

# Title

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## Contents

<b>1</b>	<b>Spring 2019</b>	<b>1</b>
1.1	1 . . . . .	1
1.2	2 . . . . .	3
	1.2.1 (a) . . . . .	3
	1.2.2 (b) . . . . .	3
1.3	3 . . . . .	4
1.4	4 . . . . .	4
	1.4.1 a . . . . .	4
	1.4.2 b . . . . .	5
	1.4.3 c . . . . .	5
1.5	5 . . . . .	6
	1.5.1 a . . . . .	6
	1.5.2 b . . . . .	6
	1.5.3 c . . . . .	7
1.6	6 . . . . .	8
	1.6.1 a . . . . .	8
	1.6.2 b . . . . .	8
	1.6.3 c . . . . .	9
1.7	7 . . . . .	9
	1.7.1 a . . . . .	10
	1.7.2 b . . . . .	11
1.8	8 . . . . .	12
	1.8.1 a . . . . .	12
	1.8.2 b . . . . .	13
	1.8.3 c . . . . .	13

## 1 Spring 2019

### 1.1 1

$A$  is diagonalizable iff  $\min_A(x)$  is separable. See further discussion here.

Claim: If  $A \in \text{GL}(m, \mathbb{F})$  is invertible and  $A^n/\mathbb{F}$  is diagonalizable, then  $A/\mathbb{F}$  is diagonalizable.

Let  $A \in \text{GL}(m, \mathbb{F})$ . Since  $A^n$  is diagonalizable,  $\min_{A^n}(x) \in \mathbb{F}[x]$  is separable and thus factors as a product of  $m$  **distinct** linear factors:

$$\min_{A^n}(x) = \prod_{i=1}^m (x - \lambda_i), \quad \min_{A^n}(A^n) = 0$$

where  $\{\lambda_i\}_{i=1}^m \subset \mathbb{F}$  are the **distinct** eigenvalues of  $A^n$ .

Moreover  $A \in \text{GL}(m, \mathbb{F}) \implies A^n \in \text{GL}(m, \mathbb{F})$ :  $A$  is invertible  $\iff \det(A) = d \in \mathbb{F}^\times$ , and so  $\det(A^n) = \det(A)^n = d^n \in \mathbb{F}^\times$  using the fact that the determinant is a ring morphism  $\det : \text{Mat}(m \times m) \longrightarrow \mathbb{F}$  and  $\mathbb{F}^\times$  is closed under multiplication.

So  $A^n$  is invertible, and thus has trivial kernel, and thus zero is not an eigenvalue, so  $\lambda_i \neq 0$  for any  $i$ .

Since the  $\lambda_i$  are distinct and nonzero, this implies  $x^k$  is not a factor of  $\mu_{A^n}(x)$  for any  $k \geq 0$ . Thus the  $m$  terms in the product correspond to precisely  $m$  **distinct linear** factors.

We can now construct a polynomial that annihilates  $A$ , namely

$$q_A(x) := \min_{A^n}(x^n) = \prod_{i=1}^m (x^n - \lambda_i) \in \mathbb{F}[x],$$

where we can note that  $q_A(A) = \min_{A^n}(A^n) = 0$ , and so  $\min_A(x) \mid q_A(x)$  by minimality.

We now claim that  $q_A(x)$  has exactly  $n \cdot m$  distinct linear factors in  $\overline{\mathbb{F}}[x]$ , which reduces to showing that no pair  $x^n - \lambda_i, x^n - \lambda_j$  share a root. and that  $x^n - \lambda_i$  does not have multiple roots.

- For the first claim, we can factor

$$x^n - \lambda_i = \prod_{k=1}^n (x - \lambda_i^{\frac{1}{n}} e^{\frac{2\pi i k}{n}}) := \prod_{k=1}^n (x - \lambda_i^{\frac{1}{n}} \zeta_n^k),$$

where we now use the fact that  $i \neq j \implies \lambda_i^{\frac{1}{n}} \neq \lambda_j^{\frac{1}{n}}$ . Thus no term in the above product appears as a factor in  $x^n - \lambda_j$  for  $j \neq i$ .

