How does natural selection change allele frequencies?

Alleles conferring resistance to insecticides and antibiotics have recently increased to high frequencies in many species of insects and bacteria.

How did this happen (within a typical species)?

Which of these factors (or others) do we need to include in the explanation?

- Population size ($N$)
- Time to last common ancestor ($T$)
- Mutation rate ($\mu$)
- Neutral polymorphism ($\pi$)
- Allele frequency ($p$)
- Survival probabilities of different genotypes
- Expected reproductive success of genotypes
Selection is a *bias* in the relationship between $p$ and $p'$. Gillespie models it as a difference in *survival* to adulthood, which is caused by phenotypic effects of $A_1$ and $A_2$. That is, $E(p') \neq p$.

**Figure 3.2:** The simple life cycle used in the fundamental model of selection.

But alternatively, it could be a difference in *reproductive success* among adults who had survived equally well regardless of genotype.
A general model of selection for two alleles (no mutation, no drift)

Let $p$ be the frequency of allele $A_1$ in the current generation [$q = 1-p = \text{freq}(A_2)$].

Let $p'$ be its frequency next generation.

Assume that the population mates at random with respect to genotypes at the $A$ locus. (This does not require truly “random” mating!)

Let $W_{11}$, $W_{12}$, and $W_{22}$ be the relative fitnesses (average surviving offspring) of the three diploid genotypes ($A_1A_1$, $A_1A_2$, $A_2A_2$).

The population's average fitness is a weighted mean of the genotypic fitnesses.

<table>
<thead>
<tr>
<th>genotype</th>
<th>$A_1A_1$</th>
<th>$A_1A_2$</th>
<th>$A_2A_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency at conception fitness (e.g., survival)</td>
<td>$p^2$</td>
<td>$2pq$</td>
<td>$q^2$</td>
</tr>
<tr>
<td>$W_{11}$</td>
<td>+</td>
<td>+</td>
<td>= 1</td>
</tr>
<tr>
<td>population mean (total) fitness</td>
<td>$p^2W_{11}$</td>
<td>$2pqW_{12}$</td>
<td>$q^2W_{22}$</td>
</tr>
<tr>
<td>$\bar{W}$</td>
<td>=</td>
<td>=</td>
<td>=</td>
</tr>
</tbody>
</table>

Dividing the genotypic components of $W$-bar by $W$-bar gives the proportional reproductive contributions of the genotypes to next generation's gene pool.

<table>
<thead>
<tr>
<th>genotype</th>
<th>$A_1A_1$</th>
<th>$A_1A_2$</th>
<th>$A_2A_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>proportion of population’s fitness</td>
<td>$p^2W_{11}/\bar{W}$</td>
<td>$2pqW_{12}/\bar{W}$</td>
<td>$q^2W_{22}/\bar{W}$</td>
</tr>
<tr>
<td>= 1</td>
<td>=</td>
<td>=</td>
<td>=</td>
</tr>
</tbody>
</table>
Next generation’s allele frequency $p'$ is the contribution of $A_1A_1$ genotypes plus one half of the contribution of $A_1A_2$ (since half of their gametes will be $A_1$).

$$p' = p^2W_{11}/\bar{W} + pqW_{12}/\bar{W} = p[pW_{11} + qW_{12}]/\bar{W}$$

The term in square brackets is the average or “marginal” fitness of allele $A_1$ (because a proportion $p$ of all $A_1$ alleles find themselves in $A_1A_1$ homozygotes). Our updating rule or recurrence equation for $p$ therefore reduces to

$$p' = p[\bar{W}_1]/\bar{W}$$

If we subtract $p$ we get the change in $p$ expected in one generation:

$$\Delta p = p' - p = p\bar{W}_1/\bar{W} - p = p(\bar{W}_1 - \bar{W})/\bar{W}$$

But the population’s mean fitness can be rewritten as a weighted average of the allelic marginal fitnesses:

$$\bar{W} = p\bar{W}_1 + q\bar{W}_2$$

By substituting the RHS into the equation for $\Delta p$ (above) and simplifying, we get

$$\Delta p = pq(\bar{W}_1 - \bar{W}_2)/\bar{W}$$
Allele-frequency histories ("trajectories") can easily be calculated by iterating the recurrence equation:

\[ p' = p \left[ \frac{W_1}{\bar{W}} \right] \]

\[ p' = f(p) \]

1. The rate of allele-frequency change is fastest at intermediate allele frequencies (when \( pq \) is greatest).

2. Rare recessive alleles (whether advantageous or harmful) are almost "invisible" to selection.

3. Smaller fitness differences lead to proportionally slower rates of allele-frequency change.
Fitnesses are often described by the selection coefficient \( s \).

