

## Genetics Exercises: The Case of Industrial Melanism

These exercises provide an opportunity to use system dynamics to describe a well-studied case of genetic adaptation – the case of industrial melanism. Figure 1 illustrates. It shows a close-up photo of two moths on a tree trunk. The photo has a black background because the tree is covered with soot. You can see the white moth clearly, but you will have to look closely to see the dark moth. It is almost totally concealed because its dark color blends with the soot. Concealment is important to moths; they usually fly at night and rest during the day (Brooks 1991). The white moth in this photo would be particularly vulnerable to predation from birds during the day. The moths in Figure 1 are two forms of the peppered moth, *Biston betularia*. The light form is called typical. The dark form is called melanic. The melanics were quite rare 150 years ago, but they became dominant in some highly polluted areas of England.

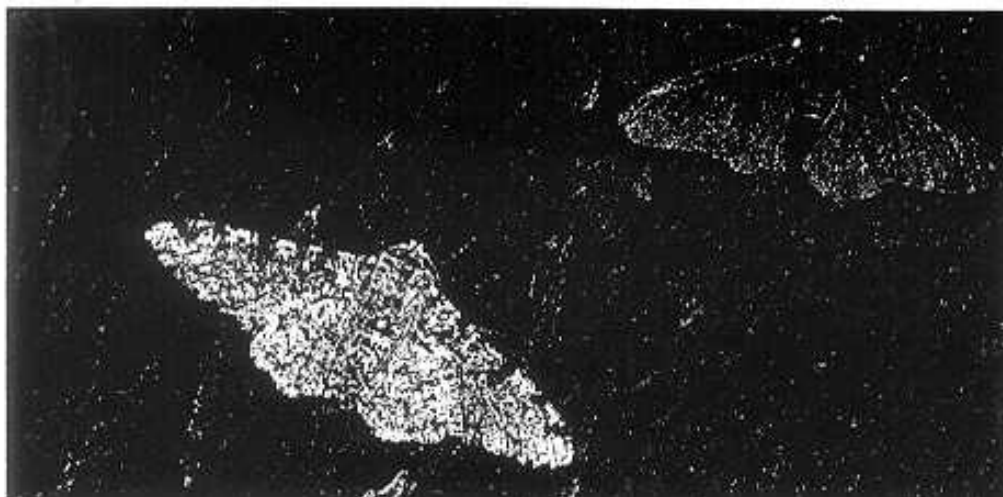


Figure 1.. Two moths on a soot-covered tree trunk.

The shift from the light to the melanic form has been called the "most striking evolutionary change in nature ever to be witnessed by Man" (Kettlewell 1973, 1). This document takes you part way toward a model to simulate this change. The exercises challenge you to finish the job.

### Building the 1st Model

Figure 2 shows the flow diagram for an introductory model of two moth populations. The black population corresponds to the melanic phenotype; the white population corresponds to the typical phenotype. Weaver and Hedrick (1995, p. 52) describe a third phenotype, the darkly mottled insularia. Let's ignore the third phenotype to keep the model simple.

The first model adopts identical assumptions for the black and white moths. They both spend 10 months in a preadult phase and 2 months as adults. Each population has 50% females; each female has 15 eggs per brood; eggs are deposited in July; eggs from white females lead to white progeny; and eggs from black females lead to black progeny. (These final assumptions make sense if the moths are pure breeding adults that self fertilize.) A single conveyor is used to represent their early months as ovum,

larva and pupa. During the preadult stage, their loss fraction can range from a low of 50% to a high of 99%. The exact loss fraction depends on the total in the preadult stages:

total\_in\_preadult\_stages = black\_ovum\_larva\_pupa+white\_ovum\_larva\_pupa  
 loss\_fraction\_in\_preadult\_stages = GRAPH(total\_in\_preadult\_stages)  
 (0.00, 0.5), (200, 0.6), (400, 0.7), (600, 0.8), (800, 0.9), (1000, 0.99)

After 10 months, the moths mature into the adult phase where both blacks and whites are exposed to a 50% bird loss fraction.