- For the second claim, we can check that  $\frac{\partial}{\partial x}(x^n - \lambda_i) = nx^{n-1} \neq 0 \in \mathbb{F}$ , and  $\gcd(x^n - \lambda_i, nx^{n-1}) = 1$  since the latter term has only the roots  $x = 0$  with multiplicity  $n - 1$ , whereas  $\lambda_i \neq 0 \implies$  zero is not a root of  $x^n - \lambda_i$ .

But now since  $q_A(x)$  has exactly distinct linear factors in  $\overline{\mathbb{F}}[x]$  and  $\min_A(x) \mid q_A(x)$ ,  $\min_A(x) \in \mathbb{F}[x]$  can only have distinct linear factors, and  $A$  is thus diagonalizable over  $\mathbb{F}$ . ■

## 1.2 2

## 1.2.1 (a)

Go to a field extension. Orders of multiplicative groups for finite fields are known.

We can consider the quotient  $K = \frac{\mathbb{F}_p[x]}{\langle \pi(x) \rangle}$ , which since  $\pi(x)$  is irreducible is an extension of  $\mathbb{F}_p$  of degree  $d$  and thus a field of size  $p^d$  with a natural quotient map of rings  $\rho : \mathbb{F}_p[x] \rightarrow K$ .

Since  $K^\times$  is a group of size  $p^d - 1$ , we know that for any  $y \in K^\times$ , we have by Lagrange's theorem that the order of  $y$  divides  $p^d - 1$  and so  $y^{p^d} = y$ .

So every element in  $K$  is a root of  $q(x) = x^{p^d} - x$ .

Since  $\rho$  is a ring morphism, we have

$$\begin{aligned} \rho(q(x)) &= \rho(x^{p^d} - x) = \rho(x)^{p^d} - \rho(x) = 0 \in K \\ &\iff q(x) \in \ker \rho \\ &\iff q(x) \in \langle \pi(x) \rangle \\ &\iff \pi(x) \mid q(x) = x^{p^d} - x \quad \text{"to contain is to divide"}. \end{aligned}$$

■

## 1.2.2 (b)

Some potentially useful facts:

- $\mathbb{GF}(p^n)$  is the splitting field of  $x^{p^n} - x \in \mathbb{F}_p[x]$ .
- $x^{p^d} - x \mid x^{p^n} - x \iff d \mid n$
- $\mathbb{GF}(p^d) \leq \mathbb{GF}(p^n) \iff d \mid n$
- $x^{p^n} - x = \prod f_i(x)$  over all irreducible monic  $f_i$  of degree  $d$  dividing  $n$ .

Claim:  $\pi(x)$  divides  $x^{p^n} - x \iff \deg \pi$  divides  $n$ .

$\implies$  : Let  $L \cong \mathbb{GF}(p^n)$  be the splitting field of  $\varphi_n(x) := x^{p^n} - x$ ; then since  $\pi \mid \varphi_n$  by assumption,  $\pi$  splits in  $L$ . Let  $\alpha \in L$  be any root of  $\pi$ ; then there is a tower of extensions  $\mathbb{F}_p \leq \mathbb{F}_p(\alpha) \leq L$ .

Then  $\mathbb{F}_p \leq \mathbb{F}_p(\alpha) \leq L$ , and so

$$\begin{aligned} n &= [L : \mathbb{F}_p] \\ &= [L : \mathbb{F}_p(\alpha)] [\mathbb{F}_p(\alpha) : \mathbb{F}_p] \\ &= \ell d, \end{aligned}$$

for some  $\ell \in \mathbb{Z}^{\geq 1}$ , so  $d$  divides  $n$ .

$\impliedby$  : If  $d \mid n$ , use the fact (claim) that  $x^{p^n} - x = \prod f_i(x)$  over all irreducible monic  $f_i$  of degree  $d$  dividing  $n$ . So  $f = f_i$  for some  $i$ .



### 1.3 3

- Sylow theorems:
- $n_p \equiv 1 \pmod{p}$
- $n_p \mid m$ .

It turns out that  $n_3 = 1$  and  $n_5 = 1$ , so  $G \cong S_3 \times S_5$  since both subgroups are normal.

There is only one possibility for  $S_5$ , namely  $S_5 \cong \mathbb{Z}/(5)$ .

There are two possibilities for  $S_3$ , namely  $S_3 \cong \mathbb{Z}/(3^2)$  and  $\mathbb{Z}/(3)^2$ .

