An Action-oriented Way to Learn Classical Genetics – Part I

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ABSTRACT

The model described enables learners to access knowledge in classical genetics in an action-oriented way. Several key constructs are covered by this model. The structure of a set of chromosomes, the simplified process of the meiosis, gender inheritance as wells as the recombination diversity of chromosomes during "offspring procreation" are highlighted in this paper.

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Introduction

Classical genetics is an important teaching topic that is first dealt with in lower secondary school and taken up again in upper secondary school. Mendel's laws are a key element of classical genetics. They only can be understood properly if students have knowledge of the structure of a set of chromosomes and the distribution of the chromosomes as well as alleles during germ cell formation. The following model can be used to facilitate students' introduction to classical genetics. With the help of this model, the topics identified below can be addressed more effectively:

1. Introduction of key concepts of genetics: genome, chromosome, gene, allele, DNA
2. Structure of a set of chromosomes
3. Simplified presentation of the mechanism of the meiosis
4. Recombination diversity of the chromosomes during "offspring procreation"
5. Mendel's laws
6. Sex-linked inheritances

This paper addresses Topics 1–4, and a subsequent article (Part II) will deal with Topics 5–6.

The Model

The model is composed of two cotton reel sets. Each of these two sets contains eight cotton reels.

The cotton reels of one set are marked with the icon for female; the ones of the other cotton reel set are marked with the icon for male (a corresponding marking can be made, for example, on the cotton reel spindle). Of the eight cotton reels, two have the same color each (i.e., two brown, two red, two green and two blue cotton reels). Thus, there are four "cotton reel pairs" per cotton reel set. In each pair, one cotton reel has a clear color and the other has a dark color (for example light red and dark red). Furthermore, the following particularity appears in the male cotton reel set: In the blue cotton reel pair, one cotton reel is of normal size, the second one is clearly smaller. For deducing Mendel's laws, variably-colored rubber bands should be wrapped around the cotton reels. The use of rubber bands is, however, not necessary for the topics addressed in this article.

Introducing Students to the Model

Students only need minimal knowledge to work on the model. They should know that living beings are comprised of cells and that the genetic substance is found in the nucleus of each single cell. On average, a human cell has a size of 50 µm (0.05 mm) and the cell nucleus takes up approximately 5%–20% of the overall volume of a cell (Kunsch & Kunsch, 2000).

The entire genetic make-up of a human being is included in the nucleus of each human cell. Mature erythrocytes and thrombocytes, which lack a cell nucleus, are an exception. This genetic make-up corresponds to a "razor-thin" thread with a length of approx. 2 meters and represents the double set of chromosomes in one cell. If a cell has to divide, this 2-meter thread must first be doubled, so that each of the two resulting daughter cells receives a copy of the genetic make-up.

Now it is easy to imagine that such a long "genetic make-up thread" is difficult to handle. In this respect, segmenting this thread into several pieces seems to be advisable. Furthermore, it is convenient if the thread is wadded up to be transported into the daughter cells. In

our model, the fragments of the "sliced DNA thread" are simply reeled up. The eight aforementioned cotton reels constitute the end product. Table 1 provides an overview of which technical terms can be explained with the described cotton reel model.

Explaining the Model

In a teacher-guided conversation, the students analyze the structure of the set of chromosomes of human cells by means of the model. Furthermore, the teacher can address the transmission of genetic information during germ cell formation. Remarks and possible questions of the teacher as well as students' answers are presented in Table 2.

Work with the Model: The "Cotton Reel Game"

In the next step, the teacher explains how meiosis, i.e., the distribution of the chromosomes on egg and sperm cells, can be simulated using this model. The students are divided into groups (of 2–4 persons) to work on the model. Each group receives two cotton reel sets / sets of chromosomes: the one of a woman and the one of a man. To be able to differentiate the two cotton reel sets, the cotton reels are marked with the icons for female and male respectively. This marking is necessary to be able to rebuild the initial sets of chromosomes of the parents later (this is particularly important when deducing Mendel's laws because the cotton reels are equipped with variably-colored rubber bands).

