Learning Mendelian Genetics Through a Simple Coin Toss Game

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Most students, whether nonscience majors or life sciences majors, have difficulty in using what they learn about basic Mendelian genetics to deduce the underlying genetic rules from the results of crosses. This is especially true for organisms that have relatively few offspring and thus the result of any one cross does not often produce the predicted ratios of phenotypes. Being able to predict ratios of genotypes and phenotypes of a cross from known parental genotypes is but a first step in understanding Mendelian genetics. The true utility of Mendelian genetics is to be able to deduce the underlying genetics from a pedigree. I have devised a simple coin toss game that allows students to grasp how Mendelian genetics works. This hands-on activity requires very little preparation or materials but provides a clear and meaningful way to demonstrate the fundamentals of Mendelian genetics. This exercise is only appropriate for simple Mendelian traits; that is, those traits determined by a single nuclear gene in a simple dominance or recessive relationship. It is not suitable for cytoplasmic/mitochondrial inheritance, nor for the complexity of varying penetrance. This exercise is most useful after the students have been introduced to Mendelian genetics and the Punnett square. This simple exercise can be fun and challenging not only for nonscience majors but for biology majors as well.

Materials

The main materials for this exercise are sets of pedigree charts (see samples in this How-To-Do-It). We also use a coin and a marker pen that students can provide. The pedigree charts already have the circles and squares connected by lines (Figure 1). Each group of 3 to 5 students is provided with pedigree charts: one "genotype" chart and several blank "phenotype" charts. The genotype chart has the genotype of select individuals noted (Figure 1a and Figure 2) and whether the trait to be simulated is dominant, recessive, or sex-linked recessive. The phenotype charts have the same number and orientation of squares and circles connected by lines but are otherwise blank. The exercise involves filling in the genotype chart by tossing a coin to determine which of the two alleles is inherited by an offspring. Thus, the exercise simulates nature; each offspring is a result of random choice of one of the two copies of the gene in each parent.

Instructors can make their own pedigree charts. A blank pedigree chart can be made using the pedigree charts in Figure 2 as a guide and adding and/or deleting individuals or generations. Alternatively, teachers can use their own or other families' pedigrees. First decide upon the type of trait: dominant, recessive, or sex-linked recessive. Then, keeping in mind the type of trait, pick the genotype for select individuals. It is easiest to indicate the genotype of the oldest (top) part of the pedigree and new individuals that marry into the pedigree.

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Procedure

1. First note the genotype for select individuals on the genotype chart. In the example given in Figure 1a, the father is heterozygous and the mother is homozygous recessive.
2. Next decide which copy of the gene corresponds to heads and tails; for example, heads = **A** and tails = **a**. Once decided, keep it the same throughout.
3. Now determine the genotype of an offspring by tossing a coin. Toss the coin for the father. This determines which copy of the gene the father contributes to his offspring. By tossing a coin, we have a 50:50 chance of getting heads, that is **A**; or getting tails, that is **a**. In the example on Figure 1, the chance of getting **a** from the mother is 100%, or 1.0, and the chance of getting **A** or **a** from the father is 50% or 0.5. Thus, there is a $1.0 \times 0.5 = 0.5$ or 50% chance of offspring with genotype **Aa** and a 50% chance of offspring with genotype **aa**. However, with the small number of offspring, the coin toss may result in all **Aa** or all **aa** offspring or any combination in between.

Similarly, the sex is determined by the sex chromosomes. In mammals, females have two X chromosomes and males have an X and a Y. The probability of the father contributing an X is 50% and Y is 50%, so on average, the offspring should be roughly 50% female and 50% male. In Figure 3, I have indicated vertical lines to indicate offspring, but there are no squares or circles below the lines to indicate their gender. Try tossing the coin, with X as heads and Y as tails to determine the sex ratio of the 10 offspring. If everyone in the class did it, the overall ratio of male to female offspring will be close to 50%, but many individual pedigree charts will have ratios different from 50:50.