Thus

- $G \cong \mathbb{Z}/(9) \times \mathbb{Z}/(5)$ , or
- $G \cong \mathbb{Z}/(3)^2 \times \mathbb{Z}/(5)$ .



### 1.4 4

Concepts Used:

- Notation:  $X/G$  is the set of  $G$ -orbits
- Notation:  $X^g = \{x \in X \mid g \cdot x = x\}$
- Burnside's formula:  $|G||X/G| = \sum |X^g|$ .

#### 1.4.1 a

Strategy: Burnside.

- Define a sample space  $\Omega = G \times G$ , so  $|\Omega| = |G|^2$ .
- Identify the event we want to analyze:  $A := \{(g, h) \in G \times G \mid [g, h] = 1\}$ .
  - Define and note:

$$A_g := \{(g, h) \mid h \in H, [g, h] = 1\} \implies A = \coprod_{g \in G} A_g.$$

- Set  $n$  be the number of conjugacy classes, note we want to show  $P(A) = n/|G|$ .
- Let  $G$  act on itself by conjugation, which partitions  $G$  into conjugacy classes.
  - What are the orbits?

$$\mathcal{O}_g = \{hgh^{-1} \mid h \in G\},$$

which is the conjugacy class of  $g$ .

– What are the fixed points?

$$X^g = \left\{ h \in G \mid hgh^{-1} = g \right\},$$

which are the elements of  $G$  that commute with  $g$ , which is precisely  $A_g$ .

- Note  $|X/G| = n$ , the number of conjugacy classes.
- Note that

$$|A| = \left| \coprod_{g \in G} A_g \right| = \sum_{g \in G} |A_g| = \sum_{g \in G} |X^g|.$$

- Apply Burnside

$$|X/G| = \frac{1}{|G|} \sum_{g \in G} |X^g|,$$

- Rearrange and use definition:

$$n|G| = |X/G||G| = \sum_{g \in G} |X^g|$$

- Compute probability:

$$P(A) = \frac{|A|}{|\Omega|} = \frac{\sum_{g \in G} |X^g|}{|G|^2} = \frac{|X/G||G|}{|G|^2} = \frac{n|G|}{|G|^2} = \frac{n}{|G|}.$$

■

### 1.4.2 b

Class equation:

$$|G| = Z(G) + \sum_{\substack{\text{One } x \text{ from each} \\ \text{conjugacy class}}} [G : Z(x)]$$

where  $Z(x) = \left\{ g \in G \mid [g, x] = 1 \right\}$ .

### 1.4.3 c

Todo: revisit.

As shown in part 1,

$$\mathcal{O}_x = \left\{ g \curvearrowright x \mid g \in G \right\} = \left\{ h \in G \mid ghg^{-1} = h \right\} = C_G(g),$$

and by the class equation

$$|G| = |Z(G)| + \sum_{\substack{\text{One } x \text{ from each} \\ \text{conjugacy class}}} [G : Z(x)]$$

Now note

- Each element of  $Z(G)$  is in its own conjugacy class, contributing  $|Z(G)|$  classes to  $n$ .
- Every other class of elements in  $G \setminus Z(G)$  contains at least 2 elements
  - Claim: each such class contributes **at least**  $\frac{1}{2}|G \setminus Z(G)|$ .

Thus

$$\begin{aligned} n &\leq |Z(G)| + \frac{1}{2}|G \setminus Z(G)| \\ &= |Z(G)| + \frac{1}{2}|G| - \frac{1}{2}|Z(G)| \\ &= \frac{1}{2}|G| + \frac{1}{2}|Z(G)| \\ \implies \frac{n}{|G|} &\leq \frac{1}{2} \frac{|G|}{|G|} + \frac{1}{2} \frac{|Z(G)|}{|G|} \\ &= \frac{1}{2} + \frac{1}{2} \frac{1}{[G : Z(G)]}. \end{aligned}$$