The instructional (as well as "playful") task of the students is to build at random the sets of chromosomes of an egg cell and of a sperm cell from the sets of chromosomes of a woman and a man, so as to "procreate" a child. The procedure is described below.

First, an egg cell is produced. It is based on the set of chromosomes/cotton reels of the mother. A student removes the first cotton reel pair (for example the brown one), interchanges the two cotton reels behind his/her back and presents his/her closed hands to a second group member, with a cotton reel hidden in each hand. This second group member plays the role of the random generator and spontaneously points to the right or the left hand. The selected cotton reel becomes part of the egg cell, while the other cotton reel is discarded. Similarly, one cotton reel is selected from cotton reel pairs 2, 3 and 4, respectively, and, thus, the set of chromosomes/cotton reels of the egg cell is completed. Afterwards, the set of chromosomes/cotton reels of the sperm cell is built according to the same method. Students list the sets of chromosomes of both germ cells on their work sheet (Figure 1). The colors of the cotton reels are already given to ensure a homogenous representation. Thus, only the degree of lightness remains to be marked. Next comes the combination of the two germ cells, which results in the set of chromosomes/cotton reels of the child. It is recorded in color on the work sheet as well.

Analysis of the Model Work

Gender inheritance. The number of girls and boys among the produced cotton reel children is determined in the class. The result is recorded on the work sheet (Figure 1). The real ratio should be set in relation to the idealized ratio. The latter can be determined by means of a crossing scheme (see work sheet). Here, the gender characteristic gives the advantage that the crossing scheme refers to chromosomes that are differently shaped and not yet to single gene variants (alleles). Chromosome representation is clearer and shows the reference to the entire set of chromosomes better.

The probability with which both genders appear can be read directly from the crossing scheme. Both woman and man can form two "different" germ cells with reference to the appearance of their sex chromosomes: One X chromosome (i.e., the light blue cotton reel) gets into 50% of the egg cells and the other X chromosome (i.e., the dark blue cotton reel) gets into the other 50%. A 50%/50% distribution also applies to the sperm cells. For the offspring, four different combination possibilities of the sex chromosomes exist, where each has a probability of 25% = 0.25. Here, two combination possibilities, respectively, determine the formation of the female or male gender. In other words, girls and boys appear with an equal probability of 50% = 0.5. Thus, the idealized ratio is 1:1.

Why do parents have no genetically identical children (apart from identical twins)? Students are asked the following two questions (1) Is it possible that, in the cotton reel game, children come into being who only inherit the light chromosomes/cotton reels of their parents? and (2) Are such children really "produced" during the cotton reel game?

The first question can be answered with a clear "yes." If the set of chromosomes of a child is only composed of light cotton reels, the child has, thus, only inherited the chromosomes/cotton reels of the grandmothers, not those of the grandfathers, from both parents. The contrary situation, in which only the dark-colored chromosomes/cotton reels (from the grandfathers) are transmitted to the children is also conceivable. The second question will often be

Table 1. Technical Terms that can be Explained by Means of the Cotton Reel Model

Description	Technical term	Model
Totality of the genetic make-up in one cell (in the nucleus, in the mitochondria and, if applicable, in the plastids)	Genome	2-meter cotton thread (corresponds to the DNA in the nucleus of a human cell, the mitochondrial DNA is not considered)
Chemical substance which the genetic make-up is composed of	DNA	Cotton thread
Larger area of the genetic make-up in the nucleus	Chromosome	Cotton reel; it corresponds to a spirally reeled-up section of the 2-meter cotton thread (even if the thread of an usual cotton reel is, of course, much longer)
Smaller area of the genetic make-up with a specific function	Gene*	Rubber band that is wrapped around the cotton reel at a specific level (a different coloring of a short thread range of the cotton reel would be more appropriate – as this is difficult to realise, rubber bands are used to simplify matters)
Different variants / types of a gene	Alleles*	Variably colored rubber bands that are at the same level of the 2 chromosomes of a pair of chromosomes
2 chromosomes of the same size and shape (the shape refers to the position of the centromere)	Pair of chromosomes / homologous chromosomes	2 chromosomes of the same color, where the color appears lighter or darker. The dark-colored chromosomes correspond to those of the father, the light-colored chromosomes to those of the mother.