In Figure 1, if the mother was also heterozygous, **Aa**, then the probability of an offspring with genotype **aa** is the probability of father contributing an **a**, 50%, and the mother contributing an **a**, 50%; that is, $0.5 \times 0.5 = 0.25$ or 25%. The same calculation will

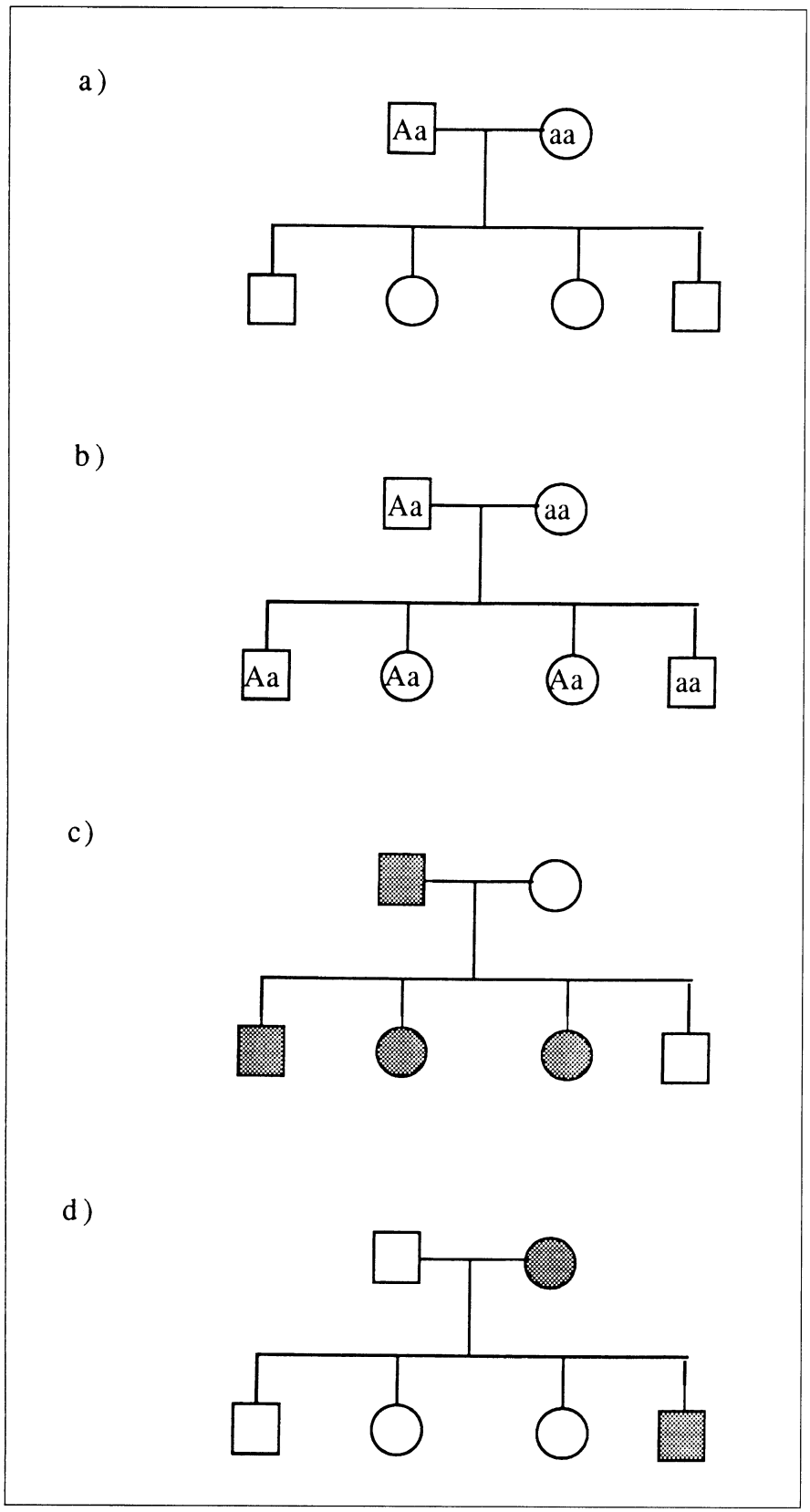

Figure 1. A simple example of a set of pedigree charts with one set of parents and four offspring. Typical of such a small pedigree, the result is ambiguous; that is, one cannot decide the rules of inheritance from the phenotype charts.
a) An example of an original genotype chart given to the students.
b) The same genotype chart after students finish their coin toss.
c) The phenotype chart for b) if the trait is dominant.
d) The phenotype chart for b) if the trait is recessive.

apply for an offspring of genotype **AA**. In calculating the probability for an offspring with genotype **Aa**, since either the mother or the father can contribute **A** and then either the mother or the father can contribute **a**, the probability of genotype **Aa** is 2 × 0.5 × 0.5 = 0.5 or 50%. This is the probability that one derives from using the Punnett square. However, the results from the coin toss for the small number of offspring in any of the pedigrees may not match these expectations. This is what makes this exercise a challenge.

