EXERCISES 7.2: SOLUTIONS

Disclaimer: These are my own solutions. It is possible that it contains some fatal errors. I appreciate it if you let me know any errors you find.

General notations: For a linear operator $T \in \mathrm{End}(V)$, μ_T denotes its minimal polynomial and χ_T denotes its characteristic polynomial. For a T-invariant subspace $W \subset V$, the notation $S_T(\alpha; W)$ denotes the ideal $\{f \in F[x] : f(T)\alpha \in W\}$, which is called the conductor of α into W. In particular, if $W = 0$, $S_T(\alpha; 0) = \{f : f(T)\alpha = 0\}$. This the T-annihilator of α, and it is also denoted by $M(\alpha; T)$ in §7.1. Let $I(T) = \cap_{\alpha \in V} S_T(\alpha; 0) = \{f \in F[x] : f(T)\alpha = 0, \forall \alpha \in V\}$. Note that μ_T is the monic generator of $I(T)$.

Exercise 2: Let $T : V \to V$ be a linear operator on a finite dimensional vector space V. Let R be the range of T and N be the null space of T. (a) Prove that R has a complementary T-invariant subspace if and only if R is independent of N. (b) If R and N are independent, prove that N is the unique T-invariant subspace complementary to R.

Proof. (a) The dimension theorem says that $\dim R + \dim N = \dim V$. If R and N are independent, we have $R \cap N = \{0\}$ and thus $\dim(R + N) = \dim R + \dim(N) = \dim(V)$, by dimension theorem. Thus $V = R + N$. Since $N \cap R = 0$, we get $V = R \oplus N$. Note that N is clearly T-invariant. Thus R has a T-invariant complementary subspace. Conversely, suppose that R has a T-invariant complementary subspace, and thus R is admissible. For any $\alpha \in V$, we have $T\alpha \in R$. The admissibility shows that there exists a $\beta \in R$ such that $T\alpha = T\beta$. Thus $\alpha - \beta \in N$. The equation $\alpha = \beta + \alpha - \beta$ implies that $V = R + N$. This means that $\dim(R \cap N) = \dim R + \dim N - \dim(R + N) = 0$. Thus $R \cap N = \{0\}$.

(b) Suppose that $V = R \oplus W$ for a T-invariant subspace $W \subset V$. We will show that $W = N$. Take $\alpha \in W$, we have $T\alpha \in W$ since W is T-invariant. On the other hand, $T\alpha \in R$ by definition. Thus $T\alpha \in R \cap W = \{0\}$, which implies that $T\alpha = 0$ and $\alpha \in N$. Thus $W \subset N$. On the other hand, we know that $\dim W = \dim V - \dim R = \dim N$. We must have $W = N$. $\square$

Exercise 8: Let $T : \mathbb{R}^3 \to \mathbb{R}^3$ be the linear operator given by the matrix

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

Find nonzero vectors $\alpha_1, \ldots, \alpha_r$ satisfying the conditions of Theorem 3.

Proof. We can compute that $\chi_T = (x-1)^3$ and $\mu_T = (x-1)^2$. Thus we have $V = Z(\alpha_1; T) \oplus Z(\alpha_2; T)$ and $p_1 = (x-1)^2, p_2 = (x-1)$. Note that α_2 is an eigenvector of 1, α_1 is in $\ker(p_1(T))$ but not an eigenvector of 1, but $Z(\alpha_1; T)$ contains an eigenvector of 1. Since $\dim Z(\alpha_1; T) = 2$, we have $T\alpha_1 \neq \alpha_1$, but $(T - I)^2\alpha_1 = 0$. We first compute the eigenspace of 1, namely, $E_T(1) = \ker(T - I)$. A simple calculation shows that

$$E_T(1) = \left\{ \begin{bmatrix} 2y + 2z \\ y \\ z \end{bmatrix} : y, z \in \mathbb{R} \right\}.$$

Since $(T - I)^2 = 0$, α_1 can be taken as any vector with $\alpha_1 \notin E_T(1)$. For example, we can take $\alpha_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$. In this case $(T - I)\alpha_1 = \begin{bmatrix} 2 \\ -1 \\ 2 \end{bmatrix}$. The vector α_2 can be taken as any vector in $E_T(1)$

which is not proportional to $(T-I)\alpha_1$. For example, we can take $\alpha_2 = \begin{bmatrix}2\\1\\0\end{bmatrix}$. The choices of α_1, α_2 are not unique. □

Exercise 9: Let A be the real matrix
$$A = \begin{bmatrix}1 & 3 & 3\\ 3 & 1 & 3\\ -3 & -3 & -5\end{bmatrix}.$$
Find an invertible real matrix $P \in \mathrm{GL}_3(\mathbb{R})$ such that $P^{-1}AP$ is in rational form.