For example, it is common practice to write \( W_{11} = 1 \), \( W_{12} = 1-hs \), and \( W_{22} = 1-s \).

If \( h = 0 \), allele 1 is dominant.

If \( h = 1 \), allele 2 is dominant.

And if \( h = 0.5 \), the heterozygotes are intermediate in fitness \( \text{(codominance or additivity)} \).

In the examples below, \( h = 0.5 \).

In the first case (red), \( s = 0.2 \). In the last case (blue), \( s = 0.004 \).
Figure 3.3: Properties of directional selection with $h = 0.5$ and $s = 0.1$. The left-hand graph shows the change in the allele frequency in a single generation. The right-hand graph shows the evolution of the allele frequency over 100 generations.
An important special case: lethal recessive alleles

W_{11} = W_{12} = 1 \quad (A_1A_x \text{ are fine.})
W_{22} = 0 \quad (A_2A_2 \text{ are dead.})

W_1 = 1 \quad \text{(marginal fitness of } A_1) \\
W_2 = [(1)\frac{1}{2}2pq + (0)q^2]/[q] = p \\
W_{bar} = p(1) + q(p) = p(1+q) = p(2-p)

\[ p' = \frac{p[W_1/W]}{p[1/p(2-p)]} = \frac{1}{2-p} \]

\text{E.g., suppose } p = 0.5

Then \( p' = 1/(2-0.5) = 1/1.5 = 0.67 \)

Peter Dawson (1970) used a recessive lethal allele in the flour beetle \textit{(Tribolium confusum)} to test this prediction of the model. His data are shown in the graphs on the right. The theoretical prediction is graphed as continuous \textit{gray lines}. Amazing!
Modes of selection: directional, balancing and disruptive

Selection may favor a certain allele unconditionally, regardless of its frequency.

Such directional or “positive” selection, if continued, will sooner or later “fix” the favored allele (i.e., increase its frequency to 1.0).

But there are other possibilities!

1. **Balancing** selection keeps two or more alleles at intermediate frequencies and prevents fixation.

2. **Disruptive** selection can fix either allele, if its frequency is already high enough.

Two kinds of balancing selection: different processes, same result

Heterozygote advantage or “overdominance”: fitness of $A_1A_2 > A_1A_1, A_2A_2$.

Negative frequency dependence: fitnesses go down as frequencies go up.

**Gillespie’s example of heterozygote advantage**

$$W_{11} = 1$$
$$W_{12} = 1 - hs = 1 - (-0.5)(0.1) = 1 + 0.05 = 1.05$$
$$W_{22} = 1 - s = 1 - 0.1 = 0.9$$

Figure 3.4: Properties of balancing selection with $h = -0.5$ and $s = 0.1$. 

\[
\begin{align*}
\Delta s^p & \quad 0.02 \\
0 & \quad 0.01 \\
0.5 & \quad 0.00 \\
1 & \quad -0.01
\end{align*}
\]

\[
\begin{align*}
P & \quad 1.00 \\
0 & \quad 0.50 \\
50 & \quad 0.00 \\
100 & \quad Generation
\end{align*}
\]
The Mukai and Burdick experiment: another recessive lethal allele

Like Dawson’s experiment with flour beetles.

But here the lethal allele (L) is *not* driven extinct by the viable allele (V).

In fact, L *increases* from a low initial frequency!

This implies that VL heterozygotes must be *fitter* than VV homozygotes.

At equilibrium (when $p(V) \approx 0.8$), which of these statements about the marginal fitnesses is true?

1. $W_V > W_L$
2. $W_V = W_L$
3. $W_V < W_L$
The best-understood case: hemoglobin S and falciparum malaria

Where Hb S is common (light gray)

Where malaria was common (darker gray)

Both common (darkest gray)

AA: “standard” β Hb
AS: resists malaria
SS: sickle-cell anemia

Note how the fitnesses depend on the environment:
AS is fitter than AA if (1) malaria is endemic and (2) there is no other defense.
Negative frequency dependence: where I’m my own worst enemy

Here the fitnesses of the genotypes (not just the marginal fitnesses of the alleles) depend on their own frequencies.