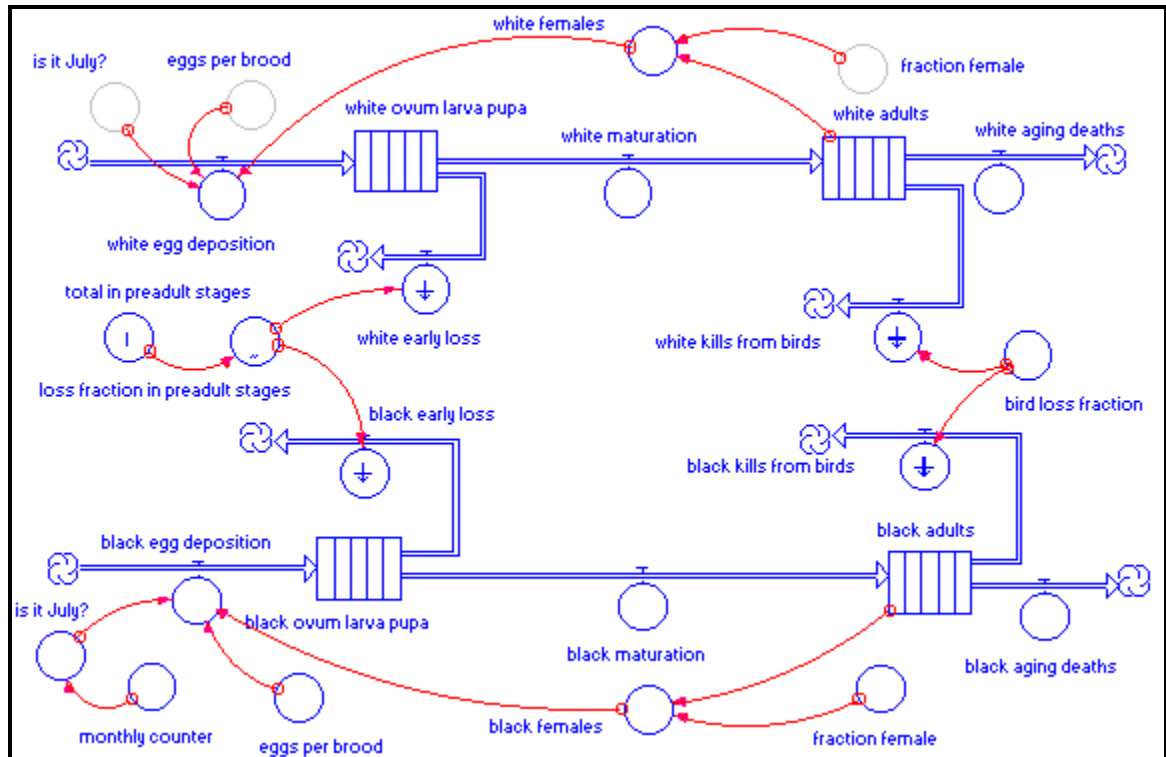


Figure 2. Introductory model of the moth populations.

### Testing the 1st Model

Figure 3 shows the simulated growth in the moth populations if the model is initialized with 2 black preadults, 2 white preadults and zero adults. The time graph shows the populations growing to a dynamic equilibrium of around 100 black adults and 100 white adults. With a total of around 200 adults, the moths are exposed to 60% losses in the preadult stage. This density dependent loss fraction is responsible for controlling the eventual size of the two populations. The 200 adults could occupy a small area, so the population in a study region might be measured in the thousands. The magnitudes aren't of interest here. It's the ratio of the two populations that we want to study.

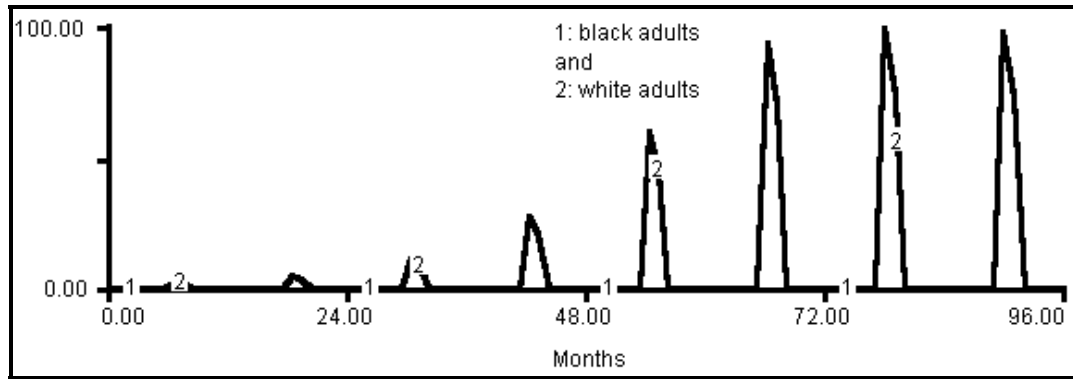


Figure 3. Results from the introductory model.

