

SOLUTIONS MANUAL

CHAPTER 1

1 There are many ways to do this. One possibility for **A** is

$$\mathbf{P} = \begin{bmatrix} 1 & 0 & 0 \\ -\frac{5}{2} & 1 & 0 \\ 2 & -1 & 1 \end{bmatrix}, \mathbf{Q} = \begin{bmatrix} 1 & -\frac{3}{2} & -8 & 11 \\ 0 & 1 & 5 & -7 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \Delta = \begin{bmatrix} 2 & 0 & 0 & 0 \\ 0 & \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\Delta^{-} = \begin{bmatrix} \frac{1}{2} & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \mathbf{G} = \mathbf{Q}\Delta^{-}\mathbf{P} = \begin{bmatrix} 8 & -3 & 0 \\ -5 & 2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

One possibility for **B** is

$$\mathbf{P} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -4 & 1 & 0 & 0 \\ 1 & -2 & 1 & 0 \\ 1 & 1 & -1 & 1 \end{bmatrix}, \mathbf{Q} = \begin{bmatrix} 1 & -2 & -3 & -5 \\ 0 & 1 & 3 & 6 \\ 0 & 0 & 0 & -2 \\ 0 & 0 & 1 & 1 \end{bmatrix}, \Delta = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -3 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

2 SOLUTIONS MANUAL

$$\Delta^- = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -\frac{1}{3} & 0 & 0 \\ 0 & 0 & \frac{1}{2} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}, \quad \mathbf{G} = \mathbf{Q}\Delta^-\mathbf{P} = \begin{bmatrix} -\frac{19}{6} & \frac{11}{3} & -\frac{3}{2} & 0 \\ \frac{7}{3} & -\frac{7}{3} & 1 & 0 \\ 0 & 0 & 0 & 0 \\ \frac{1}{2} & -1 & \frac{1}{2} & 0 \end{bmatrix}$$

- 2 There are as many generalized inverses to be found by this method as there are non-singular minors of order the rank of the matrix.

One possibility for $\mathbf{A}$ is to use the 2×2 minor in the upper right-hand corner. Its inverse is $\begin{bmatrix} 8 & -3 \\ -5 & 2 \end{bmatrix}$. The resulting generalized inverse is $\mathbf{G} =$

$$\begin{bmatrix} 8 & -3 & 0 \\ -5 & 2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

One possibility for $\mathbf{B}$ is to use the minor $\mathbf{M} = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 10 \end{bmatrix}$. Its

inverse is $\begin{bmatrix} -\frac{2}{3} & -\frac{4}{3} & 1 \\ -\frac{2}{3} & \frac{11}{3} & -2 \\ 1 & -2 & 1 \end{bmatrix}$. The resulting generalized inverse is $\mathbf{G} =$

$$\begin{bmatrix} -\frac{2}{3} & -\frac{4}{3} & 1 & 0 \\ -\frac{2}{3} & \frac{11}{3} & -2 & 0 \\ 1 & -2 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

- 3 (a) The general solution takes the form $\mathbf{x} = \mathbf{G}\mathbf{y} + (\mathbf{GA} - \mathbf{I})\mathbf{z}$. Using the generalized inverse in of A 2, we have

$$\begin{aligned} \tilde{\mathbf{x}} &= \begin{bmatrix} 8 & -3 & 0 \\ -5 & 2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} -1 \\ -13 \\ -11 \end{bmatrix} \\ &+ \left(\begin{bmatrix} 8 & -3 & 0 \\ -5 & 2 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 2 & 3 & 1 & -1 \\ 5 & 8 & 0 & 1 \\ 1 & 2 & -2 & 3 \end{bmatrix} - \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \right) \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix} \\ &= \begin{bmatrix} 31 + 8z_3 - 11z_4 \\ -21 - 5z_3 + 7z_4 \\ -z_3 \\ -z_4 \end{bmatrix} \end{aligned}$$

(b) Using the generalized inverse of $\mathbf{B}$ in 1 we get in a similar manner

$$\tilde{\mathbf{x}} = \begin{bmatrix} -8 - 5z_4 \\ 11 - 6z_4 \\ 2z_4 \\ -z_4 \end{bmatrix}$$

4 We have that

$$\mathbf{A}'\mathbf{A} = \begin{bmatrix} 6 & 1 & 11 \\ 1 & 11 & -9 \\ 11 & -9 & 31 \end{bmatrix}$$

By the Cayley–Hamilton theorem,

$$390(\mathbf{A}'\mathbf{A}) - 48(\mathbf{A}'\mathbf{A})^2 + (\mathbf{A}'\mathbf{A})^3 = 0$$

Then

$$\mathbf{T} = (-1/390)(-48\mathbf{I} + (\mathbf{A}'\mathbf{A})) = \begin{bmatrix} \frac{7}{65} & -\frac{1}{390} & -\frac{11}{390} \\ -\frac{1}{390} & \frac{37}{390} & \frac{3}{130} \\ -\frac{11}{390} & \frac{3}{130} & \frac{17}{390} \end{bmatrix}$$

