

# Qual Problems

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## 1 Problem 1

### 1.1 Part 1

*Definition:* An element  $r \in R$  is *irreducible* if whenever  $r = st$ , then either  $s$  or  $t$  is a unit.

*Definition:* Two elements  $r, s \in R$  are *associates* if  $r = \ell s$  for some unit  $\ell$ .

A ring  $R$  is a *unique factorization domain* iff for every  $r \in R$ , there exists a set  $\{p_i \mid 1 \leq i \leq n\}$  such that  $r = u \prod_{i=1}^n p_i$  where  $u$  is a unit and each  $p_i$  is irreducible.

Moreover, this factorization is unique in the sense that if  $r = w \prod_{i=1}^n q_i$  for some  $w$  a unit and  $q_i$  irreducible elements, then each  $q_i$  is an associate of some  $p_i$ .

### 1.2 Part 2

A ring  $R$  is a *principal ideal domain* iff whenever  $I \trianglelefteq R$  is an ideal of  $R$ , there is a single element  $r_i \in R$  such that  $I = (r_i)$ .

### 1.3 Part 3

An example of a UFD that is not a PID is given by  $R = k[x, y]$  for  $k$  a field.

That  $R$  is a UFD follows from the fact that if  $k$  is a field, then  $k$  has no prime elements since every non-zero element is a unit. So the factorization condition holds vacuously for  $k$ , and  $k$  is a UFD. But then we can use the following result:

**Theorem:** If  $R$  is a UFD, then  $R[x]$  is a UFD.

Since  $k$  is a UFD, the theorem implies that  $k[x]$  is a UFD, from which it follows that  $k[x][y] = k[x, y]$  is also a UFD.

To see that  $R$  is not a PID, consider the ideal  $I = (x, y)$ , and suppose  $I = (g)$  for some single  $g \in k[x, y]$ .

Note that  $I \neq R$ , since  $I$  contains no degree zero polynomials. Moreover, since  $(x) \subset I = (g)$  (and similarly for  $y$ ), we have  $g \mid x$  and  $g \mid y$ , which forces  $\deg g = 0$ .

So in fact  $g \in k$  and thus  $g$  is invertible, but then  $(g) = g^{-1}(g) = (1) = k$ , so this forces  $I = k \leq k[x, y]$ . However,  $x \notin k$  (nor  $y$ ), which is a contradiction.

## 2 Problem 2

**Lemma:** Let  $A$  be a linear operator,  $m_A(x)$  its minimal polynomial, and  $p_A(x)$  its characteristic polynomial. Then  $A$  has distinct eigenvalues  $\iff m_A(x) = p_A(x)$ .

Proof: We always have  $m_A(x) \mid p_A(x)$ , since  $p_A(A) = 0$  by Cayley-Hamilton and  $m_A(x)$  is the *minimal* polynomial for which this holds. We can also note that  $p_A(\lambda_i) = 0$  for all eigenvalues  $\lambda_i$  by construction. Moreover, if every eigenvalue is distinct, then we have  $p_A(x) = \prod_i (x - \lambda_i)$  in  $\bar{k}[x]$ .

Given an invariant factor decomposition of  $A$  with factors  $f_1 \mid f_2 \mid \cdots \mid f_n := m_A(x)$ , it is the case that if  $\lambda_i$  is an eigenvalue of  $A$ , then  $f_j(\lambda_i) = 0$  for some  $f_j$ .

But then  $m_A(\lambda_i) = 0$  for all  $\lambda_i$ , since each  $f_j$  divides  $m_A$ . So every eigenvalue is a root of  $m_A(x)$ , and thus  $\prod_i (x - \lambda_i) \mid m_A(x)$ .

But then we have both  $m_A(x) \mid p_A(x)$  and  $p_A(x) \mid m_A(x)$ , so these polynomials are equal.

□

**Lemma** If  $A$  is a linear operator and we write

$$V = \frac{k[x]}{(f_1)} \oplus \frac{k[x]}{(f_2)} \oplus \cdots \oplus \frac{k[x]}{(f_n)}$$

as an invariant factor decomposition of  $V$  as a  $k[x]$  module (defined by  $p(x) \curvearrowright \mathbf{v} := p(A)(\mathbf{v})$ ), with  $f_1 \mid f_2 \mid \cdots$ , then we always have

- $m_A(x) = f_n(x)$ , i.e. the minimal polynomial is the invariant factor of largest degree,
- $p_A(x) = \prod_{i=1}^n f_i(x)$ , i.e. the characteristic polynomial is the product of all of the invariant factors.

□

$\Leftarrow$  : Suppose  $A$  has distinct eigenvalues, then by Lemma 1 we have

$$f_n(x) = \prod_{j=1}^n f_j(x),$$

which can only happen if  $f_1(x) = f_2(x) = \cdots = f_{n-1}(x) = 1$ , in which case there is only one nontrivial invariant factor and we have

$$V \cong \frac{k[x]}{(f_n)}, \quad \text{Ann}(V) = (f_n)$$

which exhibits  $V$  as a cyclic  $k[x]$ -module and thus we have  $V = k[x]\mathbf{v}$  for some  $\mathbf{v} \in V$ .

