

## One.III Reduced Echelon Form

*Linear Algebra*, edition four

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Gauss-Jordan reduction

Here is an extension of Gauss's method with some advantages.

*Example* Start as usual by getting echelon form.

$$\begin{array}{rcl} x + y - z = 2 & & x + y - z = 2 \\ 2x - y = -1 & \xrightarrow{-2\rho_1 + \rho_2} & -3y + 2z = -5 \\ x - 2y + 2z = -1 & \xrightarrow{-1\rho_1 + \rho_3} & -3y + 3z = -3 \end{array}$$
  
$$\begin{array}{rcl} & & x + y - z = 2 \\ & \xrightarrow{-1\rho_2 + \rho_3} & -3y + 2z = -5 \\ & & z = 2 \end{array}$$

*Example* Start as usual by getting echelon form.

Now, instead of doing back substitution, continue using row operations. First make all the leading entries one.

$$\begin{array}{rcl} x + y - z & = & 2 \\ y - (2/3)z & = & 5/3 \\ z & = & 2 \end{array}$$

Finish by using the leading entries to eliminate upwards, until we can read off the solution.

$$\begin{array}{rcl}
 x + y - z & = & 2 \\
 y - (2/3)z & = & 5/3 \\
 z & = & 2
 \end{array}
 \xrightarrow[(2/3)\rho_3 + \rho_2]{\rho_3 + \rho_1}
 \begin{array}{rcl}
 x + y & = & 4 \\
 y & = & 3 \\
 z & = & 2
 \end{array}$$

Finish by using the leading entries to eliminate upwards, until we can read off the solution.

$$\begin{array}{rcl} x + y - & z = & 2 \\ y - (2/3)z = & 5/3 & \\ z = & 2 & \end{array}$$

$$\begin{array}{c} \xrightarrow{\rho_3 + \rho_1} \\ (2/3)\rho_3 + \rho_2 \end{array}$$

$$\begin{array}{rcl} x + y & = & 4 \\ y & = & 3 \\ z & = & 2 \end{array}$$

$$\xrightarrow{-\rho_2 + \rho_1}$$

$$\begin{array}{rcl} x & = & 1 \\ y & = & 3 \\ z & = & 2 \end{array}$$

Finish by using the leading entries to eliminate upwards, until we can read off the solution.

$$\begin{array}{rcl}
 x + y - z & = & 2 \\
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 \quad
 \begin{array}{l}
 \xrightarrow{\rho_3 + \rho_1} \\
 (2/3)\rho_3 + \rho_2
 \end{array}
 \quad
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$$\begin{array}{rcl}
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 y & = & 3 \\
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 \end{array}
 \quad
 \begin{array}{l}
 \xrightarrow{-\rho_2 + \rho_1}
 \end{array}$$

Using one entry to clear out the rest of a column is *pivoting* on that entry.





The final augmented matrix

$$\left(\begin{array}{cccc|c} 1 & 0 & 0 & -4/5 & 9/5 \\ 0 & 1 & 0 & 6/5 & -1/5 \\ 0 & 0 & 1 & 1/5 & -1/5 \end{array}\right)$$

gives the parametrized description of the solution set.

$$\left\{ \begin{pmatrix} 9/5 \\ -1/5 \\ -1/5 \\ 0 \end{pmatrix} + \begin{pmatrix} 4/5 \\ -6/5 \\ -1/5 \\ 1 \end{pmatrix} w \mid w \in \mathbb{R} \right\}$$

## Gauss-Jordan reduction

This extension of Gauss's Method is the *Gauss-Jordan Method* or *Gauss-Jordan reduction*.

- 1.3 *Definition* A matrix or linear system is in *reduced echelon form* if, in addition to being in echelon form, each leading entry is a 1 and is the only nonzero entry in its column.

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The cost of using Gauss-Jordan reduction to solve a system is the additional arithmetic. The benefit is that we can just read off the solution set description.

