

# Problem Set 9

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Note: I use the convention that  $\mathbf{a}$  denotes a column vector and  $\mathbf{a}^t$  a row vector, and if  $A$  is a matrix, then  $(A)_{ij} = a_{ij}$  denotes the entry in the  $i$ th row and  $j$ th column.

## 1 Problem 1

### 1.1 Part 1

Let  $A = (a_{ij})$  and consider  $\epsilon_{ij}$ , the matrix with a 1 in the  $i$ th row and  $j$ th column and zeros elsewhere.

Then, for a fixed  $(i, j)$ , if we write  $A = [\mathbf{a}_1^t, \mathbf{a}_2^t, \dots, \mathbf{a}_n^t]$  as a block matrix of column vectors, we have

$$A\mathbf{e}_{ij} = [0, 0, \dots, \mathbf{a}_i^t, 0, \dots, 0]$$

as a block matrix where  $\mathbf{a}_i^t$  occurs as the  $j$ th column.

In other words, right-multiplication by  $\mathbf{e}_{ij}$  selects column  $i$  from  $A$ , placing it in column  $j$  of a matrix of zeros.

For example, for  $(i, j) = (3, 2)$  we have

$$A\mathbf{e}_{32} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} = \begin{pmatrix} 0 & a_{13} & 0 \\ 0 & a_{23} & 0 \\ 0 & a_{33} & 0 \end{pmatrix},$$

which is a matrix that contains column 3 of  $A$  (the  $i$  value) as its 2nd column (the  $j$  value).

On the other hand, *left* multiplication by  $\mathbf{e}_{ij}$  selects the  $j$ th **row** of  $A$  and places it the  $i$ th **row** of a zero matrix, so for example we have

$$\mathbf{e}_{32}A = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ a_{21} & a_{22} & a_{23} \end{pmatrix}$$

In general, these two products will not be equal, since the first has a nontrivial column and the latter has a nontrivial row. If  $A \in Z(M_n(R))$ , these two must be equal, so we can equate corresponding entries to find that

- $a_{21} = 0$ , from comparing entries in row 3, column 1,
- $a_{23} = 0$ , from comparing entries in row 3, column 3
- $a_{22} = a_{33}$  by comparing entries in row 3, column 2.

Letting the multiplication run over all possibilities for  $\mathbf{e}_{ij}$  yields  $a_{ii} = a_{jj}$  for every pair  $i, j$  and  $a_{ij} = 0$  whenever  $i \neq j$ . Setting  $r = a_{ii} = a_{jj}$  for all  $1 \leq i, j \leq n$  forces  $A$  to be a matrix of the form

$$A = \begin{pmatrix} r & 0 & 0 & \cdots & 0 \\ 0 & r & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & r \end{pmatrix} := rI_n.$$

To see that we must have  $r \in Z(R)$ , let  $sI_n \in Z(M_n(R))$  be arbitrary, where  $s$  is not assumed to be in  $Z(R)$ . Then  $(rI_n)(sI_n) = (sI_n)(rI_n)$  by assumption, since these are matrices in the center of  $M_n(R)$ . But  $M_n(R)$  is an  $R$ -module, and so the scalars  $r, s$  commute with the module elements  $I_n$ . This means that we in fact have

$$\begin{aligned} (rI_n)(sI_n) &= (rs)I_n^2 = (rs)I_n, \\ (sI_n)(rI_n) &= (sr)I_n^2 = (sr)I_n \\ &\implies (rs)I_n = (sr)I_n \\ &\implies (rs - sr)I_n = 0_n, \end{aligned}$$

the  $n \times n$  zero matrix.

But then by equating (for example) the 1, 1 entry of the matrix  $(rs - sr)I_n$  with the corresponding entry in  $0_n$ , we find  $rs - sr = 0_R$ , which means  $rs = sr \in R$ .

Now since  $s \in R$  was arbitrary, we find that  $r \in Z(R)$  as desired.

## 1.2 Part 2

Define a map

$$\begin{aligned}\phi : Z(R) &\rightarrow Z(M_n(R)) \\ r &\mapsto rI_n.\end{aligned}$$

By part 1, this map is surjective. To see that it is also injective, we can consider  $\ker \phi = \{r \in Z(R) \mid rI_n = 0_n\}$ , which clearly forces  $r = 0_R$ . It is also a homomorphism of  $R$ -modules, since  $\phi(rx + y) = (rx + y)I_n = r(xI_n) + yI_n$ .