Note: You need not toss a coin for any homozygous parent. For example, in the example given here, you need not toss the coin for the mother since she can only contribute **a**. You also need not toss the coin for a father in the case of a sex-linked trait since the sex of the offspring requires that either the X or the Y chromosome is contributed by the father.

4. Continue for each individual that does not have the genotype written. *Faithfully* note the result of each coin toss. Even if the expected ratio of offspring genotypes is 1**Aa**: 1**aa** as in this example, if each time you tossed the coin for the father you came up with heads, that is **A**, write **Aa** for each offspring.
5. As you determine the genotype or after completing the genotype pedigree chart, fill in the phenotype pedigree chart appropriate for the trait noted on your genotype chart. For example, if your genotype chart looked like Figure 1b, and the trait was dominant, the phenotype charts would look like Figure 1c. On the other hand, if the trait was recessive, the phenotype chart would look like Figure 1d.
6. Produce a phenotype chart for your group, one for the instructor, and for each of the other groups in the class. Of course, all the phenotype charts from one group should be identical.
7. Keep the genotype chart and a copy of the phenotype chart for your group and distribute the phenotype chart to each of the other groups.

Class Discussion

I instruct each group to look at its own phenotype chart and discuss within their group whether one can

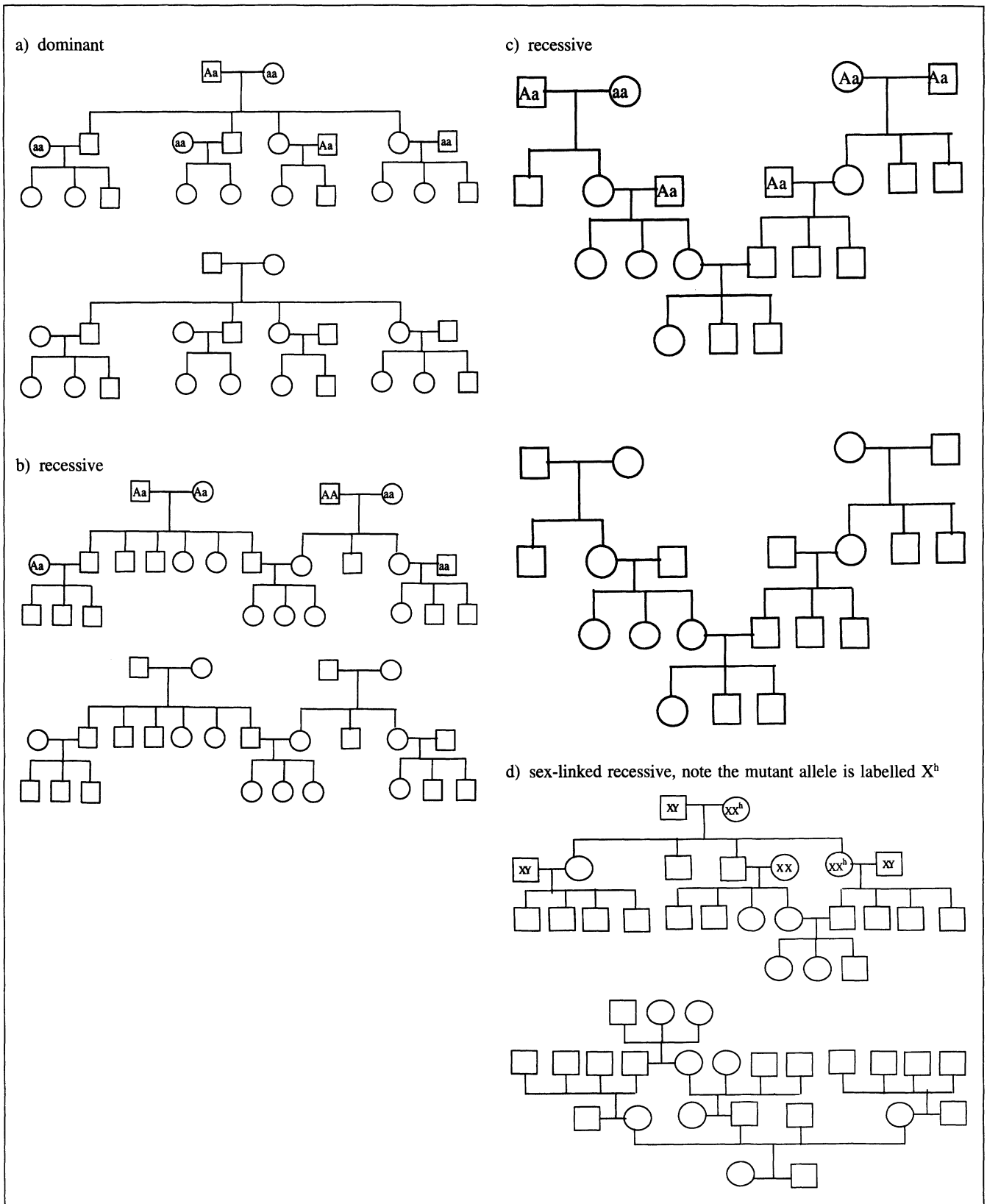

Figure 2. Samples of genotype charts and corresponding blank pedigree charts.
a) For a dominant trait. Examples of dominant disease in humans include Marfan syndrome, Alzheimer's disease, and amyotrophic lateral sclerosis or Lou Gehrig's disease.
b) For a recessive trait. Examples in humans include cystic fibrosis, sickle-cell anemia, and albinism.
c) Another example of a pedigree chart for a recessive trait.
d) For a sex-linked recessive trait. Examples in humans include hemophilia and many types of color-blindness, including the most common red-green form.

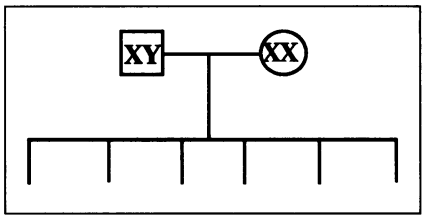

Figure 3. A sample incomplete pedigree chart to illustrate sex determination. Each vertical line indicates an offspring. By tossing a coin to decide whether the father's X or Y chromosome is passed on to his offspring, the gender of the offspring is determined, and a square for male, XY, and a circle for female, XX, can be drawn below each of the vertical lines. Any one pedigree chart can have all male, all female, or any ratio in between. For a large enough class, with ~ 30 students or more, the ratio of males to females should be close to 50:50.

