8 Engineering enzyme selectivity

Summary. Enzymes are often selective for one stereoisomers over another, which makes them useful for the preparation of stereoisomers. Selectivity can refer to substrate selectivity, which involve the separation of existing stereoisomers, or to product selectivity, which involves the creation of new stereocenters. The ability of enzymes to distinguish stereoisomers relies on their ability to position one stereoisomer for reaction better than another stereoisomer by exploiting differences in their shapes.

Learning goals

- Selectivity is the ability of proteins to distinguish between different molecules. The selectivity value, S, is the ratio of the preferred to non-preferred molecule. This value depends on comparison molecules. Selective reactivity may involve discrimination between two substrates or between two products.
- Stereoselectivity is a type of selectivity where the molecules to be distinguished are stereoisomers; enantioselectivity is a type of stereoselectvity where the stereoisomer to be distinguished are enantiomers. Many pharmaceuticals require pure enantiomers and enzyme-catalyzed reactions are a good way to make these pure enantiomers.
- Discrimination between two substrates occurs when one substrate reacts faster than the other. This substrate selectivity depends on ratio of k_{cat}/K_M for the two substrates. Tighter binding allows a substrate to occupy a larger fraction of active sites, while faster reaction allow the substrate to react faster.
- When theres are equal amounts of the two substrates, the initial ratio of substrates that react or products that form corresponds to the selectivity. At higher conversions, the relative amounts of substrate that reacts or product that forms differs from the selectivity because the amounts of the two substrates is no longer equal.
- Discrimination between two products occurs when a single substrate forms two

products. This product selectivity depends only on the relative values of k_{cat} for the two products. The relative amount of the two products is constant throughout the reaction and corresponds to the selectivity.

8.1 Introduction

Selectivity, S, is the ability to distinguish between alternatives. This ability is the key to the value of many proteins. For example, the cardiovascular antibody drug abciximab selectively binds to a receptor involved in platelet aggregation to inhibit formation of blood clots.[1] In another example, a transaminase with high selectivity for the (*S*)-amine yields the required stereoisomer of a cardiovascular drug precursor with high purity.[2]

Binding selectivity is the ability to bind one ligand more tightly than other one and was covered in Chapter 6. This chapter focusses on reaction selectivity.

Reaction selectivity is the ability to react with one substrate more quickly than another (substrate selectivity) or form one molecule more quickly than another (product selectivity). The classification as substrate or product selectivity depends on whether there are multiple possible substrates or multiple possible products.

Reaction selectivity stems from differences in reaction rates, which originate in differences in transition state energies for the competing reactions. The ratio of rates is the selectivity for that pair of molecules, eq. 8.1.

$$S_{reaction} = \frac{rate_{fast}}{rate_{slow}} \tag{8.1}$$

The words non-selective (or promiscuous), selective and highly selective describe degrees of selectivity. Avoid using the word specific to mean highly selective because specific has a different meaning in chemistry. The reaction mechanism of a selective reaction favors the formation of a particular isomer, but both isomers can form. For example, epoxidation of norbornene (bicyclo[2.2.1]hept-2-ene) favors formation of the *exo* diastereomer (oxygen close the one-carbon bridge) over the *endo* diastereomer (oxygen close to the two-carbon bridge), Fig. 8.1a. The selectivity originates the different steric hindrance between the two sides and varies with the oxidant used. A highly selective reaction may form only one detectable product, but the the reaction mechanism could also form the other one. In contrast, specific reactions are those that require formation of a particular isomer for mechanistic reasons. For example, epoxidation of *cis*-2-butene can only form the *cis*-epoxide, Fig. 8.1b. Likewise, epoxidation of *trans*-2-butene can only form the *trans*-epoxide. The reaction is a concerted addition of oxygen to the double bond without an intermediate that permits rotation of the carbon-carbon bond. The reactions in this chapter all refer to selectivity.

8.2 Stereoisomers

Isomers are non-superposable molecules with the same molecular formula. Isomers can differ in their atom connectivity (constitutional isomers) or only in shape (stereoiso-

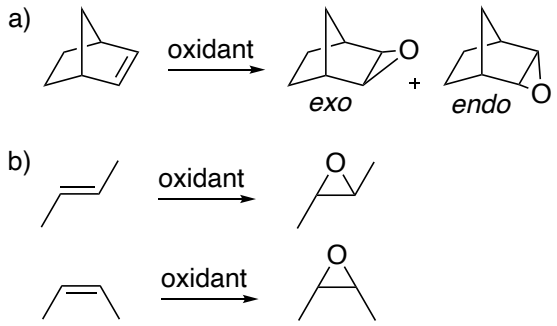

Figure 8.1. Selective reactions favor one possible product, but specific reactions form only one product because the reaction mechanism make formation of the other one impossible. a) Epoxidation of norbornene is a selective reaction. The oxygen atom can add to either face of the double bond. b) Epoxidation of 2-butene is a specific reaction: *cis*-2-butene yields only the *cis*-epoxide, while *trans*-2-butene yields only the *trans*-epoxide.

mers), Fig. 8.2. Classifying a person as a father, son, brother or uncle depends on who the person is being compared to. In the same way, isomerism classifies relationships between molecules. A given molecule may be a diastereomer, an enantiomer or a constitutional isomer depending on the comparison molecule. For example, one may recognize that a molecule is chiral, but until one has a comparison molecule, one cannot classify the relationship between the molecules.