Then the Moore–Penrose inverse is

$$\mathbf{K} = \mathbf{T}\mathbf{A}' = \begin{bmatrix} \frac{2}{39} & \frac{1}{13} & \frac{1}{39} & \frac{5}{39} \\ \frac{17}{390} & \frac{1}{65} & \frac{14}{195} & \frac{101}{390} \\ \frac{23}{390} & \frac{9}{65} & -\frac{4}{195} & -\frac{1}{390} \end{bmatrix}$$

5 By direct computation, we see that only Penrose condition (ii) is satisfied.

6 (a) For $\mathbf{M}_1$,

$$\mathbf{G}_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -\frac{3}{2} & \frac{5}{2} \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & 0 & 0 \end{bmatrix}.$$

For $\mathbf{M}_2$,

$$\mathbf{G}_2 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & -\frac{1}{2} & \frac{3}{2} \\ 0 & 0 & 0 \\ 0 & \frac{1}{10} & -\frac{1}{10} \end{bmatrix}$$

4 SOLUTIONS MANUAL

For $\mathbf{M}_3$,

$$\mathbf{G}_3 = \begin{bmatrix} \frac{1}{4} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ -\frac{3}{20} & 0 & \frac{1}{5} \end{bmatrix}$$

(b) A generalized inverse is

$$\mathbf{G} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 11 & -4 \\ 0 & -4 & \frac{3}{2} \end{bmatrix}.$$

There are infinitely many other correct answers.

$$7 \quad (\mathbf{a}) \quad \mathbf{A}'\mathbf{A} = \begin{bmatrix} 2 & -2 \\ -2 & 2 \end{bmatrix}, \mathbf{A}\mathbf{A}' = \begin{bmatrix} 2 & -2 \\ -2 & 2 \end{bmatrix}$$

Non-zero eigenvalue = 4 for both matrices. Eigenvectors

$$\begin{bmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{bmatrix}, \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix} \text{ Thus, } \mathbf{U}' = \begin{bmatrix} -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}, \mathbf{S} = \begin{bmatrix} \frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{2}} \end{bmatrix}, \mathbf{A} = [4]$$

$$\mathbf{A}^+ = \begin{bmatrix} -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} \frac{1}{2} \end{bmatrix} \begin{bmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix} = \begin{bmatrix} -\frac{1}{4} & \frac{1}{4} \\ \frac{1}{4} & -\frac{1}{4} \end{bmatrix}$$

Alternatively, by the Cayley–Hamilton Theorem

$$\mathbf{T} = \frac{1}{4}\mathbf{I}, \mathbf{K} = \mathbf{T}\mathbf{A}' = \begin{bmatrix} -\frac{1}{4} & \frac{1}{4} \\ \frac{1}{4} & -\frac{1}{4} \end{bmatrix}.$$

(b) By direct matrix multiplication, we find that (i) satisfies conditions (i) and (ii) so it is a reflexive generalized inverse, (ii) satisfies conditions (i) and (iv) so it is a least square generalized inverse, (iii) satisfies conditions (i) and (iii) so it is a minimum norm generalized inverse and (iv) satisfies conditions (i), (iii), and (iv) so it is both a least-square and minimum norm generalized inverse but not reflexive.

8 There are a number of right answers to part (a) and (b) depending on the choice of generalized inverse.

(a) We have that

$$\mathbf{XX}' = \begin{bmatrix} 2 & 2 & 2 & 1 & 1 & 1 \\ 2 & 2 & 2 & 1 & 1 & 1 \\ 2 & 2 & 2 & 1 & 1 & 1 \\ 1 & 1 & 1 & 2 & 2 & 2 \\ 1 & 1 & 1 & 2 & 2 & 2 \\ 1 & 1 & 1 & 2 & 2 & 2 \end{bmatrix}, (\mathbf{XX}')^- = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{2}{3} & -\frac{1}{3} & 0 & 0 \\ 0 & 0 & -\frac{1}{3} & \frac{2}{3} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\mathbf{X}_{mn} = \mathbf{X}'(\mathbf{XX}')^- = \begin{bmatrix} 0 & 0 & \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ 0 & 0 & \frac{2}{3} & -\frac{1}{3} & 0 & 0 \\ 0 & 0 & -\frac{1}{3} & \frac{2}{3} & 0 & 0 \end{bmatrix}.$$

(b) We have that $\mathbf{X}'\mathbf{X} = \begin{bmatrix} 6 & 3 & 3 \\ 3 & 3 & 0 \\ 3 & 0 & 3 \end{bmatrix}$, $(\mathbf{X}'\mathbf{X})^- = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{1}{3} & 0 \\ 0 & 0 & \frac{1}{3} \end{bmatrix}$ and $\mathbf{X}_{ls} =$

$$(\mathbf{X}'\mathbf{X})^-\mathbf{X}' = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix}.$$