## 1.5 5

### 1.5.1 a

- Suppose toward a contradiction  $\text{Tor}(M)$  has rank  $n \geq 1$ .
- Then  $\text{Tor}(M)$  has a linearly independent generating set  $B = \{\mathbf{r}_1, \dots, \mathbf{r}_n\}$ , so in particular

$$\sum_{i=1}^n s_i \mathbf{r}_i = 0 \implies s_i = 0_R \forall i.$$

- Let  $\mathbf{r}$  be any of these generating elements.
- Since  $\mathbf{r} \in \text{Tor}(M)$ , there exists an  $s \in R \setminus 0_R$  such that  $s\mathbf{r} = 0_M$ .
- Then  $s\mathbf{r} = 0$  with  $s \neq 0$ , so  $\{\mathbf{r}\} \subseteq B$  is *not* a linearly independent set, a contradiction. ■

### 1.5.2 b

- Let  $n = \text{rank } M$ , and let  $\mathcal{B} = \{\mathbf{r}_i\}_{i=1}^n \subseteq R$  be a generating set.
- Let  $\tilde{M} := M/\text{Tor}(M)$  and  $\pi : M \rightarrow M'$  be the canonical quotient map.
- **Claim:**  $\tilde{\mathcal{B}} := \pi(\mathcal{B}) = \{\mathbf{r}_i + \text{Tor}(M)\}$  is a basis for  $\tilde{M}$ .
  - **Linearly Independent:**

\* Suppose that

$$\sum_{i=1}^n s_i(\mathbf{r}_i + \text{Tor}(M)) = \mathbf{0}_{\tilde{M}}.$$

\* Then using the definition of coset addition/multiplication, we can write this as

$$\sum_{i=1}^n (s_i \mathbf{r}_i + \text{Tor}(M)) = \left( \sum_{i=1}^n s_i \mathbf{r}_i \right) + \text{Tor}(M) = \mathbf{0}_{\tilde{M}}.$$

\* Since  $\tilde{\mathbf{x}} = 0 \in \tilde{M} \iff \tilde{\mathbf{x}} = \mathbf{x} + \text{Tor}(M)$  where  $\mathbf{x} \in \text{Tor}(M)$ , this forces  $\sum s_i \mathbf{r}_i \in \text{Tor}(M)$ .

\* Then

$$\text{exists } \alpha \in R^\bullet \text{ such that } \alpha_i \sum s_i \mathbf{r}_i = \mathbf{0}_M.$$

\* But since  $R$  is an integral domain and  $\alpha \neq 0$ , we must have  $s_i = 0$  for all  $i$ .

– **Spanning:**

\* Write  $\pi(\mathcal{B}) = \{\mathbf{r}_i + \text{Tor}(M)\}_{i=1}^n$  as a set of cosets.

\* Letting  $\mathbf{x} \in M'$  be arbitrary, we can write  $\mathbf{x} = \mathbf{m} + \text{Tor}(M)$  for some  $\mathbf{m} \in M$  where  $\pi(\mathbf{m}) = \mathbf{x}$  by surjectivity of  $\pi$ .

\* Since  $\mathcal{B}$  is a basis for  $M$ , we have  $\mathbf{m} = \sum_{i=1}^n s_i \mathbf{r}_i$ , and so

$$\begin{aligned} \mathbf{x} &= \pi(\mathbf{m}) \\ &= \pi\left(\sum_{i=1}^n s_i \mathbf{r}_i\right) \\ &= \sum_{i=1}^n s_i \pi(\mathbf{r}_i) \\ &= \sum_{i=1}^n s_i (\mathbf{r}_i + \text{Tor}(M)), \end{aligned}$$

which expresses  $\mathbf{x}$  as a linear combination of elements in  $\mathcal{B}'$ .

### 1.5.3 c

**$M$  is not free: Claim:** If  $I \trianglelefteq R$  is a free  $R$ -module, then  $I$  is a principal ideal.

*Proof:* Let  $I = \langle B \rangle$  for some basis – if  $B$  contains more than 1 element, say  $m_1$  and  $m_2$ , then  $m_2 m_1 - m_1 m_2 = 0$  is a linear dependence, so  $B$  has only one element  $m$ .

But then  $I = \langle m \rangle = R_m$  is cyclic as an  $R$ -module and thus principal as an ideal of  $R$ . The result follows by the contrapositive.

**$M$  is rank 1:** For any module, we can take an element  $M \neq 0_M$  and consider its cyclic module  $Rm$ .

Thus the rank of  $M$  is at least 1, since  $\{m\}$  is a subset of a spanning set. It can not be linearly dependent, since  $R$  is an integral domain and  $M \subseteq R$ , so  $\alpha m = 0 \implies \alpha = 0$ .