The concept of a stereogenic unit is also useful. A stereogenic unit is the part of the molecule that makes stereoisomers possible. Chiral molecules must contain at least one stereogenic unit. For example, the stereogenic unit in *l*-alanine is the α-carbon atom containing four different substituents: HOOC-, H_2N-, H_3C-, and H. Occasionally one may encounter the term regioisomer, which refers to a special type of constitutional isomers. Regioisomers can form when a chemical reaction has different orientations or sites to choose from. For example, electrophilic aromatic substitution of bromobenzene can yield *ortho*-, *meta*-, or *para*-substituted products. These isomeric products are regioisomers.

Researchers often use the high stereoselectivity of enzymes, especially their high enantioselectivity to prepare pure stereoisomers. Most of the examples in this chapter involve enzymes distinguishing between stereoisomers.

8.2.1 Stereoisomeric purity

There are two commonly used measures for stereoisomeric purity: the ratio of stereoisomers and the stereoisomeric excess. The enantiomer ratio, *er*, or diastereromer ratio, *dr*, is simply the relative amounts of the two stereoisomers.

$$er \text{ or } dr = \frac{major\ stereoisomer}{minor\ stereoisomer}$$

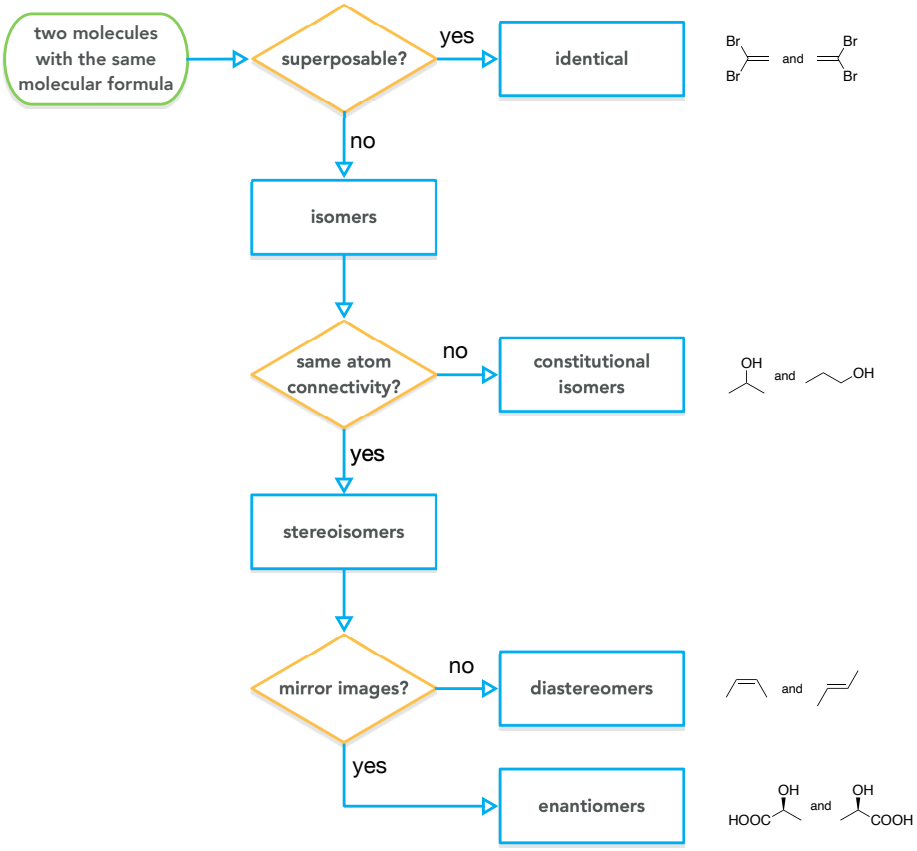

Figure 8.2. Flowchart to identify common relationships between pairs of molecules. Constitutional isomers differ in their atom connectivity, while stereoisomers differ only in their shape. Stereoisomers can be either diastereomers or enantiomers.

For example, a 9:1 mixture of *cis*- and *trans*-2-butene has a diastereomeric ratio of 9. Analytic methods like HPLC or GC with columns containing a chiral stationary phase reveal the amounts of each enantiomer.

