1. Unfolding Analysis

This is a technique that allows MDS-type analyses on ranking or rating data. Similarity data are not needed so it is easier to implement than traditional MDS. The intuition underlying the idea is to find a space in which to place both stimuli and subjects in such a way that the rank order can be modeled. There is the usual dimensional space of stimuli as in MDS, but in addition subjects are plotted in the same space as the stimuli (unlike INDSCAL where subjects are plotted in a different “weight” space). One interpretation of this common plot is that subjects are “vectors” (arrows in the space) that fold the space to produce the rank orders or ratings that you observe.

A motivating example is the number of teaspoons of sugar in a cup of tea. Everyone agrees on the same dimension of sweetness (the more sugar added, the sweeter the tea tastes) but people may differ in their preferences for how much sugar they want in their tea. Some people don’t like any sugar, some like one teaspoon, some like two, etc. This model is different from a model that posits “more is better”. Instead, unfolding posits “just the right amount is best.” The model attempts to find the points that represent the “ideal point” for each subject.

(a) Example of the “String Model” with four stimuli, which permits 7 possible ideal points on one dimension.

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1Historical note: unfolding analysis was developed at UM in the 50’s and 60’s.
I call this a string model because imagine a string stretched out on a table top and along the string are taped four pieces of paper with the letters A, B, C, and D arranged as follows:

```
A | B | C | D
---+---+---+---
```

If we pick up the string at different points and let it dangle like a mobile, we will see different orders. In fact, there are a limited number of orders that are possible (out of the $24 = 4!$ total orderings) under this string representation. These are:

```
A  B  C  D
B  A  C  D
B  C  A  D
B  C  D  A
C  B  D  A
C  D  B  A
D  C  B  A
```

The place where the string is picked up is called the “ideal” point, and the interpretation is that rank orders are determined with respect to the ideal points. The string model permits 7 of the 24 possible orderings. Some orderings are impossible, such as DABC because it is impossible to pick up the string in such a way where D is most preferred (closest to the ideal point) and A is second most preferred. The “string model” is illustrated below:

![Diagram](image)  
**Fig. 5.1** An I scale preference ordering C D B E A F, obtained by folding a J scale.
Let’s assume the idealized case with seven subjects and each subject provides one of the rank orders above. The “data matrix” is traditional because subjects go along the rows and each column refers to data on a particular variable (in this case a stimulus); contrast this to the symmetric distance matrices we used in the MDS/tree structure section of the course.

SPSS ALSCAL can run an unfolding analysis with this syntax. The shape of the matrix is rectangular, and we need to specify “/cond = row” to let SPSS know that data across rows are not comparable (e.g., a 2 from one subject may not mean the same thing as a 2 from another subject). It is possible to input “/levels = ordinal” but with such few data points the program has trouble so I’ll use “/levels=interval” in this small example. Note that the data we input has subjects along the rows. Each subject ranked the four items on the basis of most favorite, e.g., subject 2 ranked item a as 2nd, item b as 1st, etc.

```
data list free / a b c d.
begin data
1 2 3 4
2 1 3 4
3 1 2 4
4 1 2 3
4 2 1 3
4 3 1 2
4 3 2 1
end data.
alscal variables a b c d
/levels = interval
/shape = rect
/criteria=dimens(1)
/cond = row
/plot = all.
```

The solution is listed below. The stimuli and the subjects (listed as “row” in the output) are both placed along the same dimension. This is called a biplot. The program also prints out the usual stress and $r^2$ values. The SPSS plot is a little difficult to read so I constructed my own plot from the coordinate space. A graph of this one dimensional solution is presented in Figure 11-1. The output separates stimuli from subjects, but both are estimated as being along the same dimension. For example, subject 1 has a scaled value (an ideal point) of -1.3396, which is between the scaled values for stimuli A and B.

<table>
<thead>
<tr>
<th>Column</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>-1.5347</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>-0.7370</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>0.7770</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>1.5311</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Row</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>-1.3396</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>-0.9218</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>-0.2202</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 11-1: Simple example with 4 stimuli (circles) & 7 subjects (triangles represent ideal points). If you “pick up the string” at a subject’s ideal point, you will reproduce the rank order given by that subject.

In R we can use the unfolding function in the smacof package. Here I illustrate with the simple 1D example; solution is similar to the one in SPSS even though the algorithm is slightly different.

```R
# read in data
data <- rbind(c(1,2,3,4), c(2,1,3,4),
              c(3,1,2,4), c(4,0,1,2))
```
data

## [1,] 1 2 3 4
## [2,] 2 1 3 4
## [3,] 3 1 2 4
## [4,] 4 1 2 3
## [5,] 4 2 1 3
## [6,] 4 3 1 2
## [7,] 4 3 2 1

library(smacof)
out.unfold <- unfolding(data, ndim=1,
                         type="ordinal", cond="row")
summary(out.unfold)

## Subject configuration (rows):
##     D1
## [1,] -0.7650
## [2,] -0.5485
## [3,] -0.2201
## [4,] 0.0000
## [5,] 0.2211
## [6,] 0.5485
## [7,] 0.7647

## Object configuration (columns):
##     D1
## [1,] -1.1801
## [2,] -0.3492
## [3,] 0.4127
## [4,] 1.1167

## Stress per point rows:
##     SPP SPP(\%)
## [1,] 0.0000 0.0000
## [2,] 0.0000 0.0000
# Lecture Notes #11: Unfolding Analysis, PCA & FA

## 

### Stress per point columns:

<table>
<thead>
<tr>
<th></th>
<th>SPP</th>
<th>SPP(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>2</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>3</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>4</td>
<td>1.0060</td>
<td>1.0060</td>
</tr>
<tr>
<td>5</td>
<td>13.6821</td>
<td>13.6821</td>
</tr>
<tr>
<td>6</td>
<td>16.9014</td>
<td>16.9014</td>
</tr>
<tr>
<td>7</td>
<td>68.4105</td>
<td>68.4105</td>
</tr>
</tbody>
</table>

---

#plot solution

dim <- range(pretty(range(rbind(out.unfold$conf.row, out.unfold$conf.col))))
estimates <- c(out.unfold$conf.row, out.unfold$conf.col)
plot(estimates, rep(0,11), xlim=dim, ylim=dim, col=c(rep("blue",7), rep("red",4)));
main="Unfolding in the smacof package", ylab="")
subs <- as.character(1:7)
stimuli <- letters[1:4]
abline(h=0)
text(estimates[1:7], rep(0,7), subs, pos=3, col="blue")
text(estimates[8:11], rep(0,4), stimuli, pos=1, col="red")
(b) Applications of One Dimensional Unfolding

Some interesting applications of this technique have been used in political science such as the analysis of Supreme Court decisions. For each case the file shows whether a judge sided on the liberal side or the conservative side (1 or 0, respectively, so the data are binary). I present two examples for all nonunanimous court cases in 2000. Figure 11-2 is a simple one dimensional solution broken up into different types of cases; you can see for example justices Kennedy and Thomas are swing judges appearing sometimes on the liberal side but mostly on the conservative side. Special programs need to be run on binary data such as this example (ALSCAL in SPSS can handle binary data but unfolding in the smacof package in R cannot).

Figure 11-3 is a more modern type of unfolding analysis that uses a Bayesian framework to put distributions on the ideal points (so ideal distributions instead of points). Some-
Figure 11-2: 2000 Supreme Court Cases (Islam et al).
times the distributions overlap so we would expect those judges to be more likely to switch relative positions than judges where the distributions do not overlap. This example was analyzed using the MCMCpack package in R, which provides several Bayesian approaches to several common analyses.

(c) Multidimensional Unfolding

This simple “string model” can be extended to more complicated, multidimensional situations. Intuitively, there are regions in the stimulus space that correspond to the same rank order (much like in the one dimensional case where intervals on the string represent the same observed rank order). This is analogous to INDSCAL where there is both a stimulus configuration space and a subject space, but in unfolding the two are
presented together in one plot. Sometimes it helps to draw arrows from the origin to subject ideal points to help distinguish them from the points representing the items\(^2\).

A short example that you can try. Six subjects rank order their favorite colors (6 different colors are presented). Note that here subjects are not rating similarity, but are ranking the objects according to preference. 1 is most preferred; 4 is least preferred. The solution gives both a spatial configuration and also information on each subject’s preferences; both the spatial configuration and the ideal points are plotted on the same plot. The final configuration is shown in Figure 11-4.

<table>
<thead>
<tr>
<th>Subject</th>
<th>orange</th>
<th>red</th>
<th>violet</th>
<th>blue</th>
<th>green</th>
<th>yellow</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>E</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>F</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

data list free / a b c d e f.

begin data
1 2 3 4 3 2
2 1 2 3 4 3
3 2 1 2 3 4
4 3 2 1 2 3
3 4 3 2 1 2
2 3 4 3 2 1
end data.

alscal variables a b c d e f
/shape = rectangular
/level=ordinal
/condition=row
/criteria=dimens(2)
/plot all.

Another example of unfolding is one where 42 participants ordered 15 breakfast items according to their preference. The 15 items include toast, jelly doughnut, blueberry muffin, cinnamon bun, etc.

See Figure 11-5 for the two dimensional solution (given as an example). The majority of subjects have ideal points roughly at the point (0,-5), the large blob of points near danish pastry (no surprise). It isn’t clear how to interpret the two dimensional solution\(^2\).

\(^2\)Some versions of unfolding represent “ideal points” as vectors and the original rank order of the stimuli are reproduced from the projections onto the subject ideal vectors. In this type of unfolding, vectors that have similar angles mean that the questions yield similar rank orders. There are other versions where rank orders are modeled as the distance from each stimuli to the subject’s ideal point.
Figure 11-4: Color example using ALSCAL with levels=ordinal.
Figure 11-5: Two dimensional unfolding example with breakfast data set

Some R code:

```r
library(smacof)
res <- unfolding(breakfast)
dim <- range(pretty(range(rbind(res$conf.row, res$conf.col))))
plot(res, type = "p", pch = 25, col.columns = 3, ylim=dim,
     xlim=dim,
     label.conf.columns = list(label = TRUE, pos = 3, col = 3),
     col.rows = 8, label.conf.rows =
     list(label = TRUE, pos = 3, col = 8))
abline(h=0,v=0)
```

Joint Configuration Plot
that emerged in this example, but the horizontal may be a hard vs soft dimension. There are some natural clusters of breakfast items that emerged like jelly doughnut and doughnut as well as coffee cake and cinnamon bun.

(d) The Model

Unfolding analysis models a rectangular data matrix onto a dimensional space where the columns represent points in the space (and provide the interpretable dimensions) and the rows represent cases (such as subject). Just like in INDSCAL, cases should be drawn in terms of vectors. In INDSCAL however there are two separate spaces (one for stimuli and one for subjects). Unfolding analysis places both in the same plot because the individual data are modeled as ideal points embedded in the “stimulus configuration matrix.”

Distance in this model is defined as

\[ d_{is} = \sqrt{\sum_k (x_{ik} - x_{sk})^2} \]  

(11-1)

where \( i \) denotes a stimulus, \( s \) denotes the ideal point, and \( k \) is a counter for dimensions. Distance is computed with respect to an item and an ideal point. So, all stimuli are modeled with respect to their distance from an “unknown” ideal point \( s \), the technique estimates these unknown ideal points using the preference/rank/rating data that is supplied.

The applications of this model are quite broad. Any data set that involves rank orders could be analyzed with in this framework.

(e) Extensions of Unfolding Analysis

There is also the possibility of merging an MDS (or INDSCAL) with an unfolding analysis. The kind of unfolding analysis I have presented so far finds both a spatial representation and a preference structure for the same data. This is called “internal unfolding”. There is a sense in which that is asking “too much” from a data set. The type of data used in unfolding doesn’t need to include all pairwise distances; instead the technique models the preference order in terms of distance from a single point. So, before we believe a particular solution too much it should be replicated or independently validated.

There is a more sophisticated merger of MDS with unfolding. One can collect both similarity data and preference data. The program takes both pieces of information and tries to merge them (ALSCAL can do this). This is called “external unfolding” because the
spatial representation is found from different data than the preference structure, and both similarity and preference are merged into a single representation. See Carroll (1972) and also Davison’s book for more details.

Preference modeling can go in two distinct ways. Here we’ve talked about the ideal point model. This model assumes a decreasing preference function away from the ideal point in any direction. This contrasts with other ways to model preference in terms of a “more is better” framework. This notion has an increasing preference function. So, for example, more dollars are always better than less (there probably isn’t an ideal amount of money for you so that if I offered you money in excess of your ideal point you would reject it). The ideal point model treats ideal points as points on the plot and distances from ideal are computed (much like the string model in one dimension). The further away from the ideal point, the less desirable the stimuli. The “more is better” model treats “ideal points” as vectors from the origin and computes projections of each stimuli to the ideal vector—in this model one can imagine creating new stimuli that go further and further out along the “ideal vector” and those new stimuli would be more preferred.

(f) Deep thoughts . . .

There are many differences between the kind of modeling we did in ANOVA and regression and the kind of modeling we see in MDS/ADDTREE/UNFOLDING. Aside from the data structure being different, the availability of statistical tests, and all the other obvious differences, I see a fundamental distinction in what is being modeled. In ANOVA/Regression we are applying a general purpose tool to model data. But are we really modeling psychological process or underlying mechanism with ANOVA/regression? Would we say that the person’s behavior follows $\mu + \alpha + \epsilon$? Would we say that a psychological construct is determined by $\beta_0 + \beta_1 X + \epsilon$? Probably not as this is not a very convincing model of the underlying process or mechanism. Maybe it is ok for modeling a data process with noise (i.e., the “plus $\epsilon$” part). However, the type of modeling we see in MDS/ADDTREE/UNFOLDING is different. We are taking a stab at an underlying psychological process, trying to represent that process mathematically, and then testing the fit of data to the mathematical model. Different psychological processes (dimensional versus featural comparisons, increasing preference versus preference functions peaked at the ideal point), may require different mathematical representations. A benefit of this type of modeling is that when we reject a model we reject a psychological theory or mechanism. For example, if we reject the triangle inequality we know that the underlying process or mechanism doesn’t follow a distance representation, whereas when an $R^2$ in a regression is low we can’t really conclude much other than saying additivity of predictors and the associated statistical assumptions of independence, equal variance and normality may be off. If you would like to learn more about this type of modeling (a modeling that is more directly tied to psychological theory and underlying mechanisms), check out the area of mathematical psychology.

3We sometimes offer a graduate-level course on mathematical psychology.
2. Principal Components Analysis (PCA)\(^4\)

I will present PCA as a special case of MDS, and then I will “re-present” PCA in the way it is usually taught so that you will be able to communicate with others who learned it in a different way. People are not accustomed to thinking of PCA as a special case of MDS, but thinking in terms of MDS helps make this complicated procedure simple and easy to understand. You will see this theme of recasting multivariate statistical problems in terms of MDS throughout the rest of the term. That is why we spent relatively more time on MDS so that these new techniques become easier to understand.

One goal of PCA is to reduce many variables (actually, to reduce the correlation matrix of many variables) down to a more manageable set of dimensions. This is analogous to the goal of MDS where many distances are reduced to a small dimensional space.

(a) PCA as a simple extension of metric MDS (i.e., when “/levels = interval” is specified in ALSCAL or type = “interval” in smacof).

You compute a correlation matrix (or a covariance matrix, which won’t necessarily lead to the same solution) between the variables, and treat that matrix as the “similarity” matrix that you analyze with MDS using the “interval” subcommand. That’s all there is to PCA—it is identical to MDS, we interpret dimensions in the same way (though in PCA they are called “components”). If you use the “ordinal” option you have a nonmetric form of PCA.

Note that the data analyst manually creates the proximity matrix, in the case the correlation matrix, from the variables. All other interpretations of MDS (problems and tricks such as rotating, using external variables to validate the interpretation of dimensions, etc.) extend to PCA. The key difference between the data analyst manually creating the similarity matrix as opposed to the subject generating the similarity matrix is that in the former the dimensions are imposed by the analyst. Recall that one nice feature of MDS is that it permits one to “recover” the dimensions subjects are using. The approach of asking subjects to rate items on a set of variables and then manually creating a proximity matrix from those responses has the problem that the dimensions are imposed on the subject. This is not a point against PCA itself (which is identical to metric MDS) but an argument against using a proximity matrix that is created from other variables rather than observing a proximity matrix directly.