Thus by the first isomorphism theorem, we have  $Z(R) \cong Z(M_n(R))$ .

## 2 Problem 2

### 2.1 Part 1

If  $A, B$  are (skew)-symmetric, then  $A^t = \pm A$  and  $B^t = \pm B$  respectively. But then

$$(A + B)^t = A^t + B^t = \pm A + \pm B = \pm(A + B),$$

which shows that  $A + B$  is (skew)-symmetric.

### 2.2 Part 2

$\implies$  : Suppose that whenever  $A, B$  are symmetric then  $AB$  is symmetric as well.

We then have  $(AB)^t = AB$  by assumption, and then by calculation we have  $(AB^t) = B^t A^t = BA$ , so  $AB = BA$ .

$\impliedby$  : Suppose that  $AB = BA$  and  $A, B$  are symmetric. We want to show that  $AB$  is also symmetric, so we compute

$$(AB)^t = B^t A^t = BA = AB.$$

□

Now let  $B \in M_n(R)$  be arbitrary. We have

- $(BB^t)^t = (B^t)^t B^t = BB^t$ , so  $BB^t$  is symmetric,
- $(B + B^t)^t = B^t + (B^t)^t = B^t + B = B + B^t$ , so  $B + B^t$  is symmetric,
- $(B - B^t)^t = B^t - B = -(B + B^t)$ , so  $B - B^t$  is skew-symmetric

### 3 Problem 3

**Definition:** We say  $A \sim B$  in  $M_n(R)$   $\iff$  there exists an invertible  $P$  such that  $B = PAP^{-1}$ .

- Reflexive,  $A \sim A$ :

Take  $P = I_n$  the identity matrix.

- Symmetric,  $A \sim B \implies B \sim A$ :

$B = PAP^{-1} \implies BP = PA \implies P^{-1}BP = A$ , so we can take  $Q = P^{-1}$  to yield  $A = QBQ^{-1}$ .

- Transitive,  $A \sim B \& B \sim C \implies A \sim C$ :

If  $B = PAP^{-1}, C = QBQ^{-1}$ , then  $C = Q(PAP^{-1})Q^{-1} = (QP)A(QP)^{-1}$ , so take  $L = QP$  to yield  $C = LAL^{-1}$ .

**Definition:** We say  $A \sim B$  in  $M(n \times n, R)$   $\iff B = PAQ$  with  $P \in GL(n, R), Q \in GL(m, R)$ .

- Reflexive,  $A \sim A$ :

Take  $P = I_{m,n}$  the matrix with 1s on the diagonal and zeros elsewhere, and  $Q = P^t$ .

- Symmetric,  $A \sim B \implies B \sim A$ :

$B = PAQ \implies BQ^{-1} = PA \implies P^{-1}BQ^{-1} = A$ , so we can take  $S = P^{-1}, T = Q^{-1}$  to yield  $A = QBT$ .

- Transitive,  $A \sim B \& B \sim C \implies A \sim C$ :

If  $B = PAQ, C = RBS$ , then  $C = R(PAQ)S = (RP)A(QS)$ , so take  $L = RP, M = QS$  to yield  $C = LAM$ .

### 4 Problem 4

**Lemma:** The rank-nullity theorem holds over division rings.

Proof: A linear map  $\phi : D^m \rightarrow D^n$  induces a short exact sequence:

$$0 \rightarrow \ker \phi \rightarrow D^m \xrightarrow{\phi} \text{im } \phi \rightarrow 0$$

But every module over a division ring is free; in particular,  $\text{im } \phi \leq D^n$  is a module over  $D$  and is thus free. So by a lemma in class, since the right-most term is a free module, this sequence splits and we have

$$D^m \cong \ker \phi \oplus \text{im } \phi$$

and taking dimensions yields

$$m = \dim \ker(\phi) + \text{rank}(\phi).$$

□

1.  $A \in M(n \times m, D)$  has a left inverse  $B \iff \text{rank}(A) = m$ :

$\implies$  : Suppose toward the contrapositive that  $\text{rank}(A) < m$ , so  $A$  has at least one pair of linearly dependent columns. So wlog write

$$A = [\mathbf{a}_1^t, \mathbf{a}_2^t, \dots, \mathbf{a}_m^t]$$

in block form with each  $\mathbf{a}_i$  a column vector, and we can assume that  $\mathbf{a}_1, \mathbf{a}_2$  are linearly dependent.