Another measure of purity is enantiomeric excess, *ee*, usually expressed as a percent instead of a number between 0 and 1. Enantiomeric excess, is the excess of the major enantiomer over the minor enantiomer in the sample, eq 8.2. For example, a 9:1 mixture of two enantiomers has an 80% ee. Diastereomeric excess, *de*, is defined similarly.

$$ee \text{ or } de = \frac{major - minor}{major + minor} \tag{8.2}$$

This unusual way to express purity stems from the historic use of optical rotation to measure enantiomeric purity. Enantiomers rotate plane-polarized light in opposite directions. A racemic sample shows no rotation because the opposite rotations of the two enantiomers cancel out. A racemic sample has an ee of 0%. If one enantiomer is present in excess, then the excess amount of that enantiomer causes a rotation. The enantiomeric excess in percent is the size of that rotation as a fraction of the rotation for the pure enantiomer.

To convert enantiomeric excess to amounts of the individual enantiomers, one can imagine the sample to consist of an excess amount of the major enantiomer, ee, plus an amount of racemate $1 - ee$. The total amount of major enantiomer is the excess amount plus half of the racemate, eq. 8.3.

$$major_{total} = major_{excess} + \frac{racemate}{2} = ee + \frac{1 - ee}{2} \tag{8.3}$$

The total amount of the minor enantiomer is half of the amount of the racemate, eq. 8.4.

$$minor_{total} = \frac{racemate}{2} = \frac{1 - ee}{2} \tag{8.4}$$

For example, a sample with an enantiomeric purity of 80% ee consists of 80% major enantiomer in excess plus 20% racemate. Thus, the sample contains 90% of the major enantiomer and 10% of the minor enantiomer.

8.3 Product selectivity

Product selectivity occurs when an enzyme converts a substrate into several possible products and favors one or more of the possibilities. Product selectivity involves the *creation* of two possible products from a single substrate. For example, an enantioselective transaminase catalyzes the key step in the synthesis of sitagliptin, a type 2 diabetes drug[3], Fig. 8.3. The reaction is highly selective for one of the two possible enantiomers. Enantioselectivity is a particularly useful type of selectivity since pure enantiomers are difficult to make with traditional chemical methods. Enantiomers can differ in their biological effects, so most chiral drugs are marketed as single enantiomers.

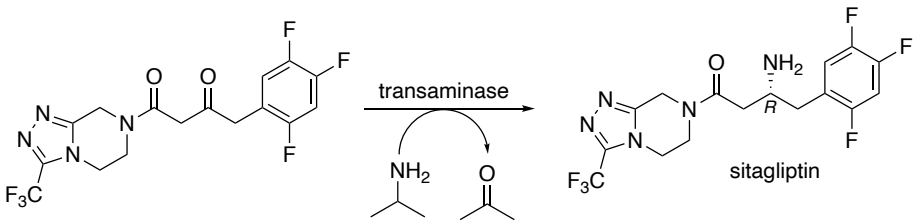

Figure 8.3. An enantioselective transaminase converts the achiral starting ketone into the (*R*)-amine. This reaction is an example of product enantioselectivity since the other possible product, the enantiomeric (*S*)-amine (not shown), forms only in trace amounts.

Product selectivity depends on the ratio of k_{cat} values for the two products, eq. 8.5. The subscript f refers to the faster-reacting substrate and subscript s refers to the slower reacting substrate. There is no contribution from binding, K_M, because there is only one substrate, so no competition is possible, Figure 8.4. The Gibbs energy difference between the two transition states is proportional to the natural logarithm of the selectivity, eq. 8.6.

$$S_{product} = \frac{(k_{cat})_f}{(k_{cat})_s} \tag{8.5}$$

$$\Delta\Delta G_{f-s} = -RTln(S_{product}) \tag{8.6}$$

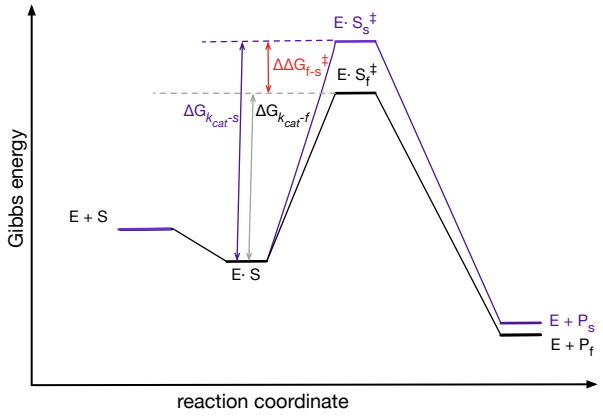

Figure 8.4. Gibbs energy diagram for product selectivity. The enzyme can convert a single substrate into one of two products. One product, P_f, forms faster because the transition state to form that product is lower in energy than the transition state to form the other product, P_s. The difference in Gibbs energy for the two transition states is the origin of the selectivity.

To measure product selectivity one measures the relative amounts of the products formed. The ratio of the products corresponds to the selectivity. This ratio remains constant as the reaction proceeds because the starting material never changes; it just decreases in amount.