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$$A \xrightarrow{\rho_i \leftrightarrow \rho_j} A \xrightarrow{\rho_j \leftrightarrow \rho_i} A \quad A \xrightarrow{k\rho_i} A \xrightarrow{(1/k)\rho_i} A \quad A \xrightarrow{k\rho_i + \rho_j} A \xrightarrow{-k\rho_i + \rho_j} A$$

(The third case requires that  $i \neq j$ .)

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We say that matrices that reduce to each other are equivalent with respect to the relationship of row reducibility. The next result justifies this, using the definition of an equivalence.

1.6 *Lemma* Between matrices, 'reduces to' is an equivalence relation.

*Proof* We must check the conditions (i) reflexivity, that any matrix reduces to itself, (ii) symmetry, that if  $A$  reduces to  $B$  then  $B$  reduces to  $A$ , and (iii) transitivity, that if  $A$  reduces to  $B$  and  $B$  reduces to  $C$  then  $A$  reduces to  $C$ .

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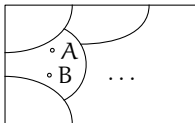
For transitivity, suppose that  $A$  reduces to  $B$  and that  $B$  reduces to  $C$ . Following the reduction steps from  $A \rightarrow \cdots \rightarrow B$  with those from  $B \rightarrow \cdots \rightarrow C$  gives a reduction from  $A$  to  $C$ .

QED

1.7 *Definition* Two matrices that are interreducible by elementary row operations are *row equivalent*.

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The diagram below shows the collection of all matrices as a box. Inside that box each matrix lies in a class. Matrices are in the same class if and only if they are interreducible. The classes are disjoint—no matrix is in two distinct classes. We have partitioned the collection of matrices into *row equivalence classes*.



## Linear Combination Lemma

## How Gauss's method acts

*Example* Consider this reduction.

$$\begin{pmatrix} 1 & 3 & | & 5 \\ 2 & 4 & | & 8 \end{pmatrix} \xrightarrow{-2\rho_1 + \rho_2} \begin{pmatrix} 1 & 3 & | & 5 \\ 0 & -2 & | & -2 \end{pmatrix} \xrightarrow{-(1/2)\rho_2} \begin{pmatrix} 1 & 3 & | & 5 \\ 0 & 1 & | & 1 \end{pmatrix} \xrightarrow{-3\rho_2 + \rho_1} \begin{pmatrix} 1 & 0 & | & 2 \\ 0 & 1 & | & 1 \end{pmatrix}$$

Denote the matrices as  $A \rightarrow D \rightarrow G \rightarrow B$ . The steps take us through these row combinations.

$$\begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix} \xrightarrow{-2\rho_1 + \rho_2} \begin{pmatrix} \delta_1 = \alpha_1 \\ \delta_2 = -2\alpha_1 + \alpha_2 \end{pmatrix} \xrightarrow{-(1/2)\rho_2} \begin{pmatrix} \gamma_1 = \alpha_1 \\ \gamma_2 = \alpha_1 - (1/2)\alpha_2 \end{pmatrix} \xrightarrow{-3\rho_2 + \rho_1} \begin{pmatrix} \beta_1 = -2\alpha_1 + (3/2)\alpha_2 \\ \beta_2 = \alpha_1 - (1/2)\alpha_2 \end{pmatrix}$$

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So: Gauss's method acts by taking linear combinations of rows.

## Linear Combination Lemma

2.3 *Lemma*    A linear combination of linear combinations is a linear combination.

For instance,  $4x_1 + 5x_2$  and  $7x_1 + 8x_2$  are linear combinations, of  $x_1$  and  $x_2$ . A linear combination of those

$$3 \cdot (4x_1 + 5x_2) + 6 \cdot (7x_1 + 8x_2)$$

yields another combination,  $54x_1 + 63x_2$ , of  $x_1$  and  $x_2$ .