As I show in the linear algebra appendix, a correlation \( r \) can be converted into a distance by the transformation \( \sqrt{2(1 - r)} \). Some people ignore the constant and the square root;

\(^4\)For the neural network/connectionist modelers in the class: PCA is equivalent to a neural network with one hidden layer such that there are as many nodes in the hidden layer as factors and every input has a connection to every node in the hidden layer.
they treat the correlation $r$ directly as a measure of similarity.

That was relatively painless. We just learned a new statistical procedure, which fell out naturally from what we already know about MDS. Now I will introduce the same procedure, PCA, the way it is usually taught. Unfortunately, some of you will find this next treatment painful.

(b) The usual pedagogical introduction to PCA

The typical intuition surrounding PCA is to create new variables as linear combinations of existing variables. You could do this in an ad hoc manner by summing up variables you think are related (giving each variable a weight of 1, just like the unit contrast, and computing the weighting sum) and treating the sum as a new variable. However, there are better ways. For example, rather than weighting each variable by one you could try to find optimal weights. How do you find these optimal weights?

First, let’s consider the case of linear regression, I know that was a long time ago in this class. Suppose you had three predictors of some dependent variable. If you didn’t know about regression you might just take the sum of the three predictors (somehow deal with scaling) and check how closely the sum maps onto the dependent variable. But, with knowledge of regression you can make better predictions under a particular definition (i.e., minimizing squared error). That is, regression finds $\beta$s to weight each variable in some optimal way. You can think of the $\beta$s as a set of contrast weights that weight variables rather than cell means. PCA uses this weighting idea and tries to find weights to create new dependent variables. But, as we will see, PCA finds the optimal weights without using a dependent variable (so in other words, it runs a regression-like analysis to find $\beta$s but doesn’t have a dependent variable). It does magic in computing a regression with no $Y$.

The underlying logic of PCA is that a set of variables $X_1, X_2, \ldots, X_p$ (where $p$ is the number of variables) can be reduced into a smaller set of variables $Y_1, Y_2, \ldots, Y_m$ (where $m$ is the desired number of dimensions). The problem is that the $Y$’s are not observed so we can’t do regression directly. But, hey, the lack of a dependent variable doesn’t have to stop us from moving forward. We seek a set of weights $A_1 = (a_{11}, a_{12}, \ldots, a_{1p})$ that when applied to all $X$’s yield $Y_1$. That is,

$$Y_1 = a_{11}X_1 + a_{12}X_2 + \ldots + a_{1p}X_p$$  \hspace{1cm} (11-2)

Similarly, we seek another set of weights $A_2$ that when applied to the same $X$’s yield $Y_2$, as in

$$Y_2 = a_{21}X_1 + a_{22}X_2 + \ldots + a_{2p}X_p$$  \hspace{1cm} (11-3)

We can continue this process to fit $Y_3$ with weights $A_3$, $Y_4$ with weights $A_4$, etc. The $Y$’s are defined such that they are orthogonal to each other.
When someone says they ran a PCA to reduce the dimensionality of their data that means they reduced the observed $X$’s (the variables) to a smaller set of $Y$’s, the composite scores. Once the $Y$’s are in hand, then subsequent analyses (such as ANOVA and regression) use the $Y$’s rather than the more numerous $X$’s.

We also want $A_1$ and $A_2$ to be orthogonal (actually, we want all pairs of weights $A$ to be orthogonal). You can think of $A_1$ and $A_2$ as contrasts defined over the predictors $X$ but instead of the data analyst choosing the weights a computer algorithm estimate the weights.

Below I discuss how we find these sets of weights $A_1, A_2, \ldots, A_p$. Each of the $A$ vectors are defined so $\sum_j a_j^2 = 1$ such that the variance of the $Y_i$ is maximized.

One way to depict these unobserved PCs is to compare with linear regression. Take a state-level data set (so 50 points) of Murder rate and Rape rate per 100,000 residents. The left panel of Figure 11-6 shows the usual regression with Murder as a predictor and Rape as a dependent variable. The vertical residuals are also shown; think back to the rubber band and stick example from regression. The right panel of Figure 11-6 shows the plot of the first PC with projections (right angles) from the point to the PC. Both scatter plots are identical in terms of the points; both variables are mean centered. Both panels of Figure 11-6 show the same data points, but the left shows the regression with vertical residuals and the right shows the principal component with residuals defined as projections (90 degrees to component).

(c) A tangent: linear algebra. See Appendix 4.

(d) Eigenvalues and Eigenvectors

We now turn attention to a key concept in PCA: eigenvalues and eigenvectors. We consider two equivalent definitions:

i. $Mx = \lambda x$

The intuition of this definition is that the effect of matrix $M$ on $x$ is identical to the effect of the single number $\lambda$ on $x$. Hence, the single number $\lambda$ contains all the relevant information about the matrix $M$ (relevant in the sense of its effect on vector $x$). Recall that matrix multiplication of a vector can be thought of geometrically—the matrix $M$ “moves” vector $x$ elsewhere in the space (a matrix has the effect of shrinking, expanding, translating, rotating, or any combination of these, a vector).

The $\lambda$’s are called eigenvalues; the $x$’s are called eigenvectors. Note that the $\lambda$’s and
Figure 11-6: Show regression versus PCA.
the x’s come in pairs in the sense that for every $\lambda$ there is an x that fits the equation above.

ii. $M = VLV'$ (spectral decomposition)

The intuition here is that the matrix M can be decomposed into “elementary” parts: V is the matrix of eigenvectors and L is the diagonal matrix of eigenvalues.

Here is an example correlation matrix. I will find eigenvalues and eigenvectors, and then compare that to the SPSS output.

\[
\begin{bmatrix}
1.00 & 0.55 & 0.43 & 0.32 & 0.28 & 0.36 \\
0.55 & 1.00 & 0.50 & 0.25 & 0.31 & 0.32 \\
0.43 & 0.50 & 1.00 & 0.39 & 0.25 & 0.33 \\
0.32 & 0.25 & 0.39 & 1.00 & 0.43 & 0.49 \\
0.28 & 0.31 & 0.25 & 0.43 & 1.00 & 0.44 \\
0.36 & 0.32 & 0.33 & 0.49 & 0.44 & 1.00 \\
\end{bmatrix}
\]

The eigenvalues are:

\[
\begin{align*}
2.89 & \\
1.02 & \\
0.65 & \\
0.56 & \\
0.49 & \\
0.39 & \\
\end{align*}
\]

The eigenvectors are in each column, in the same order as the eigenvalues.

\[
\begin{bmatrix}
0.42 & -0.39 & -0.23 & 0.46 & 0.50 & -0.39 \\
0.42 & -0.48 & -0.29 & -0.14 & -0.19 & 0.67 \\
0.41 & -0.32 & 0.56 & -0.42 & -0.26 & -0.41 \\
0.41 & 0.42 & 0.48 & 0.01 & 0.51 & 0.40 \\
0.38 & 0.45 & -0.56 & -0.52 & 0.07 & -0.25 \\
0.42 & 0.37 & 0.00 & 0.56 & -0.61 & -0.05 \\
\end{bmatrix}
\]

The ambitious reader may want to check this computation and verify (by applying the spectral decomposition formula) that the eigenvalues and eigenvectors can reproduce the original correlation matrix within round-off error.

It is useful to compare this simple matrix with SPSS output. Here is the syntax I used. Notice that I did a trick of entering the correlation matrix directly (I’m not using the begin data/end data syntax to enter raw data but instead the correlation matrix); the
FACTOR procedure can accept either raw data or matrices as input. The number 1 must be in the diagonal because that is the correlation of a variable with itself (from MDS you know we automatically have a similarity matrix if the maximum value is in the diagonal and the distance/similarity axioms hold). I’m asking for all six factors (there can be as many factors as there are variables but not more and usually the goal is to reduce the complexity so we select the number of factors to be much smaller than the number of variables) so we can see where the eigenvalues and eigenvectors appear in computer output such as SPSS.

matrix data variables = a b c d e f
   /format full
   /contents = corr
   /n = 100.

begin data
   1 0.55 0.43 0.32 0.28 0.36
   0.55 1 0.50 0.25 0.31 0.32
   0.43 0.50 1 0.39 0.25 0.33
   0.32 0.25 0.39 1 0.43 0.49
   0.28 0.31 0.25 0.43 1 0.44
   0.36 0.32 0.33 0.49 0.44 1
end data.

execute.

factor
   /matrix in(cor=*)
   /print fscore initial extraction rotation correlation repr
   /plot eigen rotation
   /criteria = factors(6).

The SPSS output follows:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Communality</th>
<th>* Factor</th>
<th>Eigenvalue</th>
<th>Pct of Var</th>
<th>Cum Pct</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.00000</td>
<td>1</td>
<td>2.88634</td>
<td>48.1</td>
<td>48.1</td>
</tr>
<tr>
<td>B</td>
<td>1.00000</td>
<td>2</td>
<td>1.01781</td>
<td>17.0</td>
<td>65.1</td>
</tr>
<tr>
<td>C</td>
<td>1.00000</td>
<td>3</td>
<td>.65258</td>
<td>10.9</td>
<td>75.9</td>
</tr>
<tr>
<td>D</td>
<td>1.00000</td>
<td>4</td>
<td>.56233</td>
<td>9.4</td>
<td>85.3</td>
</tr>
<tr>
<td>E</td>
<td>1.00000</td>
<td>5</td>
<td>.48946</td>
<td>8.2</td>
<td>93.5</td>
</tr>
<tr>
<td>F</td>
<td>1.00000</td>
<td>6</td>
<td>.39149</td>
<td>6.5</td>
<td>100.0</td>
</tr>
</tbody>
</table>

Factor Matrix:

<table>
<thead>
<tr>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
<th>Factor 5</th>
<th>Factor 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Reproduced Correlation Matrix:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>B</td>
<td>0.55000</td>
<td>1.00000*</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>C</td>
<td>0.43000</td>
<td>0.50000*</td>
<td>1.00000*</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>D</td>
<td>0.32000</td>
<td>0.25000</td>
<td>0.39000</td>
<td>1.00000*</td>
<td>0.00000</td>
<td>0.00000</td>
</tr>
<tr>
<td>E</td>
<td>0.28000</td>
<td>0.31000</td>
<td>0.25000</td>
<td>0.43000</td>
<td>1.00000*</td>
<td>0.00000</td>
</tr>
<tr>
<td>F</td>
<td>0.36000</td>
<td>0.32000</td>
<td>0.33000</td>
<td>0.49000</td>
<td>0.44000</td>
<td>1.00000*</td>
</tr>
</tbody>
</table>

The lower left triangle contains the reproduced correlation matrix; the diagonal, reproduced communalities; and the upper right triangle residuals between the observed correlations and the reproduced correlations.

There are 0 (0%) residuals (above diagonal) with absolute values > 0.05.

VARIMAX converged in 6 iterations.

Rotated Factor Matrix:

<table>
<thead>
<tr>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
<th>Factor 5</th>
<th>Factor 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>.10234</td>
<td>.17772</td>
<td>.92723</td>
<td>.12046</td>
<td>.14182</td>
</tr>
<tr>
<td>B</td>
<td>.12864</td>
<td>.22977</td>
<td>.25778</td>
<td>.07124</td>
<td>.11691</td>
</tr>
<tr>
<td>C</td>
<td>.08293</td>
<td>.93316</td>
<td>.17529</td>
<td>.16691</td>
<td>.12123</td>
</tr>
<tr>
<td>D</td>
<td>.19406</td>
<td>.16692</td>
<td>.11834</td>
<td>.93179</td>
<td>.21757</td>
</tr>
<tr>
<td>E</td>
<td>.94916</td>
<td>.07972</td>
<td>.09691</td>
<td>.18451</td>
<td>.18737</td>
</tr>
<tr>
<td>F</td>
<td>.19833</td>
<td>.12226</td>
<td>.14098</td>
<td>.21900</td>
<td>.92987</td>
</tr>
</tbody>
</table>

Factor Transformation Matrix:

<table>
<thead>
<tr>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
<th>Factor 5</th>
<th>Factor 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor 1</td>
<td>.38166</td>
<td>.41464</td>
<td>.41938</td>
<td>.40474</td>
<td>.41439</td>
</tr>
<tr>
<td>Factor 2</td>
<td>.45134</td>
<td>-.32365</td>
<td>-.38779</td>
<td>.41930</td>
<td>.36890</td>
</tr>
<tr>
<td>Factor 3</td>
<td>.56178</td>
<td>-.55740</td>
<td>.23135</td>
<td>-.48696</td>
<td>-.00570</td>
</tr>
<tr>
<td>Factor 4</td>
<td>.52155</td>
<td>.42192</td>
<td>-.46510</td>
<td>-.01244</td>
<td>-.56010</td>
</tr>
<tr>
<td>Factor 5</td>
<td>.06685</td>
<td>-.26266</td>
<td>.50322</td>
<td>.50980</td>
<td>-.61330</td>
</tr>
<tr>
<td>Factor 6</td>
<td>.24197</td>
<td>.40696</td>
<td>.38816</td>
<td>-.40397</td>
<td>.04822</td>
</tr>
</tbody>
</table>

Hi-Res Chart #2: Factor plot of factors 1, 2, 3

Factor Score Coefficient Matrix:

<table>
<thead>
<tr>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
<th>Factor 5</th>
<th>Factor 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-.04183</td>
<td>-.12951</td>
<td>1.21050</td>
<td>-.07618</td>
<td>-.10477</td>
</tr>
</tbody>
</table>
Let me walk you through this output. The first table lists the eigenvalues, and you can see that the sum of the eigenvalues equals the number of variables, in this case 6. This is a general result. The sum of the eigenvalues will be equal to the sum of the diagonal of the original matrix. Since a correlation matrix has ones in the diagonal, the sum will equal the number of variables. We call the sum of the diagonal of a matrix the trace; the trace is also equal to the sum of the eigenvalues. We’ll talk about the communalities later.

The factor matrix table has the eigenvectors in each column multiplied by the square root of its associated eigenvalue. For instance, the first column is \((.71339 .70999 .70147 .68914 .63755 .707)\) and if you divide each number by \(\sqrt{.886}\), you’ll get the first eigenvector I listed in my hand computation. So the factor matrix printed by SPSS is a normalized matrix of eigenvectors. As you can see, PCA is exactly the same as finding eigenvalues and their associated eigenvectors.

The next matrix is the reproduced correlation matrix. That is, using all the eigenvalues and eigenvectors we perfectly reproduce the original correlation matrix. Usually you don’t ask for all possible factors but a small number such as 2 or 3. The reproduced correlation matrix can be examined much like a residual matrix to see where the simplified model is messing up relative to the observed correlation matrix. Indeed, it is possible to compare the observed correlation matrix to the reproduced correlation matrix, in the spirit of a residual, to construct statistical tests (we’ll do this later).

The next two matrices are the rotation matrix (what SPSS computed as the best rotation under the extraction method you requested) and the resulting rotated factor matrix. You interpret the rotated factor matrix. The underlying space is in terms of variables; in MDS terminology you are trying to interpret the dimensions of a space that has variables as points (not subjects as points). You may find it helpful to focus on the extreme factor loadings when trying to interpret the dimensions. That is, circle the largest numbers within each dimension and look for variables that have high numbers on one dimension but low numbers on the other dimensions.

The final matrix is the factor score matrix. This matrix gives the weights that you would use to create the factor scores manually. For instance, if you wanted to assign to each subject a score on (rotated) factor 1 you multiply, for each subject, the score on the variable with the numbers in the first column of the factor score coefficient matrix. For example, \((-0.04183) \times \text{variableA} + (-0.09941) \times \text{variableB} + \ldots + (-0.16979) \times \text{variableF}\), where
for each variable you substitute the subject’s score. This allows you to create a score for each subject on each factor. In order to do this, you obviously need the raw data to plug in each subject’s scores; it cannot be done from the correlation matrix. The factor score coefficient matrix that SPSS prints out is based on the rotated solution.\(^5\) In SPSS if you multiply the factor score matrix by \(\sqrt{\lambda}\) (the eigenvalue), you get back the eigenvector.

I personally prefer to interpret the factors using the factor score coefficient matrix instead of the factor matrix because the former is expressed directly in terms of the estimated weights used to create the factors so they are analogous to \(\beta\)s in a regression. I am in a very small minority, however, as most people prefer to interpret the elements in the factor matrix. Usually the two matrices are very similar, but in some cases they may differ; when they differ, it is the factor score matrix that is interpretable. The reason has to do with features of linear combinations that are masked by correlations (see Harris, *Prime of Multivariate Statistics* for examples). The two will differ when rotations are performed (or when numbers other than 1 appear in the diagonal of the correlation matrix, as some types of factor analysis require).