8.4 Substrate selectivity

Substrate selectivity occurs when two substrates compete in the same solution. An enzyme encounters similar substrates, but reacts with some of them more rapidly than others. Proteases are a good example of substrate selectivity. Substrate selectivity involves a *separation*; the two substrates already exist and the selective reaction will transform one of them. A peptide contains multiple peptide links each of which is a different potential substrate. Proteases often favor hydrolysis of some of these links over others. For example, trypsin favors hydrolysis of peptide links after lysine or arginine residues, 8.5a. The example peptide contains fifteen amide links (fifteen possible substrates), but trypsin cleaves only two of these due to its substrate selectivity.

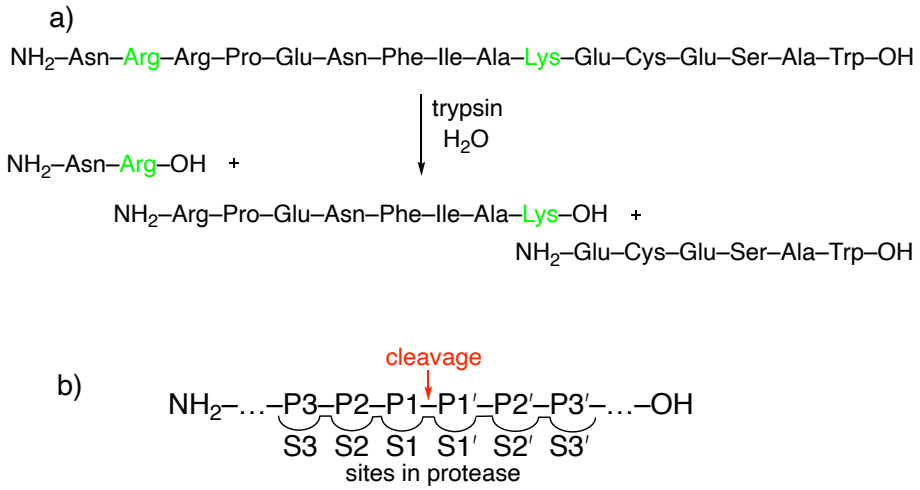

Figure 8.5. Proteases are often selective in which peptide links they cleave. a) Trypsin cleaves only two of the fifteen amide links in peptide shown. Trypsin is selective for amide links on the C-terminal side of lysine and arginine residue, except when followed by proline. b) The binding sites in the protease are numbered to indicate their distance from the catalytic site. The sites S1, S2, S3, etc. bind the N-terminal part of the peptide, while the sites S1′, S2′, S3′, etc. bind the C-terminal part of the peptide. The peptide residue naming matches the names of the binding sites: P1, P2, P3, etc. in the direction of amino terminus of the peptide and P1′, P2′, P3′, etc. in the direction of the carboxy terminus. The peptide residue naming changes as different amide bonds are positioned at the cleavage site.

Protease nomenclature describes how the peptide orients in the protease when cleavage occurs,[4] Fig. 8.5b. The numbering of the binding sites, S, indicates their distance from

the catalytic site where cleavage occurs: ….S3-S2-S1-S1′-S2′-S3′… The sites numbered without primes bind the N-terminal part of the peptide, while the sites numbered with primes bind the C-termimal part of the peptide. The sites bind both the side chains and main chain of the peptide. The catalytic site lies between S1 and S1′ and cleaves the peptide bond connecting the two residues bound in those sites. The numbering of the enzyme sites is fixed by the location of the catalytic residues. The numbering of the peptide substrate varies when different amide links are positioned at the cleavage site. The peptide numbering matches the binding sites at which it binds: NH_2….P3-P2-P1-P1′-P2′-P3′…COOH. Trypsin is selective for peptide links with lysine or arginine at the P1 position, except when the P1′ amino acid is proline. The proline at P1′ presumably disrupts catalytically productive binding.

Substrate selectivity originates from both the ability of the enzyme to bind the good substrate and also to catalyze a reaction on the good substrate. The good substrate must succeed at both, while the poor substrate may fail at either step. Poor substrates either do not bind to enzyme or bind in a way that does not lead to reaction. The selectivity between the two depends on both k_{cat} and K_M, eq. 8.7, where subscript f refers to the faster-reacting substrate and subscript s refers to the slower reacting substrate.

$$S_{substrate} = \frac{(k_{cat}/K_M)_f}{(k_{cat}/K_M)_s} \tag{8.7}$$

The tighter binding substrate will occupy a larger fraction of the enzyme active sites, while the faster catalytic step will convert more of that substrate to product. The Gibbs energy diagram, Figure 8.6, shows these two contributions to substrate selectivity graphically. In this diagram, both k_{cat} and K_M favor the faster-reacting substrate, but it is also possible that they favor different substrates, in which case the competing effects lead to a lower net selectivity.

