Q1: $\inf\{sin(n): n\geq 1\}=?$ write down the answer and prove it

$\inf\{\sin(n): n\geq 1\}=-1$，证明:

首先，$sin(n)\geq -1$，因此 $-1<=sin(n),\forall n\geq 1$.
假设存在 u 满足 $u\leq x,\forall x\in\{\sin(n): n\geq 1\}$ 且 $u>-1$
由 $\sin(\frac{3\pi}{2})=-1\in\{\sin(n): n\geq 1\}$，得 $u\leq -1$，这与 $u>-1$ 矛盾，假设不成立.
所以 $\inf\{\sin(n): n\geq 1\}=-1$.

Q2: Prove Cauchy-Schwartz inequality $\mathbf{x}^T\mathbf{y}\leq\|\mathbf{x}\|_2\|\mathbf{y}\|_2$ in two ways

方法1：
$\mathbf{x}^T\mathbf{y}=\sum_i x_iy_i$, $\|\mathbf{x}\|_2\|\mathbf{y}\|_2=\sqrt{\sum_i x_i^2}\sqrt{\sum_i y_i^2}$
要证 $\mathbf{x}^T\mathbf{y}\leq\|\mathbf{x}\|_2\|\mathbf{y}\|_2$
即证 $\sum_i x_iy_i\leq\sqrt{\sum_i x_i^2}\sqrt{\sum_i y_i^2}$
即证 $(\sum_i x_iy_i)^2\leq\sum_i x_i^2\sum_i y_i^2$
即证 $\sum_{i=1}^n x_i^2y_i^2+\sum_{i=1}^n\sum_{j=i+1}^n 2x_iy_ix_jy_j\leq\sum_{i=1}^n x_i^2y_i^2+\sum_{i=1}^n\sum_{j=i+1}^n(x_i^2y_j^2+x_j^2y_i^2)$
即证 $\sum_{i=1}^n\sum_{j=i+1}^n 2x_iy_ix_jy_j\leq\sum_{i=1}^n\sum_{j=i+1}^n(x_i^2y_j^2+x_j^2y_i^2)$
由于 $(x_iy_j-x_jy_i)^2=(x_i^2y_j^2+x_j^2y_i^2)-2x_iy_ix_jy_j\geq 0$，有 $2x_iy_ix_jy_j\leq(x_i^2y_j^2+x_j^2y_i^2),\forall i,j\in[1,n]$
因此 $\sum_{i=1}^n\sum_{j=i+1}^n 2x_iy_ix_jy_j\leq\sum_{i=1}^n\sum_{j=i+1}^n(x_i^2y_j^2+x_j^2y_i^2)$，原命题得证.

方法2：
若 $\mathbf{x}=0$ 或 $\mathbf{y}=0$，$\mathbf{x}^T\mathbf{y}=\|\mathbf{x}\|_2\|\mathbf{y}\|_2=0$，不等式成立.
否则 $\cos\langle\mathbf{x},\mathbf{y}\rangle=\frac{\mathbf{x}^T\cdot\mathbf{y}}{\|\mathbf{x}\|2\|\mathbf{y}\|2}\leq 1$，$\|\mathbf{x}\|_2\|\mathbf{y}\|_2>0$，得 $\mathbf{x}^T\mathbf{y}\leq\|\mathbf{x}\|_2\|\mathbf{y}\|_2$，不等式成立.
综上，不等式成立.

Q3: Let $\mathbf{A}$ be a matrix of size $m\times n$. Denote the range space of $\mathbf{A}$ as $R(\mathbf{A})$ and the null space of $\mathbf{A}$ as $N(\mathbf{A})$, respectively. Prove $R(\mathbf{A})=N^\perp(\mathbf{A}^T)$

$R(\mathbf{A})=\{\mathbf{Ax}|\mathbf{x}\in\mathbb{R}^n\}$
$R^\perp(\mathbf{A})=\{\mathbf{y}|\mathbf{x}^T\mathbf{y}=0,\forall\mathbf{x}\in R(\mathbf{A})\}$
$N(\mathbf{A}^T)=\{\mathbf{x}|\mathbf{A}^T\mathbf{x}=0\}$
$N^\perp(\mathbf{A}^T)=\{\mathbf{y}|\mathbf{x}^T\mathbf{y}=0,\forall\mathbf{x}\in N(\mathbf{A}^T)\}$