Note: The technical terms marked with * as well as the rubber band marking of the cotton reels are crucial to the development of Mendel's laws only.

negated, i.e., children with a light cotton reel set are only rarely produced during the cotton reel game. Why is that so? Here, reflecting on the probability of the occurrence of the light set of chromosomes/cotton reels assists understanding. First, the probability with which the light cotton reels get into an egg cell must be calculated. Here, each cotton reel pair is considered individually. The probability that the light brown cotton reel comes from the brown cotton reel pair and enters the egg cell amounts to 50% = 0.5 = 1/2. The probabilities are exactly the same for the light red, the light green and the light blue cotton reel. The probability that all four light cotton reels get into the egg cell at the same time is obtained by multiplying the individual probabilities: 1/2 x 1/2 x 1/2 x 1/2 =1/24 = 1/16 = 0.0625 = 6.25% (see multiplication rule in Campbell & Reece, 2009). The same result is obtained by reflecting on and recording the number of different egg cells that can be formed on the basis of the set of maternal chromosomes: They are 16 = 2^4. The probability of occurrence for a very specific egg cell, with only light cotton reels, then amounts to 1/16 = 0.0625 = 6.25%.

For a sperm cell, also with light cotton reels only, the probability of occurrence is exactly the same, that is 1/16 = 6.25%. The probability that the described egg cell and sperm cell meet amounts to 1/16 x 1/16 = 1/256 = approximately 0.004 = 0.4% during the cotton reel game. This means that there is theoretically one child among 256 cotton reel children who displays the designated set of chromosomes.

The probability that, in reality, parents may procreate children with a very specific, i.e., an identical set of chromosomes, is extremely low. We become aware of this when we consider that the set of chromosomes of the human being does not contain 8, but rather, 46 chromosomes. The probability of obtaining a specific egg cell or sperm cell (for example only with chromosomes of the grandmother) thus amounts to $1/2^{23}$ = 1/8,388,608 = 1/83,886%. The probability that two such germ cells meet amounts to $1/2^{23}$ x $1/2^{23}$ = $1/2^{46}$ and is, thus, extremely low.

Comparison of the Cotton-reel Meiosis with Real Meiosis

Following the cotton reel game, the cotton reel meiosis can be compared with meiosis representations in the textbook. The task of the students is to point out differences between the model and the representation in the book.

The main difference is that only the first meiotic division, the reduction division, is completed during the cotton reel game. The second meiotic division, which corresponds to mitosis, is, however, missing. During this division, the chromatids of the chromosomes are separated. If we wanted to represent the chromatids in the cotton reel model, we would have to convert each cotton reel into a cotton reel twin.

Table 2. Explanations and Questions of the Teacher regarding Understanding the Cotton Reel Model as Well as Germ Cell Formation