Proof. Let $T : \mathbb{R}^3 \to \mathbb{R}^3$ be the linear operator defined by A. We can compute the characteristic polynomial of T is $\chi_T = (x+2)^2(x-1)$ and its minimal polynomial is $\mu_T = (x+2)(x-1)$. We have $V = Z(\alpha_1;T) \oplus Z(\alpha_2;T)$, with $p_1 = (x+2)(x-1)$ and $p_2 = x+2$. Similar as the last problem, we can take α_1 arbitrary other than eigenvectors of 1 or -2, and α_2 an eigenvector of -2. Take
$$\alpha_1 = [1,0,0]^T, T\alpha_1 = [1,3,-3]^T; \alpha_2 = [1,-1,0]^T,$$
and
$$P = [\alpha_1, T\alpha_1, \alpha_2] = \begin{bmatrix}1 & 1 & 1\\ 0 & 3 & -1\\ 0 & -3 & 0\end{bmatrix}.$$
Then we have
$$AP = P\begin{bmatrix}0 & 2 & 0\\ 1 & -1 & 0\\ 0 & 0 & -2\end{bmatrix}.$$
Again, the choice of P is not unique. □

Exercise 11: Prove that if A and B are 3×3 matrices over the field F, A is similar to B if and only if they have the same characteristic polynomial and the same minimal polynomial. Give an example which shows that this is false for 4×4 matrices.

Proof. If A and B are similar, then clearly they have the same characteristic and minimal polynomial (for the minimal polynomial part, it is easy to check $I(T_A) = I(T_B)$. A different argument is: A, B represent the same linear operators with different choice of basis). Now suppose that $A, B \in \mathrm{Mat}_{3\times 3}(F)$ such that $\chi_A = \chi_B$ and $\mu_A = \mu_B$. To show that A and B are similar, it suffices to show that A and B have the same invariant factors. We know that $\deg \chi_A = 3$ and we discuss degree of μ_A. If $\deg(\mu_A) = 3$, then $\mu_A = \chi_A$, and thus A has only a single invariant factor, which is μ_A. The same is true for B. The assumption shows that A, B have the same invariant factors. Next, we assume that $\deg(\mu_A) = 2$. In this case, $\chi_A = \mu_A q_A$ for a degree one factor q_A and the invariant factors of A are $\{\mu_A, q_A = \chi_A/\mu_A\}$. Again, the assumption shows that A and B have the same invariant factors. Finally, assume that $\deg(\mu_A) = 1$. Assume that $\mu_A = (x-a)$ for some $a \in F$. This implies that $A - aI_3 = 0$ and thus $A = aI_3$. Since $\mu_B = \mu_A$, we also have $B = aI_3$. Thus $A = B$ in this case.

In the 4×4 case, we can take A such that its invariant factors are x^2, x, x and take B such that its invariant factors are x^2, x^2. Note that $\mu_A = \mu_B = x^2, \chi_A = \chi_B = x^4$. But A and B are not similar, because they have different invariant factors. Such matrices can be realized by
$$A = \begin{bmatrix}0&0&0&0\\1&0&0&0\\0&0&0&0\\0&0&0&0\end{bmatrix}, \quad B = \begin{bmatrix}0&0&0&0\\1&0&0&0\\0&0&0&0\\0&0&1&0\end{bmatrix}$$
□

Exercise 12: Let F be a subfield of the field of complex numbers, and let $A, B \in \mathrm{Mat}_{n\times n}(F)$. Prove that A and B are similar over the field of complex numbers, then they are similar over F.

We did not talk about how linear algebra behaves under field extension. Here we prove some simple useful facts regarding this problem. In the following, K is a field and F is a subfield of K, which means F is a subset of K and together with the addition and multiplication defined on K, F is also a field. You can think $K = \mathbb{C}$, F is either $\mathbb{Q}$ or $\mathbb{R}$; or $K = \left\{a + b\alpha + c\alpha^2 : \alpha = \sqrt[3]{2}, a, b, c \in \mathbb{Q}\right\}, F = \mathbb{Q}$.

Lemma 1. *Let $A \in \mathrm{Mat}_{m\times n}(F)$. If $Ax = 0$ has a nonzero solution $x \in K^n$, then $Ax = 0$ has a nonzero solution in F^n. Moreover, we have $\dim_K \{x \in K^n : Ax = 0\} = \dim_F \{x \in F^n : Ax = 0\}$.*

Note that $F \subset K$, it is natural to view A as an element in $\mathrm{Mat}_{m\times n}(K)$ and thus we can talk about solutions of $Ax = 0$ in K^n.

Proof. Let $R \in \mathrm{Mat}_{m\times n}(F)$ be the row reduced echelon form of A. The key observation is when R is viewed as an element in $\mathrm{Mat}_{m\times n}(K)$, it is still in row reduced echelon form. Note that $Ax = 0$ has a nonzero solution in K^n iff $Rx = 0$ has a nonzero solution in K^n iff the number of leading ones in R is less than n, or $\mathrm{rank}(R) < n$. Thus $Ax = 0$ has a nonzero solution in F^n. Actually, the key observation shows that $\mathrm{rank}_F(A) = \mathrm{rank}_K(A)$, where $\mathrm{rank}_K(A)$ denotes the rank of A when it is viewed as a matrix over K. The "moreover" part follows from

$$\dim_K \{x \in K^n : Ax = 0\} = n - \mathrm{rank}(R) = \dim_F \{x \in F^n : Ax = 0\}.$$

□

Remark 2. The above proof used the fact that: after elementary row operations, every matrix A can be reduced to an elementary row echelon form R, and the linear system $Ax = 0$ is equivalent to $Rx = 0$. In particular, the elementary operation $R_i \to cR_i$ (replacing a row by c times this row) for $c \neq 0$ is invertible. This is a property of *field*. Think about the following example. Let $K = \mathbb{Z}/6\mathbb{Z}$, which consists of elements $\overline{k}$ for $0 \le k \le 5$ and $k \in \mathbb{Z}$. Here $\overline{k} = k + 6\mathbb{Z}$ denotes the equivalence class. Consider its subset $F = \left\{\overline{0}, \overline{3}\right\} \subset K$. It should be easy to see that F is a field with the usual operations. In fact, $F = \mathbb{F}_2$, which is field consisting 2 elements. Note that K is not a field because $\overline{3}, \overline{2} \in K$ are nonzero, but $\overline{3} \cdot \overline{2} = \overline{0}$. Now consider the linear equation

$$x + x + x = 0.$$

Note that the above equation has a nontrivial solution $x = \overline{2}$ over K, but it does not have nontrivial solution over F. If you tried to go through the above proof, you will find that the main issue here is: while 3 is nonzero in K, it is not invertible in K.