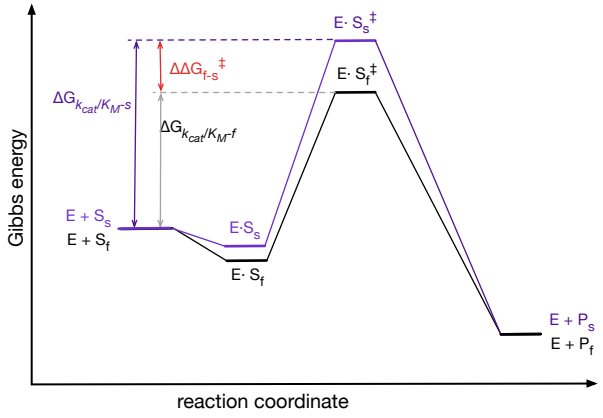

Figure 8.6. Gibbs energy diagram for two competing substrates in an enzyme-catalyzed reation. Both tighter binding and faster reaction contribute to the selectivity. S_f = faster-reacting substrate; S_s = slower-reacting substrate.

For the trypsin example, the different K_M's refer to the binding of different amide bonds in the catalytic site. To estimate K_M for the different amide bonds one could measuring K_M using substrate analogs that contain only one type of amide bond.

A common special case of substrate selectivity occurs when the two competing substrates are enantiomers. In this case the reaction is a kinetic resolution. The word resolution refers to a separation of enantiomers, while kinetic specifies that the separation relies on differences in the rates of reaction. For example, the manufacture of diltiazem, a calcium-channel blocker uses a kinetic resolution to make an enantiomerically-pure precursor,[5] Figure 8.7. Starting from a racemic mixture, the lipase catalyzes the hydrolysis of the unwanted enantiomer to the carboxylic acid, which spontaneously decarboxylates.

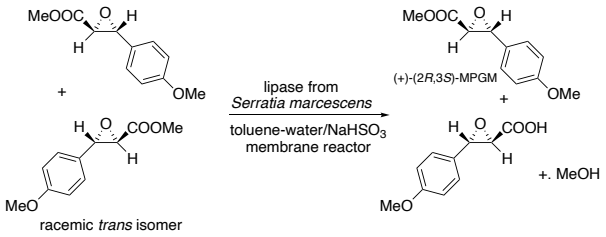

Figure 8.7. Lipase-catalyzed kinetic resolution to manufacture of an enantiopure precursor to diltiazem, a calcium-channel blocker drug. The lipase catalyzes the hydrolysis of the unwanted enantiomer to the carboxylic acid, which spontaneously decarboxylates to the aldehyde. The membrane reactor

In some cases, reversing the reaction reverses its classification as substrate selective or product selective. Reversing the reaction in Figure 8.3 by starting with a racemic mixture of amines and converting them to the ketone would create a case of substrate selectivity. The transaminase would convert the favored (*R*)-amine to the ketone leaving the (*S*)-amine unchanged and an example of a kinetic resolution. The disadvantage of a kinetic resolution is that the maximum yield of each enantiomer is 50%. If the purpose of the reaction is the manufacture of a precursor to make an enantomerically-pure drug, then only one of the enantiomers will be useful. In contrast, the maximum yield of pure enantiomer in the product selectivity case is 100%.

8.4.1 Measuring selectivity in kinetic resolutions

One way to measure reaction selectivity in a substrate selectivity case is to measure the amounts of substrates consumed or products formed at very low conversion (<5%), eqs. 8.8 or 8.9. At low conversion

$$S_{substrate} = \frac{(\text{amount of substrate reacted})_f}{(\text{amount of substrate reacted})_s} \text{ at low conversion} \qquad (8.8)$$

$$S_{substrate} = \frac{(\text{amount of product formed})_f}{(\text{amount of product formed})_s} \text{ at low conversion} \tag{8.9}$$

The low conversion is required so that the ratio of the two substrates remains constant over the time of the measurement. The equations 8.8 and 8.9 above also assume equal starting concentrations of the two substrates.

It is often inconvenient to measure the amounts of substrate consumed or product formed at low conversion. In these cases one must use more complex equations. These equations account for the fact that the composition of the substrate changes as the reaction proceeds. The relative amount of the slow-reacting substrate increases as the reaction depletes the fast-reacting substrate, Figure 8.8.

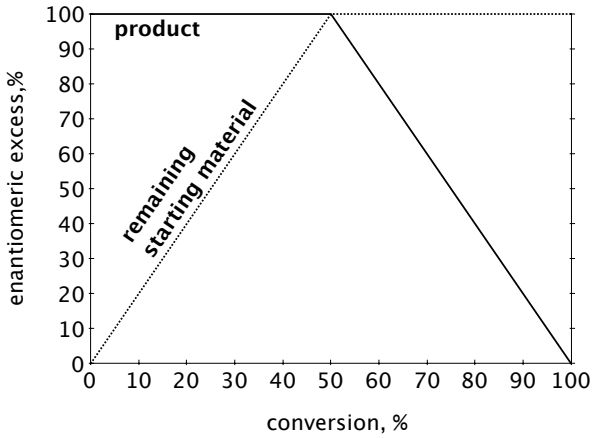

Figure 8.8. Variation of enantiomeric excess for a perfect kinetic resolution as a function of conversion. As the reaction proceeds from 0% to 50% conversion, the remaining starting material is enriched in the slow reacting enantiomer. At 50% conversion, the product consists of the fast-reacting enantiomer, while the substrate consists of the slow reacting enantiomers. The reaction should be stopped at this point. If the reaction is continued, then the enantiomeric excess of the product will decrease as it becomes contaminated with the slow-reacting enantiomer.