Figure 3 shows that the two populations would maintain a 1:1 ratio over time. The 1:1 ratio makes sense because the two populations start out with the same number of individuals in the preadult stage; they are exposed to the same losses in both stages of their life cycle; and the females have the same brood sizes. The 1:1 ratio makes sense for this model, but it does not match ratios observed in nature. Let's now consider whether genetic differences could lead to differences in the population sizes.

### Building the 2nd Model -- Add a Genetics Sector

Let's expand the introductory model to allow random mating between the black and white adults. We will use two sectors -- a main sector to simulate the population life cycle and a genetics sector simulate whether the matings lead to white or black broods. The "main sector" is shown in Figure 4 . It keeps track of the 12 month life cycle, and it assumes that black and white moths are exposed to the same loss fractions.

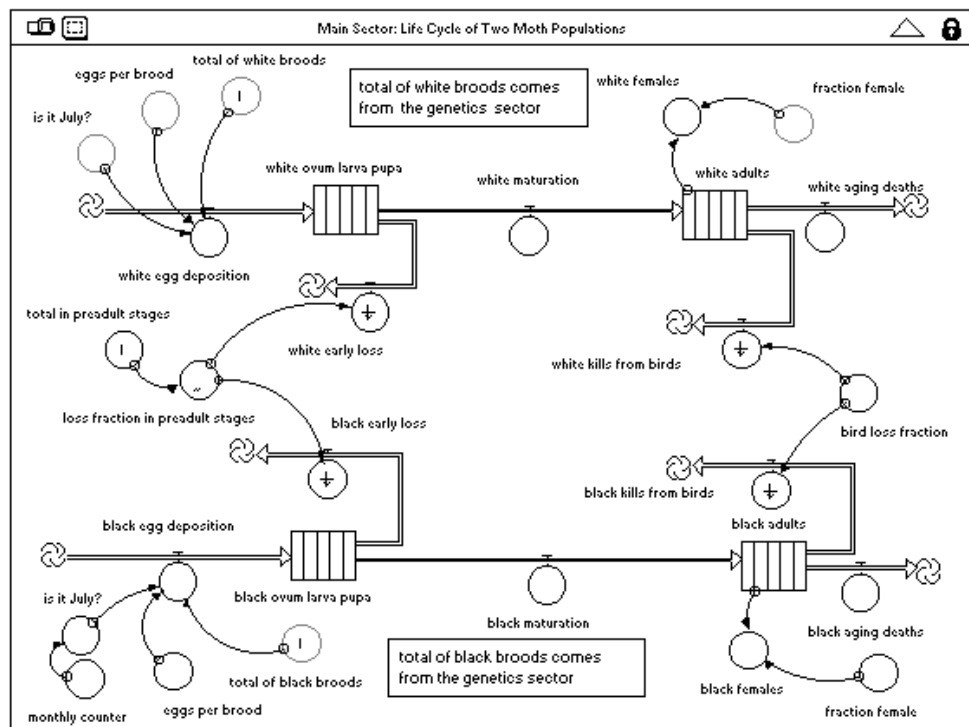


Figure 4. Main sector of the second model.

The "genetics sector" is shown in Figure 5. This sector simulates two phenotypes, black and white.

- The black (melanic) moth may be an individual with either of two genotypes (MM or Mm). (M stands for the melanic allele which is dominant; m stands for the light allele which is recessive.)
- The white (typical) moth will have only one genotype (mm). The genetics sector keeps track of the matings and resulting broods with either the black phenotype or the white phenotype.