Now suppose such a left inverse  $B$  were to exist. Write it in block form as

$$B = [\mathbf{b}_1, \mathbf{b}_2, \dots, \mathbf{b}_n]^t,$$

so each  $\mathbf{b}_i$  is a row of  $B$ .

Now if  $BA = I_m$  is to hold, noting that  $(BA)_{ij} = \langle \mathbf{b}_i, \mathbf{a}_j \rangle$ , we must have

$$I_{1,1} = \langle \mathbf{b}_1, \mathbf{a}_1 \rangle = 1$$

$$I_{1,2} = \langle \mathbf{b}_1, \mathbf{a}_2 \rangle = 0$$

$$I_{1,3} = \langle \mathbf{b}_1, \mathbf{a}_3 \rangle = 0$$

$$\vdots$$

$$I_{2,1} = \langle \mathbf{b}_2, \mathbf{a}_1 \rangle = 0$$

$$I_{2,2} = \langle \mathbf{b}_2, \mathbf{a}_2 \rangle = 1$$

$$I_{2,3} = \langle \mathbf{b}_2, \mathbf{a}_3 \rangle = 0$$

$$\vdots$$

But the claim is that this can *not* happen if  $\mathbf{a}_1, \mathbf{a}_2$  are linearly dependent. To see why, note that the linear dependence supplies elements  $d_1, d_2 \neq 0 \in D$  such that  $d_1\mathbf{a}_1 + d_2\mathbf{a}_2 = \mathbf{0}$ . But then taking inner products against, e.g.  $\mathbf{b}_1$  (that is, applying  $\langle \mathbf{b}_1, \cdot \rangle$  to everything in sight), we obtain

$$\begin{aligned} d_1\mathbf{a}_1 + d_2\mathbf{a}_2 &= \mathbf{0} \\ \implies \langle \mathbf{b}_1, d_1\mathbf{a}_1 \rangle + \langle \mathbf{b}_1, d_2\mathbf{a}_2 \rangle &= \langle \mathbf{b}_1, \mathbf{0} \rangle = 0 \\ \implies d_1\langle \mathbf{b}_1, \mathbf{a}_1 \rangle + d_2\langle \mathbf{b}_1, \mathbf{a}_2 \rangle &= \langle \mathbf{b}_1, \mathbf{0} \rangle = 0 \\ \implies d_1\langle \mathbf{b}_1, \mathbf{a}_1 \rangle + d_2\langle \mathbf{b}_1, \mathbf{a}_2 \rangle &= 0 \\ \implies d_1 + d_2\langle \mathbf{b}_1, \mathbf{a}_2 \rangle &= 0 \\ \implies \langle \mathbf{b}_1, \mathbf{a}_2 \rangle &= -\frac{d_1}{d_2} \neq 0, \end{aligned}$$

which contradicts  $\langle \mathbf{b}_1, \mathbf{a}_2 \rangle = 0$  as required by the previous equations.

$\Leftarrow$  : Suppose  $\text{rank}(A) = m$ , so  $A$  has  $m$  linearly independent columns – note that this is *all* of its columns.

Note: since row rank equals column rank, this also says that  $A$  has  $m$  linearly independent rows, so  $n \geq m$ .

Viewing  $A$  as a representative of a map  $\phi : D^m \rightarrow D^n$ , we find that  $\dim \operatorname{im} \phi = m \leq n$ . In particular, from the rank nullity theorem, we have

$$m = \dim \ker \phi + \operatorname{rank}(\phi) = \dim \ker \phi + m \implies \dim \ker \phi = 0.$$

So  $\ker A = \{\mathbf{0}\}$ , and  $A$  represents an injective map  $f_A : D^m \rightarrow D^n$ .