Remark 3. In the terminology you will learn later, Lemma 1 can be restated as follows:

$$\ker(T_A) \otimes_F K = \ker(T_A \otimes_F K),$$

where $T_A : F^n \to F^m$ is the usual linear map defined by A and $T_A \otimes_F K$ is the linear map $F^n \otimes_F K = K^n \to K^m = F^n \otimes_F K$. In other words, the short sequence

$$0 \to \ker(T_A) \otimes_F K \to K^n \to K^m$$

is still exact. This reflects the fact that K is a *flat* F-module.

Lemma 4. *Let $S = \{\alpha_1, \ldots, \alpha_r\} \in F^n$. If S is linearly dependent over K, then it is also linearly dependent over F.*

Since $F^n \subset K^n$, S can be viewed as a subset of K^n and thus we can consider linearly dependence of S over K.

Proof. Let A be the matrix $A = [\alpha_1, \ldots, \alpha_r] \in \mathrm{Mat}_{n\times r}(F) \subset \mathrm{Mat}_{n\times r}(K)$. The assumption says that $Ax = 0$ has a nonzero solution in K^r. By Lemma 1, $Ax = 0$ has a nontrivial solution in F^r, which is equivalent to say that S is linearly dependent over F. □

First proof of Exercise 12. In this proof, we assume that the characteristic of K is zero, which is true if $K = \mathbb{C}$ as in the assumption of Ex 12. Later, we will see that this assumption is unnecessary. Let $V_K = \{X \in M_{n\times n}(K) : AX = XB\}$ and $V_F = \{X \in M_{n\times n}(F) : AX = XB\}$. The assumption says that V_K is not the zero space. Thus by Lemma 1, $\dim_F V_F = \dim_K V_K \ge 1$. Let $\mathcal{B} = \{\alpha_1, \ldots, \alpha_k \in V_F\}$ be an F-basis of V_F. By Lemma 4, $\alpha_1, \ldots, \alpha_k$ are also linearly independent over K. Let $W = \left\{\sum_{i=1}^k c_i\alpha_i : c_i \in K\right\}$ be the K-span of $\mathcal{B}$. Then $W \subset V_K$ and $\dim_K W = k \ge 1$.

Lemma 1 says that $\dim_F V_F = \dim_K V_K$, and thus we have $W = V_K$ by counting dimension. We need to show there exists a matrix $Q \in V_F$ such that $\det(Q) \neq 0$.

Consider the determinant function $\det : M_{n\times n}(K) \to K$ and restrict it to V_K. The assumption says that there exists a matrix $P \in V_K$ such that $\det(P) \neq 0$. For a general element $X = \sum_{i=1}^k x_i\alpha_i$ with $x_i \in F, \alpha_i \in \mathcal{B}$, a general fact says that $\det(X) = \det(\sum_{i=1}^k x_i\alpha_i)$ is a polynomial f on the variables $x_1, \ldots, x_k$, whose coefficients in F. In other words, $f \in F[x_1, \ldots, x_k]$. A very special case is when $k = 1$ and in this case, $\det(x_1\alpha_1) = \det(\alpha_1)x_1^n$. The assumption says that there exists $x_1, \ldots, x_k \in K$ such that $f(x_1, \ldots, x_k) \neq 0$, and thus this polynomial f is nonzero. Since F has characteristic zero, there must be $y_1, \ldots, y_k \in F$ such that $f(y_1, \ldots, y_k) \neq 0$ (see Theorem 3, page 126 for this fact when there is only one variable). Note that $Q = \sum_{i=1}^k y_i\alpha_i \in V_F$ and $\det(Q) \neq 0$. We are done. □

Remark 5. The above proof used some facts on determinant and polynomials of several variables. Moreover, it only works when characteristic of F is zero. See the following for a proof which works for more general situations.

Lemma 6. *Let $A \in \mathrm{Mat}_{n\times n}(F)$, and let $\mu_{A,F}$ (resp. $\mu_{A,K}$) denote the minimal polynomial of A when viewed as a matrix over F (resp. over K). Then $\mu_{A,F} = \mu_{A,K}$.*

This fact is proved in page 192, but we did not cover the proof in class.