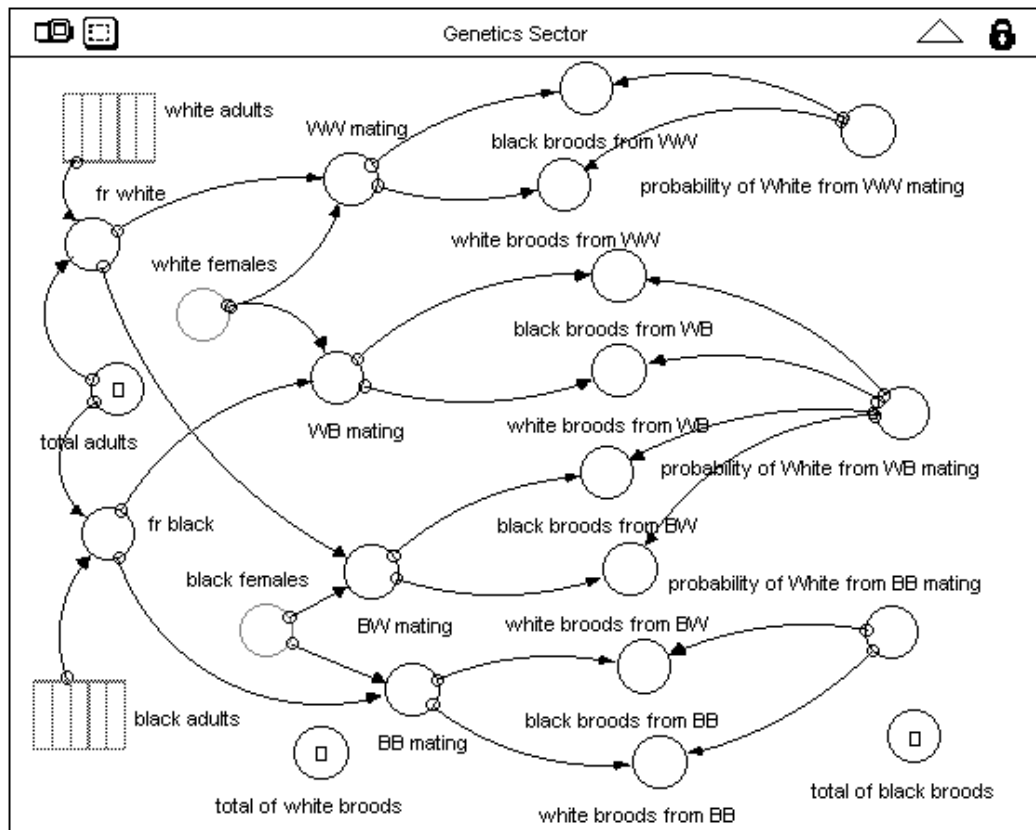


Figure 5. Genetics sector of the second model.

The genetic information is embedded in the three probabilities shown in Figure 5:

*probability\_of\_White\_from\_WW\_mating = 1*: Let's start with the probability that a mating between two white moths will lead to a white brood. A mating between two white moths is certain to lead to a white brood because both the male and the female have the white allele (m).

*probability\_of\_White\_from\_WB\_mating = .25*: Next, consider the matings between a white female and black male (or between a black female and a white male). The probability of a white brood is set at 25% based on the assumption that half of the black parents are homozygotes (MM) and half are heterozygotes (Mm). When one of the parents is a homozygote, the brood will be black, so at least 50% of the broods will be black. The other 50% of the broods are between heterozygotes, and half of these will result in a white brood. Consequently, the probability of a white brood is set at  $0.5 \times 0.5$  or 25%.

*probability\_of\_White\_from\_BB\_mating* = .0625: The third probability involves the matings between a black female and a black male. The probability of a white brood from such a mating is set at 6.25% based on the assumption that half of the black parents are homozygotes (MM) and half are heterozygotes (Mm). There is a 1 in 4 probability of heterozygotes mating, and these are the only matings with a possibility for a white brood. When heterozygotes mate, 25% of the matings will lead to a white (mm) brood. Consequently, the probability of a white brood is set at  $0.25 \times 0.25$  or 6.25%.

The genetics sector finds the number of broods from each of the eight possible matings and uses Stella's summer feature to find the total of white broods and the total of black broods. The totals are passed to the main sector to keep track of black and white egg deposition.

Now, you should remain alert to the assumptions underpinning the three probabilities. The key assumption is that the two genotypes of the melanic phenotype are equally frequent. This may be true after one generation of random mating (i.e., as described by the Hardy-Weinberg principle). But it is not necessarily true in general.