(c) Both the minimum norm and least-square inverses are reflexive. We have

$$\mathbf{X}^+ = \mathbf{X}_{mn}\mathbf{X}\mathbf{X}_{ls} = \begin{bmatrix} \frac{1}{9} & \frac{1}{9} & \frac{1}{9} & \frac{1}{9} & \frac{1}{9} & \frac{1}{9} \\ \frac{2}{9} & \frac{2}{9} & \frac{2}{9} & -\frac{1}{9} & -\frac{1}{9} & -\frac{1}{9} \\ -\frac{1}{9} & -\frac{1}{9} & -\frac{1}{9} & \frac{2}{9} & \frac{2}{9} & \frac{2}{9} \end{bmatrix}$$

- 9 (a) Let $\mathbf{G}$ be a generalized inverse of $\mathbf{A}$. A generalized inverse of $\mathbf{PAQ}$ is $\mathbf{Q}^{-1}\mathbf{GP}^{-1}$.

$$\text{Indeed, } \mathbf{PAQQ}^{-1}\mathbf{GP}^{-1}\mathbf{PAQ} = \mathbf{PAGAQ} = \mathbf{PAQ}.$$

(b) The generalized inverse is $\mathbf{GA}$ because $\mathbf{GAGA} = \mathbf{GA}$.

(c) If $\mathbf{G}$ is a generalized inverse of $\mathbf{A}$ then $(1/k)\mathbf{G}$ is a generalized inverse of $k\mathbf{A}$. We have that $k\mathbf{A}(1/k)\mathbf{G}k\mathbf{A} = \mathbf{AGA} = \mathbf{A}$.

(d) The generalized inverse is $\mathbf{ABA}$ because $(\mathbf{ABA})(\mathbf{ABA})(\mathbf{ABA}) = (\mathbf{ABA})^2(\mathbf{ABA}) = (\mathbf{ABA})(\mathbf{ABA}) = \mathbf{ABA}$.

(e) If $\mathbf{J}$ is $n \times n$ then $\frac{1}{n^2}\mathbf{J}$ is a generalized inverse of $\mathbf{J}$.

$$\mathbf{J} \frac{1}{n^2} \mathbf{J} \mathbf{J} = \mathbf{J}$$

6 SOLUTIONS MANUAL

- 10 (a) The identity and zero matrix and idempotent matrices. Also three by three matrices that satisfy the characteristic equation $\mathbf{A}^3 - \mathbf{A} = \mathbf{0}$.
 (b) Orthogonal matrices $\mathbf{A}\mathbf{A}'\mathbf{A} = \mathbf{A}$ because $\mathbf{A}'\mathbf{A} = \mathbf{I}$.
 (c) The identity matrix, the zero matrix, and an idempotent matrix.
 (d) No matrices.
 (e) Non-singular matrices

- 11 Searle's definition means that for equations $\mathbf{A}\mathbf{x} = \mathbf{y}$ for a vector $\mathbf{t}$, $\mathbf{t}'\mathbf{A} = \mathbf{0}$ implies $\mathbf{t}'\mathbf{y} = \mathbf{0}$. For (a) $\mathbf{t}'\mathbf{0} = \mathbf{0}$ for any vector $\mathbf{t}$. For (b) if $\mathbf{t}'\mathbf{X}'\mathbf{X} = \mathbf{0}$, implies $\mathbf{t}'\mathbf{U}\mathbf{A}^{1/2}\mathbf{S}\mathbf{S}'\mathbf{A}^{1/2}\mathbf{U}' = \mathbf{0}$. Multiply this by $\mathbf{U}\mathbf{A}^{-1/2}\mathbf{S}$ to get $\mathbf{t}'\mathbf{U}\mathbf{A}^{1/2}\mathbf{S} = \mathbf{t}'\mathbf{X}' = \mathbf{0}$.

- 12 By substitution, we have

$$\begin{aligned}\tilde{\mathbf{x}} &= \mathbf{G}\mathbf{y} + (\mathbf{GA} - \mathbf{I})(\mathbf{G} - \mathbf{F})\mathbf{y} + (\mathbf{I} - \mathbf{FA})\mathbf{w} \\ &= [\mathbf{G} + (\mathbf{GA} - \mathbf{I})(\mathbf{G} - \mathbf{F})]\mathbf{Ax} + (\mathbf{GA} - \mathbf{I})(\mathbf{I} - \mathbf{FA})\mathbf{w} \\ &= [\mathbf{GA} + \mathbf{GAGA} - \mathbf{GA} - \mathbf{GAFA} + \mathbf{FA}]\mathbf{x} + (\mathbf{GA} - \mathbf{I} - \mathbf{GAFA} + \mathbf{FA})\mathbf{w} \\ &= [\mathbf{GA} + \mathbf{GA} - \mathbf{GA} - \mathbf{GA} + \mathbf{FA}]\mathbf{x} + (\mathbf{GA} - \mathbf{I} - \mathbf{GA} + \mathbf{FA})\mathbf{w} \\ &= \mathbf{FAx} + (\mathbf{FA} - \mathbf{I})\mathbf{w} \\ &= \mathbf{Fy} + (\mathbf{FA} - \mathbf{I})\mathbf{w}.\end{aligned}$$