Proof. Denote $I(A, F) = \{f \in F[x] : f(A) = 0\}$ and $I(A, K) = \{f \in K[x] : f(A) = 0\}$. Then by definition $I(A, F) = \mu_{A,F}F[x], I(A, K) = \mu_{A,K}K[x]$. Note that $\mu_{A,F} \in I(A, K)$ since $\mu_{A,F}(A) = 0$ and $\mu_{A,F} \in F[x] \subset K[x]$. This shows that $\mu_{A,K}|\mu_{A,F}$. Suppose that $\deg(\mu_{A,K}) = r$, then

$$S = \{I, A, \ldots, A^r\}$$

is linearly dependent over K. Thus Lemma 4 shows that S is also linearly dependent over F. This shows that A satisfies a polynomial $f \in F[x]$ with $\deg(f) = r$. This shows $\deg(\mu_{A,F}) \leq r = \deg(\mu_{A,K})$. This condition plus $\mu_{A,K}|\mu_{A,F}$ imply that $\mu_{A,K} = \mu_{A,F}$. □

Second proof of Exercise 12. Actually, the complex field $\mathbb{C}$ can be replaced by any field K such that $F \subset K$. In the following argument, we just replace $\mathbb{C}$ by K. We first show that the rational form for A is the same whether A is viewed as a matrix over F or over K. We consider the cyclic decomposition of $T : F^n \to F^n$, where $Tx = Ax$. We have

$$F^n = Z(\alpha_1; T; F) \oplus \cdots \oplus Z(\alpha_r; T; F),$$

with invariant factors $p_1, p_2, \ldots, p_r \in F[x]$, $p_i|p_{i-1}$, where $Z(\alpha_i; T; F) = \{f(T)\alpha_i : f \in F[x]\}$. Thus the canonical rational form of A (as a matrix in $M_{n\times n}(F)$) is

$$R = \begin{bmatrix} A_1 & & \\ & \ddots & \\ & & A_r \end{bmatrix},$$

where A_i is the companion matrix of p_i.

Let $T_i : Z(\alpha_i; T; F) \to Z(\alpha_i; T; F)$ be the restriction of T to $Z(\alpha_i; A; F)$. By Theorem 1 of page 228, p_i is the minimal polynomial of T_i, namely, $p_i = \mu_{T_i,F}$. Here we add an F in the subscript to emphasize that everything is viewed as an F-vector space. By Lemma 6, we also have $p_i = \mu_{T_i,K}$, namely p_i is the minimal polynomial of $T_i : Z(\alpha_i; T; K) \to Z(\alpha_i; T; K)$, when T_i is viewed as a linear operators of K-vector space. In particular, this shows that

$$\dim_K Z(\alpha_i; T; K) = \deg p_i = \dim_F Z(\alpha_i; T; F).$$

Assume that $\deg(p_i) = d_i$. Consider the basis $\mathcal{B}_i = \left\{\alpha_i, T\alpha_i, \ldots, T^{d_i-1}\alpha_i\right\}$ of $Z(\alpha_i; T; F)$. Note that $\mathcal{B}_i \subset Z(\alpha_i; T; K)$, and by Lemma 4, $\mathcal{B}_i$ is linearly independent over K. Since $\dim_K Z(\alpha_i; T; K) = d_i$, $\mathcal{B}_i$ is also a K-basis of $Z(\alpha_i; T; K)$. Now consider $\mathcal{B} = \{\mathcal{B}_1, \ldots, \mathcal{B}_r\}$, which is an F-basis of F^n by Lemma page 209. Since the set $\mathcal{B}$ is linearly independent over F, it's linearly independent over K by Lemma 4 again. Since $|\mathcal{B}| = n, \mathcal{B} \subset F^n \subset K^n$ and $\mathcal{B}$ is K-linearly independent, we get that

$$K^n = Z(\alpha_1; T; K) \oplus \cdots \oplus Z(\alpha_r; T; K)$$

by Lemma page 209. Thus the above is indeed the cyclic decomposition of K^n by the uniqueness part of Theorem 3, page 233, and the invariant factors are still $p_1, \ldots, p_r$. Thus the rational form of A (when viewed as a matrix in $\mathrm{Mat}_{n\times n}(K)$) is still R.

Now suppose that $A, B \in \mathrm{Mat}_{n\times n}(F)$ such that A and B are similar over K. This means that the rational form of A over K is the same as the rational form of B over K. By the above discussion, the rational forms of A, B over F are also the same. Thus A and B are similar over F. □

The above proof is very complicate. Using Corollary of page 260, the proof can be greatly simplified. To do this, we prove the following

Lemma 7. *If $f, g \in F[x] \subset K[x]$. Write $gcd_F(f,g)$ (resp. $gcd_K(f,g)$) the gcd of f, g when they are viewed as elements of $F[x]$ (resp. of $K[x]$). Then*

$$gcd_F(f,g) = gcd_K(f,g).$$

This was a previous HW problem.

Proof. Suppose that $d_F = gcd_F(f,g)$ and $d_K = gcd_K(f,g)$. Recall that this means $d_F F[x] = fF[x] + gF[x]$ and $d_K K[x] = fK[x] + gK[x]$. Since there exists $f_1, g_1 \in F[x]$ with $d_F = ff_1 + gg_1$, and $ff_1 + gg_1 \in fK[x] + gK[x] = d_K K[x]$, we get $d_K | d_F$.