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*Proof* Given the set  $c_{1,1}x_1 + \cdots + c_{1,n}x_n$  through  $c_{m,1}x_1 + \cdots + c_{m,n}x_n$  of linear combinations of the  $x$ 's, consider a combination of those

$$d_1(c_{1,1}x_1 + \cdots + c_{1,n}x_n) + \cdots + d_m(c_{m,1}x_1 + \cdots + c_{m,n}x_n)$$

where the  $d$ 's are scalars along with the  $c$ 's. Distributing those  $d$ 's and regrouping gives

$$= (d_1c_{1,1} + \cdots + d_m c_{m,1})x_1 + \cdots + (d_1c_{1,n} + \cdots + d_m c_{m,n})x_n$$

which is also a linear combination of the  $x$ 's.

QED



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*Proof* For any two irreducible matrices A and B there is some minimum number of row operations that will take one to the other. We proceed by induction on that number.

In the base step, that we can go from one matrix to another using zero reduction operations, the two are equal. Then each row of B is trivially a combination of A's rows  $\vec{\beta}_i = 0 \cdot \vec{\alpha}_1 + \cdots + 1 \cdot \vec{\alpha}_i + \cdots + 0 \cdot \vec{\alpha}_m$ .

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For the inductive step assume the inductive hypothesis: with  $k \geq 0$ , any matrix that can be derived from A in k or fewer operations has rows that are linear combinations of A's rows. Consider a matrix B such that reducing A to B requires  $k + 1$  operations. In that reduction there is a next-to-last matrix G, so that  $A \longrightarrow \cdots \longrightarrow G \longrightarrow B$ . The inductive hypothesis applies to this G because it is only k steps away from A. That is, each row of G is a linear combination of the rows of A.

We will verify that the rows of  $B$  are linear combinations of the rows of  $G$ . Then the Linear Combination Lemma, Lemma 2.3 , applies to show that the rows of  $B$  are linear combinations of the rows of  $A$ .

If the row operation taking  $G$  to  $B$  is a swap then the rows of  $B$  are just the rows of  $G$  reordered and each row of  $B$  is a linear combination of the rows of  $G$ . If the operation taking  $G$  to  $B$  is multiplication of a row by a scalar  $c\rho_i$  then  $\vec{\beta}_i = c\vec{\gamma}_i$  and the other rows are unchanged. Finally, if the row operation is adding a multiple of one row to another  $r\rho_i + \rho_j$  then only row  $j$  of  $B$  differs from the matching row of  $G$ , and  $\vec{\beta}_j = r\vec{\gamma}_i + \vec{\gamma}_j$ , which is indeed a linear combinations of the rows of  $G$ . QED

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*Proof* Let  $R$  be an echelon form matrix and consider its non- $\vec{0}$  rows. First observe that if we have a row written as a combination of the others  $\vec{\rho}_i = c_1 \vec{\rho}_1 + \cdots + c_{i-1} \vec{\rho}_{i-1} + c_{i+1} \vec{\rho}_{i+1} + \cdots + c_m \vec{\rho}_m$  then we can rewrite that equation as

$$\vec{0} = c_1 \vec{\rho}_1 + \cdots + c_{i-1} \vec{\rho}_{i-1} + c_i \vec{\rho}_i + c_{i+1} \vec{\rho}_{i+1} + \cdots + c_m \vec{\rho}_m \quad (*)$$

where not all the coefficients are zero; specifically,  $c_i = -1$ . The converse holds also: given equation  $(*)$  where some  $c_i \neq 0$  we could express  $\vec{\rho}_i$  as a combination of the other rows by moving  $c_i \vec{\rho}_i$  to the left and dividing by  $-c_i$ . Therefore we will have proved the theorem if we show that in  $(*)$  all of the coefficients are 0. For that we use induction on the row number  $i$ .

The base case is the first row  $i = 1$  (if there is no such nonzero row, so that  $R$  is the zero matrix, then the lemma holds vacuously). Let  $\ell_i$  be the column number of the leading entry in row  $i$ . Consider the entry of each row that is in column  $\ell_1$ . Equation (\*) gives this.

$$0 = c_1 r_{1,\ell_1} + c_2 r_{2,\ell_1} + \cdots + c_m r_{m,\ell_1} \quad (**)$$

The matrix is in echelon form so every row after the first has a zero entry in that column  $r_{2,\ell_1} = \cdots = r_{m,\ell_1} = 0$ . Thus equation (\*\*) shows that  $c_1 = 0$ , because  $r_{1,\ell_1} \neq 0$  as it leads the row.