The rotated factor matrix is identical to the Pearson correlation of every observed variable with every rotated factor score. In other words, if you compute the factor score for each subject on factor 1 using the factor score coefficient matrix and correlated these factor scores with observed variable A, the correlation is identical to the first entry in the factor matrix (i.e., the loading of variable A on Factor 1).

The output also mentions communalities. These are the sum of squares of the rows of the loading matrix. Each variable has its own row in the factor matrix, hence its own communality. When all possible factors are included all communalities will be one (for the principal components form of factor extraction). As you remove factors, the communalities will decrease.

As with MDS we can use a scree plot to help decide on the number of factors (see Figure 11-7). The SPSS FACTOR procedure has a built in scree plot.

Usually, we aren’t interested in extracting all possible factors. Instead, we want a smaller number of factors, just like in MDS when we only wanted a few dimensions. I will rerun this example, this time requesting only two factors (the SPSS default is to take all factors having eigenvalues greater than 1). I used the same syntax as above except for omitting the subcommand /criteria = factor(6). The resulting output follows, with corresponding scree plot (Figure 11-7) and rotated factor space (Figure 11-8):

---

\(^5\)Different programs/textbooks use different terms. What SPSS refers to as factor score coefficient matrix is sometimes called the “factor pattern matrix”. What SPSS calls the factor matrix is sometimes called the “factor structure” matrix. Other terms for the various matrices are sometimes used too. Different versions of SPSS also use different terms such as “component” score coefficient matrix. One can go nuts in this literature.
### Variable Communalities

<table>
<thead>
<tr>
<th>Variable</th>
<th>Communality</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.00000 *</td>
</tr>
<tr>
<td>B</td>
<td>1.00000 *</td>
</tr>
<tr>
<td>C</td>
<td>1.00000 *</td>
</tr>
<tr>
<td>D</td>
<td>1.00000 *</td>
</tr>
<tr>
<td>E</td>
<td>1.00000 *</td>
</tr>
<tr>
<td>F</td>
<td>1.00000 *</td>
</tr>
</tbody>
</table>

#### Factor Loadings

<table>
<thead>
<tr>
<th>Factor 1</th>
<th>Factor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.71339</td>
</tr>
<tr>
<td>B</td>
<td>0.70999</td>
</tr>
<tr>
<td>C</td>
<td>0.70147</td>
</tr>
<tr>
<td>D</td>
<td>0.68914</td>
</tr>
<tr>
<td>E</td>
<td>0.63755</td>
</tr>
<tr>
<td>F</td>
<td>0.70703</td>
</tr>
</tbody>
</table>

#### Final Statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Communality</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.66008 *</td>
</tr>
<tr>
<td>B</td>
<td>0.73789 *</td>
</tr>
<tr>
<td>C</td>
<td>0.59699 *</td>
</tr>
<tr>
<td>D</td>
<td>0.65564 *</td>
</tr>
<tr>
<td>E</td>
<td>0.61299 *</td>
</tr>
<tr>
<td>F</td>
<td>0.64056 *</td>
</tr>
</tbody>
</table>

#### Reproduced Correlation Matrix

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.66008*</td>
<td>-0.14449</td>
<td>-0.19636</td>
<td>-0.00634</td>
<td>0.00186</td>
<td>0.00143</td>
</tr>
<tr>
<td>B</td>
<td>0.69449</td>
<td>0.73789*</td>
<td>-0.15466</td>
<td>-0.03372</td>
<td>0.07709</td>
<td>-0.00062</td>
</tr>
<tr>
<td>C</td>
<td>0.62634</td>
<td>0.65466</td>
<td>0.59699*</td>
<td>0.04429</td>
<td>-0.05002</td>
<td>-0.04448</td>
</tr>
<tr>
<td>D</td>
<td>0.32634</td>
<td>0.28372</td>
<td>0.34571</td>
<td>0.65564*</td>
<td>-0.20255</td>
<td>-0.15669</td>
</tr>
<tr>
<td>E</td>
<td>0.27814</td>
<td>0.23291</td>
<td>0.30002</td>
<td>0.63255</td>
<td>0.61299*</td>
<td>-0.18121</td>
</tr>
<tr>
<td>F</td>
<td>0.35857</td>
<td>0.32062</td>
<td>0.37448</td>
<td>0.64669</td>
<td>0.62121</td>
<td>0.64056*</td>
</tr>
</tbody>
</table>

The lower left triangle contains the reproduced correlation matrix; the diagonal, reproduced communalities; and the upper right triangle residuals between the observed correlations and the reproduced correlations.

There are 8 (53.0%) residuals (above diagonal) with absolute values > 0.05.

VARIMAX converged in 3 iterations.
Factor Transformation Matrix:

<table>
<thead>
<tr>
<th></th>
<th>Factor 1</th>
<th>Factor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor 1</td>
<td>.72133</td>
<td>.69259</td>
</tr>
<tr>
<td>Factor 2</td>
<td>-.69259</td>
<td>.72133</td>
</tr>
</tbody>
</table>

Factor Score Coefficient Matrix:

<table>
<thead>
<tr>
<th></th>
<th>Factor 1</th>
<th>Factor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>.44284</td>
<td>-.10436</td>
</tr>
<tr>
<td>B</td>
<td>.50647</td>
<td>-.17233</td>
</tr>
<tr>
<td>C</td>
<td>.39572</td>
<td>-.06124</td>
</tr>
<tr>
<td>D</td>
<td>-.11706</td>
<td>.46665</td>
</tr>
<tr>
<td>E</td>
<td>-.14991</td>
<td>.47506</td>
</tr>
<tr>
<td>F</td>
<td>-.07852</td>
<td>.43547</td>
</tr>
</tbody>
</table>

You can see that this reproduced correlation matrix isn’t a perfect reproduction of the original correlation matrix, but it isn’t too far off from the matrix of observed correlations. Thus, the first two factors (aka eigenvectors) provide a reasonable representation of the six variables.

Eigenvalues and eigenvectors are useful in many respects. Google, the internet search company, uses eigenvectors as the guts of their search engine. A distance matrix is set up indicating which web pages call which web pages (a “link” matrix) and the eigenvectors of that matrix are used in Google’s PageRank algorithm to decide how to rank the importance of web pages that emerge from a search (aside from any ad dollars a company has paid Google to make their page show up first...).

(e) Eigenvalues and eigenvectors in R

Here is just show that to get the eigenvalues and the eigenvectors from a covariance or a correlation matrix as input. Mimic the earlier description of a simple spectral decomposition of the 6x6 correlation matrix on page 11-19.

```r
cors <- c(1, 0.55, 0.43, 0.32, 0.28, 0.36, 0.55, 1, 0.5, 0.25, 0.31, 0.32, 0.43, 0.5, 1, 0.39, 0.25, 0.33, 0.32, 0.25, 0.39, 1, 0.43, 0.49, 0.28, 0.31, 0.25, 0.43, 1, 0.44, 0.36, 0.32, 0.33, 0.49, 0.44, 1)
cormat <- matrix(cors, 6, 6, byrow = T)
cormat
```
Figure 11-7: Scree plot for six variables.
Figure 11-8: Rotated factor space for six variables.
### Lecture Notes #11: Unfolding Analysis, PCA & FA

```
 cofmat <- matrix(c(1, 0.55, 0.43, 0.32, 0.28, 0.36,
                   0.55, 1, 0.5, 0.25, 0.31, 0.32,
                   0.43, 0.5, 1, 0.39, 0.25, 0.33,
                   0.32, 0.25, 0.39, 1, 0.43, 0.49,
                   0.28, 0.31, 0.25, 0.43, 1, 0.44,
                   0.36, 0.32, 0.33, 0.49, 0.44, 1)), nrow = 6, ncol = 6)

pca <- svd(cofmat)
pca

$u
[1,] -0.4199064  0.3853701 -0.2303903 -0.464546537
[2,] -0.4179033  0.4792903 -0.288917090 -0.142878565
[3,] -0.4128937  0.3210685  0.558477833 -0.42244477
[4,] -0.4056314 -0.4213843  0.484598681  0.00933956
[5,] -0.3752666 -0.4504563 -0.562761718 -0.524235768
[6,] -0.4161638 -0.3717662  0.003621186  0.557298457

$v
[1,] -0.4199064  0.3853701 -0.2303903 -0.464546537
[2,] -0.4179033  0.4792903 -0.288917090 -0.142878565
[3,] -0.4128937  0.3210685  0.558477833 -0.42244477
[4,] -0.4056314 -0.4213843  0.484598681  0.00933956
[5,] -0.3752666 -0.4504563 -0.562761718 -0.524235768
[6,] -0.4161638 -0.3717662  0.003621186  0.557298457
```

Here I show how to recreate the original matrix with the eigenvalue/eigenvector pairs (for 1 eigenvector; for 1 and 2; for 1, 2, and 3; etc).

```r
# little function in R to recreate the input matrix from # the eigenvalue/eigenvector pairs
decomp <- function(pca, dim) {
  beta <- diag(pca$d)[1:dim, 1:dim]
  if (dim == 1) beta <- as.matrix(beta)
  u <- pca$u[, 1:dim]
  v <- t(pca$v)[1:dim, ]
  return(round(t(u %% beta %% v), 2))
}

decomp(pca, 1)
```

```
## [1,] 0.51 0.51 0.50 0.49 0.45 0.50
## [2,] 0.51 0.50 0.49 0.45 0.50
## [3,] 0.50 0.49 0.48 0.47 0.44 0.49
## [4,] 0.49 0.48 0.47 0.44 0.45
## [5,] 0.45 0.45 0.44 0.41 0.45
## [6,] 0.50 0.50 0.49 0.45 0.50
```

```r
decomp(pca, 2)
```

```
## [1,] 0.66 0.69 0.63 0.33 0.28 0.36
## [2,] 0.69 0.74 0.65 0.28 0.23 0.32
## [3,] 0.63 0.65 0.60 0.35 0.30 0.37
## [4,] 0.33 0.28 0.35 0.66 0.63 0.65
## [5,] 0.28 0.23 0.30 0.63 0.61 0.62
## [6,] 0.36 0.32 0.37 0.65 0.62 0.64
```

```r
decomp(pca, 3)
```
## Lecture Notes #11: Unfolding Analysis, PCA & FA

### \(\text{decomp}(\text{pca}, 4)\)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>[1]</td>
<td>0.69</td>
<td>0.74</td>
<td>0.54</td>
<td>0.25</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>[2]</td>
<td>0.74</td>
<td>0.79</td>
<td>0.55</td>
<td>0.19</td>
<td>0.34</td>
<td>0.32</td>
</tr>
<tr>
<td>[3]</td>
<td>0.54</td>
<td>0.55</td>
<td>0.80</td>
<td>0.52</td>
<td>0.09</td>
<td>0.38</td>
</tr>
<tr>
<td>[4]</td>
<td>0.25</td>
<td>0.19</td>
<td>0.52</td>
<td>0.81</td>
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<tr>
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<td>0.34</td>
<td>0.09</td>
<td>0.45</td>
<td>0.82</td>
<td>0.62</td>
</tr>
<tr>
<td>[6]</td>
<td>0.36</td>
<td>0.32</td>
<td>0.38</td>
<td>0.65</td>
<td>0.62</td>
<td>0.64</td>
</tr>
</tbody>
</table>

### \(\text{decomp}(\text{pca}, 5)\)

<table>
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<td>0.70</td>
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<td>0.26</td>
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<td>0.19</td>
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<td>0.43</td>
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<td>0.90</td>
<td>0.52</td>
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<td>0.24</td>
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<tr>
<td>[4]</td>
<td>0.26</td>
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<td>0.45</td>
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### \(\text{decomp}(\text{pca}, 6)\)

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<td>0.14</td>
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<td>0.33</td>
</tr>
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<td>0.45</td>
<td>0.21</td>
<td>0.32</td>
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<tr>
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<td>0.38</td>
<td>0.14</td>
<td>0.45</td>
<td>0.94</td>
<td>0.47</td>
<td>0.50</td>
</tr>
<tr>
<td>[5]</td>
<td>0.24</td>
<td>0.37</td>
<td>0.21</td>
<td>0.47</td>
<td>0.98</td>
<td>0.44</td>
</tr>
<tr>
<td>[6]</td>
<td>0.35</td>
<td>0.33</td>
<td>0.32</td>
<td>0.50</td>
<td>0.44</td>
<td>1.00</td>
</tr>
</tbody>
</table>

# using all 6 recreates the original matrix perfectly

### \(\text{decomp}(\text{pca}, 6)\)

<table>
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<tbody>
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<td>0.55</td>
<td>0.43</td>
<td>0.32</td>
<td>0.28</td>
<td>0.36</td>
</tr>
<tr>
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<td>0.50</td>
<td>0.25</td>
<td>0.31</td>
<td>0.32</td>
</tr>
<tr>
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<td>1.00</td>
<td>0.39</td>
<td>0.25</td>
<td>0.33</td>
</tr>
<tr>
<td>[4]</td>
<td>0.32</td>
<td>0.25</td>
<td>0.39</td>
<td>1.00</td>
<td>0.43</td>
<td>0.49</td>
</tr>
<tr>
<td>[5]</td>
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<td>0.31</td>
<td>0.25</td>
<td>0.43</td>
<td>1.00</td>
<td>0.44</td>
</tr>
<tr>
<td>[6]</td>
<td>0.36</td>
<td>0.32</td>
<td>0.33</td>
<td>0.49</td>
<td>0.44</td>
<td>1.00</td>
</tr>
</tbody>
</table>
The R appendix mentions several packages for doing PCA. These packages typically take the raw data as input, internally compute the correlation or covariance matrix (user specifies which one they want), and produce a variety of output, some of the packages also produce a variety of useful plots as shown later in these lecture notes as I work through some examples.

(f) More intuition on PCA

One way to gain intuition about PCA is by using a graphical device that uses squares as observed variables and circles as unobserved variables. A factor is an unobserved variable. We draw arrows from the circles to the square to indicate that according the model the unobserved factor “creates” the observed variable. The factor score corresponds to an individual’s value on the unobserved variable. An element in the eigenvector is the numerical value associated with each arrow (e.g. the 3rd element of the eigenvector corresponds to the weight, or arrow, that one multiplies the factor score to yield the observed score). See Figure 11-9. A second factor would be represented with a second circle, and the associated eigenvector would be represented by new arrows emerging from the new circle to each of the observed variables. In PCA the two factors (F1 and F2) are independent from each other (recall that eigenvectors are orthogonal), but there are extensions that allow the factors to correlate.

We will come back to these types of representations in Lecture #13 when discussing structural equation modeling (SEM). SEM allows one to set some arrows (elements in the eigenvector) to zero in order to allow for statistical tests of research hypotheses. If you predict that a particular observed variable is unrelated to the underlying factor, then you will want to test whether the value of the eigenvector corresponding to that variable is zero. SEM also allows much more such as allowing correlations between factors, testing regression models in the context of simultaneous creation of factors, and more complicated latent variable models such as latent growth curves.

(g) Published example using PCA: depression and rumination

This example comes from a short paper I did with Wendy Treynor and Susan Nolen-Hoeksema (Treynor, Gonzalez, and Nolen-Hoeksema, 2003, *Cognitive Therapy and Research*, 27, 247-59). We studied a standard self-report scale of rumination that has 22 items. Using PCA we noted that 10 items within the scale formed two dimensions: one dimension we interpreted as pondering (cognitive aspect of rumination) and the other dimension we interpreted as brooding (affective aspect of rumination). There were over 1300 participants from a community based sample. Figure 11-10 shows the key aspects from the PCA output: the eigenvalues and their percentage accounted for measures, the scree plot, the components matrix, and the components plot. We’ll discuss the details in class.
Figure 11-9: LEFT: Representation of a single factor (F1) and its corresponding observed variables (X1 to X6). RIGHT: Representation of two factors (F1 and F2) and corresponding observed variables (X1 to X6).
Figure 11-10: PCA from rumination example. The components plot shows two clusters of five items.
(h) Creating factors from raw data

It is instructive to examine how to compute the factors from the information supplied in the SPSS output. This will be useful when you want to plot subjects in the computed space rather than variables and will also make it clearer how PCA works.

Here I will present two examples—one that is simple and can show the hand computations, another that is with actual data.

The first example is taken from Harris, *A Primer of Multivariate Statistics*. The following table shows five subjects measured on two variables (here data are entered in the way one would for ANOVA and regression with each row being a different subject).

