], critical thinking skills [25] or an improved understanding about nature of science [3, 4, 26, 27] of students after reading adapted scientific literature. The main reason for adapting an article instead of using the original is the often high demands on text comprehensibility. Through adaptation, the texts are modified to fit the pre-knowledge of the new target group, i.e. high school students or undergraduate students, but maintain important structural motifs, like the organizational, argumentative, and goal-directed structure – and thus implicitly characteristics of science [1, 3].

Several steps have to be performed in order to adapt the article properly (see tab. 1). The most crucial step is the first one: determining the background knowledge of the target group, i.e. the students, as this determines the subsequent steps. Since the education system in Germany is federally organized, we used the local science curriculum standards as a guidance for determining students' background knowledge. Based on these standards, it is to be expected that the students in the selected grade level have prior knowledge of intermolecular interactions, the structure of a biological cell as well as electromagnetic radiation. Nevertheless, this also means that the method of X-ray diffraction and the evaluation of X-ray diffraction images is not part of the anticipated competencies, which is why careful adaptation is required.

Tab. 1. Performed steps for adapting the Crick and Watson paper.

Step	Action
1	Identifying students background knowledge
2	Selection of the main content
3	Adding short section about the methodical approach
4	Re-writing section on chemical background
5	Re-writing section on the analysis of the X-ray patterns
6	Re-writing section on the configuration of the double helix
7	Re-writing section on the crystalline form
8	Re-writing introduction section
9	Re-writing discussion section
10	Re-writing title and abstract

Based on the considerations made in step 1, we decided which content from the article we want to include in the adaptation, and in which order we want to present them. In the original paper, Crick and Watson first present the already known facts about the chemical structure of the DNA molecule and then proceed to construct the double helix structure model based on crystallographic arguments, mainly focused on the work of Astbury and Bell as well as Franklin, Wilkins, and Gosling. From this model, the authors derive atomic distances inside the molecule and its density and verify them against crystallographic information, previous studies and stereochemical arguments. A detailed view on the hydrogen bonds between the nucleotides, some remarks about the structure of the water-free form of the DNA (A-DNA) as well as a concluding discussion end the article. When selecting the content for the customization, some information was omitted to shorten the article. Details on the sugar group, the isomerism, and the cytosine derivative 5-methylcytosine have been removed. Also, the explanations to the A-DNA have been shortened.

Contrary to classical scientific articles of modern science, this article is not presented IMRaD-like, especially missing a Methods section. This is not only the case because the IMRaD structure wasn't fully established in the 1950s [28], but also because the article is rather theoretical and does not present results derived from new experiments. Still, Crick and Watson work methodologically by generating and optimizing their DNA model; the authors themselves describe their method as the "classical method of trial and error" [12, p. 81]. To represent this and to simplify the reading, we added a section called "Methodological approach" (step 3), where we summarize the methodology of Crick and Watson by using existing paragraphs from the following section.

In the remaining steps 4 to 10, we rewrote the respective sections. This means that we used the original material and carefully checked whether the content was suitable for the students according to our analysis in step 1 or whether we wanted to retain the information (step 2). To make the crystallographic arguments of Crick and Watson understandable, we included a copy of the X-ray diffraction image of Franklin and Gosling [18], also known as "photo 51", with explanatory annotations about the parameters of the helix, that can be derived from the image. Additionally, we created three new graphics: Two figures with the purpose to define the components of the DNA molecule (e.g. nucleotide or nucleoside) and one figure to show the calculated distances in the double helix (fig. 3). At the end of the article, we included the acknowledgement made by Crick and Watson and listed the used references.

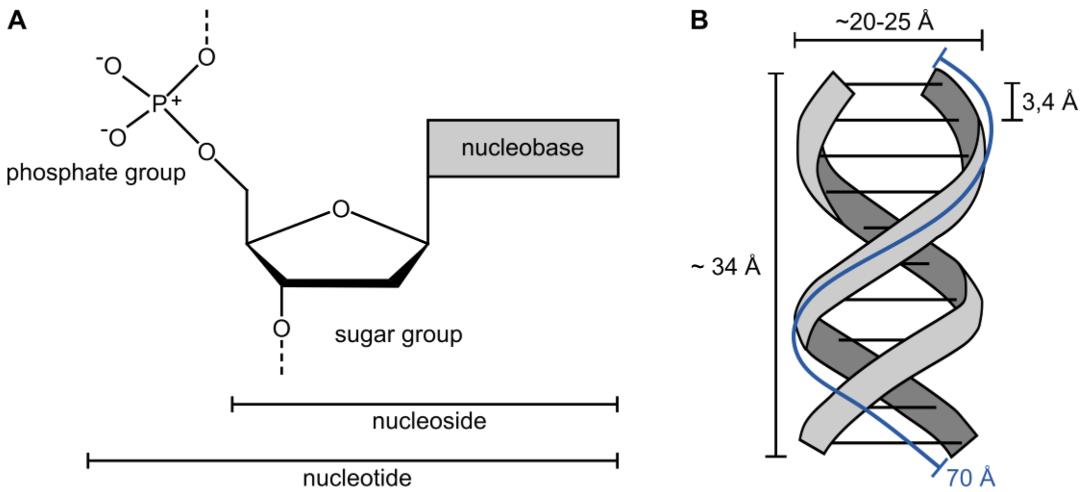

Fig. 3. Additional illustrations of the adaptation. Fig. A shows one of two additional graphics that serve as an overview of the various chemical terms. Fig. B summarizes the calculated distances of the DNA double helix.