- 13 The matrix $(\mathbf{I} - \mathbf{GA})$ is idempotent so it is its own generalized inverse. The requested solution is

$$\begin{aligned}\mathbf{w} &= (\mathbf{I} - \mathbf{GA})(\mathbf{G} - \mathbf{F})\mathbf{y} + (\mathbf{I} - \mathbf{GA})(\mathbf{FA} - \mathbf{I})\mathbf{z} \\ &= (\mathbf{GA} - \mathbf{FA} - \mathbf{GAGA} + \mathbf{GAFA})\mathbf{x} + (\mathbf{FA} - \mathbf{GAFA} - \mathbf{I} + \mathbf{GA})\mathbf{z} \\ &= (\mathbf{GA} - \mathbf{FA} - \mathbf{GA} + \mathbf{GA})\mathbf{x} + (\mathbf{FA} - \mathbf{GA} - \mathbf{I} + \mathbf{GA})\mathbf{z} \\ &= (\mathbf{G} - \mathbf{F})\mathbf{Ax} + (\mathbf{FA} - \mathbf{I})\mathbf{z} \\ &= (\mathbf{G} - \mathbf{F})\mathbf{y} + (\mathbf{FA} - \mathbf{I})\mathbf{z}.\end{aligned}$$

- 14 (a) Since $\mathbf{A}$ has full-column rank, so does $\mathbf{A}'\mathbf{A}$ (see, for example, Gruber (2014) Theorem 6.4). Also $\mathbf{A}'\mathbf{A}$ has full-row rank so it is non-singular. As a result, since $\mathbf{AGA} = \mathbf{A}$, $\mathbf{A}'\mathbf{AGA} = \mathbf{A}'\mathbf{A}$ and $\mathbf{GA} = \mathbf{I}$. Then $\mathbf{GAG} = \mathbf{G}$ and $\mathbf{GA}$ is a symmetric matrix.
 (b) Since $\mathbf{A}$ has full-row rank, $\mathbf{A}'$ has full-column rank. Then $\mathbf{G}'$ is a left inverse of $\mathbf{A}'$ and $\mathbf{G}'\mathbf{A}' = \mathbf{I}$, so $\mathbf{AG} = \mathbf{I}$ and $\mathbf{G}$ is a right inverse. Then $\mathbf{GAG} = \mathbf{G}$ and $\mathbf{AG}$ is a symmetric matrix.

- 15 Suppose that the singular value decomposition of $\mathbf{A} = \mathbf{S}'\mathbf{A}^{1/2}\mathbf{U}'$. Then $\mathbf{A}'\mathbf{A} = \mathbf{U}\mathbf{A}\mathbf{U}'$, $(\mathbf{A}'\mathbf{A})^p = (\mathbf{U}\mathbf{A}\mathbf{U}')^p(\mathbf{U}\mathbf{A}\mathbf{U}') = \mathbf{U}\mathbf{A}^p\mathbf{U}'$. Then since $\mathbf{T}(\mathbf{A}'\mathbf{A})^{r+1} = (\mathbf{A}'\mathbf{A})^r$, $\mathbf{T}\mathbf{U}\mathbf{A}^{r+1}\mathbf{U}' = \mathbf{U}\mathbf{A}^r\mathbf{U}'$. Post-multiply both sides of this equation by $\mathbf{U}\mathbf{A}^{-r}\mathbf{U}'$ to obtain $\mathbf{T}\mathbf{U}\mathbf{A}\mathbf{U}' = \mathbf{U}\mathbf{U}'$. Now post-multiply both sides by $\mathbf{U}\mathbf{A}^{-1/2}\mathbf{S}$ so that $\mathbf{T}\mathbf{U}\mathbf{A}\mathbf{U}'\mathbf{U}\mathbf{A}^{1/2}\mathbf{S} = \mathbf{U}\mathbf{U}'\mathbf{U}\mathbf{A}^{1/2}\mathbf{S} = \mathbf{U}\mathbf{A}^{1/2}\mathbf{S}$ and thus $\mathbf{T}\mathbf{A}'\mathbf{A}\mathbf{A}' = \mathbf{A}'$.

