Orthogonality and Inner Product Spaces

Question 1:

Let $F = \mathbb{R}$ or $\mathbb{C}$ and V be an inner product space over F.
Show that the function $\alpha : V \to V^\vee$ defined by $\alpha(y) = \langle -, y\rangle$ is injective, and that it is linear when $F = \mathbb{R}$.
Let V then be finite dimensional and $\{v_1, ..., v_n\}$ be an orthonormal basis of V. Let $f \in V^\vee$. Show that $f = \displaystyle\sum_{i=1}^{n} f(v_i)\langle -, v_i\rangle$

Proof:

Let $y, z \in V$ where $\alpha(y) = \alpha(z)$. If $y = z$ then α is injective.
Indeed, since $\langle -, y\rangle = \langle -, z\rangle$ then $\langle -, y - z\rangle = 0$ by additivity in the second component.
Consider $\langle y - z, y - z\rangle = 0$. That must mean $y - z = 0$. Thus $y = z$.

We can see α is linear over $\mathbb{R}$ since:

$$\alpha(y + z) = \langle -, y + z\rangle = \langle -, y\rangle + \langle -, z\rangle = \alpha(y) + \alpha(z)$$

$$\alpha(cy) = \langle -, cy\rangle = c\langle -, y\rangle = c\alpha(y)$$

for any $c \in \mathbb{R}$.

Since f is linear, it can be fully described by where it takes the basis of its domain (for any vector in the domain can be written as a linear combination of basis vectors). So, it suffices to show $f(v_j) = \displaystyle\sum_{i=1}^{n} f(v_i)\langle v_j, v_i\rangle$ for any v_j in the orthonormal basis. Indeed, since $\langle v_j, v_i\rangle = 0$ for $i \neq j$ and $\langle v_j, v_j\rangle = 1$:

$$\sum_{i=1}^{n} f(v_i)\langle v_j, v_i\rangle = f(v_j)$$

Question 2:

Show that the differentiation map is not normal with respect to any inner product.

Proof:

Suppose for sake of contradiction that T is normal.

We know that differentiation is nilpotent. Thus, the characteristic polynomial of T is t^k. In particular, this splits. And thus, by Schur's Theorem, there exist an orthonormal basis β such that $[T]_\beta$ is upper triangular.

This combined with the fact that $[T]_\beta$ is normal implies that it is also diagonal based on Theorem 6.16 in *Linear Algebra* by Spence.

But the only eigenvalues of T is 0 because it is nilpotent. Thus $[T]_\beta = 0$ which means $T = 0$ regardless of basis. And so, $0 = T(x) = 1$, which is a contradiction.

Question 3:

Let T be a normal operator on V Show the following:
(a) $||T(x)|| = ||T^*(x)||$ for all $x \in V$
(b) If x is an eigenvector of T with eigenvalue λ, then x is an eigenvector of T^* with eigenvalue $\bar{\lambda}$.
(c) If λ and λ' are distinct eigenvalues of T, $x \in E_\lambda$ and $x \in E_\lambda$, then $\langle x, x' \rangle = 0$

Proof:

(a) Since T is normal,

$$||T(x)||^2 = \langle T(x), T(x) \rangle = \langle T^*T(x), x \rangle = \langle TT^*(x), x \rangle = \langle T^*(x), T^*(x) \rangle = ||T^*(x)||^2$$

which implies $||T(x)|| = ||T^*(x)||$

(b) First we prove $T - \lambda I$ is normal if T is normal:

$$\begin{aligned}(T - \lambda I)^*(T - \lambda I) &= (T^* - \overline{\lambda} I)(T - \lambda I)\\ &= T^*T - T^*\lambda I - \overline{\lambda} T + |\lambda|^2 I\\ &= TT^* - T\overline{\lambda} I - \lambda T^* + |\lambda|^2 I\\ &= (T - \lambda I)(T^* - \overline{\lambda} I)\\ &= (T - \lambda I)(T - \lambda I)^*\end{aligned}$$

Now, by part (a), if $T(x) = \lambda(x)$ and $x \neq 0$,

$$||T^*(x) - \overline{\lambda} x|| = ||(T^* - \overline{\lambda} I)x|| \overset{(a)}{=} ||(T - \lambda)x|| = ||T(x) - \lambda x|| = 0$$

which implies $T^*(x) = \overline{\lambda} x$.

(c) By part (b), if we let x and x' be non-zero,

$$\lambda \langle x, x' \rangle = \langle T(x), x' \rangle = \langle x, T^*(x') \rangle \overset{(b)}{=} \langle x, \overline{\lambda'} x \rangle = \lambda' \langle x, x' \rangle$$

And since λ and λ' are distinct, $\langle x, x' \rangle = 0$

Question 4:

Let F be $\mathbb{R}$ or $\mathbb{C}$, and V a finite-dimensional inner product space over F. Let $T : V \to V$ be a linear operator. Show that T is normal if and only if there exists a polynomial $f(t) \in F[t]$ such that $T^* = f(T)$.