<table>
<thead>
<tr>
<th>Subject</th>
<th>X₁</th>
<th>X₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>-7</td>
<td>-3</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>-1</td>
</tr>
</tbody>
</table>

The variance-covariance matrix and the correlation matrix for these data are:

**Covariance Matrix**

<table>
<thead>
<tr>
<th>variable</th>
<th>X₁</th>
<th>X₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>X₁</td>
<td>17.5</td>
<td>7</td>
</tr>
<tr>
<td>X₂</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

**Correlation Matrix**

<table>
<thead>
<tr>
<th>variable</th>
<th>X₁</th>
<th>X₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>X₁</td>
<td>1</td>
<td>.748</td>
</tr>
<tr>
<td>X₂</td>
<td>.748</td>
<td>1</td>
</tr>
</tbody>
</table>

First, I’ll do a PC on the covariance matrix. The eigenvalues of the covariance matrix are 20.635 and 1.865. Note that the sum of these two eigenvalues equals the sum of the diagonal of the covariance matrix (17.5 + 5 = 22.5). The two eigenvectors are (.913, .409) and (-.409, .913). The first factor is created by taking the first eigenvector and multiplying that with the data matrix (i.e., .913X₁ + .409X₂); similarly for the second factor. The subject values for each factor are listed below:
In this way, factors are created directly from data and the eigenvectors. One can go backwards from the factors back to the data by taking the transpose of the eigenvector matrix (described later), e.g., raw data $X_1$ can be reproduced by taking $0.913 \text{factor1} - 0.409 \text{factor2}$, and raw data $X_2$ can be reproduced by taking $0.409 \text{factor1} + 0.913 \text{factor2}$.

For example, we can recreate the observed score for the first subject by taking that subject’s two factor scores, multiplying each by the values of the eigenvector, resulting in $0.913 \times 1.826 + (-0.409) \times (-0.818) = 2$.

If you convert the raw data to Z-scores and repeat everything I did above but with Z-scores the covariance matrix will be identical to the correlation matrix. In that case, the eigenvalues are 1.748 and 0.252 (again, their sum is identical to the sum of the diagonal, which in this case is 2), and the two eigenvectors are $(-0.707, -0.707)$ and $(0.707, -0.707)$. Thus, the first eigenvector is like the unit contrast $(1, 1)$ and the second eigenvector is like the $(1, -1)$ contrast. This suggests that the first factor is assessing something about how the two variables sum whereas the second factor is assessing something about the difference between the two variables. The table of Z-scores and corresponding factor scores (following the same computation as above but with Z-scores instead of raw data) is below:

<table>
<thead>
<tr>
<th>Subject</th>
<th>ZX$_1$</th>
<th>ZX$_2$</th>
<th>Factor 1</th>
<th>Factor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.478</td>
<td>0</td>
<td>-0.388</td>
<td>0.338</td>
</tr>
<tr>
<td>2</td>
<td>0.956</td>
<td>0.447</td>
<td>-0.992</td>
<td>0.3599</td>
</tr>
<tr>
<td>3</td>
<td>0.239</td>
<td>1.34</td>
<td>-1.12</td>
<td>-0.780</td>
</tr>
<tr>
<td>4</td>
<td>-1.673</td>
<td>-1.341</td>
<td>2.132</td>
<td>-0.235</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>-0.447</td>
<td>0.316</td>
<td>0.316</td>
</tr>
</tbody>
</table>

Again, it is possible to go backwards from the factor scores to the original Z-scores. So, the distinction between doing a principal components on a covariance matrix versus a correlation matrix boils down to whether you want to analyze raw data or Z-scores. When variables are measured on different scales (such as height, weight, a 7pt scale, reaction time) the results from a covariance matrix may be difficult to interpret because you have to keep scale in mind; a correlation matrix renormalizes everything so all

---

6 For those following the matrix algebra. If the eigenvector matrix has the eigenvectors as the columns, the PC factors are created using the columns of the eigenvector matrix whereas the raw scores are created from the PC factors using the rows of the eigenvector matrix.
variables are on the same scale. Also, if some variables have much larger variances than other variables, a PCA on the covariance matrix may be influenced by the variables with greater variance; this points to one advantage for doing PCA on the correlation matrix. The correlation matrix forces all variables to have the same variance and thus to be on the same scale.

In this second example I will use the raw data from the track dataset (record times for each country across different track events for men). Here I will show some additional features of PCA and make connections to SPSS output. The syntax is given by:

```
data list free /country (A20) m100 m200 m400 m800 m1500 k5 k10 marathon.
begin data
Argentina 10.39 20.81 46.84 1.81 3.7 14.04 29.36 137.72
Australia 10.31 20.06 44.84 1.74 3.57 13.28 27.66 128.3
Austria 10.44 20.81 46.82 1.79 3.6 13.26 27.72 135.9
Belgium 10.34 20.68 45.04 1.73 3.6 13.22 27.45 135.9
Bermuda 10.28 20.58 45.91 1.8 3.75 14.68 30.55 146.62
Brazil 10.22 20.43 45.21 1.73 3.66 13.62 28.62 133.13
Burma 10.64 21.52 48.3 1.8 3.85 14.45 30.28 139.95
Canada 10.17 20.22 45.36 1.76 3.63 13.55 28.09 131.58
Chile 10.34 20.8 46.2 1.79 3.71 13.61 29.3 134.03
China 10.51 21.04 47.3 1.81 3.73 13.9 29.13 133.53
Columbia 10.43 21.05 46.1 1.82 3.74 13.49 27.88 131.35
CookIs 12.18 23.2 52.94 2.02 4.24 16.7 35.38 164.7
CostaR 10.94 21.9 48.66 1.87 3.84 14.03 28.81 136.58
Czechosl 10.35 20.65 45.64 1.76 3.58 13.42 28.19 134.32
Denmark 10.56 20.52 45.89 1.78 3.61 13.5 28.11 130.78
Dominica 10.14 20.65 46.8 1.82 3.82 14.91 31.45 154.12
Finland 10.43 20.69 45.49 1.74 3.61 13.27 27.52 130.87
France 10.11 20.38 45.28 1.73 3.57 13.34 27.97 132.3
EastG 10.12 20.33 44.87 1.73 3.62 13.17 27.42 129.92
WestG 10.16 20.37 44.5 1.73 3.53 13.21 27.61 132.23
UK 10.11 20.21 44.93 1.7 3.51 13.01 27.51 129.13
Greek 10.22 20.71 45.56 1.78 3.64 14.59 28.45 134.6
Guatemala 10.98 21.82 48.4 1.89 3.8 14.16 30.11 139.33
Hungary 10.26 20.62 46.02 1.77 3.62 13.49 28.44 132.58
India 10.6 21.42 45.73 1.76 3.73 13.77 28.81 131.98
Indonesia 10.59 21.49 47.8 1.84 3.92 14.73 30.79 148.83
Ireland 10.61 20.96 46.3 1.79 3.56 13.32 27.81 132.35
Israel 10.71 21 47.8 1.77 3.72 13.66 28.93 137.55
Italy 10.01 19.72 45.26 1.73 3.6 13.23 27.52 131.08
Japan 10.34 20.81 45.86 1.79 3.64 13.41 27.72 128.63
Kenya 10.46 20.66 44.92 1.73 3.55 13.1 27.38 129.75
SouthK 10.34 20.89 46.9 1.79 3.77 13.96 29.23 136.25
NorthK 10.91 21.94 47.3 1.85 3.77 14.13 29.67 130.87
Luxembourg 10.35 20.77 47.4 1.82 3.67 13.64 29.08 141.27
Malaysia 10.4 20.92 46.3 1.82 3.8 14.64 31.01 154.1
Mauritius 11.19 22.45 47.7 1.88 3.82 15.06 31.77 152.23
Mexico 10.42 21.3 46.1 1.8 3.65 13.46 27.95 129.2
Netherlands 10.52 20.95 45.1 1.74 3.62 13.36 27.61 129.02
NewZealand 10.51 20.88 46.1 1.74 3.54 13.21 27.7 128.98
Norway 10.55 21.16 46.71 1.76 3.62 13.34 27.69 131.48
Papua 10.96 21.78 47.9 1.9 4.01 14.72 31.36 148.22
Philippines 10.78 21.64 46.24 1.81 3.83 14.74 30.64 145.27
Poland 10.16 20.24 45.36 1.76 3.6 13.29 27.89 131.58
Portugal 10.53 21.17 46.7 1.79 3.62 13.13 27.38 128.65
```
Note that some of these times are in seconds and other times are in minutes. This is not a problem for the FACTOR procedure in SPSS because it is based on the correlation matrix, which is independent of scale. The resulting output is (abbreviated):

```
Variable       Communality * Factor Eigenvalue Pct of Var Cum Pct
              *               *     *     *     *
M100          1.00000 * 1  6.62215  82.8  82.8
M200          1.00000 * 2  0.87762  11.0  93.7
M400          1.00000 * 3  0.15932  2.0   95.7
M800          1.00000 * 4  0.12405  1.6   97.3
M1500         1.00000 * 5  0.07988  1.0   98.3
K5            1.00000 * 6  0.06797  .8   99.1
K10           1.00000 * 7  0.04642  .6   99.7
MARATHON      1.00000 * 8  0.02260  .3  100.0
```

Factor Matrix:

```
Factor 1  Factor 2
M100 .81718  .53106
M200 .86717  .43246
M400 .91520  .23259
M800 .94875  .01164
M1500 .95937  -.13096
K5  .93766  -.29231
K10  .94384  -.28747
MARATHON .87990  -.41123
```

```
Final Statistics:
Variable       Communality * Factor Eigenvalue Pct of Var Cum Pct
              *               *     *     *     *
M100          .94981 * 1  6.62215  82.8  82.8
M200          .93900 * 2  0.87762  11.0  93.7
M400          .89169  *
M800          .90027  *
M1500         .93754  *
K5            .96466  *
K10           .97346  *
```

However, in more general situations some programs may define principal components on the covariance matrix, and then scale will matter. In that case, the investigator should put the variables on the same scale otherwise some events will receive less “weight” than they deserve. Watch out—not all versions of SPSS allow the FACTOR procedure to analyze a covariance matrix.
Reproduced Correlation Matrix:

<table>
<thead>
<tr>
<th></th>
<th>M100</th>
<th>M200</th>
<th>M400</th>
<th>M800</th>
<th>M1500</th>
<th>K5</th>
<th>K10</th>
<th>MARATHON</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-.01566</td>
<td>-.03026</td>
<td>-.02546</td>
<td>-.01420</td>
<td>.00845</td>
<td>.01391</td>
<td>.01930</td>
</tr>
<tr>
<td>M200</td>
<td>.93830</td>
<td>.93900</td>
<td>-.04349</td>
<td>-.02114</td>
<td>-.00035</td>
<td>.00868</td>
<td>.00240</td>
<td>.01100</td>
</tr>
<tr>
<td>M400</td>
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<td>.89422</td>
<td>.89169</td>
<td>-.00084</td>
<td>-.01229</td>
<td>-.01155</td>
<td>-.00973</td>
<td>-.00465</td>
</tr>
<tr>
<td>M800</td>
<td>.78149</td>
<td>.82776</td>
<td>.87101</td>
<td>.90027</td>
<td>.00936</td>
<td>-.02261</td>
<td>-.02307</td>
<td>-.02354</td>
</tr>
<tr>
<td>M1500</td>
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<td>.77530</td>
<td>.84756</td>
<td>.90868</td>
<td>.93754</td>
<td>-.00974</td>
<td>-.00844</td>
<td>-.03245</td>
</tr>
<tr>
<td>K5</td>
<td>.61101</td>
<td>.68670</td>
<td>.79016</td>
<td>.88621</td>
<td>.93785</td>
<td>.96466</td>
<td>.00560</td>
<td>-.01307</td>
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<tr>
<td>K10</td>
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<td>.69414</td>
<td>.79694</td>
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<tr>
<td>MARATHON</td>
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<td>.58518</td>
<td>.70964</td>
<td>.83002</td>
<td>.94525</td>
<td>.94869</td>
<td>.94332</td>
<td></td>
</tr>
</tbody>
</table>

The lower left triangle contains the reproduced correlation matrix; the diagonal, reproduced communalities; and the upper right triangle residuals between the observed correlations and the reproduced correlations.

There are 0 (0.0%) residuals (above diagonal) with absolute values > 0.05. VARIMAX converged in 3 iterations.

Rotated Factor Matrix:

<table>
<thead>
<tr>
<th></th>
<th>Factor 1</th>
<th>Factor 2</th>
</tr>
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<tbody>
<tr>
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<td>.93519</td>
</tr>
<tr>
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<td>.89291</td>
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<tr>
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<td>.54306</td>
<td>.77252</td>
</tr>
<tr>
<td>M800</td>
<td>.71240</td>
<td>.62670</td>
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<tr>
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<td>.81333</td>
<td>.52539</td>
</tr>
<tr>
<td>K5</td>
<td>.90194</td>
<td>.38881</td>
</tr>
<tr>
<td>K10</td>
<td>.90346</td>
<td>.39651</td>
</tr>
<tr>
<td>MARATHON</td>
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<td>.26095</td>
</tr>
</tbody>
</table>

Factor Transformation Matrix:

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<th></th>
<th>Factor 1</th>
<th>Factor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor 1</td>
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<td>.65124</td>
</tr>
<tr>
<td>Factor 2</td>
<td>-.65124</td>
<td>.75888</td>
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</tbody>
</table>

Factor Score Coefficient Matrix:

<table>
<thead>
<tr>
<th></th>
<th>Factor 1</th>
<th>Factor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>M100</td>
<td>-.30042</td>
<td>.53957</td>
</tr>
<tr>
<td>M200</td>
<td>-.22153</td>
<td>.45922</td>
</tr>
<tr>
<td>M400</td>
<td>-.06771</td>
<td>.29112</td>
</tr>
<tr>
<td>M800</td>
<td>.10008</td>
<td>.10337</td>
</tr>
<tr>
<td>M1500</td>
<td>.20712</td>
<td>-.01890</td>
</tr>
<tr>
<td>K5</td>
<td>.32436</td>
<td>-.16055</td>
</tr>
<tr>
<td>K10</td>
<td>.32148</td>
<td>-.15576</td>
</tr>
<tr>
<td>MARATHON</td>
<td>.40598</td>
<td>-.26906</td>
</tr>
</tbody>
</table>
Figure 11-11: Rotated factor space for six variables.
The factor score coefficient matrix can be used to create the factors. First, convert all raw data into Z-scores. In SPSS you can create Z-scores through the DESCRIPTIVES command using the “/SAVE” subcommand. This will append to your data file Z-scores of all the variables you listed. The variable names will be the same except that the letter Z is added to the beginning of each variable name. Once all variables have been converted to Z-scores, then you can use the factor score coefficient matrix for weights. For example, factor 1 = (-.300*ZM100) + (-.2215*ZM200) + ... + (.40598*ZMARATH). Make sure you understand where I got these weights from the output. You could compute factor scores either for the rotated solution or for the unrotated solution just by using the proper factor score coefficient matrix (i.e., to create the unrotated factors rerun the FACTOR procedure with the subcommand /rotation=norotate and you’ll get the needed factor score coefficients weights for the unrotated solution). It is safest to compute factor scores on whichever factor structure you are going to interpret (if you interpret the rotated factor space, then compute the factor scores for the rotated factors). Fortunately, the FACTOR procedure has a way of computing the factor scores and saving them into your data matrix. Just add the line “/SAVE reg(all)” to the FACTOR command (see Appendix 2).