### Testing the 2nd Model

Figure 6 shows the simulated behavior of the second model starting with the same set of initial conditions used in the introductory model. The populations still reach dynamic equilibrium in around eight years, and we still see a total of around 200 adults. But the mix of blacks and whites is much different than before. Figure 6 shows around 175 blacks and only 22 whites. We now have an 8:1 ratio of blacks to whites even though both the blacks and whites are exposed to the same loss fractions in the preadult stage and in the adult stage of their life cycle. The 8:1 ratio of blacks to whites arises from the random mating and the dominance of the melanic (M) allele.

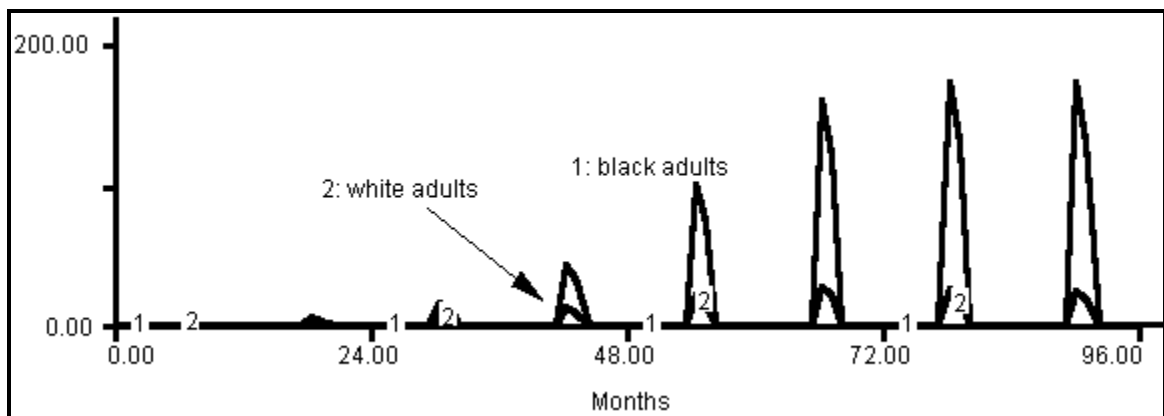


Figure 6. Simulated behavior of the second moth model.

The second model does a good job in combining the population life cycle of the two moth populations with the genetics sector. We are now able to simulate the differences in the relative size of the populations due to their genetic differences. In this first test, we observe an 8:1 ratio of black moths to white moths. The 8:1 ratio is a logical result of the assumptions adopted so far.

But we face three problems with this model:

1. First, the 8:1 ratio does not agree with observations from the era prior to industrialization. The black moths were certainly not 8 times more prevalent than the white moths. Indeed, the black moths were quite rare in the era prior to industrialization.
2. The second problem is closely related to the first -- this model does not deal with concealment and bird predation. In its present form, we are not in a position to simulate industrial melanism.
3. Finally, the model relies on probabilities derived from the assumption that the two genotypes of the melanic phenotype are equally frequent. A more general approach would involve a model with each genotype simulated explicitly.

This collection of exercises challenges you to expand and improve the model to deal with these problems. Seven introductory exercises have been designed for students beginning their study of genetics. The exercises are organized around the challenge of simulating industrial melanism with relatively minor changes in the existing model.

### 1. Build and Verify

Build the second model and verify that it generates the behavior shown in Figure 6.

### 2. Predation Losses Depend on the Soot Index

Introduce a soot index, a model input which will range from 0 to 1. Set the index to 0 to represent conditions prior to industrial development; a value of 1 represents the highly polluted conditions shown in Figure 1. Then define separate loss fractions from bird predation as shown below

```
white_moth_bird_loss_fr = GRAPH(Soot_Index)
(0.00, 0.1), (0.25, 0.3), (0.5, 0.5), (0.75, 0.7), (1.00, 0.9)
```

```
black_moth_bird_loss_fr = GRAPH(Soot_Index)
(0.00, 0.9), (0.25, 0.7), (0.5, 0.5), (0.75, 0.3), (1.00, 0.1)
```

With the soot index at zero, the white moths are well concealed, so they are exposed to only 10% losses from birds. The blacks, on the other hand, would be highly visible, and they are exposed to 90% losses. If the index moves to 1.0, the opposite extreme, the whites become much more visible to the birds and are exposed to 90% losses. With the index at 1.0, the blacks would be well concealed and experience only 10% losses. Notice that the graphs set the losses for both black and white moths at 50% if the index is at the intermediate value of 0.5.