Proof:

If $T^* = f(T)$ then $T^*T = f(T)T = Tf(T) = TT^*$, proving the backward implication.

Now we prove the forward implication. Suppose T is normal.

We know the characteristic polynomial of T splits over $\mathbb{C}$ with complex roots.

And since V is finite dimensional, we know there exist a orthonormal basis β such that $[T]_\beta$ is upper triangular.

Since T is normal, this means $[T]_\beta$ is diagonal. Furthermore, $[T^*]_\beta = [T]_\beta^*$.

So if $[T]_\beta = \begin{pmatrix} \lambda_1 & & \\ & \ddots & \\ & & \lambda_n \end{pmatrix}$ then $[T^*]_\beta = [T]_\beta^* = \begin{pmatrix} \overline{\lambda_1} & & \\ & \ddots & \\ & & \overline{\lambda_n} \end{pmatrix}$

We just need to show that $\exists f \in F[t]$ such that $f(T) = T^* \Rightarrow f([T]_\beta) = [T^*]_\beta$.

Since $[T]_\beta$ is diagonal, we need to find a polynomial f where $f(\lambda_j) = \overline{\lambda_j}$ for all $j \in [1, n]$.

Let $\lambda_1, ..., \lambda_n$ be the distinct eigenvalues of T.

Define $f_j(t) = \prod_{i \neq j}^{n} \frac{t - \lambda_i}{\lambda_j - \lambda_i}$. Notice that $f_j(\lambda_j) = 1$ and $f_j(\lambda_i) = 0$ for all $j \neq i$.

Now define $f(t) = \sum_{i=1}^{n} \overline{\lambda_i} f_i(t)$. Observe that $f(\lambda_j) = \overline{\lambda_j}$ for any eigenvector of T.

If $F = \mathbb{C}$ we are done since $f \in \mathbb{C}[t]$. But we need to show that if $F = \mathbb{R}$ then $f \in \mathbb{R}[t]$.

By fundamental theorem of algebra, the roots of $P_T(t)$ are real, or come in conjugate pairs. Let λ_r be a real root of $P_T(t)$ and consider f_r. By definition, the complex factors of f_r come in conjugate pairs. Let μ and $\overline{\mu}$ be any arbitrary pair of complex roots.

Well,

$$\frac{(t-\mu)(t-\overline{\mu})}{(\lambda_r - \mu)(\lambda_r - \overline{\mu})} = \frac{t^2 - t\mu - t\overline{\mu} - |\mu|^2}{\lambda_r^2 - \lambda_r\mu - \lambda_r\overline{\mu} - |\mu|^2} = \frac{t^2 - 2tRe(\mu) - |\mu|^2}{\lambda_r^2 - 2\lambda_r Re(\mu) - |\mu|^2}$$

which is an entirely real polynomial. So f_r only has real coefficients.

For f_c where λ_c is complex, only the factor $\dfrac{t-\overline{\lambda_c}}{\lambda_c-\overline{\lambda_c}}$ does not appear with a conjugate counterpart. Let $\lambda_d = \overline{\lambda_c}$. Well, f is defined to have pairs $\overline{\lambda_c}f_c + \overline{\lambda_d}f_d$ as summands. We can factor out the real polynomial $g_c = \displaystyle\prod_{c\neq i\neq d}^{k} \frac{t-\lambda_i}{\lambda_c-\lambda_i}$ from f_c. Notice that this is the same real factor of f_d since $|\lambda_d| = |\lambda_c|$ and $Re(\lambda_d) = Re(\lambda_c)$. And therefore:

$$\begin{aligned}
\overline{\lambda_c}f_c + \overline{\lambda_d}f_d &= \lambda_d f_c + \lambda_c f_d \\
&= g_c\left(\frac{\lambda_d(t-\lambda_d)}{(\lambda_c-\lambda_d)} - \frac{\lambda_c(t-\lambda_c)}{(\lambda_d-\lambda_c)}\right) \\
&= g_c\left(\frac{\lambda_d t - \lambda_d^2 + \lambda_c t - \lambda_c^2}{\lambda_c-\lambda_d}\right) \\
&= g_c\left(\frac{2Re(\lambda_c)t - 2Re(\lambda_c^2)}{2Re(\lambda_c)}\right) && \text{(since } \lambda_d^2 = (\overline{\lambda_c})^2 = \overline{\lambda_c^2}\text{)}
\end{aligned}$$

which is also an entirely real polynomial. Thus, $f \in \mathbb{R}[t]$, completing the proof.