

## Discretionary Note

Anish Krishna Lakkapragada

**IF YOU USE THIS FILE TO CHEAT, YOU ARE NOT ONLY STUPID BUT YOU ARE CHEATING YOURSELF OUT OF THE ABILITY TO FALL IN LOVE WITH MATH.** Furthermore, I am not smarter than you and my solutions did not always get a perfect score.

**CONTENT STARTS ON NEXT PAGE.**

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## Math 225- HW 11 Due: Dec 9 by Midnight

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Submit the first two problems, along with any three additional problems of your choice.

1. • Prove that if  $U$  and  $T$  simultaneously diagonalizable then  $U$  and  $T$  commute. i.e.  $UT = TU$

If  $U$  and  $T$  are simultaneously diagonalizable, this means that  $[T]_\beta$  and  $[U]_\beta$  are diagonal matrices. The product of two diagonal matrices is obviously commutative (i.e. if matrices  $X$  and  $Y$  are diagonal,  $XY = YX$ ). Thus, if  $U$  and  $T$  are simultaneously diagonalizable then:

$$\begin{aligned}[T]_\beta[U]_\beta &= [U]_\beta[T]_\beta \\ [TU]_\beta &= [UT]_\beta \\ TU &= UT\end{aligned}$$

- Conclude that if matrices  $A, B$  are simultaneously diagonalizable then  $A, B$  commute  
If  $A$  and  $B$  are simultaneously diagonalizable then we know that  $\exists Q$  invertible s.t.  $Q^{-1}AQ$  and  $Q^{-1}BQ$  are diagonal and so, using the logic that the product of two diagonal matrices is commutative, we have:

$$\begin{aligned}Q^{-1}AQQ^{-1}BQ &= Q^{-1}BQQ^{-1}AQ \\ Q^{-1}ABQ &= Q^{-1}BAQ \\ AB &= BA\end{aligned}$$

- Let  $T$  be diagonalizable linear operator on a finite dimensional vector space, then  $T$  and  $T^m$  are simultaneously diagonalizable for any  $m$  positive integer.

Because  $T$  is diagonalizable,  $[T]_\beta$  is a diagonal matrix. Thus,  $[T^m]_\beta = \underbrace{[T]_\beta \dots [T]_\beta}_{m \text{ times}} = \underbrace{[T]_\beta \dots [T]_\beta}_{m \text{ times}} = \prod_{i=1}^m [T]_\beta$ . Because  $[T]_\beta$  is diagonal,  $[T^m]_\beta = \prod_{i=1}^m [T]_\beta$  is also diagonal  $\Rightarrow T$  and  $T^m$  are simultaneously diagonalizable.

2. a) For any vector  $w \in E_\lambda$ ,  $T(w) = \lambda w \in E_\lambda$ . Let us define  $u = \lambda w$ . Because  $T(u) = T(\lambda w) = \lambda T(w) = \lambda^2 w = \lambda u$ ,  $u = \lambda w \in E_\lambda$ . Thus we have shown  $\forall w \in E_\lambda, T(w) \in E_\lambda \Rightarrow E_\lambda$  is a  $T$ -invariant subspace of  $V$ .
- b) Let us define this  $T$ -cyclic subspace generated by  $v$  as  $W \leq V$ .  $W$  can be expressed as  $\text{Span}\{v, T(v), \dots, T^n(v)\}$ . We now show that  $\forall w \in W, T(w) \in W$ . By definition,  $\forall w \in W$  can be expressed as  $w = \sum_{i=0}^n c_i T^i(v)$  and so  $T(w) = c_n T^{n+1}(v) + \sum_{i=1}^n c_i T^i(v)$ . Because  $T^{n+1}(v)$  can be expressed as a linear combination of  $\{v, T(v), \dots, T^n(v)\}$ , this means that  $T(w)$  can be expressed as a linear combination of  $\{v, T(v), \dots, T^n(v)\} \Rightarrow T(w) \in \text{Span}\{v, T(v), \dots, T^n(v)\} \Rightarrow T(w) \in W$ . Thus, we have shown  $\forall w \in W, T(w) \in W \Rightarrow W$  is a  $T$ -invariant subspace of  $V$ .
- c) The  $T$ -cyclic subspace  $W$  can be given by  $W = \text{Span}\{v, T(v), \dots, T^n(v)\}$ . We now prove both directions of this statement:

1. If  $w \in W$ ,  $w = g(T)v$

If  $w \in W$ ,  $w$  can be expressed as  $\sum_{i=0}^n c_i T^i(v) = U(v)$ , where  $U = \sum_{i=0}^n c_i T^i$  is an operator. Defining  $g(x) = \sum_{i=0}^n c_i x^i$ ,  $U = g(T)$  and so we have that  $w = g(T)v$ .