On the other hand, $d_F | f$ and $d_F | g$ in $F[x]$. Thus there exists $f', g' \in F[x]$ such that $f = d_F f', g = d_F g'$. By definition of d_K, there exists $f_2, g_2 \in K[x]$ such that $d_K = ff_2 + gg_2 = d_F(f'f_2 + g'g_2)$. Thus $d_F | d_K$. We are done. □

Proof of Exercise 12 using Theorems in Section 7.4. Let $M = xI - A \in \mathrm{Mat}_{n\times n}(F[x]) \subset \mathrm{Mat}_{n\times n}(K[x])$ and let $\delta_k(M; F)$ (resp. $\delta_k(M; K)$) be the greatest common divisors of determinants of all $k \times k$ submatrices of M when viewed as a matrix over F (resp. over K). Let $p_1(F), \ldots, p_r(F)$ be the invariant factors of A when viewed as a matrix over F. Similarly, we define $p_i(K)$. Section 7.4 told us that $p_i(F)$ can be computed using $\delta_k(M; F)/\delta_{k-1}(M; F)$ $1 \le k \le n$. Since gcd are independent of field extension by last lemma, we get $p_i(F) = p_i(K)$. This shows that the rational form of A is independent of the field we consider. □

Comment: If you learn a little bit more algebra, you will find that the above proof can be simplified further. In fact, for $p \in F[x]$ we have

$$(F[x]/pF[x]) \otimes_F K = K[x]/pK[x]. \tag{0.1}$$

The cyclic decomposition of F^n is

$$\begin{aligned} F^n &= Z(\alpha_1; T; F) \oplus \cdots \oplus Z(\alpha_r; T; F) \\ &= F[x]/p_1F[x] \times \cdots \times F[x]/p_rF[x]. \end{aligned}$$

After taking tensor product with $\otimes_F K$, we get

$$K^n = K[x]/p_1K[x] \times \cdots \times K[x]/p_rK[x].$$

This shows that the invariant factors of a matrix is independent of field extension. The essential part of the above proof is just equation (0.1).

Exercise 13: Let $A \in \mathrm{Mat}_{n\times n}(\mathbb{C})$ be a matrix such that every eigenvalue of A is real. Show that A is similar to a matrix with real entries.

Proof. Let $p_i, 1 \le i \le r$, be the invariant factors of A. Note that each p_i is a factor of f_A. By assumption, $f_A = \prod (x - c_i)^{e_i}$ with each $c_i \in \mathbb{R}$. Thus each factor of f_A has the form $\prod (x - c_i)^{s_i}$ with $0 \le s_i \le e_i$, which is in $\mathbb{R}[x]$. Thus $p_i \in \mathbb{R}[x]$ and its companion matrix has entries in $\mathbb{R}$. Thus the rational form of A has entries in $\mathbb{R}$. □

Remark 8. Let us compare the terminologies used in Ex 12 and Ex 13. For $A, B \in \mathrm{Mat}_{n\times n}(F)$, then "$A$ and B are similar ***over*** F" means that there exists a matrix $P \in \mathrm{GL}_n(F)$ such that $PAP^{-1} = B$. See Ex 12. For $A \in \mathrm{Mat}_{n\times n}(\mathbb{C})$, then "$A$ is similar to a matrix with real entries" means that there exists a matrix $B \in M_{n\times n}(\mathbb{R})$ and there exists a matrix $P \in \mathrm{GL}_n(\mathbb{C})$ such that $A = PBP^{-1}$. In Ex 13, we can say that A is similar to a matrix $B \in \mathrm{Mat}_{n\times n}(\mathbb{R})$ over $\mathbb{C}$, not over $\mathbb{R}$.

Exercise 14: Let $T : V \to V$ with $\dim V < \infty$. Show that there is a vector $\alpha \in V$ with the property: if $f(T)\alpha = 0$ for $f \in F[x]$, then $f(T) = 0$. Such a vector is called a separating vector for the algebra $F[x]$. When T has a cyclic vector, give a direct proof that any cyclic vector is a separating vector.

Proof. We first assume that T has a cyclic vector, which means $V = Z(\alpha; T)$ for a cyclic vector α. We will show that the cyclic vector α is a separating vector. If $f(T)\alpha = 0$, then $f(T)h(T)\alpha = 0$ for any $h \in F[x]$ (because $f(T)$ commutes with $h(T)$). Since V is spanned by $h(T)\alpha$, we get that $f(T)v = 0$ for any $v \in V$. This shows that $f(T) = 0$ and thus α is a separating vector.

In general, consider the cyclic decomposition

$$V = Z(\alpha_1; T) \oplus \cdots \oplus Z(\alpha_r; T),$$

with invariant factors $p_1, \ldots, p_r$, and $p_i | p_{i-1}$. Note that p_1 is the annihilator of α_1 and is also the minimal polynomial of T. We claim that α_1 is a separating vector. In fact, if $f \in F[x]$ and $f(T)\alpha_1 = 0$, we have $f \in S_T(\alpha_1; 0) = p_1 F[x]$. Thus $f = p_1 g$ for some $g \in F[x]$. We have $f(T) = p_1(T)g(T) = 0$ since $p_1(T) = 0$. (One can also show that $f(T)\alpha_i = 0$ for all $i \geq 1$ directly using $p_i | p_1$ and thus $p_i | f$. This also implies that $f(T)v = 0$ for any $v \in V$.) □

Exercise 15: This is the above Lemma 6.

Exercise 16: Let A be an $n \times n$ matrix with real entries such that $A^2 + I = 0$. Prove that n is even, and if $n = 2k$, then A is similar over the field of real numbers to a matrix of the block form

$$\begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix},$$

where I is the $k \times k$ identity matrix.