unambiguously decide whether the trait was a dominant, recessive, or sex-linked recessive. The challenge for the instructor is to provide genotype charts that result in unambiguous phenotype charts most of the time. One way to ensure that particular genotypes arise is to indicate the genotype for key individuals or have a cross to an individual with a particular genotype. Some examples of genotype charts I have used in class are given in Figure 2. It is useful to have a variety of genotype charts, some with many offspring, others with more generations, and others with combinations of these. One may choose to have a genotype chart that often results in an ambiguous phenotype chart, since it is important that students recognize that pedigrees can be ambiguous. In those cases in which the resulting pedigree is ambiguous, I instruct the students to write the genotypes consistent with the alternative.

Once the group has finished analyzing its own phenotype chart, the group can then discuss the phenotype charts of other groups. The challenge here is to determine the genetic rules by which such a phenotype chart can result. Depending on the number of groups, I allow greater time for group discussion. This group discussion time among students is valuable for learning and should not be hastened.

While students are doing this, I reproduce each of the phenotype charts on an overhead transparency that I have prepared before class of each blank phenotype chart. This is also the time for the instructor to check on the phenotype chart, first to ensure that it can result from the assigned genotype and, second, to determine whether the phenotype chart unambiguously indicates one type of trait.

After students have had adequate time to analyze the phenotype charts, I lead a class discussion of each phenotype chart. A good starting point is to ask the group producing the phenotype chart whether it feels that the rules of inheritance for the trait can be decided unambiguously. If the group decided that the chart is ambiguous, the rest of the class can go through the exercise of what the genotypes of individuals must be if the trait is recessive, dominant, or sex-linked. In this process, sometimes it may be determined that the group was wrong and that the trait can only be due to one or another type of inheritance. In any case, it is valuable for the instructor to lead the discussion, assuming that the group producing the phenotype chart has reached the correct conclusion. Inevitably, the group discussion will reveal the error and why it is erroneous. If the group producing the phenotype chart decided that the chart is unambiguous, it is the job of the rest of the class to decide which type of trait it is. This can be quite lively with students providing the reason for suggesting one or another type of trait and another student saying, "Well, but what about