2. If  $w = g(T)v$ ,  $w \in W$

We can express polynomial  $g$  as  $g(x) = \sum_{i=0}^n c_i x^i$ . Thus, we have that  $w = g(T)v = \sum_{i=0}^n c_i T^i(v) \Rightarrow w \in \text{Span}\{v, T(v), \dots, T^n(v)\} \Rightarrow w \in W$ .

d) Because  $V$  is a  $T$ -cyclic subspace of itself, we can express  $V = \text{Span}(\{v, T(v), T^2(v), \dots, T^n(v)\})$ . Thus, this means  $\forall z \in V$ ,  $z = \sum_{i=0}^n c_i T^i(v) \Rightarrow$  because  $U(v) \in V$ ,  $U(v)$  can be expressed as a linear combination of  $T^i(v)$ . Note that if  $U$  commutes with  $T$ , that means  $UT^2 = UTT = TUT = TTU = T^2U$ , or more generally  $UT^\alpha = T^\alpha U$  for  $\alpha \geq 0$ . Thus, we have that for  $i \geq 0$ :

$$\begin{aligned} UT^i &= T^i U \\ UT^i(v) &= T^i U(v) \\ U(T^i(v)) &= T^i(\sum_{k=0}^n c_k T^k(v)) \\ U(T^i(v)) &= \sum_{k=0}^n c_k T^{i+k}(v) \end{aligned}$$

Setting  $a = T^i(v)$ , we have:

$$U(a) = \sum_{k=0}^n c_k T^k(a)$$

Thus, we can clearly see that  $U = g(T)$ , where polynomial  $g$  is given by  $g(x) = \sum_{k=0}^n c_k x^k$ .

e) There are two cases in this scenario: (1) all vectors in  $V$  are eigenvectors or (2) not all vectors in  $V$  are eigenvectors. We address both cases below:

1. All vectors in  $V$  are eigenvectors

This means that  $\forall v \in V, T(v) = \lambda v$  where  $\lambda \in \mathbb{F}$ . Let us define two vectors  $a, b \in V$  and compute  $T(a+b)$ :

$$T(a+b) = \lambda_{a+b}(a+b)$$

However, by linearity, we also have that  $T(a+b) = T(a) + T(b) = \lambda_a a + \lambda_b b$ . Thus, we have that:

$$\begin{aligned} T(a+b) &= T(a+b) \\ \lambda_{a+b}(a+b) &= \lambda_a a + \lambda_b b \end{aligned}$$

This means that  $\lambda_{a+b} = \lambda_a = \lambda_b \Rightarrow \forall v \in V, T(v) = \lambda_a v \Rightarrow T = cI$  where  $c \in \mathbb{F}$ .

2. Not all vectors in  $V$  are eigenvectors

This means that  $\exists v \neq 0 \in V$  s.t.  $T(v) \neq \lambda v$ ,  $\forall \lambda \in \mathbb{F}$ . Consider the set  $\{v, T(v)\}$ . In order for the set of vectors  $\{a, b\}$  to be linearly independent, neither  $a$  nor  $b$  can be expressed as a scalar multiple of the either vector. Because we know that  $\forall \lambda \in \mathbb{F}$ ,  $T(v) \neq \lambda v$ ,  $\{v, T(v)\}$  are a linearly independent set of two vectors  $\Rightarrow$  because  $\dim(V) = 2$ ,  $\{v, T(v)\}$  serve as a basis for  $V \Rightarrow V = \text{Span}(\{v, T(v)\}) \Rightarrow V$  is a  $T$ -cyclic subspace of itself.

3. I didn't do this question.

4. (a) We use induction to prove this statement.

1. Base Case: Single element  $v_1$

If  $n = 1$ , then given  $\sum_{i=1}^n v_i \in W \Rightarrow v_1 \in W$ .

2. Inductive Step: Given  $v_1, \dots, v_{k-1} \in W$ , prove that  $v_k \in W$   
 For proof by contrapositive, let us assume that  $v_k \notin W$ . Let us define  $v = v_1 + \dots + v_n$ . We start with our given:

$$\begin{aligned} v &= v_1 + \dots + v_n \in W \\ v &= (v_1 + \dots + v_{k-1}) + v_k + (v_k + \dots + v_n) \\ v_1 + \dots + v_{k-1} &= v - v_k - (v_k + \dots + v_n) \end{aligned}$$

Because  $W$  is a subspace, it is closed under addition. Thus, because  $v_k \notin W \Rightarrow v - v_k - (v_k + \dots + v_n) \notin W \Rightarrow v_1 + \dots + v_{k-1} \notin W$ . By proof by contrapositive, we have proven if  $v_1, \dots, v_{k-1}$ , then  $\in W, v_k \in W$ .