But any injective *set* map  $f : S_1 \rightarrow S_2$  has a left-inverse  $g$  such that  $g \circ f = \operatorname{id}_{S_1}$ . So  $f_A : D^m \rightarrow D^n$  as a *set* map has a left inverse  $g_B : D^n \rightarrow D^m$  satisfying  $g_B \circ f_A = \operatorname{id}_{D^m}$ . But then taking the matrix associated to  $g_B$  yields a matrix  $B \in M(m \times n, D)$  such that  $BA = I_m$  as desired.  $\square$

2.  $A$  has a right inverse  $B \iff \operatorname{rank}(A) = n$ :

$\implies$  : By a similar argument, supposing that  $\operatorname{rank} A < n$  but  $AB = I_n$  for some  $B$ , we find that  $A$  has at least two linearly dependent *rows* this time, say  $\mathbf{a}_1, \mathbf{a}_2$ , whereas we obtain a system of equations of the form  $\langle \mathbf{a}_i, \mathbf{b}_k \rangle = \delta_{ik}$  where  $\mathbf{b}_i$  are now the columns of  $B$ .

In a similar manner, the linear dependence forces, say,  $\langle \mathbf{a}_2, \mathbf{b}_1 \rangle \neq 0$ , which is a contradiction.

$\impliedby$  : By another similar argument, we find that  $A$  represents a map  $f_A : D^m \rightarrow D^n$ , and since  $\operatorname{rank} A = \dim \operatorname{im} A = n$ , we find that  $A$  represents a surjective map  $f_A$ . Surjective set maps have *right* inverses, so there is some  $g_B : D^n \rightarrow D^m$  such that  $f_A \circ g_B = \operatorname{id}_{D^n}$ , and when translated to matrices this yields  $AB = I_n$ .  $\square$

## 5 Problem 5

### 5.1 Part 1

$\impliedby$  : Suppose that  $A\mathbf{x} = \mathbf{b}$  has a solution  $\mathbf{x}$ .

Write  $A = [\mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_m]^t$  in block form with each  $\mathbf{a}_i$  a row of  $A$ . By definition, a solution to this equation is a  $\mathbf{x} = (x_i)$  such that for each  $i$ , we have  $\langle \mathbf{a}_i, \mathbf{x} \rangle = b_i$  (by carrying out the matrix multiplication).

But

$$\begin{aligned} \langle \mathbf{a}_i, \mathbf{x} \rangle &= b_i \\ \implies \sum_{j=1}^m a_{ij}x_j &= b_i, \end{aligned}$$

which says that the collection  $x_1, \dots, x_n$  solves the equation

$$a_{i1}x_1 + a_{i2}x_2 + \dots + a_{im}x_m = b_i$$

for every  $i$ , which is exactly the statement that the  $x_i$  simultaneously solve the given system.

$\implies$  : Suppose that the given system has a simultaneous solutions  $x_1, x_2, \dots, x_n$ , and consider the matrix equation  $A\mathbf{x} = \mathbf{b}$ .

Letting  $\mathbf{x} = [x_1, x_2, \dots, x_n]$ , we can rewrite

$$b_i = a_{i1}x_1 + a_{i2}x_2 + \dots + a_{im}x_m = \langle \mathbf{a}_i, \mathbf{x} \rangle,$$

where  $\mathbf{a}_i = [a_{i1}, a_{i2}, \dots, a_{im}]$ .

But then  $\mathbf{a}_i$  is the  $i$ th row of  $A$ , and  $A\mathbf{x} = \mathbf{b}$  has a solution iff there is a  $\mathbf{x}$  such that  $\langle \mathbf{a}_i, \mathbf{x} \rangle = b_i$  for all  $i$ , which is exactly what we've constructed.

## 5.2 Part 2

Noting that applying a row operation to  $A$  is the same as taking the product  $EA$  for some elementary matrix  $E$ , we can write  $A_1 = \left(\prod_{i=1}^{\ell} E_i\right) A$  and  $B_1 = \left(\prod_{i=1}^{\ell} E_i\right) B$ ,

thus

$$\begin{aligned} A\mathbf{x} &= \mathbf{b} \\ \implies E_{\ell}A\mathbf{x} &= E_{\ell}\mathbf{b} \\ \implies E_{\ell-1}E_{\ell}A\mathbf{x} &= E_{\ell-1}E_{\ell}\mathbf{b} \\ &\vdots \\ \implies E_1E_2 \cdots E_{\ell}A\mathbf{x} &= E_1E_2 \cdots E_{\ell}\mathbf{b} \\ \implies A_1\mathbf{x} &= B_1 \end{aligned}$$

## 5.3 Part 3

1.  $AX = B$  has a solution  $\iff \text{rank}(A) = \text{rank}(C)$ :

Note that we can only have  $\text{rank } C \geq \text{rank } A$ .