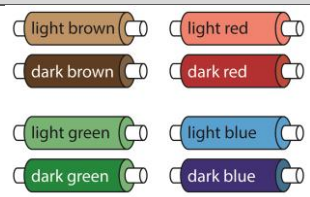
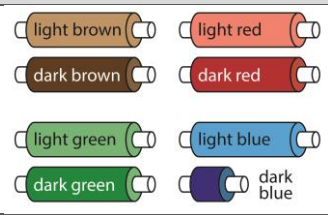
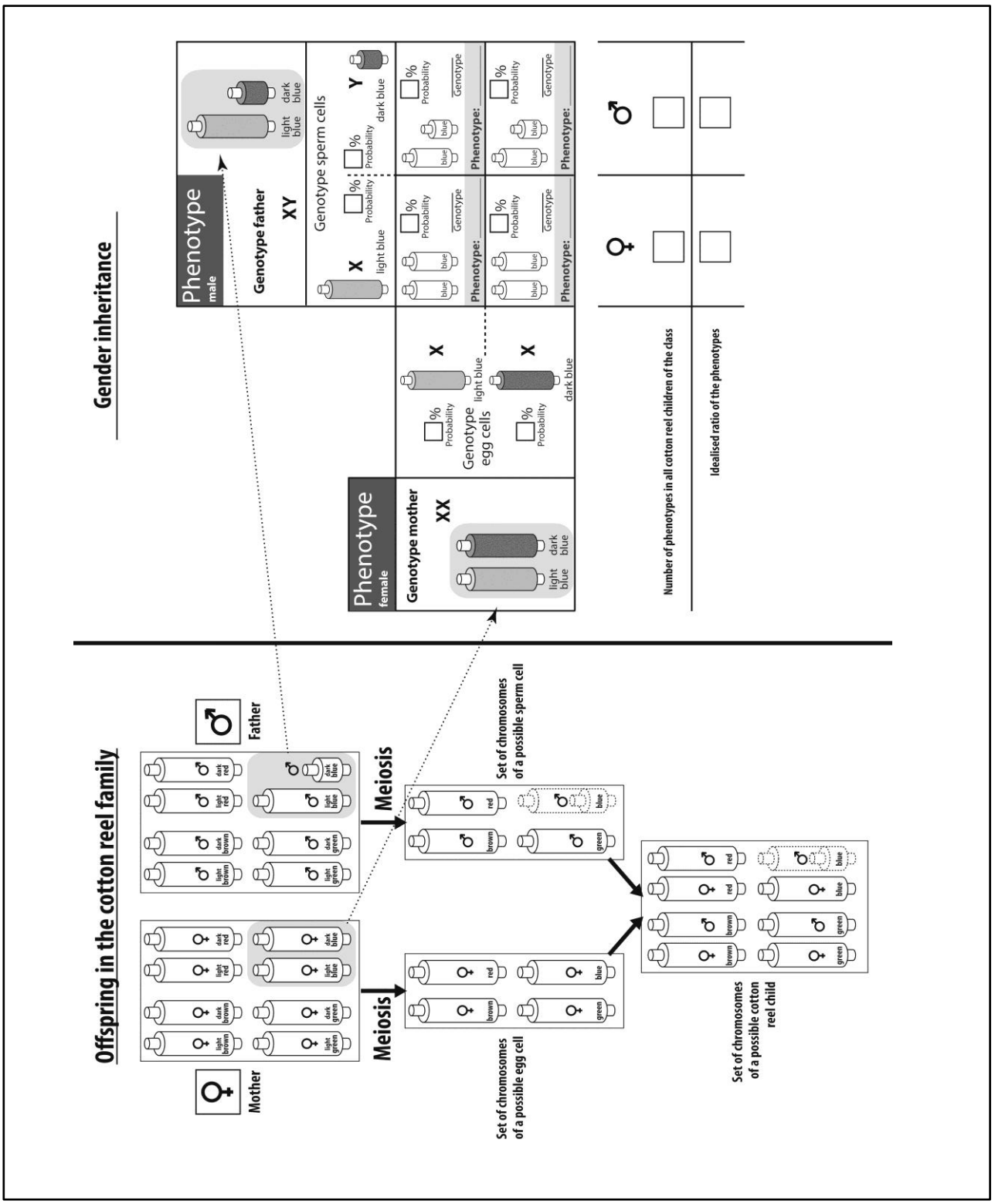
Note: 46 chromosomes are present in the nucleus of human cells. A corresponding model with 46 cotton reels is however too complex. For simplification, the number of cotton reels is reduced to 8.	
A colored **figure** of a set of chromosomes/cotton reels is shown. Contrary to the model described at the beginning, the icons for female and male are missing in this figure. It is also done without rubber bands, i.e., without marking the genes.	
Task: Describe the displayed "set of chromosomes" Which particularity sticks out here?	**Possible student answer:** The set of chromosomes contains 8 chromosomes. What sticks out in the model is that 2 chromosomes (more precisely: 2 cotton reels) have the same color. 4 pairs of chromosome are thus present. In each pair, one chromosome has a lighter, the other a darker coloring.
Note: In a set of chromosomes, each chromosome appears twice or in pairs. This means that each gene appears twice as well.	
Task: Explain (rather: figure) why each chromosome (each cotton reel color) appears twice.	**Possible student answer:** A human being receives genetic information from both his mother as well as from his father.
Note: The dark cotton reels correspond to the paternal chromosomes, the light cotton reels to the maternal chromosomes.	
A colored **figure** of a second set of chromosomes/cotton reels is shown. This set of chromosomes is that of another person.	
Task: Describe to what extent the second set of chromosomes is different from the first one.	**Possible student answer:** In the second set of chromosomes, the blue pair of chromosomes is built up differently. One chromosome is of normal size, the other one is strongly shortened.
Note: The inhomogeneous pair of chromosomes corresponds to the sex chromosomes (heterochromosomes). The long chromosome is designated as X, the short one as Y. The second set of chromosomes displays the combination XY and is therefore that of a man. The first set of chromosomes with 2 sex chromosomes of the same size XX is that of a woman. The other pairs of chromosomes of the same shape, which are not sex chromosomes, are designated as autosomes.	
Task: Assume that two persons have decided to have children. They transmit their chromosomes to their offspring. But before that, the chromosomes must first get into the germ cells – i.e., into egg cells and sperms. Justify which of the mechanisms mentioned in the following is the most probable for the transmission of genetic information during germ cell formation: a) All 8 chromosomes of each parent get into the germ cells – both into the egg cell as well as into the sperm – and are transmitted to the child. b) Only 4 chromosomes of each parent get into the germ cells. Here, pairs of chromosomes are transmitted. In this case other pairs of chromosomes get into the sperm cell than in the egg cell. The blue and green pair of chromosomes, for example, are transmitted in the egg cell and the brown and red pair of chromosomes get into the sperm. c) Only 4 chromosomes of each parent get into the germ cells. Here, one chromosome of each pair of chromosomes is transmitted. Four different chromosomes (cotton reel colors) are thus present both in the egg cell as well as in the sperm.	