However, the rank is at most 1 since  $R$  is commutative. If we take two elements  $\mathbf{m}, \mathbf{n} \in M$ , then since  $m, n \in R$  as well, we have  $nm = mn$  and so

$$(n)\mathbf{m} + (-m)\mathbf{n} = 0_R = 0_M$$

is a linear dependence. 2  $M$  is **torsion-free**:

Let  $x \in \text{Tor}M$ , then there exists some  $r \neq 0 \in R$  such that  $rx = 0$ . But  $x \in R$  and  $R$  is an integral domain, so  $x = 0$ , and thus  $\text{Tor}(M) = \{0_R\}$ . ■

## 1.6 6

### 1.6.1 a

Define the set of proper ideals

$$S = \left\{ J \mid I \subseteq J < R \right\},$$

which is a poset under set inclusion.

Given a chain  $J_1 \subseteq \dots$ , there is an upper bound  $J := \bigcup J_i$ , so Zorn's lemma applies.

### 1.6.2 b

$\implies :$

We will show that  $x \in J(R) \implies 1 + x \in R^\times$ , from which the result follows by letting  $x = rx$ .

Let  $x \in J(R)$ , so it is in every maximal ideal, and suppose toward a contradiction that  $1 + x$  is **not** a unit.

Then consider  $I = \langle 1 + x \rangle \leq R$ . Since  $1 + x$  is not a unit, we can't write  $s(1 + x) = 1$  for any  $s \in R$ , and so  $1 \notin I$  and  $I \neq R$

So  $I < R$  is proper and thus contained in some maximal proper ideal  $\mathfrak{m} < R$  by part (1), and so we have  $1 + x \in \mathfrak{m}$ . Since  $x \in J(R)$ ,  $x \in \mathfrak{m}$  as well.

But then  $(1 + x) - x = 1 \in \mathfrak{m}$  which forces  $\mathfrak{m} = R$ .

$\Leftarrow$

Fix  $x \in R$ , and suppose  $1 + rx$  is a unit for all  $r \in R$ .

Suppose towards a contradiction that there is a maximal ideal  $\mathfrak{m}$  such that  $x \notin \mathfrak{m}$  and thus  $x \notin J(R)$ .

Consider

$$M' := \left\{ rx + m \mid r \in R, m \in M \right\}.$$

Since  $\mathfrak{m}$  was maximal,  $\mathfrak{m} \subsetneq M'$  and so  $M' = R$ .



So every element in  $R$  can be written as  $rx + m$  for some  $r \in R, m \in M$ . But  $1 \in R$ , so we have

$$1 = rx + m.$$

So let  $s = -r$  and write  $1 = sx - m$ , and so  $m = 1 + sx$ .

Since  $s \in R$  by assumption  $1 + sx$  is a unit and thus  $m \in \mathfrak{m}$  is a unit, a contradiction.

So  $x \in \mathfrak{m}$  for every  $\mathfrak{m}$  and thus  $x \in J(R)$ .

### 1.6.3 c

- $\mathfrak{N}(R) = \left\{ x \in R \mid x^n = 0 \text{ for some } n \right\}$ .
- $J(R) = \text{Spec}_{\max}(R) = \bigcap_{\mathfrak{m} \text{ maximal}} \mathfrak{m}$ .

We want to show  $J(R) = \mathfrak{N}(R)$ .

$\mathfrak{N}(R) \subseteq J(R)$ :

We'll use the fact  $x \in \mathfrak{N}(R) \implies x^n = 0 \implies 1 + rx$  is a unit  $\iff x \in J(R)$  by (b):

$$\sum_{k=1}^{n-1} (-x)^k = \frac{1 - (-x)^n}{1 - (-x)} = (1 + x)^{-1}.$$

$J(R) \subseteq \mathfrak{N}(R)$ :

Let  $x \in J(R) \setminus \mathfrak{N}(R)$ .

Since  $R$  is finite,  $x^m = x$  for some  $m > 0$ . Without loss of generality, we can suppose  $x^2 = x$  by replacing  $x^m$  with  $x^{2m}$ .