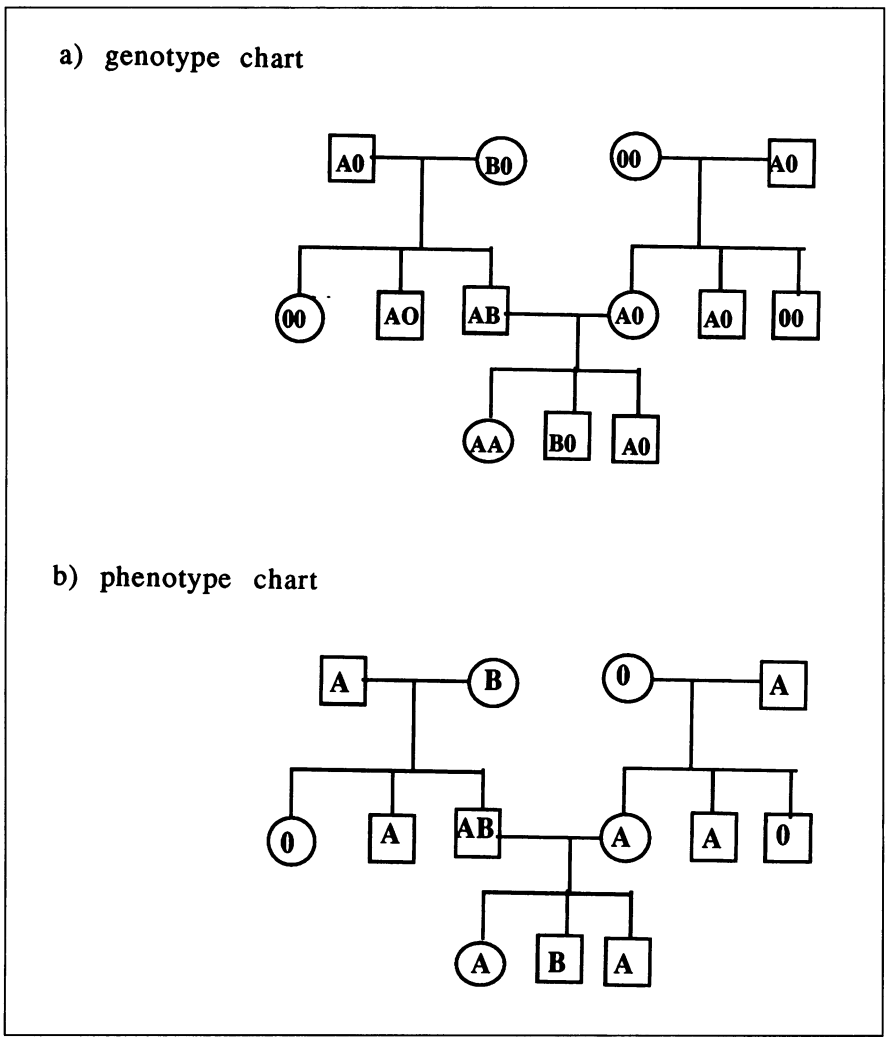

Figure 4. An example of genotype and the corresponding phenotype chart for ABO blood type, which is a co-dominant trait.

that individual?" Through this process, students truly grasp the meaning of dominant, recessive and sex-linked inheritance. Also in this process, students learn the importance of having multiple generations and more offspring in determining the rules of inheritance for a particular trait.

Extension of the Exercise

After this exercise, students are better able to appreciate pedigrees in textbooks and historical pedigrees, such as the incidence of hemophilia in Queen Victoria's large family mentioned in a variety of human genetics textbooks reprinted from McKusick (1969).

A good follow-up homework assignment is to have students research their own family pedigree. It may be helpful to provide a list of Mendelian human traits, such as those traits determined by single nuclear genes found in many genetic texts (though many emphasize disease traits). A handy list of non-disease physical traits can be found in Winchester & Wejksnora (1996). A good resource for human genetic disease is the Online Mendelian Inheritance in Man, OMIM (TM) which lists more than 5,000 human genetics diseases.

One pedigree that most students can construct uses the ABO blood type, which is actually a codominant trait. An example of a genotype and phenotype chart for blood type is given in Figure 4. In this case of codominance, O is recessive to A and B, but A and B are codominant; that is, both forms are expressed. So if an individual has blood type A, her/his genotype can be either AA or AO. Similarly, blood type B can be due to either BB or BO. The genotype of AB, however, can only be AB.

Conclusion

Understanding the fundamentals of Mendelian genetics is important for biological sciences majors as well as the general public. This coin toss game graphically illustrates simple Mendelian inheritance and the difficulty in determining the genetics of traits by just looking at the pedigree. The exercise is useful for a wide range of student backgrounds. By having students actually "do" crosses, key features of basic Mendelian inheritance are vividly grasped by the students.

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