Proof. Let $V = \mathbb{R}^n$ and $T : V \to V$ be the linear operator defined by $Tx = Ax$. Here an element in V is viewed as a column vector. Since $A^2 + I = 0$, we get $T^2 + I = 0$. Thus $f = x^2 + 1 \in I(T)$ and thus the minimal polynomial μ_T divides f. Since f is irreducible and $\mu_T \neq 1$, we get $\mu_T = f = x^2 + 1$. Let

$$V = Z(\alpha_1; T) \oplus Z(\alpha_2; T) \cdots \oplus Z(\alpha_k; T)$$

be the cyclic decomposition of V with $\alpha_1, \ldots, \alpha_k \in V$. Let p_i be the T-annihilators of α_i, namely, $p_1, \ldots, p_k$ are the invariant factors of T. We have $p_1 = \mu_T = x^2 + 1$ and $p_i | p_{i-1}$ for $i \geq 2$. Since p_1 is irreducible, we have $p_i = x^2 + 1$ for each i. Since $\dim Z(\alpha_i; T) = \deg(p_i) = 2$, we get $\dim V = 2k$ is even. Let $\beta_i = T\alpha_i$. Then $\{\alpha_i, \beta_i\}$ is a basis of $Z(\alpha_i; T)$. Let $\mathcal{B} = \{\alpha_1, \ldots, \alpha_k, \beta_1, \ldots, \beta_k\}$, which is an ordered basis of V. Note that $T\alpha_i = \beta_i, T\beta_i = T^2\alpha_i = -\alpha_i$. We get

$$[T]_{\mathcal{B}} = \begin{bmatrix} 0 & -I \\ I & 0 \end{bmatrix}.$$

□

Exercise 17: Let T be a linear operator on a finite-dimensional vector space V. Suppose that

(a) the minimal polynomial for T is a power of an irreducible polynomial;
(b) the minimal polynomial is equal to the characteristic polynomial.

Show that no non-trivial T-invariant subspace has a complementary T-invariant subspace.

Proof. We prove this by contradiction. Suppose that W_1 is a T-invariant nontrivial subspace ($W_1 \neq 0, W_1 \neq V$) and W_1 has a complementary T-invariant subspace W_2. Let $\mathcal{B}_i$ be an ordered basis of W_i. Then $\mathcal{B} = \mathcal{B}_1 \cup \mathcal{B}_2$ is an ordered basis of V. Assume $A_i = [T]_{\mathcal{B}_i}$, we get

$$[T]_{\mathcal{B}} = \begin{bmatrix} A_1 & 0 \\ 0 & A_2 \end{bmatrix}.$$

This shows that $\chi_T = \chi_{T_1}\chi_{T_2}$, where $T_i = T|_{W_i}$ and χ_T denotes the characteristic polynomial of T. The assumption says that $\chi_T = p^r$ for an irreducible polynomial of p and a positive integer r. Thus $\chi_{T_i} = p^{r_i}$ with $r_i > 0, r_1 + r_2 = r$. Let μ_{T_i} be the minimal polynomial of T_i. Then $\mu_{T_i} | \chi_{T_i}$. Thus

$\mu_{T_i} = p^{s_i}$ for some integer s_i with $1 \le s_i \le r_i$. Let $s = \max\{s_1, s_2\}$ and $g = p^s \in F[x]$. By the choice of s, we have $g(A_1) = g(A_2) = 0$. Note that for any polynomial $h \in F[x]$, we have

$$h([T]_{\mathcal{B}}) = \begin{bmatrix} h(A_1) & \\ & h(A_2) \end{bmatrix}.$$

(Check this for monomials x^n first, which follows from a simple block matrix calculation.) In particular, since $g(A_1) = g(A_2) = 0$, we have $g([T]_{\mathcal{B}}) = 0$. This shows that the minimal polynomial of T divides $g = p^s$ (actually it is clear that the minimal polynomial is exactly $g = p^s$). Now since $s < s_1 + s_2 \le r_1 + r_2$, we have $g \ne \chi_T = p^r$. This contradicts assumption (b). $\square$

Exercise 18: If T is a diagonalizable linear operator, then every T-invariant subspace has a complementary T-invariant subspace.

Proof. Let $W \subset V$ be a T-invariant subspace. We first show that $T|_W$ is diagonalizable. In fact $\mu_{T|_W}$ divides μ_T, which is a product of distinct linear factors. This shows that $T|_W$ is diagonalizable.

Let $c_1, \dots, c_k$ be distinct eigenvalues of T and let $E_T(c_i) = \ker(T - c_i I)$. The condition T is diagonalizable means that

$$V = E_T(c_1) \oplus \cdots \oplus E_T(c_k).$$

Let $\mathcal{B}'_1 = \{\alpha_1, \dots, \alpha_s\}$ be a basis of W which consists of eigenvectors of T. We can assume this because $T|_W$ is diagonalizable. Since all distinct eigenvalues of T are $c_1, \dots, c_k$, we have $T\alpha_j = c_{i_j}\alpha_j$ for some index i_j with $1 \le i_j \le k$. After re-arrangement if necessary, we can assume that $\alpha_1, \dots, \alpha_{s_1} \in E_T(c_1), \alpha_{s_1+1}, \dots, \alpha_{s_2} \in E_T(c_2), \dots, \alpha_{s_{k-1}+1}, \dots, \alpha_{s_k} \in E_T(c_k)$. Here $s_k = s$. Assume that $\dim E_T(c_i) = r_i$, then $r_i \ge s_i$. Since α_i are linearly independent, we can extend $\alpha_{s_{i-1}+1}, \dots, \alpha_{s_i}$ to a basis

$$\alpha_{s_{i-1}+1}, \dots, \alpha_{s_i}, \beta_{s_i+1}, \dots, \beta_{r_i}$$

of $E_T(c_i)$. Let $W' = \mathit{Span}\{\beta_{s_i+1}, \dots, \beta_{r_i} : 1 \le i \le k\}$. Then clearly $V = W \oplus W'$ and W' is T-invariant. (Here W' is T-invariant because it has a basis which consists of eigenvectors of T). $\square$

A different proof. This exercise is a special case of Theorem 11 (page 264) of the textbook. The following is a proof based on the proof of Theorem 11.