- (b) Let us define  $U$  as a non-trivial  $T$ -invariant subspace of  $V$ . If  $T$  is a diagonalizable linear operator, that means its eigenvectors  $v_1, v_2, \dots, v_n$  form a basis for  $V$ . Because  $U$  is a non-trivial subspace,  $\exists v \neq 0 \in U$ . Furthermore, given that  $\forall v \neq 0 \in U \leq V$ ,  $v$  can be written as a linear combination of  $\{v_1, \dots, v_n\}$ , we can define the nonempty set of eigenvectors which all elements of  $U$  are a linear combination of as  $\{u_1, \dots, u_k\} \Rightarrow \text{Span}(\{u_1, \dots, u_k\}) = U$ . Note that  $\{u_1, \dots, u_k\}$  are all part of the basis  $\{v_1, \dots, v_n\}$  for  $V$  and so they are all linearly independent. Thus, we can conclude the linearly independent and generating set of eigenvectors  $\{u_1, \dots, u_k\}$  forms a basis for  $U$  and so  $T|_U$  is diagonalizable.
- (c) Because  $v_1, v_2, \dots, v_n \in V$  all correspond to distinct eigenvalues, they are all linearly independent. Given these  $n$  linearly independent vectors and that  $\dim(V) = n$ , we can conclude that the eigenvectors  $v_1, v_2, \dots, v_n$  form a basis for  $V$ . This means that  $V = \text{Span}(\{v_1, v_2, \dots, v_n\})$ . Let us define vector  $v = v_1 + v_2 + \dots + v_n$ . Note that  $\text{Span}(\{v, T(v), \dots, T^n(v)\}) = \text{Span}(\{\sum_{i=1}^n v_i, \sum_{i=1}^n \lambda_i v_i, \dots, \sum_{i=1}^n \lambda_i^n v_i\})$ . We can write out this transformation from the eigenvectors  $v_1, \dots, v_n$  to  $\sum_{i=1}^n v_i, \sum_{i=1}^n \lambda_i v_i, \dots, \sum_{i=1}^n \lambda_i^n v_i$  as such:

$$\begin{bmatrix} 1 & 1 & \dots & 1 \\ \lambda_1 & \lambda_2 & \dots & \lambda_n \\ \vdots & \ddots & \ddots & \vdots \\ \lambda_1^n & \lambda_2^n & \dots & \lambda_n^n \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^n v_i \\ \sum_{i=1}^n \lambda_i v_i \\ \vdots \\ \sum_{i=1}^n \lambda_i^n v_i \end{bmatrix}$$

Note that the leftmost matrix above, which I refer to as  $V$ , is the Vandermonde matrix (pg 230.) Because all  $\forall 0 \leq i < j \leq n, \lambda_i \neq \lambda_j$ ,  $\det(V) = \prod_{0 \leq i < j \leq n} (\lambda_j - \lambda_i) \neq 0 \Rightarrow V$  is invertible  $\Rightarrow$  because  $\{v_1, v_2, \dots, v_n\}$  serve as a basis for  $V$ , so does  $\{\sum_{i=1}^n v_i, \sum_{i=1}^n \lambda_i v_i, \dots, \sum_{i=1}^n \lambda_i^n v_i\} \Rightarrow V = \text{Span}(\{v, T(v), \dots, T^n(v)\}) \Rightarrow V$  is a  $T$ -cyclic subspace of itself.

5. (a) We prove both directions of this statement below:

1. If  $T$  is diagonalizable,  $V$  is the direct sum of one-dimensional  $T$ -invariant subspaces

If  $T$  is diagonalizable, that means that eigenvectors  $v_1, v_2, \dots, v_n \in V$  serve as a basis for  $V$ . This means  $V = \text{Span}(\{v_1, \dots, v_n\}) = \{\sum_{i=1}^n c_i v_i : c_i \in \mathbb{R}\} = \{\sum_{i=1}^n T(\frac{c_i}{\lambda_i} v_i)\}$ . Let us define the set  $W_j = \{cv_j : c \in \mathbb{F}\}$  for a given eigenvector  $v_j$ . Note that  $W_j$  is a one-dimensional subspace as  $W_j$  is composed of scalar multiples of one unique vector,  $v_j$ . Furthermore,  $W_j$  is a  $T$ -invariant subspace

as  $\forall w \in W_j, T(w)$  is equal to a scalar multiple of  $v_j \Rightarrow w \in W_j$ . Furthermore, because  $\{v_1, \dots, v_n\}$ , serve as a basis, that means that all the eigenvectors are linearly independent  $\Rightarrow$  for  $0 \leq i < j \leq n$ ,  $W_i \cap W_j = \emptyset$  and so we have that  $V = \{\sum_{i=1}^n c_i v_i : c_i \in \mathbb{R}\} = W_1 \oplus W_2 \cdots \oplus W_n$ .