$\implies$  :

Suppose that  $AX = B$  has a solution; then  $\mathbf{b}$  is in the column space of  $A$ . But this says that

$$\text{span}(\{\mathbf{a}_i\}) = \text{span}(\{\mathbf{a}_i\} \cup \{\mathbf{b}\}),$$

where  $\mathbf{a}_i$  are the columns of  $A$ . But then taking dimensions on both sides yields  $\text{rank } A = \text{rank } C$ , since the rank of the dimension of the column space.

$\Leftarrow$  :

Suppose  $\text{rank } A = \text{rank } C$ ; then the

$$\dim \text{span}(\{\mathbf{a}_i\}) = \dim \text{span}(\{\mathbf{a}_i\} \cup \{\mathbf{b}\}),$$

which says that  $\mathbf{b}_i$  is in the column space of  $A$ , and thus  $AX = B$  has a solution.  $\square$

2. The solution is unique  $\iff \text{rank}(A) = m$ .

$\implies$  : To the contrapositive, Suppose  $\text{rank}(A) < m$ . Then by rank-nullity,  $\dim \ker A > 0$ , so there is a vector  $\mathbf{v} \neq \mathbf{0}$  such that  $A\mathbf{v} = \mathbf{0}$ . But noting that  $\mathbf{x} = \mathbf{0}$  is always a solution to  $A\mathbf{x} = \mathbf{0}$ , this yields two distinct solutions.

$\Longleftarrow$  :

Suppose that  $\text{rank}(A) = m$ . Then by rank-nullity,  $\dim \ker A = 0$ , so  $\ker A = \{\mathbf{0}\}$ . Now suppose  $\mathbf{v}_1, \mathbf{v}_2$  are potentially distinct solutions to  $A\mathbf{x} = \mathbf{b}$ .

Then,

$$\begin{aligned} A\mathbf{v}_1 &= A\mathbf{v}_2 = \mathbf{b} \\ \implies A\mathbf{v}_1 - A\mathbf{v}_2 &= \mathbf{b} - \mathbf{b} = \mathbf{0} \\ \implies A(\mathbf{v}_1 - \mathbf{v}_2) &= \mathbf{0} \\ \implies \mathbf{v}_1 - \mathbf{v}_2 &\in \ker A \\ \implies \mathbf{v}_1 - \mathbf{v}_2 &= \mathbf{0} \\ \implies \mathbf{v}_1 &= \mathbf{v}_2, \end{aligned}$$

which shows that any solution is unique.

## 5.4 Part 4

We want to show that  $A\mathbf{x} = \mathbf{0}$  has a nontrivial solution  $\iff \text{rank}(A) < m$ .

$\implies$  : Suppose  $A\mathbf{v} = \mathbf{0}$  for some  $\mathbf{v} \neq \mathbf{0}$ . Then  $\dim \ker A \geq 1$ , and by rank nullity we must have  $m = \dim \ker A + \text{rank}(A)$ . But this immediately forces  $\text{rank}(A) \leq m - 1$ .

$\Longleftarrow$  : Suppose  $\text{rank}(A) < m$ . Then again by rank nullity, this forces  $\dim \ker A \geq 1$ , so  $A$  has a nontrivial kernel and thus there is a nontrivial solution to  $A\mathbf{x} = \mathbf{0}$ .

## 6 Problem 6

The goal is to show that any matrix  $A \in M(m \times n, R)$  is *equivalent* to a matrix  $D$  of the described form, so  $A = PDQ$  for some matrices  $P, Q$ . Since  $S$  is in fact the set of Smith Normal Forms for such matrices, it suffices to show that  $SNF(A)$  can be obtained by left and right multiplication by invertible matrices. Moreover, since row operations can be performed by left-multiplication of elementary matrices, and column operations by right-multiplication.