It is possible to plot the factor scores for each country based on the factor structure. This factor space with individual cases plotted as points is usually useful in research, but it is rarely used. This is in the spirit of the individual space in INDSCAL and the other plot with variables is analogous to the stimulus configuration space. Here is a version of this plot in R on the unrotated solution, so the first component is essentially the sum of all events and the second is essentially the difference between short and long events.

```r
library(FactoMineR)
library(factoextra)
data <- read.table("track.data")
data <- data.frame(data[, -1], row.names=data[, 1])
names(data) <- c("M100", "M200", "M400", "M800", "M1500", "K5", "K10", "MARATHON")
out.pca.track <- PCA(data, scale.unit=T, ncp=2, graph=FALSE)
# could instead run the standard R pca command
# out.pca <- prcomp(data, scale=T, retx=T)

# print eigenvalues and loadings; same as SPSS unrotated
# for standardized
out.pca.track$eig
```

*You could equivalently compute Z-scores manually using the compute command. Take each variable, subtract the mean, and divide the difference by the standard deviation.*
## comp 1 6.62214613 82.7768266
## comp 2 0.87761829 10.9702287
## comp 3 0.15932114 1.9915143
## comp 4 0.12404939 1.5506173
## comp 5 0.07988027 0.9985034
## comp 6 0.06796515 0.8495644
## comp 7 0.04641953 0.5802441
## comp 8 0.02260010 0.2825012
## cumulative percentage of variance
## comp 1 82.77683
## comp 2 93.74706
## comp 3 95.73857
## comp 4 97.28919
## comp 5 98.28769
## comp 6 99.13725
## comp 7 99.71750
## comp 8 100.00000

tout.pca.track$var$cor

## Dim.1 Dim.2
## M100 0.8171850 0.53105812
## M200 0.8671665 0.43245706
## M400 0.9152012 0.23258563
## M800 0.9487545 0.01164452
## M1500 0.9593714 -0.13096330
## K5 0.9376633 -0.29231413
## K10 0.9438353 -0.28747025
## MARATHON 0.8798965 -0.41122586

# produce plat
fviz_pca_ind(out.pca.track, col.ind = "#00AFBB", repel = TRUE)

## Warning: ggrepel: 6 unlabeled data points (too many overlaps). Consider increasing max.overlaps
#rotated solution through GPArotate package

```r
library(GPArotation)
#slightly different algorithm than SPSS
Varimax(out.pca.track$var$cor)
```

## Orthogonal rotation method varimax converged.

### Loadings:

```r
# Dim.1 Dim.2
M100 0.281 0.933
M200 0.383 0.890
M400 0.549 0.768
M800 0.717 0.621
M1500 0.817 0.519
K5 0.905 0.382
K10 0.906 0.390
```
# when you try different programs you get slightly different results  
# there are too many different ways of doing things, especially in FA

```r
varimax(out.pca.track$var$cor)
```

```r
## $loadings
## Loadings:
## Dim.1 Dim.2
## M100 0.277 0.934
## M200 0.379 0.892
## M400 0.545 0.771
## M800 0.714 0.625
## M1500 0.815 0.523
## K5 0.903 0.386
## K10 0.905 0.394
## MARATHON 0.936 0.258

## $rotmat
## [,1] [,2]
## [1,] 0.7607065 0.6490960
## [2,] -0.6490960 0.7607065
```

# and another way

```r
library(psych)
out.pca.psych <- principal(data, nfactors=2,
             rotate="varimax", covar=F)
```

```r
out.pca.psych
```
## Principal Components Analysis

```
## Call: principal(r = data, nfactors = 2, rotate = "varimax", covar = F)
## Standardized loadings (pattern matrix) based upon correlation matrix
##
##       RC1  RC2 h2  u2 com
## M100  0.28 0.93 0.95 0.050 1.2
## M200  0.38 0.89 0.94 0.061 1.3
## M400  0.55 0.77 0.89 0.108 1.8
## M800  0.71 0.62 0.90 0.100 2.0
## M1500 0.81 0.52 0.94 0.062 1.7
##   K5  0.90 0.39 0.96 0.035 1.4
##   K10 0.90 0.39 0.97 0.027 1.4
##MARATHON 0.94 0.26 0.94 0.057 1.2
##
## SS loadings 4.20 3.30
## Proportion Var 0.53 0.41
## Cumulative Var 0.53 0.94
## Proportion Explained 0.56 0.44
## Cumulative Proportion 0.56 1.00
##
## Mean item complexity = 1.5
## Test of the hypothesis that 2 components are sufficient.
##
## The root mean square of the residuals (RMSR) is 0.02
## with the empirical chi square 0.96 with prob < 1
##
## Fit based upon off diagonal values = 1
```

Why is Cook Islands an outlier?
The biplot puts both the variable space and the subject space on the same plot (two spaces in the same plot, in the spirit of unfolding). Look at R’s biplot() command which runs with both princomp and prcomp. The package psych also has a biplot command to interface with its fa() and principal() commands. Here I use the biplot command in the package factoextra to plot the PCA I ran in the previous command.

```r
fviz_pca_biplot(out.pca.track, label = "all", col.var = "red",
                 ggtheme = theme_minimal())
```
I've just put you through a lot of difficult material. The basic idea is that most people use Figure 11-11, the plot of the variable space. But I think that the figure with the individual points plotted is just as, if not more, useful.

As we saw before there is a relation between the variables and the factor scores. The correlation between each variable and a factor is identical to an entry in the factor matrix. For example, I took the track data, converted all scores to Z-scores, used the factor score coefficient matrix from the rotated solution to create the rotated factors, and then correlated each factor with each raw variable. Here are the correlations between manually created factor 1 and each of the raw variables for the track data:

```
M100  M200  M400  M800  M1500  K5  K10  MARATHON
factor 1 0.274 0.3763 0.5431 0.7126 0.8137 0.9018 0.9034 0.9352
```
Do you recognize these correlations? Look at the first column of the rotated factor matrix for the track data and you’ll see that these correlations are identical to the entries in the first column. Thus, the factor matrix contains the correlations between each raw variable and each factor. Similarly, if you correlate the second factor with each observed variable, you would recreate the second column of the rotated factor matrix.

Recall that the factors themselves are not directly observed; they are created from the factor coefficient score matrix. This same connection between the correlations and the factor matrix holds for any factor score coefficient matrix (e.g., regardless of whether one uses the rotated or unrotated factor coefficient matrix). To verify this, let me try the same thing with the unrotated factors. When you correlate the unrotated factors with each observed variable, you get back the correlations printed in the unrotated factor matrix. Here are the correlations for the first unrotated factor; double check that these are the same correlations within roundoff error as those in the unrotated factor matrix.

<table>
<thead>
<tr>
<th></th>
<th>M100</th>
<th>M200</th>
<th>M400</th>
<th>M800</th>
<th>M1500</th>
<th>K5</th>
<th>K10</th>
<th>MARATHON</th>
</tr>
</thead>
<tbody>
<tr>
<td>factor 1</td>
<td>0.81765</td>
<td>0.86761</td>
<td>0.91594</td>
<td>0.94866</td>
<td>0.95903</td>
<td>0.93734</td>
<td>0.94347</td>
<td>0.87942</td>
</tr>
</tbody>
</table>

Communalities correspond to the percent of variance in each observed variable accounted for by the factors. PCA requires that the factors be orthogonal, thus we can use the old formula from regression that the total $R^2$ is equal to the sum of the individual Pearson correlations squared. So, we have for the first variable M100 an $R^2 = .2743^2 + .93519^2 = .9498$; for the second variable M200 an $R^2 = .3764^2 + .89291^2 = .9390$, etc. Again, these are the percent of variance in each observed variable accounted for by the linear combination of principal components that have been extracted (in this example, two). If all principal components are extracted, then the observed variables will be reproduced perfectly and all $R^2$s are equal to 1. The communalities will remain invariant to rotation. You should check this (same communalities regardless of whether you use the factor matrix or the rotated factor matrix).

The computed factor scores for each subject are useful because they can be analyzed like any other variable—either as a predictor or a dependent variable in a subsequent analysis. For instance, you may want to test whether the factor scores for the men differ from the factor scores for the women. You could simply perform a two sample $t$-test comparing the mean factor score for men to the mean factor score for women. Later I will present techniques that merge principal components with ANOVA-like techniques that have the ability to test hypotheses between groups.

In practice most people don’t use the actual factor scores. Instead, people take a sensible short cut. If we interpret the first factor in the track example to be the four long distance variables, then it seems silly to include the four short distance events in the computation of the first factor. Similarly, it seems silly to include the four long events in...
the computation of the second factor (short distance events). So most people use some kind of cutoff of the factor loadings (or factor scores). In effect to define factor 1 people use the weights (0, 0, 0, 0,.21, .32, .32, .41) so that the four short events get weights of zero and to define factor 2 they use the weights (.54, .46, .28, .1, 0, 0, 0, 0). Some people even go further and don’t bother giving such specific weights to the items that get nonzero weights. Why not just use the weights (0,0,0,1,1,1,1) and (1,1,1,0,0,0,0) for the two factors respectively? Hey, those look mighty close to two contrasts (yes, they are related to contrasts as we will see in Lecture Notes 12). This short cut makes sense to me because we are defining factors based on overall pattern. It is more likely that the general weights such as (0,0,0,1,1,1,1) will replicated over different studies; it is less likely that the specific weights of, say, (-.3, -.2, -.07, .1, .21, .32, .32, .41) that a program may use to create factor 1 will replicate across different studies. So both for ease in interpreting the factors (variables are either “in or out”, for you Project Runway TV show fans) and for robustness, it makes sense to take this short cut. SPSS, as far as I can tell, doesn’t allow this short cut to occur in how it saves factor scores to the data file. You’ll need to do this manually through the COMPUTE command. Oh, one detail you should be mindful about is that the factor score weights do have some information about scale, so you may want to deviate from just using “1s” as weights for the variables that define the factor. For example, it wouldn’t make much sense to add a variable measured in seconds to a variable measured in minutes (or add a variable that is measured in seconds to one that is measured as a 7 point Likert scale).

Machine learning implements this idea of sending some variables to 0 in the form of a systematic algorithm. For example, there is a machine learning algorithm for doing PCA. It adds a penalty for having too many nonzero terms; mathematically if a term is close to 0 then the penalty sends it to be zero. This is pretty much what we do in PCA when we send loadings below a threshold to 0. There are many algorithms in the machine learning literature that do this, for example, there is one based on absolute values, which they call an L1 norm but amounts to being a city block distance metric, and another based on euclidean values, which they call an L2 norm but amounts to being euclidean distance. There is even one that combines both L1 and L2 norms, called elastic net. There are versions of these penalty functions not only for PCA but for other statistical techniques including regression. In the application to regression the logic is that $\beta$s close to 0 actually get sent to 0, so that all that remains are the key predictors. This allows one to select predictors from an arbitrary large list of predictors. This technique of sending some terms to 0 (whether the terms are $\beta$s or factor weights or other statistical estimates) is also known as the Lasso technique and is based on sum of absolute values (L1); the version based on sum of squared values (L2) shrinks parameters rather than specifically sending some to 0. The package glmnet in R performs this type of sparsity for regression models.

A key limitation of current machine learning algorithms is that the estimates are biased and we don’t understand their standard errors. We know they are biased because unbiased estimates emerge when optimal solutions are computed, such as computing all
the $\beta$s in a regression model. When some terms such as $\beta$s are sent to 0, then we no longer have unbiased estimates and it is difficult to estimate the standard error of biased estimates. We saw something similar to deal with multicollinearity (ridge regression is essentially this idea using an L2 norm) where we sacrificed unbiased parameters to get smaller standard errors; there is a connection between ridge regression and these more general approaches. One solution is to use permutation or resampling techniques like bootstrapping to estimate standard errors. Another solution is not to worry at all about confidence intervals and hypothesis testing and instead adopt a different criterion such as cross validation. The idea of cross validation is that one partitions a sample into “training” and “testing” parts, say 80% training and 20% testing. One estimates the model on the training subset and then uses the testing subset to see how well the model works (such as computing MSE, computing misclassification rate, etc). So cross validation evaluates models based on how well the model performs in out of sample prediction (where sample means the subset of data used to estimate the model).

Here is an example of sparsity using the sparsepca package in R. This process of shrinking small coefficients to 0 is also known as regularization or penalization depending on the literature you read. Another R package that you may want to look at is the more general regsem package.

```r
library(sparsepca)
# example from help file
# create a data set with intentionally redundant variables
m <- 10000
V1 <- rnorm(m, 0, 290)
V2 <- rnorm(m, 0, 300)
V3 <- -0.1*V1 + 0.1*V2 + rnorm(m, 0, 100)
X <- cbind(V1=V1, V2=V1, V3=V1, V4=V1, V5=V2, V6=V2, V7=V2, V8=V2, V9=V3, V10=V3)
X <- X + matrix(rnorm(length(X), 0, 1), ncol = ncol(X), nrow = nrow(X))
# Compute SPCA
out <- spca(X, k=3, alpha=1e-3, beta=1e-3, center = TRUE, scale = FALSE, verbose=0)
print(out)
```

```
## Standard deviations:
## [1] 595.408 579.000 137.215
## Eigenvalues:
## [1] 354510.78 335241.51 18828.06
## Sparse loadings:
## [,1] [,2] [,3]
```
The output is relatively easy to interpret because many of the small terms were sent to 0. For comparison here is the same data analysed with a traditional PCA, centering the data as with the spca example and only printing out the first 3 components rounded to 3 decimal places. You can see the clutter of small coefficients got dropped but the values kept are slightly different (that’s because the sparse version introduced bias).

```r
out.pca <- prcomp(X, center = T, scale = F)
round(out.pca$sdev[1:3], 3)

## [1] 596.334 579.919 140.129

round(out.pca$rotation[, 1:3], 3)
```
There are many different approaches for doing these types of analyses. The better ones also perform cross-validation to aid the decision of the tuning parameters, like the glmnet package for regression.

As a bonus, there is the screeplot for the full blown PCA, with a clear elbow at 3 components.

```r
screeplot(out.pca, type = "lines")
```
The corrplot package provides some additional visualizations that works well with FactoMineR and factoextra (for more packages see the R appendix at the end of these notes).

```r
library(FactoMineR)
library(factoextra)
library(corrplot)
# run pca with 3 dimensions
out.PCA <- PCA(X, ncp = 3, graph = FALSE, scale.unit = T)
give_eigenvalue(out.PCA)

##
## eigenvalue variance.percent
## Dim.1 4.504921e+00 4.504921e+01
## Dim.2 3.996728e+00 3.996728e+01
## Dim.3 1.498195e+00 1.498195e+01
## Dim.4 8.597069e-05 8.597069e-04
## Dim.5 1.241010e-05 1.241010e-04
## Dim.6 1.228511e-05 1.228511e-04
## Dim.7 1.180758e-05 1.180758e-04
## Dim.8 1.134588e-05 1.134588e-04
## Dim.9 1.127435e-05 1.127435e-04
## Dim.10 1.117188e-05 1.117188e-04
## cumulative.variance.percent
## Dim.1 45.04921
## Dim.2 85.01649
## Dim.3 99.99844
## Dim.4 99.99930
## Dim.5 99.99942
## Dim.6 99.99954
## Dim.7 99.99966
## Dim.8 99.99978
## Dim.9 99.99989
## Dim.10 100.00000

# scree plot
fviz_eig(out.PCA, addlabels = TRUE, ylim = c(0, 50))
```
Creative plot of variables on two dimensional space based on the cos measure (discussed later). Note the clustering of 4 variables, 4 variables and 2 variables, which is exactly how this hypothetical data set was constructed (used for the sparsity example).

```r
fviz_pca_var(out.PCA, col.var = "cos2", gradient.cols = c("#00AFBB", "#E7B800", "#FC4E07"), repel = TRUE)
```
And great looking plot of the contribution of each variable for each factor.

```r
extra.PCA <- get_pca_var(out.PCA)
# plot of most contributing variables
corrplot(extra.PCA$contrib, is.corr = FALSE)
```
(i) PCA “assumptions”

- linearity must hold! Because PCA is based on correlations, your scatterplots should be adequate representations of your data, otherwise the factors as linear combinations of data wouldn’t make much sense. Nonlinearities and outliers will distort the correlations and covariances, hence will distort PCA.

- the correlation matrix is not “degenerate” (e.g., the observed matrix is not the identity matrix meaning all correlations are 0, there aren’t linearly dependent variables meaning some correlations are 1)

- linear combinations of the variables (i.e., the factors, aka components) must make sense (one shouldn’t have combinations between “apples” and “oranges”)

(j) Test of significance in PCA
If you performed a PCA on the covariance matrix, you can create tests on the eigenvalues and build confidence intervals around them. Standard theory shows that under the usual assumptions (e.g., multivariate normal distribution) a sample eigenvalue $\hat{\lambda}$ has a normal distribution with mean equal to population $\lambda$ and variance equal to $\frac{2\lambda^2}{N}$. This leads to the usual “estimate” and “standard error of the estimate” we saw in Psychology 613. Thus, a confidence interval can be constructed by

$$\hat{\lambda} \pm 1.96 \sqrt{\frac{2\lambda^2}{N}}$$

You can also construct a test comparing the reproduced matrix to the observed matrix. The test is distributed as $\chi^2$ and you need to compare your computed test statistic to the value in the $\chi^2$ table. Here is the test statistic with definition of terms coming right after:

$$\chi^2 \sim -(N - \frac{2P}{3} - \frac{M}{3} - \frac{11}{6}) \ln \left| \frac{\hat{R}}{R} \right|$$

where $N$ is the number of subjects, $P$ is the number of principal components requested, $M$ is the number of variables in the covariance matrix, $\hat{R}$ is the reproduced covariance matrix, $R$ is the observed covariance matrix, and in this equation the vertical bars refer to the determinant of the matrix embedded between the vertical bars. I won’t explain the determinant here except to point out that the determinant is identical to the product of all the eigenvalues (e.g., if there the matrix is $10 \times 10$, then the determinant is identical to the product of all 10 eigenvalues). The degrees of freedom for this $\chi^2$ test are $((P - M)^2 - M - P)/2$. I don’t think many programs print out tests in the context of principal components analysis, so if you want these tests you’ll have to do them by hand (or write your own code in R).