- 16 Any singular idempotent matrix would have the identity matrix for a generalized inverse. For example, $\mathbf{M} = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$

- 17 Assume that $\mathbf{B}^-\mathbf{A}^-$ is a generalized inverse of $\mathbf{AB}$. Then

$$\mathbf{ABB}^-\mathbf{A}^-\mathbf{AB} = \mathbf{AB}$$

Pre-multiply the above equation by $\mathbf{A}^-$ and post-multiply it by $\mathbf{B}^-$. Then

$$\mathbf{A}^-\mathbf{ABB}^-\mathbf{A}^-\mathbf{ABB}^- = \mathbf{A}^-\mathbf{ABB}^-$$

so that $\mathbf{A}^-\mathbf{ABB}^-$ is idempotent.

Now suppose that $\mathbf{A}^-\mathbf{ABB}^-$ is idempotent. Then

$$\mathbf{A}^-\mathbf{ABB}^-\mathbf{A}^-\mathbf{ABB}^- = \mathbf{A}^-\mathbf{ABB}^-$$

Pre-multiply this equation by $\mathbf{A}$ and post-multiply it by $\mathbf{B}$ to obtain

$$\mathbf{AA}^-\mathbf{ABB}^-\mathbf{A}^-\mathbf{ABB}^-\mathbf{B} = \mathbf{AA}^-\mathbf{ABB}^-\mathbf{B}.$$

By virtue of $\mathbf{AA}^-\mathbf{A} = \mathbf{A}$ and $\mathbf{BB}^-\mathbf{B} = \mathbf{B}$, we get

$$\mathbf{ABB}^-\mathbf{A}^-\mathbf{AB} = \mathbf{AB}$$

so that $\mathbf{B}^-\mathbf{A}^-$ is a generalized inverse of $\mathbf{AB}$.

- 18 See Exercise 15 for an example where a matrix and its generalized inverse are not of the same rank.

First assume that $\mathbf{G}$ is a reflexive generalized inverse of $\mathbf{A}$. From $\mathbf{AGA} = \mathbf{A}$ $\text{rank}(\mathbf{A}) \leq \text{rank}(\mathbf{G})$. Likewise from $\mathbf{GAG} = \mathbf{G}$ $\text{rank}(\mathbf{G}) \leq \text{rank}(\mathbf{A})$ so that $\text{rank}(\mathbf{G}) = \text{rank}(\mathbf{A})$.

On the other hand suppose that $\mathbf{G}$ is a generalized inverse of $\mathbf{A}$ with the same rank r as $\mathbf{A}$. We can find non-singular matrices $\mathbf{P}$ and $\mathbf{Q}$ where

$$\mathbf{PAQ} = \begin{bmatrix} \mathbf{I}_r & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \text{ and as a result, } \mathbf{A} = \mathbf{P}^{-1} \begin{bmatrix} \mathbf{I}_r & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \mathbf{Q}^{-1}$$

$\mathbf{A}$ generalized inverse takes the form

$$\mathbf{G} = \mathbf{Q} \begin{bmatrix} \mathbf{I}_r & \mathbf{C}_{12} \\ \mathbf{C}_{21} & \mathbf{C}_{22} \end{bmatrix} \mathbf{P}$$

Because $\mathbf{G}$ has rank r and the first r columns are linearly independent, $\mathbf{C}_{22} = \mathbf{C}_{12}\mathbf{C}_{21}$. The verification that $\mathbf{G}$ is a reflexive generalized inverse follows by straightforward matrix multiplication.

8 SOLUTIONS MANUAL

19 We have that

$$\begin{aligned} \mathbf{AGA} &= \mathbf{P}^{-1} \begin{bmatrix} \mathbf{D} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \mathbf{Q}^{-1} \mathbf{Q} \begin{bmatrix} \mathbf{D}^{-1} & \mathbf{X} \\ \mathbf{Y} & \mathbf{Z} \end{bmatrix} \mathbf{P} \mathbf{P}^{-1} \begin{bmatrix} \mathbf{D} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \mathbf{Q}^{-1} \\ &= \mathbf{P}^{-1} \begin{bmatrix} \mathbf{D} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{D}^{-1} & \mathbf{X} \\ \mathbf{Y} & \mathbf{Z} \end{bmatrix} \begin{bmatrix} \mathbf{D} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \mathbf{Q}^{-1} \\ &= \mathbf{P}^{-1} \begin{bmatrix} \mathbf{I} & \mathbf{DX} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{D} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \mathbf{Q}^{-1} = \mathbf{P}^{-1} \begin{bmatrix} \mathbf{D} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \mathbf{Q}^{-1} = \mathbf{A}. \end{aligned}$$