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The inductive step is much the same as the base step. Again consider equation (\*). We will prove that if the coefficient  $c_i$  is 0 for each row index  $i \in \{1, \dots, k\}$  then  $c_{k+1}$  is also 0. We focus on the entries from column  $\ell_{k+1}$ .

$$0 = c_1 r_{1, \ell_{k+1}} + \cdots + c_{k+1} r_{k+1, \ell_{k+1}} + \cdots + c_m r_{m, \ell_{k+1}}$$

By the inductive hypothesis  $c_1, \dots, c_k$  are all 0 so this reduces to the equation  $0 = c_{k+1} r_{k+1, \ell_{k+1}} + \cdots + c_m r_{m, \ell_{k+1}}$ . The matrix is in echelon form so the entries  $r_{k+2, \ell_{k+1}}, \dots, r_{m, \ell_{k+1}}$  are all 0. Thus  $c_{k+1} = 0$ , because  $r_{k+1, \ell_{k+1}} \neq 0$  as it is the leading entry. QED



Summarizing the prior two lemmas: Gauss's method acts by taking linear combinations of the rows, systematically eliminating any linear relationship among those rows.

*Example* In this non-echelon form matrix the third row is the sum of the first and second.

$$\begin{pmatrix} 1 & -1 & 3 \\ 2 & 0 & 4 \\ 3 & -1 & 7 \end{pmatrix}$$

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But after Gauss's method

$$\begin{array}{l} \xrightarrow{-2\rho_1+\rho_3} \\ \xrightarrow{-3\rho_1+\rho_3} \end{array} \begin{pmatrix} 1 & -1 & 3 \\ 0 & 2 & -2 \\ 0 & 2 & -2 \end{pmatrix} \xrightarrow{-\rho_2+\rho_3} \begin{pmatrix} 1 & -1 & 3 \\ 0 & 2 & -2 \\ 0 & 0 & 0 \end{pmatrix}$$

the only linear relationship among the nonzero rows

$$c_1 \cdot (1 \ -1 \ 3) = c_2 \cdot (0 \ 2 \ -2)$$

is the trivial relationship  $c_1 = c_2 = 0$ , since the equation of first entries gives that  $c_1 = 0$  and then the equation of second entries gives  $c_2 = 0$ .

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*Proof* Fix a number of rows  $m$ . We will proceed by induction on the number of columns  $n$ .

The base case is that the matrix has  $n = 1$  column. If this is the zero matrix then its echelon form is the zero matrix. If instead it has any nonzero entries then when the matrix is brought to reduced echelon form it must have at least one nonzero entry, which must be a 1 in the first row. Either way, its reduced echelon form is unique.

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For the inductive step we assume that  $n > 1$  and that all  $m$  row matrices having fewer than  $n$  columns have a unique reduced echelon form. Consider an  $m \times n$  matrix  $A$  and suppose that  $B$  and  $C$  are two reduced echelon form matrices derived from  $A$ . We will show that these two must be equal.

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Let  $\hat{A}$  be the matrix consisting of the first  $n - 1$  columns of  $A$ . Observe that any sequence of row operations that bring  $A$  to reduced echelon form will also bring  $\hat{A}$  to reduced echelon form. By the inductive hypothesis this reduced echelon form of  $\hat{A}$  is unique, so if  $B$  and  $C$  differ then the difference must occur in column  $n$ .