The amount of enrichment varies depending on the enantioselectivity of the reaction, Figure 8.9

The equation below[6] predicts the enantioselectivity, *E*, from the conversion (*c*, value between zero and one) and the enantiomeric excess of the product, ee_p, eq. 8.10.

$$E = \frac{\ln[1 - c(1 + ee_p)]}{\ln[1 - c(1 - ee_p)]} \tag{8.10}$$

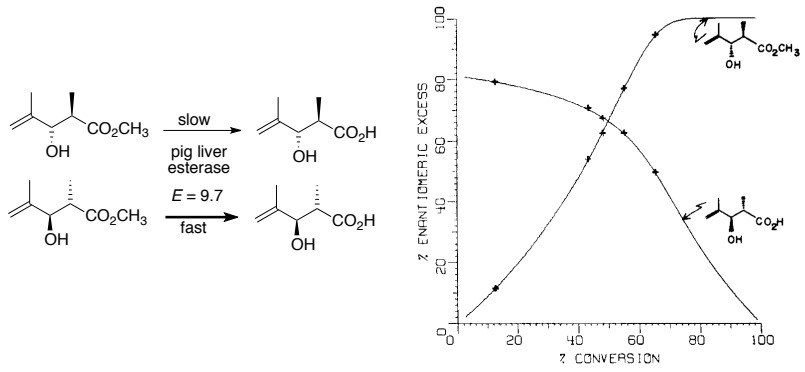

Figure 8.9. An imperfect kinetic resolution. The kinetic resolution of the racemic ester shown catalyzed by pig liver esterase has a moderate enantioselectivity of 9.7. The maximum enantiomeric excess of the product is approximately 80% as low conversion, while the enantiomeric excess of the remaining starting material can be >95% as high conversion.

If you know the value of conversion and the enantiomeric excess of the product, then it is straightforward to calculate the enantioselectivity. For example, if the enantiomeric excess of the product is 90% at 40% conversion, then the enantioselectivity of this reaction is

$$E = \frac{\ln[1-(0.40)(1+0.90)]}{\ln[1-(0.40)(1-0.90)]} = \frac{\ln[(0.24)]}{\ln[(0.96)]} = 35$$

A web tool encodes eq. 8.10 to simplify this calculation: http://biocatalysis.uni-graz.at/biocatalysis-tools/enantio. It also encodes similar equations that can calculate enantioselectivity from ee_s and c or from ee_p and ee_s. Thus, one can calculate the enantioselectivity of a kinetic resolution using any two of the following values: ee_p, ee_s, or c.

However, if you already know the enantioselectivity and would like to calculate the conversion needed to get a certain enantiomeric excess of the product, then you must use an iterative method to solve the equation because you cannot rearrange eq. 8.11 to solve for c. For example, if your reaction has an enantioselectivity of 35 and you would like the enantiomeric excess of the product to be at least 92%, then

$$35 = \frac{\ln[1-c(1.92)]}{\ln[1-c(0.08)]} \tag{8.11}$$

Solving this equation iteratively using WolframAlpha or a Python script in the supporting information yields c = 0.295. (Less elegantly, one can also try different values of c with $ee_p = 92\%$ in the web tool cited above until the calculated enantioselectivity matches 35.) If you try to solve eq. 8.11 for c when ee_p is a higher value of 95%, you get

a negative value for *c* indicating that is it impossible. An enantioselectivity of 35 is too low to ever yield product with 95% ee.

8.5 Molecular basis of stereoselectivity

8.5.1 Ketoreductases

Since stereoisomers differ only in shape, the only way to distinguish them is by their shapes. In two cases - reduction of ketones and hydrolysis of secondary alcohol esters - researchers have proposed simple models that predict the favored enantiomer based on the relative sizes of the substituents. These models imply that enzymes also choose the favored enantiomer based on the relative sizes of the substituents and that all such enzymes have similarly-shaped active sites.

In the 1960's Prelog carried out many yeast-catalyzed reductions of ketones and noticed that the product alcohols usually had a similar shape. He proposed a simple model or rule based on the relative sizes of the ketone substituents.[7] The rule states that yeast-catalyzed reductions of ketones yield the alcohol enantiomer shown below where L represents a larger substituent and S represents a smaller substituentFig. 8.10a. If the priorities of the substituents are O > L > S, then the alcohol has the (*S*)-configuration. The example reactions in Fig. 8.10b proceed according to Prelog's rule yielding the alcohols shown with high enantiomeric purity. Note that the stereochemical descriptors for the product alcohols differ because the priority of the small substituent (methyl or chloromethyl) changes. Prelog's rule defines the shape of the molecule, not the R/S naming of the alcohol.