Analogous tests for PCA on a correlation matrix exist but the formulas are much longer to write out because they have to take into account the standardization (i.e., change of scale).

(k) Rotations

A rotation can be defined as a matrix operation (see the linear algebra appendix for details). Denoting the rotation matrix $T$ and the initial factor matrix $L$, we define a new rotated factor matrix by the matrix multiplication $LT$. Note that the communalities are unaffected by the choice of transformation. That is, the communalities are the diagonal elements of the matrix $LL'$ and are identical to the diagonal elements of $L^*L^*$.

---

9In multivariate statistics programs you may sometimes encounter an error that says “matrix not positive definite”. Essentially, that means that the determinant is zero or negative, which means that it is not possible to invert the matrix and that at least one eigenvalue is zero or negative. Causes of this could be that some of the variables are linearly dependent, you used the “pairwise method” for dealing with missing data, or perhaps a variable is a constant. For a deeper discussion of this and related problems see Wothke’s (1993) chapter in Bollen & Long, *Testing Structural Equations Models*. 
where the prime denotes transpose and $*$ denotes a rotated space. Communalities can be interpreted as the length of a vector, and length is unaffected by rotation.

Thurstone suggested several criteria (or desiderata) for rotations. One was that variables should load onto some factors and not others (i.e., leading to entries of 0 in each column of the factor matrix). One trick to accomplish this goal is to compute the variance of the communalities, and then perform an ANOVA-like decomposition on this variance into something akin to between and within sums of squares. The *quartimax* rotation tries to maximize the sum of squares of all elements in the factor matrix (i.e., rotate to get numbers as far apart as possible, thus increasing sum of squares). Quartimax tends to find a single “all purpose” first factor on which all variables load (something analogous to a unit vector). Some people don’t like this because it goes against one of Thurstone’s desiderata that variables should load on some factors and not others. All variables will likely load highly on the single common factor.

Kaiser suggested that it may be better to work with each column of the factor matrix; that is, define a rotation that maximizes the sum of squares loading for each column of the factor matrix. Further, he suggested that before maximizing each column should be normalized by dividing each row of the factor matrix by the square root of the communality for that variable. This is the technique known today as *varimax* (which can be either raw or normalized depending on whether or not the factor matrix was first normalized). This is the default rotation in SPSS.

(i) PCA is useful in dealing with multicollinearity in regression. Recall that predictors that are highly correlated create problems for the standard errors of regression slopes. If your analysis problem has predictors that are highly correlated, you might be able to reduce the predictors down to a smaller set of uncorrelated factors. Simply run a PCA prior to the regression to create factors, and then use the factors as predictors instead of the larger set of correlated predictors. Later, we’ll discuss a more general technique that allows you to create factors and run regressions simultaneously (rather than two steps).

(m) Consensus Analysis

PCA appears in many analyses. One use is in consensus analysis. Take the track and country example I used earlier in this notes. I showed how to analyze it by correlating the 8 events with each other, which gave us an understanding of how records for the events relate to each other. Another analysis would be to correlate each country with each other, so take the 8 records for country i and correlate with the 8 records for country j. Do that for all countries i and j. This generates a correlation matrix measuring how similar each country is to every other country. Now do a PCA on that matrix. If the first component accounts for a large percentage of the variance, then you can use the loadings of each country on the first component as a “competence score.” Those countries that
have fast times across all 8 events are faster than countries with lower loadings.

Anthropologists use this type of analysis when assessing cultural competence of informants. Ask several informants the same set of questions. Correlate across informants to create an informant by informant correlation matrix (just like the country by country correlation matrix above for the track example) and do a PCA. Informants that have loadings on the first component “know” or are experts about their own culture and can be weighted more than informants with lower loadings. I’m just giving a basic outline of the technique, but it is just PCA on a correlation matrix.

3. Independent Components Analysis (ICA)

ICA can be seen as an extension of PCA that is gaining popularity in signal processing and multivariate time series analyses. The basic idea of the model is that it assumes the observed signals $X$ are composed of unknown sources $S$ that are “mixed” or summed together. To get the intuition of ICA an analogy is helpful. Imagine you are at a wedding. There are sounds coming from many sources: the band through the speakers, the sounds on the dance floor, a heated family discussion at one of the tables, etc. If you put microphones at different locations of the room you’ll pick up the closest sounds but also the background noise. Each of those microphones is picking up a mixture of sounds. ICA solves the problem of “unmixing” the signals to get just the nearby sounds (e.g., the signal coming from the microphone near the family discussion would be purged of the sounds from the dance floor, the band and other sounds, the signal coming from the microphone near the dance floor would be purged of the sounds from the band and the family discussion, etc.).

To sketch out the model in symbols. We observe matrix $X$ and model is

$$ X = WS $$

where $S$ is the matrix that contains the original uncontaminated sources and $W$ is the mixing matrix. So what we observe, $X$, is a result of mixing the original sources $S$. The problem the algorithm solves is finding both unknown $W$ and unknown $S$. If we can figure out $W$, then we can apply the inverse of $W$ to the observed $X$ to recover the unknown $S$.

To make this work the assumption ICA makes is that the components are independent and not normally distributed. The reason we don’t want to assume normality is that normal distributions do not have tall spikes or long tails, and we, essentially, need that information in order to pull off this “unmixing” wonder. Normal distributions don’t have kurtosis, and ICA makes use of kurtosis. The framework of ICA extends PCA because it uses the single value decomposition to help estimate the “mixing” matrix.

I’ll present an interesting visual example where I take two images (two source matrices $S$), create new “mixed up” images (analogous to the microphones that pick up primarily one
signal but also some extra background sound) by applying matrix $W$ to the $S$ matrices. First, let’s get two images loaded up into R. These will play the role of the true sources.

```r
library(fastICA)
# install bioconductor and EBImage; uncomment next lines if
# (!requireNamespace('BiocManager', quietly = TRUE))
# install.packages('BiocManager') BiocManager::install()
# BiocManager::install(c('EBImage'))
library("EBImage")

# some vacation pictures from Austria
S1 <- readImage("austria1.jpg")
S2 <- readImage("austria2.jpg")
# make image size smaller for speed
S1 <- resize(S1, w = dim(S1)[1]/5, filter = "bilinear")
S2 <- resize(S2, w = dim(S2)[1]/5, filter = "bilinear")
# convert to grayscale
S1 <- channel(S1, "gray")
S2 <- channel(S2, "gray")
# add back the 3rd dim in array
dim(S1) <- c(dim(S1), 1)
dim(S2) <- c(dim(S2), 1)

par(mfrow = c(1, 2))
display(normalize(S1), method = "raster", frame = 1)
display(normalize(S2), method = "raster", frame = 1)
mtext("Two Pictures: Originals", outer = T, line = -5, side = 3)
```
Now I’ll mix those two pictures to create two new ones that are different composites of both pictures. I will treat these two new mixed images as the signals we observe. We will pretend that we don’t the originals (nor the mixing matrix) and will see if we can recover the original images from these composite images. In the mixed images, note how the clouds from one of the original pictures has been added to the other, the tree branches in the foreground of one of the original pictures has been added to the other, etc. Essentially, both pictures are distorted combinations of the two originals.

```r
# mix both
W <- matrix(c(0.8, 0.2, 0.5, 0.67), ncol = 2, byrow = TRUE)
X1 <- W[1, 1] * S1 + W[1, 2] * S2
X2 <- W[2, 1] * S1 + W[2, 2] * S2
```
Finally, the ICA analysis. We can “unmix” these two images using ICA. I’ll create a new data matrix with both pictures in the same matrix, and run an ICA with two components. I need to change the dimensions of the output of the ICA so that the output can display correctly. I do not make use of original S nor the mixing matrix W in what I do below.
data <- cbind(X1, X2)
model <- fastICA(data, n.comp = 2, method = "C")

# fix dimensions of ICA output separately for each # component
S1_hat <- model$S[, 1]
dim(S1_hat) <- dim(X1)
S2_hat <- model$S[, 2]
dim(S2_hat) <- dim(X2)

# sometimes the negative comes out of ICA so need to # rescale e.g., S2_hat <- max(S2_hat) - S2_hat
par(mfrow = c(1, 2))
display(normalize(S1_hat), method = "raster", frame = 1)
display(normalize(S2_hat), method = "raster", frame = 1)
mtext("Two Pictures: \
     ICA Recovered the Originals from\n     the Mixed Up Mess",
     outer = T, line = -5, side = 3)

Two Pictures:
ICA Recovered the Originals from
the Mixed Up Mess
You can find more examples on the web, including demonstrations with sounds (the microphones example). I think we’ll see more applications of ICA in the next few years as people learn how to use it. Various applications of ICA include removing the noise due to eye blinks from EEG data.

A key extension of ICA and other methods presented so far in these lecture notes and in lecture notes 10 is that we need to have a model of error (that is, the “plus epsilon” part of the model we saw in ANOVA and regression). We now transition into methods that begin to add a model of error to the ideas developed in LN 10 and LN-11.

We can use the intuition of ICA as unmixing a set of observed data into underlying unobserved signals to get a handle of what needs to be done in handling the “plus \( \epsilon \)” idea. In the analogous way that we partition sum of squares into the systematic part (ss between or ss regression) and the error part (ss error or ss residual, for ANOVA and regression respectively) we can think of using PCA-like procedures to “unmix” (analogous to what I demonstrated ICA is doing) a covariance matrix into the systematic part (the underlying signals we care about) and the error part.

4. Factor Analysis

A limitation of principal components analysis is that it doesn’t handle error (i.e., there was no \( \epsilon \) term in our PCA discussions). We need a way to separate out variance that is due to a common factor from variance that is unique to the specific variable from error variance. We can represent this graphically by adding error terms to the model we presented earlier for PCA (see Figure 11-12).

One trick is to put communality estimates in the diagonals of the correlation matrix rather than 1. The trick forms the basis of factor analysis (FA), which attempts to deal with error in measurement. This particular form of FA is now outdated because structural equation modelling (SEM) can do a better job of dealing with error. In any case, factor analysis has historical interest because it recognized that the limitation of PCA was that it did not account for error. Also, rotations are not possible in SEM but one can perform rotations in FA.

A major note: researchers in this literature are pretty fussy about using the word “factor” to apply only to Factor Analysis and not other methods such as PCA. I use the word factor rather loosely and synonymously with other terms like components. For me, it is the model that carries the key information like whether there are error terms as depicted in Figure 11-12. Since many of these concepts are related to each other and in some situations are special cases of more general concepts, I am not as fussy as many of my colleagues. Also, that the same program can be used to estimate most of these things (PCA, exploratory FA, confirmatory FA, etc) just adds to the confusion among users that these may not be as distinct as some methodologists would prefer them to be.
Figure 11-12: Representation of a single factor (F1), its corresponding observed variables (X1 to X6), and the errors.
(a) The Big Debate in FA: What To Put In The Diagonal? Some suggest putting the reliability estimates of each variable in the diagonal of the correlation matrix (rather than the 1), some suggest putting the $R^2$ of the regression with that variable as the DV and all other variables as the IV. It is possible to show that these two correspond to lower and upper bounds, respectively, on the true communality (see Harris, *Primer to Multivariate Statistics*).

Regardless of what is placed in the diagonal, the sum of the diagonals will be less than the number of variables, as in PCA because numbers less than one are being placed in the diagonal. Further, the goal of FA is to estimate the diagonals in a manner that minimizes the number of nonzero eigenvalues. In PCA no eigenvalues can be zero (unless the variables were linearly independent).

In the FA framework, communality is the percentage of variance in a variable explained by the common factor. Denoting communality for variable $i$ as $h_i^2$ we have

$$1 = h_i^2 + u^2$$  \hspace{1cm} (11-6)

where $u^2$ is the variance of everything else. The term $u^2$ is usually decomposed further into two parts:

$$u^2 = s^2 + c^2$$  \hspace{1cm} (11-7)

where $s^2$ is specific variance estimated as (reliability - communality), and error variance $c^2$ is estimated as $1 -$ reliability. Note that in this framework, reliability is a sum of variance explained by both common and specific factors. Reliability may be measured in several ways (e.g., directly in the form of test-retest, in the form of internal consistency). More on reliability when I discuss structural equations modeling later in the term.

The structural model for FA is that each observed variable $i$ is a weighted sum of common factor scores plus a unique factor score associated with that variable:

$$X_i = \beta_1 F_1 + \beta_2 F_2 + \ldots + \beta_k F_k + \epsilon_i$$  \hspace{1cm} (11-8)

where $F_k$ are the common factors, $\epsilon_i$ is the usual error term, and there is no intercept because the variables are assumed centered.

Thus, there is key conceptual difference between PCA and FA. The latter tries to separate factor variance from specific and error variance. PCA lumps specific and error variance into factor variance. The number of factors may be part of the estimation, depending on the method of extraction.

One needs to be careful when interpreting the eigenvectors when communalities other than one are used. The reason is that the trace of the correlation matrix (sum of the
diagonals) will be less than the number of variables. See Harris’ *Primer of Multivariate Statistics* for a more complete discussion of the complexities of factor analysis. Further, the creation of factor scores is tricky in FA because the presence of unique and common factors creates an indeterminacy problem, hence the various methods of computing factor scores in SPSS (see Grice, 2001, *Psychological Methods*, for a review).

5. Misc issues in PCA & FA

(a) Factor extraction

There are many different types of factor extraction methods. Some are based on maximum likelihood methods and some people have argued that those techniques are on stronger statistical footing than the traditional PCA I presented here. There are other procedures that have “funny” properties, such as principal axis factoring, which permits communalities to be greater than 1. But all of this is beyond the scope of this course and I don’t want to dwell on FA given that there are other more modern techniques available. In Lecture Notes 13, we’ll move on to a related technique, structural equations modelling (SEM), that is better behaved than both FA and PCA. SEM many techniques as special cases including FA, PCA, regression, path analysis, and ANOVA. SEM also serves as a foundation for some interesting generalizations, such as merging (a) clustering of variables and/or subjects simultaneous to (b) fitting of factors, testing correlation matrices across different groups, estimation of latent growth curves, and many more techniques.

(b) Number of factors

Much research has now shown that looking at screeplots or using the criterion of eigenvalues greater than 1 (when using correlation matrices) is not optimal. One technique that has emerged is Parallel Analysis.

Parallel analysis is also known as Humphrey-Ilgen parallel analysis. Parallel analysis is now often recommended as the best method to assess the number of factors (Velicer, Eaton, and Fava, 2000; Lance, Butts, and Michels, 2006). Parallel analysis selects the factors that have fit beyond that expected by chance (so there is an underlying statistical model). The actual data are factor analyzed, and separately one does a factor analysis of a matrix of random numbers representing the same number of cases and variables. For both actual and random solutions, the number of factors on the x axis and cumulative eigenvalues on the y axis is plotted. Where the two lines intersect determines the number of factors to be extracted. Though not available directly in SPSS or SAS, O’Connor (2000) presents programs to implement parallel analysis in SPSS, SAS, and MATLAB. These programs are located at https://people.ok.ubc.ca/brioccon/nfactors/nfactors.html.
The paran (available through CRAN) and paramap (available at the website in the previous sentence) libraries in R compute parallel analysis.

For a recent review of several methods to identify the number of factors see Auerswald and Moshagen, 2019, Psychological Methods, 24, 468-491.
Appendix 1: ALSCAL SYNTAX: UNFOLDING ANALYSES

The syntax for an unfolding analysis is similar to that for an MDS or and INDSCAL. Here is an example for a one dimensional solution.

```
alscal variables a b c d
   /levels = ordinal
   /shape = rect
   /criteria = dimens(1)
   /cond = row
   /plot all.
```

The /LEVELS subcommand can take ORDINAL, INTERVAL or RATIO as arguments (usually ORDINAL will be most appropriate). The /SHAPE subcommand is rectangular because one enters a subject by variable matrix, and there should be more subjects than variables. The /COND=ROW subcommand means that comparisons are meaningful only within a row. For example, within a row if a subject assigns a 3 to the first stimulus and a 5 to the second stimulus, we can infer that the subject intended to assign a greater number to the second stimulus. In this case, 3 and 5 occur on the same row because they come from the same subject so they can be meaningfully compared. On the other hand, if another subject assigns a 2 to the first stimulus we cannot compare that the first subject assigned a 3 to the first stimulus and the second subject assigned a 2; these two numbers appear on different rows and thus are not comparable. MacCallum and colleagues have an article on the uses and abuses of “CONDITION” (1977, *Psychometrika*, 42, 297-305).