Thus, $\mathbf{A}$ is a generalized inverse of $\mathbf{G}$. Also

$$\begin{aligned} \mathbf{GAG} &= \mathbf{Q} \begin{bmatrix} \mathbf{D}^{-1} & \mathbf{X} \\ \mathbf{Y} & \mathbf{Z} \end{bmatrix} \mathbf{P} \mathbf{P}^{-1} \begin{bmatrix} \mathbf{D} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \mathbf{Q}^{-1} \mathbf{Q} \begin{bmatrix} \mathbf{D}^{-1} & \mathbf{X} \\ \mathbf{Y} & \mathbf{Z} \end{bmatrix} \mathbf{P} \\ &= \mathbf{Q} \begin{bmatrix} \mathbf{D}^{-1} & \mathbf{X} \\ \mathbf{Y} & \mathbf{Z} \end{bmatrix} \begin{bmatrix} \mathbf{D} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{D}^{-1} & \mathbf{X} \\ \mathbf{Y} & \mathbf{Z} \end{bmatrix} \mathbf{P} \\ &= \mathbf{Q} \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{YD} & \mathbf{0} \end{bmatrix} \begin{bmatrix} \mathbf{D}^{-1} & \mathbf{X} \\ \mathbf{Y} & \mathbf{Z} \end{bmatrix} \mathbf{P} \\ &= \mathbf{Q} \begin{bmatrix} \mathbf{D}^{-1} & \mathbf{X} \\ \mathbf{Y} & \mathbf{YDX} \end{bmatrix} \mathbf{P} = \mathbf{G} \end{aligned}$$

if $\mathbf{YDX} = \mathbf{Z}$.

In Exercise 1, a generalized inverse for $\mathbf{B}$ could be

$$\mathbf{G} = \mathbf{Q} \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & -\frac{1}{3} & 0 & 2 \\ 0 & 0 & \frac{1}{2} & 3 \\ 1 & 2 & 3 & 4 \end{bmatrix} \mathbf{P} = \begin{bmatrix} -\frac{91}{6} & -\frac{25}{3} & \frac{31}{2} & -32 \\ \frac{31}{3} & \frac{17}{3} & -13 & 32 \\ 0 & 0 & 2 & -8 \\ \frac{7}{2} & 2 & -\frac{7}{2} & 7 \end{bmatrix}$$

This matrix is non-singular. However, $\mathbf{B}$ is a 4×4 matrix of rank 3.

20 (a) A generalized inverse of $\mathbf{AB}$ would be $\mathbf{B}'\mathbf{G}$. Notice that

$$\mathbf{ABB}'\mathbf{GAB} = \mathbf{AIGAB} = \mathbf{AGABB} = \mathbf{AB}.$$

(b) Let $\mathbf{G}$ be a generalized inverse of $\mathbf{L}$. Then a generalized inverse of $\mathbf{LA}$ would be $\mathbf{A}^{-1}\mathbf{G}$. Observe that

$$\mathbf{LAA}^{-1}\mathbf{GLA} = \mathbf{LGLA} = \mathbf{LA}.$$

21 The matrix itself.

22 (a) Let $\mathbf{H}$ be a generalized inverse different from $\mathbf{G}$. We must find an $\mathbf{Z}$ so that

$$\begin{aligned}\mathbf{H} &= \mathbf{G} + \mathbf{Z} - \mathbf{GAZAG}. \text{ Let } \mathbf{Z} = \mathbf{H} - \mathbf{G} + \mathbf{GAG}. \text{ Then} \\ \mathbf{G} + \mathbf{H} - \mathbf{G} + \mathbf{GAG} - \mathbf{GA}(\mathbf{H} - \mathbf{G} + \mathbf{GAG})\mathbf{AG} \\ &= \mathbf{H} + \mathbf{GAG} - \mathbf{GAHAG} + \mathbf{GAGAG} - \mathbf{GAGAGAG} \\ &= \mathbf{H} + \mathbf{GAG} - \mathbf{GAG} + \mathbf{GAG} - \mathbf{GAG} = \mathbf{H}.\end{aligned}$$

(b) If we can generate all generalized inverses, we generate all solutions.