4 Learning opportunities

This context offers the potential for various learning objectives. As outlined in Section 2, the historical development leading up to the development of Crick and Watson's model was far from straightforward, which offers a learning opportunity concerning the development of science as well as the influence of other scientists on science. This is highly connected to aspects of NOS, e.g. the tentative nature, the theory-laden nature, or the empirical nature of scientific knowledge [29], but also sheds light on the

importance of communication in science, as the results of other groups form the basis for one's own work.
In this case, this influence is reflected in several facts: Since the different ratios between the nucleotides were initially interpreted as uncertainties in measurements, it was assumed that the four bases adenine, thymine (or uracil), guanine and cytosine occur with equal frequency. This led to Levene’s inaccurate tetranucleotide hypothesis [15]. Similar, based on density measurements from Astbury that did not distinguish between the A and B forms of DNA and without the new X-ray diffraction pattern of Franklin and Gosling, Pauling and Corey modeled the DNA as three strands with the backbone in the center of the helix (see fig. 2) [20, 30]. This erratic development emphasizes that scientific knowledge has a tentative character and that its results can be subject to reinterpretation at any time [29]. However, this also applies to the results of Crick and Watson: in their article, they only depict two instead of three hydrogen bonds between guanine and cytosine [12, p. 89]. Because of doubts concerning the exact structure of guanine, they nevertheless suggest a third hydrogen bond. The adaptation addresses both this and Pauling and Corey's model, which is critically disproven by Crick and Watson. Only the impact of Levene’s tetranucleotide hypothesis cannot be shown by the adaptation alone. However, in order to use this for teaching, the adaptation can be used as a starting point for further discussion.
This historical case also opens debates about ethical questions. What role did Rosalind Franklin play in the whole process and is she a victim of sexism? Was research data stolen from her by Crick and Watson? These questions are highly debated among historians [30–33] and by far from easy to answer, which is why we would like to emphasize that we are no experts in these particular questions. If educators wish to debate this aspect in class, we strongly recommend an open approach, hearing both sides of historians. Specifically, this debate revolves around the question of whether or not Franklin knew about and approved the sharing of research data to Crick and Watson. This is still ongoing: A recent *Nature* comment [32] describes previously unstudied documents suggesting that Franklin was an equal contributor and knew that the data were shared with Crick and Watson. In addition, at least according to Crick and Watson, her data were not used for model building, but for its verification [32]. In their article from 1953, firstly communicating their model, they declared that they were “not aware of the details” and have only “been stimulated by a knowledge of the general nature of the unpublished experimental results and ideas” of the work of Franklin and Gosling [19, p. 737]. In 1954, they generally repeat this statement in an footnote but add that “without this data the formulation of our structure would have been most unlikely, if not impossible” [12, p. 82]. How to interpret the phrases “details” and “general nature” as well as to what extent these statements are trustworthy, everybody has to decide for themselves.
However, to be accurate, three things should be made clear: First, the X-ray diffraction image (“photo 51”) was taken by the often-forgotten Raymond Gosling – and not by Franklin, who supervised him at that time. Second, Crick and Watson should have asked for permission to use the data, and they should have made it clearer what they were doing with the data. Whether they used the data for modeling or for verification is irrelevant in terms of good scientific practice. And lastly, it is pretty safe to say, that Franklin’s scientific achievements were not give enough credit by Crick, Watson and Wilkins.
Another learning opportunity concerns the modeling of the DNA structure and is strongly connected with the case of Rosalind Franklin. In her research, Franklin used a bottom-up approach: On the basis of gathered evidence she hypothesized a structure which fits the data best. If the hypothesis does not fit all the available data, she rejected it. In contrast, Crick and Watson worked top-down and built real physical models based on known bond angles and distances, ignoring most of the evidence [30]. Interestingly this also includes Chargaff rules which were not used to *construct* the model (according to statements made by Crick and Watson) but which can be *explained* with the model. The conclusion of an actual *physical* parity of adenine with thymine and guanine with cytosine from the 1:1 base ratios according to Chargaff is – historically at least – incorrect, although often made in textbooks [30]. The difference of the approaches of Franklin and Crick/Watson directly opens the opportunity to discuss scientific modelling in general. Often scientific models are known as the product of science, depicting a phenomenon of the natural world in a simplified way, while scientist, and Crick and Watson in particular, also *use* models in the process as a tool for generating the knowledge. In the framework of Upmeier zu Belzen et al.'s [34] modeling competence, this fact can therefore be used to improve students' modeling competence from Level I, in which models are described as the object of illustration of a phenomenon, to Level II or III, in which students acquire competencies in the construction and appropriate use of models.

Conclusion

In conclusion, the adaptation of scientific literature, particularly the seminal work of Crick and Watson on the structure of DNA, offers a rich opportunity for science education. By delving into the historical context and different methodological approaches employed by scientists, students have the opportunity for learning several concepts beside the scientific content itself. Especially focused on NOS, students can explore the tentative nature of scientific findings, the influence of social factors on research, and the ethical considerations inherent in scientific practice. Furthermore, analyzing the contrasting approaches of scientists like Rosalind Franklin and Crick/Watson provides a platform for discussing scientific modeling and foster modeling competencies.

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