---

10 The default for /CONDITION is MATRIX, meaning that all numbers within the same matrix are comparable but not across matrices. This is exactly the behavior one wants when running an MDS or an INDSCAL but not when running an unfolding analysis.
Appendix 2: FACTOR procedure in SPSS

The procedure FACTOR in SPSS performs principal components, among other things. The basic syntax is as follows:

```
FACTOR
   /variables LIST-OF-VARIABLES
   /print initial correlation extraction rotation fscore
   /plot eigen rotation
   /criteria factors(2)
   /extraction pc
   /rotation varimax
   /save reg(all) .
```

List all the variables you want to analyze in the `VARIABLES` subcommand. For purposes of keeping track of missing data, you can list a larger set of variables under the `VARIABLES` subcommand and then do repeated factor analyses on subsets of the variables using the `ANALYSIS` subcommand (analogous to the regression command).

The `PRINT` subcommand is useful to ask for the initial solution so you can see the unrotated solution, the correlation matrix, the rotated solution and the factor matrix (the later matrix contains the eigenvectors of the correlation matrix).

It is useful to request plots of the rotated solution as well as the eigenvalues. The latter plot is in the form of a scree plot, like we performed in MDS, and helps us decide on the number of factors.

Just as in ALSCAL, we specify the number of factors. The SPSS default is to print all factors that have an eigenvalue greater than 1, but I prefer the explicit syntax where you specify number of factors.

The final three subcommands specify the method of extraction (in this class we have only discussed “PC”, or principal components), which rotation (e.g., varimax, quartimax, norotate), and to save the factor scores for all computed factors using the regression method. Saving the factor scores is useful because you can plot subjects in the factor space rather than merely the variables (see the track data in these lecture notes for an example). To have the factor scores for the unrotated solution print out and save, you need to specify `/rotation=norotate`. 
Appendix 3: Input/output of matrices in SPSS

It is sometimes convenient to run a PCA or factor analysis directly from the correlation matrix. For instance, if you have a published paper that presents the correlation matrix but you don’t have access to the raw data, and you want to run your own PCA. Reasons for wanting to do this may include 1) the investigator didn’t present a PCA, 2) you don’t like the rotation that was used and you want to try your own, and 3) you want to look at more factors than were presented in the original paper.

Instead of a data list free command you use the syntax below. Note that you need to tell the program how many subjects the correlation is based on; there is no way the program could automatically know the sample size from merely looking at the correlation matrix.

```
matrix data variables = gest gaze verb
    /format free
    /contents=corr
    /n=24.

begin data
    [correlation matrix goes here; it can be lower half and the diagonals must be all 1's]
end data.

factor
    /matrix in(corr=*)
    [etc with the usual factor commands].
```

The meaning of the asterisk in “(corr=*)” is to use whatever data is active in the current data editor as opposed to reading in a file. It is possible to read in a file that already has a correlation matrix saved (say from a previous SPSS command) by replacing the asterisk with a file name (and full path). The CORRELATION command can compute correlations and save them for later use. Simply add this line to the rest of the junk you would add to the CORRELATION command:

```
/matrix = out(corr=*)
```

Again, the asterisk means to use the current available data set (i.e., what is currently “living” in the data editor of SPSS). The key phrase is “in” or “out”, which instructs SPSS programs to apply the following instructions to either A or B. In some versions of SPSS one uses /matrix out(filename) and /matrix in(cor=filename) instead of the * syntax, but I’m not clear on which version requires which syntax.

There is an analogous procedure called PROXIMITIES that could be used to input matrices into ALSCAL. For example,

```
proximities variables LIST
    /view = variables
    /measure = corr
    /matrix = out(temp)
```

will save the correlation matrix into a file temp, which can then be read into ALSCAL.
Appendix 4: Relevant Functions and packages in R

1. Unfolding analyses can be done in either the package munfold or smacof. The munfold algorithm uses a simple extension of single value decomposition (see Linear Algebra appendix). There are also tools in the MCMCpack package using Bayesian approaches to unfolding models, which I used to plot the Supreme Court data and the estimated distribution of each justice earlier in these lecture notes. As I mentioned in an earlier lecture notes, the Bayesian approach places uncertainty in a different place (the parameter rather than the data) and so each parameter (in this case each justice’s ideal point) has its own distribution that can be plotted.

2. PCA and factor analyses can be done with the princomp function and factanal functions, respectively. Also, take a look at the prcomp function. There are supporting functions, like screeplot and loadings, that are also helpful in extracting relevant pieces from the PCA and FA output. Package psych also has additional PCA and FA functions including biplots. Package GPArotation has additional rotation features that can be used in several pca and fa commands in R.

3. factoextra provides many additional functions for plotting PCA and FA.

4. The package Correlplot provides some interesting plots such as correlograms and biplots that can be used for understanding the information in correlation matrices. It incorporates ideas both from PCA and principal FA. Take a look at the package corrplot too.

5. The paran package computes parallel analysis, which is becoming a standard way to decide on the number of factors or components needed in an FA or PCA. See also the paramap package, which can be downloaded at https://people.ok.ubc.ca/brioconn/nfactors/nfactors.html.
Appendix 5: Brief review of linear algebra

1. Linear algebra is important in multivariate statistical techniques (such as factor analysis) so you will probably encounter it in subsequent statistics courses. But also fields where complicated statistics are not used rely on linear algebra. In the field of color vision, linear algebra was used to solve the color constancy problem. Connectionist models rely heavily on linear algebra (at least the simple models do).

2. In this class I will only review the linear algebra that is relevant to the statistical material I want to present. You should be able to work comfortably with matrices and vectors (i.e., add, subtract, multiply, and “divide”). If you want to understand many of the concepts used in statistics such as degrees of freedom and orthogonality I recommend you take a course in linear algebra.

3. Vectors

A vector is a column (or row) of numbers that have a particular order. The total number of entries in the vector is its dimension. The ordered pair \((X, Y)\) is a vector of dimension 2. The contrast \((1, -2, 1, 0)\) is a vector of dimension 4. A column of \(N\) data points in SPSS is a vector of dimension \(N\).

A vector can be expressed either as a row or as a column. For example, here is a row vector

\[
\begin{pmatrix}
0 \\
1 \\
-1
\end{pmatrix}
\]

and here is a column vector

\[
\begin{pmatrix}
0 \\
1 \\
-1
\end{pmatrix}
\]

Keeping track of whether a vector is a column or a row will become important later.

Geometrically, vectors define a point in an \(N\)-dimensional space, where \(N\) is the number of elements in the vector. For example, in high school you dealt with ordered pairs such as \((2, 4)\) and plotted points on a two dimensional Cartesian grid. Such an ordered pair is a vector of dimension 2.

Vectors can be given a more detailed geometric interpretation. Simply draw a line between the origin and the point (place an arrowhead at the point to indicate direction). With such line segments it is possible to talk about angles between points as well as distances.

We can use this geometric intuition to conceptualize the correlation. First, think of an \(N\)-dimensional space (where \(N\) refers to the number of subjects). The column \(X\) contains \(N\)
elements (one for each subject) and defines one point in that N-dimensional space. That is, each subject gets his own dimension and the point X in that space represents all the observations for variable X. The column of Y numbers similarly defines a point in the N-dimensional space. Now you have two vectors (X and Y) in an N-dimensional space. There will be an angle between these two vectors. The cosine of that angle is equal to the Pearson correlation.

Addition and multiplication by a scalar (a real number) is done element by element. For example, to add 5 to a vector we must make the 5 into a vector and then add the two vectors:

\[
\begin{pmatrix}
1 \\
-2 \\ 1
\end{pmatrix}
+ 
\begin{pmatrix}
5 \\
5 \\ 5
\end{pmatrix}
= 
\begin{pmatrix}
6 \\
3 \\ 6
\end{pmatrix}
\]

but multiplication by a scalar is simply:

\[
\begin{pmatrix}
1 \\
-2 \\ 1
\end{pmatrix}
* 2
= 
\begin{pmatrix}
2 \\
-4 \\ 2
\end{pmatrix}
\].

Thus, while multiplication can be in the form of a scalar, addition must be between two vectors of the same dimension (i.e., the scalar 5 was written out as a column vector).

We need to define the operation called “dot product,” which is the multiplication of two vectors each having the same dimension. A dot product is an element by element multiplication followed by a sum of the products. For example, consider the two vectors \( \mathbf{A} = (2 \ 4 \ 6) \) and \( \mathbf{B} = (5 \ 3 \ 1) \). The dot product \( \mathbf{A} \cdot \mathbf{B} \) is a single number: \( 2*5 + 4*3 + 6*1 = 28 \).

Note that the dot product is related to sums of squares in the sense that a product of a vector with itself leads to sum of squares of the elements. Thus, the sum of squared deviations from the mean, which we dealt with in ANOVA, is simply the dot product of the deviation vector with itself.

Another example of the dot product involves computing contrasts over means. Denote \( \lambda \) as the contrast vector and \( \mathbf{X} \) as the vector of means, the contrast value is found by the dot product between \( \lambda \) and \( \mathbf{X} \) (denoted \( \lambda \mathbf{X} \)), which is much simpler to write than the form using the sum notation \( \sum_{i=1}^{T} \lambda_i X_i \).

4. Matrices

A matrix is simply a table of numbers with I rows and J columns. The dimension of a matrix is defined by the number of rows and the number of columns (i.e., IxJ). The reason for developing a mathematical language for matrices is that they occur often so it is convenient to know how to work with them (e.g., operations analogous to adding, multiplying, dividing,
and transforming that we all know how to do with numbers). Note that a single number can
be treated as a matrix having one row and one column. So, what you know about number
systems (such as the rationals or the reals) is just a special case of a more general system for
matrices. There are even systems more general than matrices but we won’t get into that here
(these general theories fall in the domain of abstract algebra).

A matrix can also be viewed as a collection of vectors. For example, an 10x20 matrix can
be viewed as 10 vectors of dimension 20 (or as 20 vectors of dimension 10). The term
“dimension” is singular; e.g., we say a matrix has dimension 10x20.

Examples of matrices include a data file in SPSS where the rows are subjects and the columns
are grouping codes/dependent variables. Consider the small data file with four subjects; the
first column codes subject number, the second column codes condition, and the third column
represents the observed data.

\[
\begin{pmatrix}
1 & 1 & 4 \\
2 & 1 & 6 \\
3 & 2 & 1 \\
4 & 2 & 2 \\
\end{pmatrix}
\]

Two matrices are equal if and only if both are of the same dimension and all corresponding
entries are equal.

Addition and subtraction of matrices occurs element by element. Thus, two matrices must be
of the same size to perform addition and subtraction.

Consider matrix A = \( \begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix} \) and matrix B = \( \begin{pmatrix} 4 & 4 \\ 5 & 5 \end{pmatrix} \). Addition is:

\[
\begin{pmatrix}
1 & 2 \\
3 & 4 \\
\end{pmatrix} + \begin{pmatrix}
4 & 4 \\
5 & 5 \\
\end{pmatrix} = \begin{pmatrix}
1 + 4 & 2 + 4 \\
3 + 5 & 4 + 5 \\
\end{pmatrix} = \begin{pmatrix}
5 & 6 \\
8 & 9 \\
\end{pmatrix}
\]

Multiplication of matrices involves a bunch of dot products. Consider the multiplication of
matrix M (3x2) with matrix N (2x3). This yields a 3x3 matrix MN that contains all possible
dot products of the rows of M with the columns of N. That is, the MN matrix has in the 1,1
entry the dot product of row 1 from M with column 1 from N, the MN matrix has in the 2,1

\[
\begin{pmatrix}
1 & 2 \\
3 & 4 \\
\end{pmatrix} \cdot \begin{pmatrix}
4 & 4 \\
5 & 5 \\
\end{pmatrix} = \begin{pmatrix}
1 \cdot 4 + 2 \cdot 4 & 1 \cdot 4 + 2 \cdot 5 \\
3 \cdot 4 + 4 \cdot 5 & 3 \cdot 4 + 4 \cdot 5 \\
\end{pmatrix} = \begin{pmatrix}
10 & 18 \\
26 & 34 \\
\end{pmatrix}
\]
entry the dot product of row 2 from M with column 1 from N, the MN matrix has in the 3,2
entry the dot product of row 3 from M with column 2 from N, etc.

For example, consider the product of matrix A and matrix B above. We know that the product
of a $2 \times 2$ matrix with a $2 \times 2$ matrix will lead to a $2 \times 2$ matrix.

$$
\begin{pmatrix}
1 & 2 \\
3 & 4
\end{pmatrix}
\begin{pmatrix}
4 & 4 \\
5 & 5
\end{pmatrix}
= 
\begin{pmatrix}
? & ? \\
? & ?
\end{pmatrix}
$$

First, compute the dot product of the first row of A (large, bold font) with the first column of
B (large, bold font). The result is printed in the first row/first column of the righthand matrix
(in large, bold font).

$$
\begin{pmatrix}
1 & 2 \\
3 & 4
\end{pmatrix}
\begin{pmatrix}
4 & 4 \\
5 & 5
\end{pmatrix}
= 
\begin{pmatrix}
14 & ? \\
? & ?
\end{pmatrix}
$$

Second, compute the dot product of the first row of A with the second column of B

$$
\begin{pmatrix}
1 & 2 \\
3 & 4
\end{pmatrix}
\begin{pmatrix}
4 & 4 \\
5 & 5
\end{pmatrix}
= 
\begin{pmatrix}
14 & 14 \\
? & ?
\end{pmatrix}
$$

Third, compute the dot product of the second row of A with the first column of B

$$
\begin{pmatrix}
1 & 2 \\
3 & 4
\end{pmatrix}
\begin{pmatrix}
4 & 4 \\
5 & 5
\end{pmatrix}
= 
\begin{pmatrix}
14 & 14 \\
32 & ?
\end{pmatrix}
$$

Continue this process until you exhaust all cells in the product matrix. So the typical way one
multiplies matrices with each other is to take dot products of all combinations of rows from
the matrix on the left with all columns from the matrix on the right.
There is a type of matrix multiplication that is cell by cell, e.g., a 3 x 3 matrix times a 3 x 3 matrix yields a 3 x 3 matrix where each cell in the resulting matrix is a product of the two cells. This is called a Hadamard product.

The concept of division by matrices is somewhat tricky. Recall from elementary school that one way to define division is in terms of multiplication by the reciprocal. For example, it is the same operation to divide by 5 as it is to multiply by $\frac{1}{5}$. Obviously, a number multiplied with its own reciprocal will equal 1. The intuition underlying division by matrices is to find a way to define the notion of a reciprocal. We know that this general notion needs to satisfy the property that matrix A multiplied by “the reciprocal” should give the matrix analog of I (the identity matrix that has 1’s in the diagonal and 0’s everywhere else).

The inverse of a matrix is similarly defined: the inverse of matrix A, denoted $A^{-1}$, is defined so that $A^{-1}A = I$, where I is the identity matrix, which has 1’s in the diagonal and zeros everywhere else. This is in a form analogous to $5^{-1}5 = 1$ in the case of numbers. The computation of an inverse is not a simple matter and is beyond the scope of this course.

An example will help. Consider the matrix $A$ and its inverse $A^{-1}$. Verify for yourself that the product on the left hand side yields a matrix with ones in the diagonal and zero everywhere else. The identity matrix $I$ is the matrix analog of the number 1.

$$AA^{-1} = I$$

$$\begin{pmatrix}
1 & 2 \\
3 & 4
\end{pmatrix}
\begin{pmatrix}
-2 & 1 \\
1.5 & -.5
\end{pmatrix}
= 
\begin{pmatrix}
1 & 0 \\
0 & 1
\end{pmatrix}$$

5. Transpose

Transposing a matrix involves switching the rows and columns. Essentially, row $i$ becomes column $i$, and column $j$ becomes row $j$, for all rows and columns. Here is an example. The transpose of this matrix

$$\begin{pmatrix}
1 & 2 \\
3 & 4 \\
5 & 6
\end{pmatrix}$$

is this second matrix

$$\begin{pmatrix}
1 & 3 & 5 \\
2 & 4 & 6
\end{pmatrix}$$
The transpose is usually denoted by a superscript prime as in matrix $A'$. Some people use the superscript “t” instead of a prime.