2. If  $V$  is the direct sum of one-dimensional  $T$ -invariant subspaces,  $T$  is diagonalizable

Let us define  $V = W_1 \oplus W_2 \cdots \oplus W_k$  and the one basis vector for the  $j$ th subspace  $W_j$  as  $v_j$ . Because  $W_j$  is one-dimensional and a subspace (thus closed under addition and scalar multiplication),  $W_j = \{cv_j : c \in \mathbb{F}\}$ . Furthermore, because  $W_j$  is  $T$ -invariant and  $v_j \in W$ ,  $T(v_j) \in W_j \Rightarrow T(v_j) \in \{cv_j : c \in \mathbb{F}\} \Rightarrow v_j$  is an eigenvector of  $T_{W_j}$  as  $T(v_j) = kv_j$  where  $k \in \mathbb{F}$ . Because  $V$  is a *direct* sum of  $W_1, \dots, W_k$ , the individual basis vector  $v_j$  for each subspace is linearly independent from all of the vectors in  $\{v_1, \dots, v_{j-1}\} \cup \{v_{j+1}, \dots, v_k\} \Rightarrow \{v_1, \dots, v_k\}$  are linearly independent<sup>1</sup>. Furthermore,  $V = W_1 \oplus W_2 \cdots \oplus W_k$  means that  $V$  contains all possible linear combinations of  $\{v_1, \dots, v_k\} \Rightarrow V = \text{Span}(\{v_1, \dots, v_k\})$ . Thus we can conclude that the linearly independent and generating eigenvectors  $\{v_1, \dots, v_k\}$  forms a basis for  $V$  and so  $T$  is diagonalizable.

- b) Let us define the unordered basis for the  $T$ -invariant subspace  $W_j$  as  $\beta_j$ . This means that the ordered basis  $\gamma$  for vector space  $V$  can be given as  $\gamma = \beta_1 \cup \beta_2 \cdots \cup \beta_k$ . We now try to understand what the matrix  $[T]_\beta$  looks like. Note that  $\forall v \in \beta_j, v \in W_j$  and so  $T(v) = T_{W_j}(v) \in W_j \Rightarrow T(v)$  can be expressed as a linear combination of  $\beta_j$ . Thus,  $[T]_\beta$  will be given as a collection of block matrices  $[T_{W_j}]_{\beta_j}$  along the diagonal:

$$[T]_\beta = \begin{bmatrix} [T_{W_1}]_{\beta_1} & 0 & \cdots & 0 \\ 0 & [T_{W_2}]_{\beta_2} & \cdots & 0 \\ 0 & \ddots & \ddots & 0 \\ 0 & 0 & 0 & [T_{W_k}]_{\beta_k} \end{bmatrix}$$

From this matrix, it is obvious that:

$$\begin{aligned} \det(T) &= \det([T]_\beta) = \prod_{i=1}^k \det([T_{W_i}]_{\beta_i}) = \prod_{i=1}^k \det(T_{W_i}) \\ \det(T) &= \prod_{i=1}^k \det(T_{W_i}) \end{aligned}$$

6. To prove this law, we compare the LHS with the RHS. The LHS can be given as:

$$\begin{aligned} \|x + y\|^2 + \|x - y\|^2 &= \langle x + y, x + y \rangle + \langle x - y, x - y \rangle = \langle x, x + y \rangle + \langle y, x + y \rangle + \langle x, x - y \rangle - \langle y, x - y \rangle \\ &= \langle x, x \rangle + \langle x, y \rangle + \langle y, x \rangle + \langle y, y \rangle + \langle x, x \rangle - \langle x, y \rangle - \langle y, x \rangle + \langle y, y \rangle = 2\langle x, x \rangle + 2\langle y, y \rangle \end{aligned}$$

We now compare this with the RHS:

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<sup>1</sup>This can be trivially proven by induction by the following proof:  $\{v_1\}$  is a linearly independent set,  $\{v_1, v_2\}$  is a linearly independent set,  $\{v_1, v_2, v_3\}$  is a linearly independent set, and so on until  $\{v_1, \dots, v_n\}$  is a linearly independent set. I believe we did this proof in class.

$$2\|x\|^2 + 2\|y\|^2 = 2\langle x, x \rangle + 2\langle y, y \rangle$$

Thus, we can clearly see that the LHS = RHS and so we have proven this law.