If  $1 - x$  is not a unit, then  $\langle 1 - x \rangle$  is a nontrivial proper ideal, which by (a) is contained in some maximal ideal  $\mathfrak{m}$ . But then  $x \in \mathfrak{m}$  and  $1 - x \in \mathfrak{m} \implies x + (1 - x) = 1 \in \mathfrak{m}$ , a contradiction.

So  $1 - x$  is a unit, so let  $u = (1 - x)^{-1}$ .

Then

$$\begin{aligned} (1 - x)x &= x - x^2 = x - x = 0 \\ \implies u(1 - x)x &= x = 0 \\ \implies x &= 0. \end{aligned}$$

### 1.7 7

Work with matrix of all ones instead. Eyeball eigenvectors. Coefficients in minimal polynomial: size of largest Jordan block Dimension of eigenspace: number of Jordan blocks

## 1.7.1 a

Let  $A$  be the matrix in the question, and  $B$  be the matrix containing 1's in every entry.

- Noting that  $B = A + I$ , we have

$$\begin{aligned} B\mathbf{x} &= \lambda\mathbf{x} \\ \iff (A + I)\mathbf{x} &= \lambda\mathbf{x} \\ \iff A\mathbf{x} &= (\lambda - 1)\mathbf{x}, \end{aligned}$$

so we will find the eigenvalues of  $B$  and subtract one from each.

- Note that  $B\mathbf{v} = \left[ \sum v_i, \sum v_i, \dots, \sum v_i \right]$ , i.e. it has the effect of summing all of the entries of  $\mathbf{v}$  and placing that sum in each component.
- We proceed by finding  $p$  eigenvectors and eigenvalues, since the JCF and minimal polynomials will involve eigenvalues and the transformation matrix will involve (generalized) eigenvectors.
- Claim: each vector of the form  $\mathbf{p}_i := \mathbf{e}_1 - \mathbf{e}_{i+1} = [1, 0, 0, \dots, 0 - 1, 0, \dots, 0]$  where  $i \neq j$  is also an eigenvector with eigenvalues  $\lambda_0 = 0$ , and this gives  $p - 1$  linearly independent vectors spanning the eigenspace  $E_{\lambda_0}$

- Compute

$$B\mathbf{p}_i = [1 + 0 + \dots + 0 + (-1) + 0 + \dots + 0] = [0, 0, \dots, 0]$$

- So every  $\mathbf{p}_i \in \ker(B)$ , so they are eigenvectors with eigenvalue 0.
- Since the first component is fixed and we have  $p - 1$  choices for where to place a  $-1$ , this yields  $p - 1$  possibilities for  $\mathbf{p}_i$
- These are linearly independent since the  $(p - 1) \times (p - 1)$  matrix  $[\mathbf{p}_1^t, \dots, \mathbf{p}_{p-1}^t]$  satisfies

$$\det \begin{bmatrix} 1 & 1 & 1 & \dots & 1 \\ -1 & 0 & 0 & \dots & 0 \\ 0 & -1 & 0 & \dots & 0 \\ 0 & 0 & -1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & -1 \end{bmatrix} = (1) \cdot \det \begin{bmatrix} -1 & 0 & 0 & \dots & 0 \\ 0 & -1 & 0 & \dots & 0 \\ 0 & 0 & -1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & -1 \end{bmatrix} = (-1)^{p-2} \neq 0.$$

where the first equality follows from expanding along the first row and noting this is the first minor, and every other minor contains a row of zeros.

- Claim:  $\mathbf{v}_1 = [1, 1, \dots, 1]$  is an eigenvector with eigenvalue  $\lambda_1 = p$ .

- Compute

$$B\mathbf{v} = \left[ \sum_{i=1}^p 1, \sum_{i=1}^p 1, \dots, \sum_{i=1}^p 1 \right] = [p, p, \dots, p] = p[1, 1, \dots, 1] = p\mathbf{v}_1,$$

thus  $\lambda_1 = p$

- $\dim E_{\lambda_1} = 1$  since the eigenspaces are orthogonal and  $E_{\lambda_0} \oplus E_{\lambda_1} \leq F^p$  is a subspace, so  $p > \dim(E_{\lambda_0}) + \dim E_{\lambda_1} = p - 1 + \dim E_{\lambda_1}$  and it isn't zero dimensional.