23 (a) We have that

$$\begin{aligned}[\mathbf{U} \ \mathbf{V}] \begin{bmatrix} \Lambda^{-1/2} & \mathbf{C}_1 \\ \mathbf{C}_2 & \mathbf{C}_3 \end{bmatrix} \begin{bmatrix} \mathbf{S} \\ \mathbf{T} \end{bmatrix} [\mathbf{S}' \ \mathbf{T}'] \begin{bmatrix} \Lambda^{1/2} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{U}' \\ \mathbf{V}' \end{bmatrix} [\mathbf{U} \ \mathbf{V}] \begin{bmatrix} \Lambda^{-1/2} & \mathbf{C}_1 \\ \mathbf{C}_2 & \mathbf{C}_3 \end{bmatrix} \begin{bmatrix} \mathbf{S} \\ \mathbf{T} \end{bmatrix} \\ = [\mathbf{U} \ \mathbf{V}] \begin{bmatrix} \Lambda^{-1/2} & \mathbf{C}_1 \\ \mathbf{C}_2 & \mathbf{C}_3 \end{bmatrix} \begin{bmatrix} \Lambda^{1/2} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Lambda^{-1/2} & \mathbf{C}_1 \\ \mathbf{C}_2 & \mathbf{C}_3 \end{bmatrix} \begin{bmatrix} \mathbf{S} \\ \mathbf{T} \end{bmatrix} \\ = [\mathbf{U} \ \mathbf{V}] \begin{bmatrix} \mathbf{I} & 0 \\ \mathbf{C}_2 \Lambda^{1/2} & 0 \end{bmatrix} \begin{bmatrix} \Lambda^{-1/2} & \mathbf{C}_1 \\ \mathbf{C}_2 & \mathbf{C}_3 \end{bmatrix} \begin{bmatrix} \mathbf{S} \\ \mathbf{T} \end{bmatrix} = [\mathbf{U} \ \mathbf{V}] \begin{bmatrix} \Lambda^{-1/2} & \mathbf{C}_1 \\ \mathbf{C}_2 & \mathbf{C}_2 \Lambda^{1/2} \mathbf{C}_1 \end{bmatrix}\end{aligned}$$

if and only if $\mathbf{C}_3 = \mathbf{C}_2 \Lambda^{1/2} \mathbf{C}_1$.

(b) Observe that

$$\mathbf{X} = [\mathbf{S}' \ \mathbf{T}'] \begin{bmatrix} \Lambda^{1/2} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{U}' \\ \mathbf{V}' \end{bmatrix} \text{ and } \mathbf{G} = [\mathbf{U} \ \mathbf{V}] \begin{bmatrix} \Lambda^{-1/2} & \mathbf{C}_1 \\ \mathbf{C}_2 & \mathbf{C}_3 \end{bmatrix} \begin{bmatrix} \mathbf{S} \\ \mathbf{T} \end{bmatrix}.$$

Then

$$\begin{aligned}\mathbf{GX} &= [\mathbf{U} \ \mathbf{V}] \begin{bmatrix} \Lambda^{-1/2} & \mathbf{C}_1 \\ \mathbf{C}_2 & \mathbf{C}_3 \end{bmatrix} \begin{bmatrix} \mathbf{S} \\ \mathbf{T} \end{bmatrix} [\mathbf{S}' \ \mathbf{T}'] \begin{bmatrix} \Lambda^{1/2} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{U}' \\ \mathbf{V}' \end{bmatrix} \\ &= [\mathbf{U} \ \mathbf{V}] \begin{bmatrix} \mathbf{I} & 0 \\ \mathbf{C}_2 \Lambda^{1/2} & 0 \end{bmatrix} \begin{bmatrix} \mathbf{U}' \\ \mathbf{V}' \end{bmatrix}\end{aligned}$$

is symmetric if and only if $\mathbf{C}_2 = 0$.

(c) Observe that

$$\begin{aligned}\mathbf{XG} &= [\mathbf{S}' \ \mathbf{T}'] \begin{bmatrix} \Lambda^{1/2} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{U}' \\ \mathbf{V}' \end{bmatrix} [\mathbf{U} \ \mathbf{V}] \begin{bmatrix} \Lambda^{-1/2} & \mathbf{C}_1 \\ \mathbf{C}_2 & \mathbf{C}_3 \end{bmatrix} \begin{bmatrix} \mathbf{S} \\ \mathbf{T} \end{bmatrix} \\ &= [\mathbf{S}' \ \mathbf{T}'] \begin{bmatrix} \mathbf{I} & \Lambda^{1/2} \mathbf{C}_1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{S} \\ \mathbf{T} \end{bmatrix}\end{aligned}$$

is symmetric if and only if $\mathbf{C}_1 = 0$.

10 SOLUTIONS MANUAL

24 For $\mathbf{M}$, we have

$$\mathbf{XMX} = \mathbf{X}(\mathbf{X}'\mathbf{X})^+\mathbf{X}'\mathbf{X} = \mathbf{X} \text{ by Theorem 10}$$

$$\mathbf{MXM} = (\mathbf{X}'\mathbf{X})^+\mathbf{X}'\mathbf{X}(\mathbf{X}'\mathbf{X})^+\mathbf{X}' = (\mathbf{X}'\mathbf{X})^+\mathbf{X}'$$

$$\mathbf{XM} = \mathbf{X}(\mathbf{X}'\mathbf{X})^+\mathbf{X}', \text{ a symmetric matrix by Theorem 10}$$

$$\mathbf{MX} = (\mathbf{X}'\mathbf{X})^+\mathbf{X}'\mathbf{X}, \text{ a symmetric matrix by Penrose axiom applied to } \mathbf{X}'\mathbf{X}$$