### 3. Verify that the White Moths Dominate Under Clean Conditions

Run the new model with the soot index set to zero. The simulation should show the combination of white and black moths reaching dynamic equilibrium with approximately 200 adults (as in the previous examples). But the low loss fraction of the white moths will allow them to predominate. Your simulation should show a ratio of approximately 10:1 in favor of the whites.

#### 4. Simulating Industrial Melanism

Now run the new model over 480 months to simulate a four decade period in which urban pollution gradually changes the soot index from 0 to 1. Turn in a time graph of the size of the black and white adult populations over the 480 month period. Does the model simulate industrial melanism?

#### 5. Range of Possible Results

Review Kettlewell's (1973, p. 135) frequency map of the *Biston betularia* and its two melanics at 83 locations in Britain. It shows that melanics totally dominated in some cities (especially in the midlands), but they were entirely absent in other areas (like northern Scotland). Suppose we were to assume that the only important difference between these areas is the soot index. Is the model from the previous exercise capable of showing this wide range of population results due entirely to changes in the soot index?

#### 6. Sensitivity to the Bird Loss Fractions

The bird loss fractions from exercise #2 change from 10% to 90% in a simple, linear manner. Review the information on bird predation from field observations (Kettlewell 1973) or from visibility experiments (Weaver and Hedrick 1995, p. 425). Then change the graph functions based on what you learn and repeat the simulation from exercise #4 to learn the importance of your change in the loss fractions.

#### 7. Sensitivity to the Mix of Homozygotes and Heterozygotes

The probabilities in the previous exercises are based on the assumption that the black phenotype is comprised of a 50/50 mix of homozygotes (MM) and heterozygotes (Mm). Change the probabilities to reflect a situation with 25% homozygotes, and repeat the simulation in exercise #4. Then change the probabilities to represent a population with 75% homozygotes, and repeat the simulation. Is the simulated pattern of melanism altered in a significant manner.

Two additional exercises are provided for student with special interest in genetics. They challenge you to expand the generality of the genetics model by treating each genotype in an explicit manner.

#### 8. Simulate Three Genotypes with Stocks

The existing model assigns one stock to the black phenotype and a second stock to the white phenotype. This approach is easy to understand when thinking about the color of the moths, but it may be confusing when we think about the genotypes. Revise the model to make the genotypes explicit. There are three genotypes, each of which must be simulated by assigning stocks to the preadult phase and the adult phase:

- the mm genotype corresponds to the white moths;
- the MM and Mm genotypes corresponds to the black moths.

Revise the genetics sector to simulate random matings among the three populations and introduce a new

set of probabilities to keep track of the three types of broods. Now, run the new model with the soot index at zero. Do the MM blacks turn out to comprise 50% of the black population as assumed in the previous model (the model in the 4th exercise)? How do the ratios of black to white moths compare with the previous model? Run the new model with the soot index increasing over time. How do the results compare with the previous model?

### 9. Simulate Six Genotypes with Stocks

The previous models concentrate on white (typical) moths and black (melanic) moths, but there is a third phenotype: the darkly mottled insularia ( $M'$ ). The insularia ( $M'$ ) is dominant to the typical; the melanic ( $M$ ) is dominant to both of the other alleles. Expand the previous model to keep track of the insularia population. You will now have six genotypes, so you will need six pairs of stocks to keep track of each genotype in the preadult and adult phases. The phenotype populations may be calculated as converters:

- The black (melanic) population would be based on the  $MM$ ,  $MM'$  and  $Mm$  genotypes.
- The molted (insularia) population would be comprised of the  $M'M'$  and  $M'm$  genotypes.
- The white (typical) population is the  $mm$  genotype.

Be sure to assign a separate loss fraction to the darkly mottled insularia as a function of the soot index. Also, adopt predation assumptions that are suitable for a moth whose coloring is intermediate between the melanic and typical moths. Run the new model with the soot index increasing over time. How do the new results compare with the results from the model with only three genotypes?