- Using that the eigenvalues of  $A$  are  $1 + \lambda_i$  for  $\lambda_i$  the above eigenvalues for  $B$ ,

$$\begin{aligned} \text{Spec}(B) &:= \{(\lambda_i, m_i)\} = \{(p, 1), (0, p-1)\} \implies \chi_B(x) = (x-p)x^{p-1} \\ &\implies \text{Spec}(A) = \{(p-1, 1), (-1, p-1)\} \implies \chi_A(x) = (x-p+1)(x+1)^{p-1} \end{aligned}$$

Note: we can always read off the *characteristic* polynomial from the spectrum.

- The dimensions of eigenspaces are preserved, thus

$$JCF_{\mathbb{Q}}(A) = J_{p-1}^1 \oplus (p-1)J_{-1}^1 = \left[ \begin{array}{c|c|c|c|c|c} p-1 & 0 & 0 & \cdots & 0 & 0 \\ \hline 0 & -1 & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & -1 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & \ddots & \ddots & 0 \\ \hline 0 & 0 & 0 & \cdots & -1 & 0 \\ \hline 0 & 0 & 0 & \cdots & 0 & -1 \end{array} \right].$$

- The matrix  $P$  such that  $A = PJP^{-1}$  will have columns the bases of the generalized eigenspaces.
- In this case, the generalized eigenspaces are the usual eigenspaces, so

$$P = [\mathbf{v}_1, \mathbf{p}_1, \dots, \mathbf{p}_{p-1}] = \left[ \begin{array}{cccccc} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & -1 & 0 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & 0 & 0 \\ 1 & 0 & 0 & -1 & 0 & 0 \\ 1 & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 0 & 0 & 0 & 0 & -1 \end{array} \right].$$

### 1.7.2 b

For  $F = \mathbb{F}_p$ , all eigenvalues/vectors still lie in  $\mathbb{F}_p$ , but now  $-1 = p-1$ , making  $(x-(p-1))(x+1)^{p-1} = (x+1)(x+1)^{p-1}$ , so  $\chi_{A, \mathbb{F}_p}(x) = (x+1)^p$ , and the Jordan blocks may merge.

- A computation shows that  $(A+I)^2 = pA = 0 \in M_p(\mathbb{F}_p)$  and  $(A+I) \neq 0$ , so  $\min_{A, \mathbb{F}_p}(x) = (x+1)^2$ .
  - Thus the largest Jordan block corresponding to  $\lambda = -1$  is of size 2
- Can check that  $\det(A) = \pm 1 \in \mathbb{F}_p^\times$ , so the vectors  $\mathbf{e}_1 - \mathbf{e}_i$  are still linearly independent and thus  $\dim E_{-1} = p-1$ 
  - So there are  $p-1$  Jordan blocks for  $\lambda = 0$ .

Summary:

$$\begin{aligned} \min_{A, \mathbb{F}_p}(x) &= (x+1)^2 \\ \chi_{A, \mathbb{F}_p}(x) &\equiv (x+1)^p \\ \dim E_{-1} &= p-1. \end{aligned}$$

Thus

$$JCF_{\mathbb{F}_p}(A) = J_{-1}^2 \oplus (p-2)J_{-1}^1 = \left[ \begin{array}{cc|c|c|c|c} -1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & -1 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & \ddots & \ddots & 0 \\ \hline 0 & 0 & 0 & \cdots & -1 & 0 \\ \hline 0 & 0 & 0 & \cdots & 0 & -1 \end{array} \right].$$

To obtain a basis for  $E_{\lambda=0}$ , first note that the matrix  $P = [\mathbf{v}_1, \mathbf{p}_1, \dots, \mathbf{p}_{p-1}]$  from part (a) is singular over  $\mathbb{F}_p$ , since

$$\begin{aligned} \mathbf{v}_1 + \mathbf{p}_1 + \mathbf{p}_2 + \cdots + \mathbf{p}_{p-2} &= [p-1, 0, 0, \dots, 0, 1] \\ &= [-1, 0, 0, \dots, 0, 1] \\ &= -\mathbf{p}_{p-1}. \end{aligned}$$

We still have a linearly independent set given by the first  $p-1$  columns of  $P$ , so we can extend this to a basis by finding one linearly independent generalized eigenvector.