**Possible student answers:** a) Inappropriate mechanism, as the child would then have 16 chromosomes per cell, the grandchild 32 chromosomes, etc. b) Inappropriate mechanism. Possible justifications: How can we determine which pairs of chromosomes get into the egg cell and which into the sperm? If there were a determination, it should be the same for all humans. In this example, the sex chromosomes (here: blue pair of chromosomes) are always transmitted by the mother. The result would be female offspring only. If the number of pairs of chromosomes were not even (4) but uneven, (e.g., 3), different amounts of chromosomes should get into the egg cell and the sperm cell. This seems to be improbable. In the initial figures/sets of chromosomes, each pair of chromosomes is comprised of 2 chromosomes (cotton reels) of different color lightness, where the light colors correspond to the maternal chromosomes and the dark colors to the paternal chromosomes. It can be concluded from this color pattern that no pairs of chromosomes are inherited but that never more than one chromosome of each pair of chromosomes is transmitted to the child from the mother as well as from the father. c) Appropriate mechanism, as the child, just like the parents, has a set of 8 chromosomes. In the germ cells there are 4 chromosomes with each chromosome type (i.e., each cotton reel color) and thus also each gene being represented once.
Note: The selection of which chromosome of each pair of chromosomes gets into a germ cell occurs randomly. This random **principle** during the formation of egg cells and sperms can be understood by means of the model.	

Figure 1. Work Sheet



This means that each cotton reel appears twice, where the two identical cotton reels are held together by a rubber band. This rubber band corresponds to the centromere. It is also possible to use the cotton reel model to represent the cell cycle and mitosis. In the G1 phase, eight individual cotton reels are present. In the S (synthesis) phase, the individual cotton reels are doubled and 8 cotton reel twins are produced. These continue to exist during the G2 phase. During mitosis, the cotton reel twins are then separated and 8 individual cotton reels respectively get into the two daughter cells. The individual cotton reels thus represent one-chromatid chromosomes and the cotton reel twins represent two-chromatid chromosomes. However, the two-chromatidity of the chromosomes is not considered in the cotton reel game presented here.

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References

Campbell, N.A., & Reece J.B. (2009). *Biologie* [Biology], 8th ed. Munich: Pearson.

Kunsch, K., & Kunsch, S. (2000). *Der Mensch in Zahlen* [Man in numbers]. 2nd ed. Heidelberg: Spektrum Akademischer Verlag.

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