Consider a homogeneous system of equations for which  $A$  is the matrix of coefficients.

$$\begin{aligned}
 a_{1,1}x_1 + a_{1,2}x_2 + \cdots + a_{1,n}x_n &= 0 \\
 a_{2,1}x_1 + a_{2,2}x_2 + \cdots + a_{2,n}x_n &= 0 \\
 &\vdots \\
 a_{m,1}x_1 + a_{m,2}x_2 + \cdots + a_{m,n}x_n &= 0
 \end{aligned}
 \tag{*}$$

By Theorem One.I.1.5 the set of solutions to that system is the same as the set of solutions to  $B$ 's system

$$\begin{aligned}
 b_{1,1}x_1 + b_{1,2}x_2 + \cdots + b_{1,n}x_n &= 0 \\
 b_{2,1}x_1 + b_{2,2}x_2 + \cdots + b_{2,n}x_n &= 0 \\
 &\vdots \\
 b_{m,1}x_1 + b_{m,2}x_2 + \cdots + b_{m,n}x_n &= 0
 \end{aligned}
 \tag{**}$$

and to  $C$ 's.

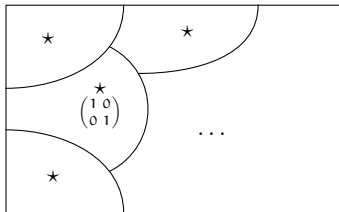
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 &\vdots \\
 c_{m,1}x_1 + c_{m,2}x_2 + \cdots + c_{m,n}x_n &= 0
 \end{aligned}
 \tag{***}$$

With  $B$  and  $C$  different only in column  $n$ , suppose that they differ in row  $i$ . Subtract row  $i$  of  $(***)$  from row  $i$  of  $(**)$  to get the equation  $(b_{i,n} - c_{i,n}) \cdot x_n = 0$ . We've assumed that  $b_{i,n} \neq c_{i,n}$  and so we get  $x_n = 0$ . Thus  $x_n$  is not a free variable and so in  $(**)$  and  $(***)$  the  $n$ -th column contains the leading entry of some row, since in an echelon form matrix any column that does not contain a leading entry is associated with a free variable.

But now, with  $B$  and  $C$  equal on the first  $n - 1$  columns, by the definition of reduced echelon form their leading entries in the  $n$ -th column are in the same row. And, both leading entries would have to be 1, and would have to be the only nonzero entries in that column. Therefore  $B = C$ . QED



So the reduced echelon form is a canonical form for row equivalence: the reduced echelon form matrices are representatives of the classes.



*Example* To decide if these two are row equivalent

$$\begin{pmatrix} 3 & 2 & 0 \\ 1 & -1 & 2 \\ 4 & 1 & 2 \end{pmatrix} \quad \begin{pmatrix} 3 & 1 & -2 \\ 6 & 2 & -4 \\ 1 & 0 & 2 \end{pmatrix}$$

use Gauss-Jordan elimination to bring each to reduced echelon form and see if they are equal.

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$$\begin{pmatrix} 3 & 2 & 0 \\ 1 & -1 & 2 \\ 4 & 1 & 2 \end{pmatrix} \quad \begin{pmatrix} 3 & 1 & -2 \\ 6 & 2 & -4 \\ 1 & 0 & 2 \end{pmatrix}$$

use Gauss-Jordan elimination to bring each to reduced echelon form and see if they are equal. The results are

$$\begin{array}{l} \xrightarrow{-(1/3)\rho_1 + \rho_2} \quad \xrightarrow{-1\rho_2 + \rho_3} \quad \xrightarrow{(1/3)\rho_1} \quad \xrightarrow{-(2/3)\rho_2 + \rho_1} \\ \xrightarrow{-(4/3)\rho_1 + \rho_3} \end{array} \begin{pmatrix} 1 & 0 & 4/5 \\ 0 & 1 & -6/5 \\ 0 & 0 & 0 \end{pmatrix}$$

and

$$\begin{array}{l} \xrightarrow{-2\rho_1 + \rho_2} \quad \xrightarrow{\rho_2 \leftrightarrow \rho_3} \quad \xrightarrow{(1/3)\rho_1} \quad \xrightarrow{-(1/3)\rho_2 + \rho_1} \\ \xrightarrow{-(1/3)\rho_1 + \rho_3} \end{array} \begin{pmatrix} 1 & 0 & 2 \\ 0 & 1 & -8 \\ 0 & 0 & 0 \end{pmatrix}$$

and therefore the original matrices are not row equivalent.