Solving  $(A - I\lambda)\mathbf{x} = \mathbf{v}_1$  is our only option (the others won't yield solutions). This amounts to solving  $B\mathbf{x} = \mathbf{v}_1$ , which imposes the condition  $\sum x_i = 1$ , so we can choose  $\mathbf{x} = [1, 0, \dots, 0]$ .

Thus

$$P = [\mathbf{v}_1, \mathbf{x}, \mathbf{p}_1, \dots, \mathbf{p}_{p-2}] = \left[ \begin{array}{cccccc} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 0 & -1 & 0 & 0 & 0 \\ 1 & 0 & 0 & -1 & 0 & 0 \\ 1 & \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & 0 & 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{array} \right].$$

## 1.8 8

Concepts used:

- $\zeta_n := e^{\frac{2\pi i}{n}}$ , and  $\zeta_n^k$  is a primitive  $n$ th root of unity  $\iff \gcd(n, k) = 1$   
 – In general,  $\zeta_n^k$  is a primitive  $\frac{n}{\gcd(n, k)}$ th root of unity.
- $\deg \Phi_n(x) = \varphi(n)$
- $\varphi(p^k) = p^k - p^{k-1} = p^{k-1}(p-1)$  (proof: for a nontrivial gcd, the possibilities are  $p, 2p, 3p, 4p, \dots, p^{k-2}p, p^{k-1}p$ .)
- $\text{Gal}(\mathbb{Q}(\zeta)/\mathbb{Q}) \cong \mathbb{Z}/(n)^\times$

Let  $K = \mathbb{Q}(\zeta)$

### 1.8.1 a

- $\zeta := e^{2\pi i/8}$  is a primitive 8th root of unity
- The minimal polynomial of an  $n$ th root of unity is the  $n$ th cyclotomic polynomial  $\Phi_n$

- The degree of the field extension is the degree of  $\Phi_8$ , which is

$$\varphi(8) = \varphi(2^3) = 2^{3-1} \cdot (2 - 1) = 4.$$

- So  $[\mathbb{Q}(\zeta) : \mathbb{Q}] = 4$ .

### 1.8.2 b

- $\text{Gal}(\mathbb{Q}(\zeta)/\mathbb{Q}) \cong \mathbb{Z}/(8)^\times \cong \mathbb{Z}/(4)$  by general theory
- $\mathbb{Z}/(4)$  has exactly one subgroup of index 2.
- Thus there is exactly **one** intermediate field of degree 2 (a quadratic extension).

### 1.8.3 c

- Let  $L = \mathbb{Q}(\zeta, \sqrt[4]{2})$ .
- Note  $\mathbb{Q}(\zeta) = \mathbb{Q}(i, \sqrt{2})$ 
  - $\mathbb{Q}(i, \sqrt{2}) \subseteq \mathbb{Q}(\zeta)$ 
    - \*  $\zeta_8^2 = i$ , and  $\zeta_8 = \sqrt{2}^{-1} + i\sqrt{2}^{-1}$  so  $\zeta_8 + \zeta_8^{-1} = 2/\sqrt{2} = \sqrt{2}$ .
  - $\mathbb{Q}(\zeta) \subseteq \mathbb{Q}(i, \sqrt{2})$ :
    - \*  $\zeta = e^{2\pi i/8} = \sin(\pi/4) + i \cos(\pi/4) = \frac{\sqrt{2}}{2}(1 + i)$ .
- Thus  $L = \mathbb{Q}(i, \sqrt{2})(\sqrt[4]{2}) = \mathbb{Q}(i, \sqrt{2}, \sqrt[4]{2}) = \mathbb{Q}(i, \sqrt[4]{2})$ .
  - Uses the fact that  $\mathbb{Q}(\sqrt{2}) \subseteq \mathbb{Q}(\sqrt[4]{2})$  since  $\sqrt[4]{2}^2 = \sqrt{2}$
- Conclude

$$[L : \mathbb{Q}] = [L : \mathbb{Q}(\sqrt[4]{2})] [\mathbb{Q}(\sqrt[4]{2}) : \mathbb{Q}] = 2 \cdot 4 = 8$$

using the fact that the minimal polynomial of  $i$  over any subfield of  $\mathbb{R}$  is always  $x^2 + 1$ , so  $\min_{\mathbb{Q}(\sqrt[4]{2})}(i) = x^2 + 1$  which is degree 2.