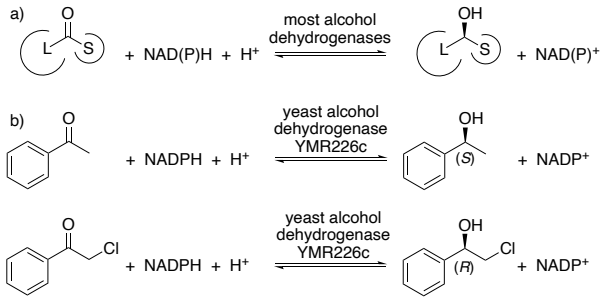

Figure 8.10. Prelog's rule predicts which alcohol enantiomer forms faster during the alcohol-dehydrogenase-catalyzed reduction of ketones. The rule is based on the relative sizes of the ketone substituents. a) Dehydrogenase-catalyzed reduction of ketones favors formation of the enantiomer shown where L is a large substituent and S is a small substituent. b) Yeast alcohol dehydrogenase YMR226c catalyzes the reduction of acetophenone and α-chloroacetophenone according to Prelog's rule. The shape of both product alcohols matches the shape predicted by Prelog's rule despite their opposite R/S designation the chlorine substituent.

To test if a reductase reaction fits Prelog's rule one first orients the product alcohol so that 1) C–O bond points upward to the top of the page and 2) C–O bond points out of

the plane of the page toward the reader. In this orientation, if the large substituent lies to the left, then the reaction follows Prelog's rule. If it lies to the right, then it does not and can be said to follow anti-Prelog selectivity. Any discussion of whether a reaction follows Prelog's rule must include the phrase 'larger substituent' or 'smaller substituent' because that is the basis for the rule regardless of the stereochemical descriptor.

The transition state for an alcohol-dehydrogenase-catalyzed reduction of a ketone orients the carbonyl carbon of the ketone near the hydride of the reduced nicotinamide, Figure 8.11. There are two ways, differing by a 180° rotation along the carbonyl C–O bond, to orient the ketone. These two orientations yield opposite enantiomers and place the large and small substituents in different regions of the enzyme. Prelog's rule implies that most alchohol dehydrogenases have similarly shaped regions that bind the ketone and that the shape more closely matches the top transition state in Figure 8.11

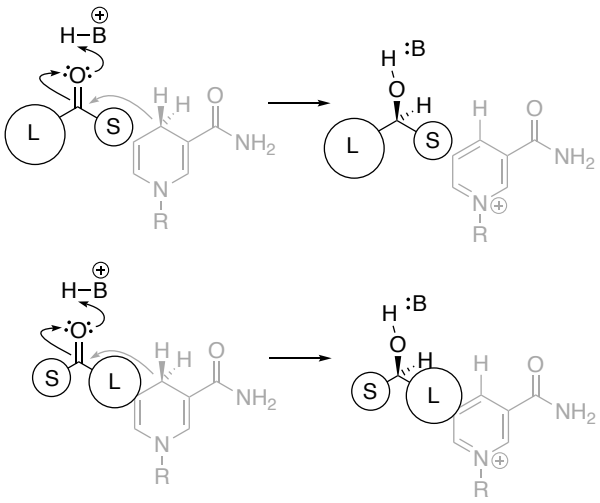

Figure 8.11. Two transition states for the alcohol-dehydrogenase-catalyzed reduction of ketones. In both cases the ketone lies above the plane of the reduced nicotinamide ring and the hydride transfer is to the bottom face of the ketone carbonyl group. The two transition states differ in which face of the ketone carbonyl faces the reduced nicotinamide; that is, they differ by a 180° rotation along the carbonyl C–O bond. The upper transition state is the one that corresponds to Prelog's rule.

The x-ray crystal structures of alcohol dehydrogenases show that most of them have ketone-binding regions that match Prelog's rule, Figure 8.12. These pockets orient the ketone for reaction. In this example, the substrate is not a ketone, but an aldehyde so that both orientations yield an achiral alcohol. Nevertheless, the structure shows the large and small pockets.