Using the singular value decomposition recall that if $\mathbf{X} = \mathbf{S}'\mathbf{\Lambda}^{1/2}\mathbf{U}'$, $\mathbf{X}^+ = \mathbf{U}\mathbf{\Lambda}^{-1/2}\mathbf{S}$. Then

$$\mathbf{M} = (\mathbf{X}'\mathbf{X})^+\mathbf{X}' = \mathbf{U}\mathbf{\Lambda}^{-1}\mathbf{U}'\mathbf{U}\mathbf{\Lambda}^{1/2}\mathbf{S} = \mathbf{U}\mathbf{\Lambda}^{-1/2}\mathbf{S}.$$

For $\mathbf{W}$, we have

$$\mathbf{XWX} = \mathbf{XX}'(\mathbf{XX}')^+\mathbf{X} = \mathbf{X} \text{ applying Theorem 10 to } \mathbf{X}',$$

$$\mathbf{WXW} = \mathbf{X}'(\mathbf{XX}')^+\mathbf{XX}'(\mathbf{XX}')^+ = \mathbf{X}'(\mathbf{XX}')^+, \text{ by the reflexivity of } (\mathbf{XX}')^+,$$

$$\mathbf{XW} = \mathbf{XX}'(\mathbf{XX}')^+ \text{ applying the Penrose condition to } \mathbf{XX}',$$

$$\mathbf{WX} = \mathbf{X}'(\mathbf{XX}')^+\mathbf{X} \text{ by Theorem 10.}$$

Using the singular value decomposition $\mathbf{W} = \mathbf{X}'(\mathbf{XX}')^+ = \mathbf{U}\mathbf{\Lambda}^{1/2}\mathbf{S}\mathbf{S}'\mathbf{\Lambda}^{-1}\mathbf{S} = \mathbf{U}\mathbf{\Lambda}^{-1/2}\mathbf{S} = \mathbf{X}^+$.

25 By direct verification of Penrose conditions

$$\mathbf{UNU}'\mathbf{UN}^{-1}\mathbf{U}'\mathbf{UNU}' = \mathbf{UNN}^{-1}\mathbf{NU}' = \mathbf{UNU}',$$

$$\mathbf{UN}^{-1}\mathbf{U}'\mathbf{UNU}'\mathbf{UN}^{-1}\mathbf{U}' = \mathbf{UN}^{-1}\mathbf{NN}^{-1}\mathbf{U}' = \mathbf{UN}^{-1}\mathbf{U}',$$

$$\mathbf{UN}^{-1}\mathbf{U}'\mathbf{UNU}' = \mathbf{UU}', \text{ a symmetric matrix, and}$$

$$\mathbf{UNU}'\mathbf{UN}^{-1}\mathbf{U}' = \mathbf{UU}', \text{ a symmetric matrix.}$$

26 Again by direct verification of the Penrose axioms

$$\mathbf{PAP}'\mathbf{PA}^+\mathbf{P}'\mathbf{PAP}' = \mathbf{PAA}^+\mathbf{AP}' = \mathbf{PAP}',$$

$$\mathbf{PA}^+\mathbf{P}'\mathbf{PAP}'\mathbf{PA}^+\mathbf{P}' = \mathbf{PA}^+\mathbf{AA}^+\mathbf{P}' = \mathbf{PA}^+\mathbf{P}',$$

$$\mathbf{PAP}'\mathbf{PA}^+\mathbf{P}(\mathbf{PA}^+\mathbf{P}'\mathbf{PAP}')' = (\mathbf{PA}^+\mathbf{AP}')' = \mathbf{P}(\mathbf{A}^+\mathbf{A})'\mathbf{P}' = \mathbf{PA}^+\mathbf{AP}'$$

and similarly

$$(\mathbf{PAP}'\mathbf{PA}^+\mathbf{P}')' = \mathbf{P}(\mathbf{AA}^+)' \mathbf{P}' = \mathbf{PAA}^+\mathbf{P}'.$$

27 (a) Using the singular value decomposition of $\mathbf{X}$

$$\mathbf{X}^+(\mathbf{X}^+)' = \mathbf{U}\mathbf{\Lambda}^{-1/2}\mathbf{S}(\mathbf{U}\mathbf{\Lambda}^{-1/2}\mathbf{S})' = \mathbf{U}\mathbf{\Lambda}^{-1/2}\mathbf{S}\mathbf{S}'\mathbf{\Lambda}^{-1/2}\mathbf{U}' = \mathbf{U}\mathbf{\Lambda}^{-1}\mathbf{U}' = (\mathbf{X}'\mathbf{X})^+.$$

(b) Again using the singular value decomposition of $\mathbf{X}$

$$(\mathbf{X}')^+\mathbf{X}^+ = \mathbf{S}'\mathbf{\Lambda}^{-1/2}\mathbf{U}'\mathbf{U}\mathbf{\Lambda}^{-1/2}\mathbf{S} = \mathbf{S}'\mathbf{\Lambda}^{-1}\mathbf{S} = (\mathbf{XX}')^+.$$