Since T is diagonalizable, the minimal polynomial $\mu_T = (x-c_1)\dots(x-c_k)$ for distinct $c_1, \dots, c_k$. Assume that $\chi_T = (x-c_1)^{r_1}\dots(x-c_k)^{r_k}$ is the characteristic polynomial of T. Let $V = W_1 \oplus \cdots \oplus W_k$ be the primary decomposition of V, namely, $W_i = \ker(T - c_i I)^{r_i}$. Let W be a T-invariant subspace of V. We first claim that

$$W = (W \cap W_1) \oplus \cdots \oplus (W \cap W_k).$$

In fact, for any $\alpha \in W$, we can write $\alpha = \alpha_1 + \cdots + \alpha_k$ with each $\alpha_i \in W_i$. Let $E_i : V \to W_i$ be the projection map, which is known to have the form $h_i(T)$ for a polynomial h_i, see Corollary in page 221. We have $\alpha_i = E_i\alpha = h_i(T)\alpha \in W$ since W is T-invariant. This shows the above decomposition.

Next, we show that each $W \cap W_i$ has a T-invariant complement in W_i. For this, it suffices to show that $W \cap W_i$ is T-admissible subspace of W_i, namely, if $f \in F[x], \alpha \in W_i$ with $f(T)\alpha \in W \cap W_i$, then there exists $\beta \in W \cap W_i$ such that $f(T)\alpha = f(T)\beta$. Note that, for $\alpha \in W_i$, we have $T\alpha = c_i\alpha$ and thus $f(T)\alpha = f(c_i)\alpha$. Suppose for some $\alpha \in W_i$ and $f \in F[x]$, we have $f(T)\alpha = f(c_i)\alpha \in W_i \cap W$. If $f(c_i) = 0$, we just take $\beta = 0$, which satisfies $f(T)\alpha = f(T)\beta = 0$. If $f(c_i) \ne 0$, the above condition means that $\alpha \in W \cap W_i$, and we just take $\beta = \alpha$, which satisfies $f(T)\alpha = f(T)\beta$.

Thus for each i, there is a T-invariant subspace $W'_i \subset W_i$ such that

$$W_i = (W \cap W_i) \oplus W'_i.$$

Take $W' = W'_1 \oplus \cdots \oplus W'_k$, which is still T-invariant. The above shows that

$$V = W_1 \oplus \cdots \oplus W_k = \bigoplus_i (W \cap W_i) \oplus W'_i = W \oplus W'.$$

This finishes the proof. $\square$

Remark 9. If T is diagonalizable, we actually have $W_i = \operatorname{Ker}(T - c_iI)^{r_i} = \operatorname{Ker}(T - c_iI)$. Thus the decompositions used in the above two different proofs are the same. Moreover, the first solution gives a direct proof that $W \cap W_i$ has a complement in W_i. Essentially, the above two proofs are the same. Apparently, the second approach works for more general case.

Exercise 19: Let T be a linear operator on the finite dimensional space V. Prove that T has a cyclic vector if and only if the following is true: Every linear operator U which commutes with T is a polynomial in T.

Proof. We assume that T has a cyclic vector α. Let $U : V \to V$ be a linear operator such that $TU = UT$. Note that, we have $UT^2 = UTT = TUT = T^2U$. Similarly, it is easy to check that $UT^i = T^iU$ for any $i \geq 0$. Since α is a cyclic vector, $V = \mathit{Span}\left\{\alpha, T\alpha, \ldots, T^{n-1}\alpha\right\}$, where $n = \dim V$. Since $U(\alpha) \in V$, we can write

$$U(\alpha) = a_0\alpha + \cdots + a_{n-1}T^{n-1}\alpha,$$

for some $a_0, a_1, \ldots, a_{n-1} \in F$. (Here there is no requirement for a_i. If U is the zero operator, then all a_i are zero. If U is nonzero, there is at least one a_i is nonzero.)

Let $g = a_0 + a_1x + \cdots + a_{n-1}x^{n-1} \in F[x]$. By choice, we have

$$U\alpha = g(T)\alpha.$$

We claim that $U = g(T)$, namely, $U\beta = g(T)\beta$ for all $\beta \in V$. Actually this follows easily from the above equation and the fact that $V = Z(\alpha; T)$. Here are some details. Since $V = \mathit{Span}\left\{\alpha, T\alpha, \ldots, T^{n-1}\alpha\right\}$, it suffices to show that

$$U(T^i\alpha) = g(T)(T^i\alpha), i = 0, 1, \ldots, n-1.$$

For $i = 0$, this follows from the definition of g. If $i = 1$, we have

$$U(T\alpha) = TU(\alpha) = T(g(T)\alpha) = g(T)(T\alpha).$$

Similarly, for any $i > 0$, we have

$$U(T^i\alpha) = T^i(U\alpha) = T^i(g(T)\alpha) = g(T)(T^i\alpha).$$

This shows that $U = g(T)$.