Three approaches to increase the enantioselectivity of reductases are substrate modification, screening for a more enantioselective enzyme, and engineering a more enantioselective enzyme. Reductases usually show higher enantioselectivity toward ketones

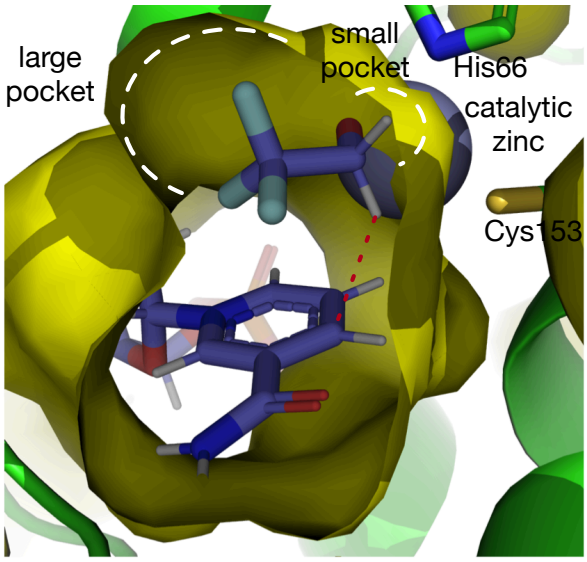

Figure 8.12. Active site of yeast alcohol dehydrogenase containing bound NAD^+ and 1,1,1-trifluoroethanol (pdb id: 5ehv). The nicotinamide ring of NAD^+ is at the bottom, while the 1,1,1-trifluoroethanol is coordinated to the catalytic zinc at the top. The side chains of His66, Cys153 and Cys43 (not visible) coordinate the catalytic zinc. Oxidation of 1,1,1-trifluoroethanol involves transfer of a hydride from the alcohol to the nicotinamide C4 along the red dotted line. The distance from nicotinamide C4 carbon and the C2 of 1,1,1-trifluoroethanol is 3.5 Å suggesting a catalytically productive orientation. The yellow surface shows the limits of the active site pocket. The large pocket containing the trifluoromethyl substitutent and the small pocket containing a hydrogen substituent are marked by white dashed curves.

with larger size differences between the two substituents. For example many reductases show high enantioselectivity toward acetophenone, which has phenyl and methyl as the ketone substituents. In contrast, most reductases show low enantioselectivity toward 3-hexanone, which as ethyl and *n*-propyl substituents. Thus, choosing a substrate with larger differences in size in the two substituents will often increase the enantioselectivity.

In some cases, the synthetic goal, say a pharmaceutical precursor, requires reducing a ketone with similarly-sized substituents. In these cases, the choices are screening for more enantioselective reductases or engineering a more enantioselective reductase by modifying the binding pockets. For example, enantioselective reduction of 3-hexanone requires the enzyme to distinguish between an ethyl and an n-propyl substituent. Most alcohol dehydrogenases show low enantioselectivity, presumably because they have difficulty distinguishing between the similarly-sized substituents. Koesoema and coworkers found a yeast enzyme that showed high enantioselectivity (E >200 favoring the (*S*)-enantiomer).[8] An x-ray crystal structure of the enzyme suggested that Trp288 limits the size of the small pocket. Docking suggests that the ethyl substituent fit in the small pocket, but fitting the *n*-propyl group in the small pocket places the ketone group too far from the catalytic zinc. The non-productive orientation prevents formation of the (*R*)-enantiomer.

In an engineering example, the manufacture of an antibiotic required the reduction of tetrahydrothiophene-3-one, where the difference in size stems from a CH_2 versus a sulfur, Figure 8.13.[9] The initial enzyme showed poor enantioselectivity (E = 4.4), but evolution to modify the substrate binding pockets dramatically increased the enantioselectivity to E = 285.

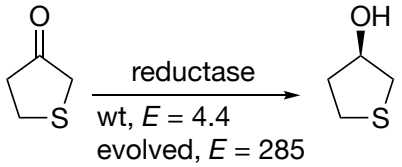

Figure 8.13. The synthesis of an antibiotic required the enantioselective reduction of tetrahydrothiophene-3-one, where the ketone substituents differ subtly in size. The wild-type ketoreductase showed an enantioselectivity of only 4.4, but the evolved enzyme, which contained ten substitutions, showed a 65-fold higher enantioselectivity of 285.

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Problems

1. Draw an achiral molecule and identify its plane of symmetry. Draw two regioisomers that can result from the electrophilic aromatic substitution of toluene with chlorine. Draw a pair of achiral diastereomers and a pair of chiral diastereomers.

Supporting Information

Code Block S8.1 Python script to calculate the enantioselectivity of a reaction using eq. 8.10.

```
"""
This script calculates the enantioselctivity, E, of a
```

```
kinetic resolution from the measured values of percent
conversion and enantiomeric excess of the product in percent.
"""
import math  # load math functions needed to calculate logarithms

# enter values for percent conversion and enantiomeric excess of the product
percentconv = raw_input('What is the conversion in percent? (default = 25)') or 25
percenteep = raw_input('What is the enantiomeric excess of the product in percent? (default

# calculate enantioselectivity and round to one digit after decimal
def ecalc(percentconv,percenteep):
  conv = percentconv/100.0 # convert percent to a fraction between 0 & 1
  eep = percenteep/100.0
  E = round((math.log(1-conv*(1+eep)))/(math.log(1-conv*(1-eep))),1)
  # math.log(x) calculates the natural logarithm of x
  return E
print 'If the enantiomeric excess of the product is',percenteep,'\b% ee at',percentconv,'\b%
```