In this made-up example, the fitness of the heterozygote is always halfway between those of the homozygotes, so there’s never any heterozygote advantage.

\[
W_{11} = 1.0 - 0.05p^2 \\
W_{22} = 1.0 - 0.1q^2 \\
W_{12} = \frac{1}{2}(W_{11} + W_{22})
\]
Frustrated bumblebees go to differently colored elderflower orchids.

Flowers give no reward to bees.

Naïve bees alternate between colors.

The rarer color therefore tends to get more visits per flower.

Fitnesses equalize at \( P(\text{yellow}) = 0.6-0.7 \) in experimental populations (right).

Natural populations have \( P(\text{yellow}) = 0.69 \).
Negative frequency dependence is probably very common.

It will arise from competition for resources of almost any kind.

Also escape from diseases, predators and other enemies.

Some classic examples:
- Self-incompatibility alleles in plants
- Sex ratios and mating strategies
- Major histocompatibility (MHC) alleles in all vertebrates

Positive frequency dependence is not so common.

Would it tend to maintain genetic polymorphism? Or eliminate it?

"Trans-specific polymorphism" of self-incompatibility alleles in members of the family Solanaceae. Some S-alleles in tobacco (Nicotiana) are more closely related to S-alleles in Petunia than to some other S-alleles in their own species!
How and when do typical genes contribute to fitness?

A major puzzle: Most genes appear to be unnecessary!

Half or more can be “knocked out” (fully disabled) in yeast, worms, flies and even mice, without any obvious phenotypic effects (in the lab, anyway).

But these genes are maintained in evolution, so they must be useful. How?

Two hypotheses:

(1) Most are “special-purpose” genes needed only under certain circumstances (stresses that occur in nature but not in the lab).

(2) Most are “fine-tuning” genes that increase the efficiency or accuracy of some physiological or developmental process in most environments.

Experimental test devised by Joe Dickinson:

Compete “no-phenotype knockouts” against genotypes that are identical except for the knockout, and let natural selection measure their relative fitnesses.

Dickinson talked Janet Shaw (a yeast cell biologist) and John Thatcher (an undergraduate) into helping him try to do this with yeast.
How to ask cells if they miss a (random) gene

Mark either the random, “no-phenotype” knockout, or the wild-type parent, with lacZ so that you can score their relative numbers on indicator plates.

Start populations with equal numbers of wild-type and knockout cells; grow them for many generations in complete (rich) liquid media.

Sample the populations every 10-20 generations and score the relative numbers of marked and unmarked cells.
Plot the frequency of the knockout as a function of generations (A, C). Also plot the log of the ratio of the allele frequencies \([\ln(q/p)]\) versus generation (B, D). The slope of this (straight) line is an estimate of the selection coefficient (-s).

Gene TD64

Gene TD63

\[ s = 0.045 \]

\[ s = 0.004 \]
Summary of results for 27 “no-phenotype” knockouts

Nineteen mutations (70%) showed statistically significant fitness defects ranging from 0.3% \((s = 0.003)\) to 23% \((s = 0.23)\).

Among these, the typical (median) selection coefficient was 1-2%.

Six mutations (22%) were not statistically distinguishable from neutral. (Five of the six appeared to be weakly deleterious, and one appeared to be beneficial.)

A more sensitive experimental design (with larger populations and allele-frequency assays) would probably show most of these to be significant, raising the fraction of deleterious no-phenotype knockouts to 85-90%.

Two of the 27 knockouts (7%) were significantly advantageous, with “negative” coefficients of \(s = -0.005\) and \(s = -0.007\).
Conclusion: Most genes make modest contributions to fitness. This finding (in bacteria, too) supports the “fine-tuning” hypothesis. Such small effects could not be detected except by natural selection.

Figure 3.1: The observed frequency of the *medionigra* allele in the scarlet tiger moth population compared to the expected frequency assuming a 10 percent disadvantage.

What other (non-selective) population process might explain this trend?
"Homework" problem: Let FF homozygotes have a fitness of 1.0 ($W_{FF}=1$), and assume F/S heterozygotes have intermediate fitness ($h = \frac{1}{2}$). Very roughly, what is the fitness of the SS homozygotes, in the ethanol-soaked environment?