Conversely, suppose that T does not have a cyclic vector, we will construct a linear operator $U : V \to V$, which is not a polynomial of T. Consider the cyclic decomposition of V:

$$V = Z(\alpha_1; T) \oplus Z(\alpha_2; T) \oplus \cdots \oplus Z(\alpha_r; T),$$

as in the cyclic decomposition theorem. The condition "T does not have a cyclic vector" implies that $r \geq 2$. Let p_i be the annihilator of α_i, we have $p_2 | p_1$.

Let $U = E_2$, the projection operator of V onto $Z(\alpha_2; T)$. Then $UT = TU$. This can be checked easily or it follows from Theorem 10, p214. We prove that U is not a polynomial of T by contradiction. Suppose that $U = g(T)$ for a polynomial $g \in F[x]$. Note that for any $\alpha \in Z(\alpha_1; T)$, we have $g(T)\alpha = U\alpha = 0$. Thus $p_1 | g$ because p_1 is the annihilator of α_1. On the other hand, $p_2 | p_1$ and thus $p_2 | g$. This means that g is a multiple of the annihilator of α_2. Thus $g(T)\alpha_2 = 0$. This contradicts to $U\alpha_2 = \alpha_2$. We are done. $\square$

Exercise 20: Let V be a finite dimensional vector space over the field F and $T : V \to V$ be a linear operator. We ask when it is true that every non-zero vector in V is a cyclic vector for T. Prove that this is the case if and only if the characteristic polynomial for T is irreducible over F.

Proof. Assume that the characteristic polynomial χ_T of T is irreducible in $F[x]$. In particular, $\mu_T = \chi_T$. Given any $\alpha \in V, \alpha \neq 0$, we need to show that $Z(\alpha; T) = V$. Let p_α be the T-annihilator of α, we have $p_\alpha | \mu_T$. But μ_T is irreducible, and thus we have $p_\alpha = \mu_T$. Thus $\dim_F Z(\alpha; T) = \deg(p_\alpha) = \deg(\chi_T) = \dim V$. We have $Z(\alpha; T) = V$.

Conversely, suppose that every nonzero vector in V is a cyclic vector. Take $\alpha \neq 0$, we have $V = Z(\alpha; T)$. Suppose that μ_T is reducible, namely, $\mu_T = gh$ with $g, h \in F[x]$, $\deg(g) = k < n, \deg(h) = m < n$, where $n = \dim V$. Consider the vector $\beta = g(T)\alpha \neq 0$. Since $h(T)\beta = \mu_T(T)\alpha = 0$, the T-annihilator p_β of β divides $h(T)$. By Theorem 1 of page 228, we have $\dim Z(\beta; T) = \deg(p_\beta) \leq \deg h = m < n$. Thus $Z(\beta; T) \neq V$ and β is not a cyclic vector of V. $\square$

Exercise 21: Let $A \in \mathrm{Mat}_{n\times n}(\mathbb{R})$. Let $T : \mathbb{R}^n \to \mathbb{R}^n$ be the operator defined by A and $U : \mathbb{C}^n \to \mathbb{C}^n$ be the operator defined by A. If the only subspaces invariant under T are $\mathbb{R}^n$ and the zero subspace, then U is diagonalizable.

Proof. Let $\alpha \in \mathbb{R}^n$ be any nonzero vector and consider $Z(\alpha; T)$. Since $Z(\alpha; T)$ is a nonzero T-invariant subspace of $\mathbb{R}^n$, the assumption says that $Z(\alpha; T) = \mathbb{R}^n$. This shows that every nonzero vector of $\mathbb{R}^n$ is a cyclic vector. Exercise 20 says that $\mu_T = \chi_T$ is irreducible. We know that any irreducible polynomial over $\mathbb{R}$ is either linear or quadratic $ax^2 + bx + c$ with $a, b, c \in \mathbb{R}, b^2 - 4ac < 0$. Either case, $\mu_T = \chi_T$ has no repeated roots over $\mathbb{C}$. Thus U is diagonalizable. Note that $\mu_U = \mu_A = \mu_T$, namely no matter if you see A as a matrix over $\mathbb{R}$ or over $\mathbb{C}$, its minimal polynomial is the same. See Exercise 12. □

Remark 10. Exercise 21 seems too easy because in this case we can only have $n = 1$ or 2. The following general case is true. Let F be a field of characteristic 0 and $A \in \mathrm{Mat}_{n\times n}(F)$. Suppose that $\overline{F}$ is an algebraically closed field such that $F \subset \overline{F}$. (Example: F is $\mathbb{Q}$ or $\left\{a + b\alpha + c\alpha^2 : a, b, c \in \mathbb{Q}\right\}$ with $\alpha^3 = 2, \alpha \in \mathbb{R}$; and $\overline{F} = \mathbb{C}$.) Let $T : F^n \to F^n$ be the linear operator defined by A. If the only subspaces invariant under T are 0 and F^n itself, then A is diagonalizable over $\overline{F}$. In this general case, the dimension of V can be arbitrary. The proof is the same as the above once we know the following fact: if F has characteristic zero and $f \in F[x]$ is irreducible, then f has no repeated roots over $\overline{F}$. See Lemma of page 266 and Theorem 12 for its generalizations. If characteristic of F is finite, the above is false. In fact, if characteristic of F is finite, it is possible to find irreducible polynomial $f \in F[x]$, such that over an algebraic closure of F, $f = (x - c)^p$ for some positive integer p.

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