6. Here I’ll give some applications of vectors and matrices with simple things like means, variances, and contrasts.

A variance can be written as follows. Let $X$ be a column vector of data, $1$ be a row vector of 1’s (same number of elements as $X$), and $N$ be the sample size. The variance can now be expressed as

$$\frac{X^t X - (X^t 1)(X^t 1)}{N - 1}$$

Many of the things we’ve learned can be re-formulated in terms of matrix algebra. For example, the structural model for regression, which we wrote as

$$Y_i = \beta_0 + \beta_1 X_i + \epsilon_i \quad (11-9)$$

for subjects $i = 1, \ldots, N$. With matrix algebra we can write the regression structural model in a general way

$$Y = X\beta + \epsilon \quad (11-10)$$

where $Y$, $\beta$, and $\epsilon$ are vectors and $X$ is a matrix, as shown below:

$$
\begin{pmatrix}
Y_1 \\
\vdots \\
Y_N \\
\end{pmatrix} = 
\begin{pmatrix}
1 & X_1 \\
\vdots & \vdots \\
1 & X_N \\
\end{pmatrix}
\begin{pmatrix}
\beta_0 \\
\beta_1 \\
\vdots \\
\end{pmatrix} + 
\begin{pmatrix}
\epsilon_1 \\
\vdots \\
\epsilon_N \\
\end{pmatrix} \quad (11-11)
$$

You should check your understanding that Equation 11-9 is identical to Equation 11-10. Equation 11-10 is more compact because it is the same regardless of the number of predictors (i.e., when you add more predictors to the regression structural model, all that changes is the number of columns of matrix $X$ and the number of rows of vector $\beta$—you still write Equation 11-10 the same way).

The correlation coefficient can also be reformulated in terms of matrix algebra. First, I need to define the length (in Euclidean distance) of a vector. Length is simply the square root of the dot product of a vector with itself (think back to the Minkowski distance metric when we did MDS), and is usually denoted with two double horizontal lines as in the length of vector $X$ is $\|X\|_2$. In symbols, the length of vector $X$ is the
∥X∥_2 = \sqrt{X^tX} \quad (11-12)
= \sqrt{\sum X_i^2} \quad (11-13)

with the subscript 2 referring to the Euclidean length (also known as Euclidean norm). Again, think back to the Minkowski distance where there are other possible length measures such as the absolute value (denoted with a subscript 1), which is equivalent to the “city block” distance metric.

The Pearson correlation between data vectors a and b is defined as

r = \frac{a^t b}{\|a\|_2 \|b\|_2} \quad (11-14)

The correlation is identical to the cosine of the angle between vector a and vector b (which are both in N dimensional space). These vectors a and b should be “mean centered” (i.e., the mean subtracted from data point) to establish the origin.

The correlation can be given a distance interpretation when all data are converted to Z-scores. This forces data to have a variance of 1, which is identical to forcing all vectors to have the same length. To show this, I first note that the distance between two vectors X & Y (i.e., the distance between the two tips of the arrows) is denoted d(X,Y) and is equal to \|X-Y\|_2 where the vertical bars denote length as defined above. The term d(X,Y)^2 can be decomposed by the law of cosines (recall that law from high school):

d(X,Y)^2 = \|X\|_2^2 + \|Y\|_2^2 − 2\|X\|_2 \|Y\|_2 \cos \theta \quad (11-15)

Because the two vectors have been normalized to have unit length (the Z-score transformation did this) and noting that the cosine of \theta is identical to the correlation, Equation 11-15 simplifies to

d(X,Y) = \sqrt{1 + 1 − 2r} \quad (11-16)
= \sqrt{2 − 2r} \quad (11-17)

Thus, the correlation is related to distance in the special case when the vectors on which the distance is being defined are converted to Z-scores. One simply takes the square root of a linear transformation of r, where the slope and intercept of the linear transformation are both 2.

7. Develop the geometry associated with the weighted average of vectors.

In class I will show the special vectors (1 0 0), (0 1 0), and (0 0 1) in 3d space and define the notion of vectors spanning a (sub)space.

---

\(^{11}\text{I can’t resist throwing in a challenge to those students who have had some linear algebra. Show that the two-sample t-test is equal to the cotangent of the angle between the data vector and the grouping vector (both vectors in N-dimensional space) times } \sqrt{N−2}.\)
8. Projection and regression

The predictor variables span a space, which most likely does not include the observed vector $Y$. Linear regression simply “projects” the observed vector $Y$ onto the space spanned by the predictor variables. That projection defines a new vector $\hat{Y}$, which contains the predicted values, i.e., the fits of the model, of the regression line. The usual least-squares regression just performs a projection. The parameters of the structural model (e.g., the intercept and the slope(s)) are simply another—equivalent—way to characterize the projection vector.

Projection of vector $b$ on vector $a$ is defined as $\frac{a^T b}{a^T a}$. An example is the mean, which can be thought of as a projection onto the unit vector. For example, for a vector of data $b = (1 \ 2 \ 3)$ one can project vector $b$ onto the unit vector $a = (1 \ 1 \ 1)$. Here is the computation:

$$
\text{projection} = \frac{\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix}}{\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} = 2 \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}
$$

which has the form mean times the unit vector.

In regression, we are projecting the data vector $Y$ onto the column space of the predictor matrix $X$ to find $\hat{Y}$, which is in the space spanned by the predictors. The residuals represent the distance between $Y$ and $\hat{Y}$. There is a nice conceptual representation of this in the figure below. The observed dependent variable $Y$ is in a $N$ dimensional space. The model is the subspace spanned by linear combinations of the predictors, which has dimensionality of number of parameters. This partitions the degrees of freedom by number of parameters in the model and $N$ minus number of parameters in the error.
9. More regression in linear algebra

The betas in a regression are computed using the following linear algebra form:

\[ \beta = (X^tX)^{-1}X^tY \]  \hspace{1cm} (11-18)

The way to derive this is to start with the usual regression ignoring the error term. The term \( \beta \) is our unknown and both \( Y \) and \( X \) are known (i.e., we know the predictors and the dependent variable but we don’t know the weights \( \beta \)).

\[ Y = X\beta \]  \hspace{1cm} (11-19)

Just like in high school algebra we want to solve for the unknown \( \beta \) so need to “divide both sides by \( X \)” in order to isolate \( \beta \), but this requires the inverse because we are dealing with matrices. However, inverses are difficult to deal with for rectangular matrices, so we first convert \( X \) into a symmetric square matrix by multiplying both sides by \( X^t \) because the product \( X^tX \) is a square symmetric matrix (it is like an uncentered sum of squares matrix between predictor variables). Once we do that we can take the inverse of \( X^tX \) and multiply...
both sides by the inverse. Recalling that the inverse has the property that multiplying a matrix by its inverse leads to the identity matrix we have the following

\[ Y = X\beta \quad (11-20) \]
\[ X^tY = X^tX\beta \quad (11-21) \]
\[ (X^tX)^{-1}X^tY = (X^tX)^{-1}X^tX\beta \quad (11-22) \]
\[ (X^tX)^{-1}X^tY = 1\beta \quad (11-23) \]
\[ (X^tX)^{-1}X^tY = \beta \quad (11-24) \]

10. Special matrices

A diagonal matrix is one whose off diagonals are all zero, as in

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & 3 & 0 \\
0 & 0 & 16
\end{pmatrix}
\]

Identity matrix is a diagonal matrix such that all entries in the diagonal equal 1, as in

\[
\begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

The identity has the special property that a matrix times the identity equals the original matrix (much like multiplying a number by 1). The identity matrix is usually denoted by a capital I. Thus, \( AI = IA = A \). The inverse of a matrix has the property that when it is multiplied with its original matrix, the product is one (much like when \( 1/5 \) is multiplied by 5, the result is one). This can be denoted by \( AA^{-1} = A^{-1}A = I \).

A scalar matrix is a diagonal matrix where all entries in the diagonal are equal to each other. The identity matrix is a special case of a scalar matrix where all elements in the diagonal equal 1. The scalar matrix comes into play in, say, ANOVA where we assume equality of variances. MSE plays the role of the scalar (i.e., in the between-subjects ANOVA the MSE appears in each element of the diagonal representing the “variance” of that group and the off diagonals are all 0 because the groups are independent).

A symmetric matrix has the property that \( A = A^t \). That is, the element \( a_{ij} \) equals \( a_{ji} \) for all \( i \) and \( j \).
Another special matrix is the orthonormal matrix. This is a set of orthogonal vectors put into columns of a matrix and the columns of the matrix are normalized by the length of the respective column. For example, consider the two contrasts (1,-1,0) and (1,1,-2) that we may use in a 3-group between-subjects ANOVA. Put those contrasts into a matrix along with the unit vector to represent the grand mean.

```r
x <- cbind(c(1, 1, 1), c(1, -1, 0), c(1, 1, -2))

# display matrix
x
```

```
## [,1] [,2] [,3]
## [1,] 1  1  1
## [2,] 1 -1  1
## [3,] 1  0 -2
```

```r
library(far)

x.orthonorm <- orthonormalization(x)
x.orthonorm
```

```
## [,1]       [,2]       [,3]
## [1,] 0.5773503 0.7071068 0.4082483
## [2,] 0.5773503-0.7071068 0.4082483
## [3,] 0.5773503 0.0000000-0.8164966
```

Each column in X now has a length of 1 (e.g., think Euclidean distance and square each entry in a column, sum and take the sqrt). This is the length computation of Equation 11-12. We saw in ANOVA that the programs sometimes converted our contrasts into another set of contrasts that were normalized. This is the operation we saw back then.

A good orthonormalization routine can also “fill in” missing contrasts. Here is an example where I drop the last (1,1,-2) contrasts, run the smaller matrix through orthonormalization() and it “finds” the missing orthogonal contrast. It can do this because with two orthogonal contrasts (unit and 1,-1,0) there is only one more contrast that is orthogonal to both of the contrasts already in the mix. Here the unit contrast counts as one of the contrasts (unlike last semester where we didn’t directly count the unit contrast, such as in our statement “there are as many orthogonal contrasts as groups minus 1”; the minus 1 is the unit contrast).

```r
x.new <- x[, -3]
x.new
```

```
x.new
```

## [,1] [,2] [,3]
## [1,] 0.5773503 0.7071068 0.4082483
## [2,] 0.5773503-0.7071068 0.4082483
## [3,] 0.5773503 0.0000000-0.8164966

```
Orthonormal matrices have special properties (like the determinant is equal to 1 or -1; the determinant is defined elsewhere in these notes).

11. Rotation

Rotations can also be easily expressed in the language of matrices. A vector can be rotated by angle $\theta$ using the rotation matrix of sines and cosines. For example, the vector $V = (2 \ 1)$ can be rotated 90 degrees counter clockwise by multiplying with the matrix as follows

$$
\begin{pmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
2 \\
1
\end{pmatrix} = 
\begin{pmatrix}
-1 \\
2
\end{pmatrix}
$$

(11-25)

where $\theta$ is the angle of rotation, in this case 90 degrees counter clockwise.

Rotations are defined on pairs of axes. When you have more than two axes, you need to define rotations on all possible pairs. Rotation matrices are orthogonal so it is possible to multiply them together (order is irrelevant). So, if you have three dimensions and want to consider a rotation, you’ll need to perform three pairwise rotations. Each rotation will have its own matrix. You can summarize the entire operation by a single matrix $T$, which is the product of the three individual pairwise rotation matrices $T_1$, $T_2$, and $T_3$.

12. Eigenvalues and eigenvectors (aka characteristic roots and characteristic vectors)

The basic idea about eigenvalues is that they decompose and summarize a given matrix into smaller chunks of information. The definition is given by this equation where $A$ is a matrix, $\lambda$ is a single number, and $X$ is vector:

$$AX = \lambda X$$  

(11-26)
The meaning of this equation is very simple. Whatever matrix \( A \) does to the vector \( X \) when they are multiplied (the left hand side) is identical to what the single number \( \lambda \) does to \( X \) (the right hand side). Thus, the single number \( \lambda \) completely captures what matrix \( A \) does to \( X \). We can then use the single number \( \lambda \) instead of the matrix \( A \) when we want to study the effects of multiplying by a large matrix. Suppose \( A \) was a 1000 \( \times \) 1000 matrix. If Equation 11-26 holds for a particular vector \( X \), then there is a sense in which the single number \( \lambda \) does the same thing to vector \( X \) as what matrix \( A \) does to vector \( X \).

As you can probably guess, the \( \lambda \) and the \( X \) are related to each other; they come in pairs.

Here is a simple numerical example. Let \( A \) be the matrix

\[
\begin{pmatrix}
3 & 0 \\
0 & 2
\end{pmatrix}
\]

Matrix \( A \) has two pairs of eigenvalues and eigenvectors. One pair is \( \lambda_1 = 3 \) and \( X_1 = (1 \ 0) \); you should check that \( AX_1 = \lambda_1 X_1 \). The second pair is \( \lambda_2 = 2 \) and \( X_2 = (0 \ 1) \), and you should double check that \( AX_2 = \lambda_2 X_2 \).

Eigenvalues and eigenvectors are important in what is known as a spectral decomposition (here, for real, symmetric matrices). The spectral decomposition takes matrix \( A \) and decomposes as follows:

\[
A = L \Lambda L^T
\]

(11-27)

where \( A \) is a real, symmetric matrix, \( \Lambda \) is a diagonal matrix whose elements are the eigenvalues of \( A \), and \( L \) is the matrix that has the eigenvectors of \( A \) as columns.

Here is a numerical example. This matrix

\[
A = \begin{pmatrix}
2 & 1 \\
1 & 2
\end{pmatrix}
\]

has eigenvalues 3 and 1, with eigenvectors \((.707, .707)\) and \((.707, -.707)\), respectively. You should check that the following matrix multiplication reproduces the original matrix \( A \)

\[
\begin{pmatrix}
.707 & .707 \\
.707 & -.707
\end{pmatrix}
\begin{pmatrix}
3 & 0 \\
0 & 1
\end{pmatrix}
\begin{pmatrix}
.707 & .707 \\
.707 & -.707
\end{pmatrix}
\]

One application of spectral decomposition is in reduction of information. Once matrix \( A \) is decomposed I can take fewer eigenvalue/eigenvector pairs and approximate the original matrix. For instance, only taking the first eigenvalue/eigenvector pair of matrix \( A \), I get this
approximation to matrix $A$:

$$
\hat{A} = \begin{pmatrix}
0.707 \\
0.707
\end{pmatrix}
\begin{pmatrix}
3 \\
0.707 \quad 0.707
\end{pmatrix}
= \begin{pmatrix}
1.499 \\
1.499
\end{pmatrix}
\begin{pmatrix}
1.499 \\
1.499
\end{pmatrix}
$$

Thus, we approximate the original matrix $A$ with only one eigenvalue/eigenvector pair. The savings in terms of number of elements to store increases as the matrix $A$ gets large.

This idea of the eigenvalue/vector decomposition is now popular in machine learning circles in terms of an autoencoder. First we “encode” a matrix using a dimension reduction procedure like computing eigenvectors. That strips the key properties from the “noise” (e.g., the first two or three eigenvectors could be taken as the key property and the remaining eigenvectors treated as noise). Second, “decode” from the key properties to reproduce a new matrix using only those key properties. The example in the previous paragraph where I took a $2 \times 2$ matrix, saved the first eigenvalue/vector pair, and then used that eigenvalue/vector pair to reconstruct a new matrix is an example of such an autoencoder (encode then decode) procedure.

Here is an example using a picture of a human face. The picture is just a matrix of gray scale values. Each square (pixel) is white, black or a shade of gray.
I did an eigenvalue/vector decomposition of this image and created this animation. On the right side is the display of each eigenvector and on the left side is the resulting image using the cumulative eigenvectors. So the first eigenvector is merely a set of dark and light gray patches (not at all a human shape), the second eigenvector adds more detail, and slowly each progressive eigenvector adds more detail such as distinguishing the head and shoulders from the background and eventually distinguishing the shading around the nose and other facial features. The left starts to look like a human image as the additional eigenvectors add more (high frequency) information. Eventually, additional eigenvectors don’t improve the resulting image. The frames switch about every 2 seconds with a new eigenvector appearing on the right and that eigenvector added to the previous eigenvectors (i.e., the $L\Lambda L^T$ computation of the resulting matrix where the new eigenvector gets added to $L$ as another column and the
These ideas are used in image processing, compact storage of electronic information, and transmission of information over the web.

\(^{12}\)The animation works when opening the pdf file in Adobe Reader; other pdf viewers may or may not work.