We proceed by induction on  $m + n$ .

For the base case  $m + n = 2$ , this can only yield a  $1 \times 1$  matrix, and the result holds vacuously.

For the inductive step, we will proceed by considering the top-left  $2 \times 2$  block, say  $M = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$ ,

and showing it can be reduced to a block of the form  $M' = \begin{bmatrix} d_1 & 0 \\ 0 & d_2 \end{bmatrix}$  where  $d_1 \mid d_2$ . Then the sub-matrix obtained by deleting the row and column containing  $d_1$  is a strictly smaller matrix, allowing the inductive hypothesis to be applied.



Moreover, note that if we are able to perform this reduction by a series of left and right multiplications, this will yield  $A_1 = P_1 A Q_1$ , and inductively we will have  $A_r = (P_r \cdots P_2 P_1) A (Q_1 Q_2 \cdots Q_r)$ , so each matrix will remain equivalent at every step.

Note: since  $R$  is a PID, it is also a Euclidean domain, so we can compute greatest common divisors.

We'll first reduce the top-left entry and eliminate the bottom-left entry.

Let  $d = \gcd(a, c)$ , so we can write  $d = sa + tc$  for some  $s, t \in R$ . We would like to construct an operation that replaces  $a$  in  $M$  with  $d$ .

So let  $\ell_1, \ell_2$  be parameters to be determined; we can then compute

$$P_1 A = \begin{bmatrix} s & t \\ \ell_1 & \ell_2 \end{bmatrix} \begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} d & sb + td \\ \ell_1 a + \ell_2 c & \ell_1 b + \ell_1 d \end{bmatrix},$$

where we now only have to choose  $\ell_1, \ell_2$  so that the first matrix appearing is invertible.

This lets us engineer an inverse matrix

$$\begin{aligned} P_1^{-1} &:= \begin{bmatrix} \ell_2 & -t \\ -\ell_1 & s \end{bmatrix} \\ \implies P_1 P_1^{-1} &= \begin{bmatrix} s & t \\ \ell_1 & \ell_2 \end{bmatrix} \begin{bmatrix} \ell_2 & -t \\ -\ell_1 & s \end{bmatrix} \\ &= \begin{bmatrix} s\ell_2 - t\ell_1 & -ts + st \\ \ell_1\ell_2 - \ell_2\ell_1 & -t\ell_1 + s\ell_2 \end{bmatrix}, \end{aligned}$$

which just says that we need to pick  $\ell_1, \ell_2$  such that  $s\ell_1 - t\ell_2 = 1$ , since the off-diagonal entries vanish because  $R$  is commutative.

But this can be done by writing  $a = dk_1$  and  $c = dk_2$ , since  $d$  was their gcd, then

$$d = sa + tc = sdk_1 + tdk_2 \implies 1 = sk_1 + tk_2,$$

so just choose  $\ell_1 = k_1, \ell_2 = -k_2$  to yield  $P_1 P_1^{-1} = I_2$ .

We can now use the fact that in the matrix  $P_1 A$ , we can observe that since  $d$  divides  $a$  and  $c$ , it divides  $\ell_1 a + \ell_2 c$ . So write  $k_1 d = \ell_1 a + \ell_2 c$ , we can then perform a row operation by left-multiplying:

$$Q_1 A P_1 := \begin{bmatrix} 1 & 0 \\ -k & 1 \end{bmatrix} \begin{bmatrix} d & sb + td \\ \ell_1 a + \ell_2 c & \ell_1 b + \ell_1 d \end{bmatrix} = \begin{bmatrix} d & sb + td \\ 0 & -k(sb + td) + \ell_1 b + \ell_1 d \end{bmatrix}.$$

We now carry out the same process with the *row* instead of the first *column*. This begins by computing  $d^1 = \gcd(d, sb + td)$ , where we can immediately note that  $d^1$  divides  $d$ , and then doing column operations (i.e. right-multiplying by some  $P_2$ ) to obtain a matrix of the form  $Q_1 A P_1 P_2 :=$

$$\begin{bmatrix} d & 0 \\ ? & ? \end{bmatrix}.$$