We can now note that if  $\deg f_n = \dim V = m$ , we have

$$k[x]/(f_n) = \text{span}_{k[x]} \{1, x, \dots, x^{m-1}\} \iff V \cong k[x]\mathbf{v} = \text{span}_{k[x]} \{1\mathbf{v}, x\mathbf{v}, \dots, x^{m-1}\mathbf{v}\},$$

But then noting that the  $k[x] \curvearrowright V$  by  $w \mapsto xw$ , so  $k[T] \curvearrowright V$  by  $w \mapsto Tw$ .

$\Rightarrow$  :

Suppose

$$V = \text{span}_k \{\mathbf{v}, A\mathbf{v}, A^2\mathbf{v}, \dots, A^{n-1}\mathbf{v}\} := \text{span}_k \mathcal{B}$$

where  $\dim_k V = n$ .

Then  $A^n\mathbf{v}$  is necessarily a linear combination of these basis elements, and in particular, there are coefficients  $c_i$  (not all zero) such that

$$A^n\mathbf{v} = \sum_{i=0}^{n-1} c_i A^i\mathbf{v}.$$

This means that with respect to the basis  $\mathcal{B}$ ,  $A$  has the following matrix representation:

$$[A]_{\mathcal{B}} = \begin{bmatrix} 0 & 0 & \dots & 0 & c_0 \\ 1 & 0 & \dots & 0 & c_1 \\ 0 & 1 & \dots & 0 & c_2 \\ & & \ddots & & \vdots \\ 0 & 0 & \dots & 1 & c_{n-1} \end{bmatrix},$$

which we compute by considering the images of all basis elements under  $A$ .

Letting  $\mathcal{B} = \{\mathbf{w}_i := A^i\mathbf{v} \mid 0 \leq i \leq n-1\}$ , we have

$$\begin{aligned}
\mathbf{w}_0 &:= \mathbf{v} \mapsto A\mathbf{v} := \mathbf{w}_1 \\
\mathbf{w}_1 &:= A\mathbf{v} \mapsto A^2\mathbf{v} := \mathbf{w}_2 \\
\mathbf{w}_2 &:= A^2\mathbf{v} \mapsto A^3\mathbf{v} := \mathbf{w}_3 \\
&\vdots \quad \vdots \\
\mathbf{w}_{n-2} &:= A^{n-2}\mathbf{v} \mapsto A^{n-1}\mathbf{v} := \mathbf{w}_{n-1} \\
\mathbf{w}_{n-1} &:= A^{n-1}\mathbf{v} \mapsto A^n\mathbf{v} = \sum_{i=0}^{n-1} c_i A^i \mathbf{v}_i := \sum_{i=0}^{n-1} c_i \mathbf{w}_i.
\end{aligned}$$

### 3 Problem 3

#### 3.1 Part 1

Let  $\mathbf{v} = [0, 1, 0]^t$ , We compute

$$M\mathbf{v} = \begin{bmatrix} 1 & 0 & x \\ 0 & 1 & 0 \\ y & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1(0) + 0(1) + x(0) \\ 0(0) + 1(1) + 0(0) \\ y(0) + 0(1) + 1(0) \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} = 1 \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix},$$

which shows that  $\mathbf{v}$  is an eigenvector of  $M$  with eigenvalue  $\lambda = 1$ .

#### 3.2 Part 2

Noting that the rank is the dimension of the column space, we find that

- $\text{rank}(M) \geq 1$ , since it is not the zero matrix,
- $\text{rank}(M) \geq 2$ , since neither  $[1, 0, y]^t$  or  $[x, 0, 1]^t$  can be in the span of  $[0, 1, 0]^t$ , and
- $\text{rank}(M) = 3 \iff \det(M) \neq 0$ .

So we compute

$$\det_M(x, y) = \begin{vmatrix} 1 & 0 & x \\ 0 & 1 & 0 \\ y & 0 & 1 \end{vmatrix} = 1(1 - 0) - 0(1 - xy) + x(-y) = 1 - xy,$$

and so  $\det_M(x, y) = 0 \iff xy = 1$ . Thus

$$\text{rank}(M) = \begin{cases} 3 & xy = 1 \\ 2 & \text{else.} \end{cases}$$

### 3.3 Part 3

Since  $M$  is diagonalizable  $\iff M$  is full rank, which in this case means  $\text{rank}(M) = 3$ , we have

$$S = \left\{ (x, y) \in \mathbb{R}^2 \mid M \text{ is diagonalizable} \right\} = \left\{ \left( x, \frac{1}{x} \right) \mid x \in \mathbb{R} \setminus \{0\} \right\} \subset \mathbb{R}^2.$$