先证 $\forall\mathbf{u}\in R(\mathbf{A}),\mathbf{u}\in N^\perp(\mathbf{A}^T)$:
假设 $\mathbf{u}\in R(\mathbf{A})$，则 $\exists\mathbf{v}\in\mathbb{R}^n,\mathbf{Av}=\mathbf{u}$.
任取 $\mathbf{x}\in N(\mathbf{A}^T)$，有 $\mathbf{A}^T\mathbf{x}=0$，$(\mathbf{A}^T\mathbf{x})^T=\mathbf{x}^T\mathbf{A}=0$，$\mathbf{x}^T\mathbf{Av}=\mathbf{x}^T\mathbf{u}=0$.
所以 $\mathbf{u}\in N^\perp(\mathbf{A}^T)$，结论得证.

再证 $\forall\mathbf{u}\in N^\perp(\mathbf{A}^T),\mathbf{u}\in R(\mathbf{A})$:
即证 $\forall\mathbf{u}\in R^\perp(\mathbf{A}),\mathbf{u}\in N(\mathbf{A}^T)$.
假设 $\mathbf{u}\in R^\perp(\mathbf{A})$，则 $\forall\mathbf{x}\in\mathbb{R}^n,(\mathbf{Ax})^T\mathbf{u}=0$，即 $\forall\mathbf{x}\in\mathbb{R}^n,\mathbf{x}^T(\mathbf{A}^T\mathbf{u})=0$.
因此 $\mathbf{A}^T\mathbf{u}=0$，即 $\mathbf{u}\in N(\mathbf{A}^T)$，结论得证.

综上，$R(\mathbf{A})=N^\perp(\mathbf{A}^T)$ 得证.

Q4: For any two matrices, prove $trace(\mathbf{AB}) = trace(\mathbf{BA})$

假设 $\mathbf{A} \in \mathbb{R}^{n\times m}$，$\mathbf{B} \in \mathbb{R}^{m\times n}$：
$trace(\mathbf{AB}) = \sum_{i=1}^{n}(\mathbf{AB})_{ii} = \sum_{i=1}^{n}\sum_{j=1}^{m}\mathbf{A}_{ij}\mathbf{B}_{ji} = \sum_{j=1}^{m}\sum_{i=1}^{n}\mathbf{B}_{ji}\mathbf{A}_{ij} = \sum_{j=1}^{m}(\mathbf{BA})_{jj} = trace(\mathbf{BA})$

Q5: Prove a useful inequality: $\mathbf{A} \succeq 0 \Leftrightarrow \langle \mathbf{A}, \mathbf{B}\rangle \geq 0$ for all $\mathbf{B} \succeq 0$

假设 $A, B \in \mathbb{R}^{n\times n}$：

先证充分性 $\mathbf{A} \succeq 0 \Rightarrow \langle \mathbf{A}, \mathbf{B}\rangle \geq 0, \forall \mathbf{B} \succeq 0$:
特征值分解 $\mathbf{A} = \mathbf{P}^T\mathbf{CP}, \mathbf{B}^T = \mathbf{Q}^T\mathbf{DQ}$，其中 $\mathbf{P}, \mathbf{Q}$ 为单位正交阵
$\langle \mathbf{A}, \mathbf{B}\rangle = trace(\mathbf{AB}^T) = trace(\mathbf{P}^T\mathbf{CPQ}^T\mathbf{D}^T\mathbf{Q}) = trace(\mathbf{CPQ}^T\mathbf{D}^T\mathbf{QP}^T)$
由于 $\mathbf{PQ}^T\mathbf{D}^T\mathbf{QP}^T$ 对角元素非负，$trace(\mathbf{CPQ}^T\mathbf{D}^T\mathbf{QP}^T) \geq 0$，即 $\langle \mathbf{A}, \mathbf{B}\rangle \geq 0$

再证必要性 $\langle \mathbf{A}, \mathbf{B}\rangle \geq 0, \forall \mathbf{B} \succeq 0 \Rightarrow \mathbf{A} \succeq 0$:
假设 $\mathbf{A} \not\succeq 0$，则 $\exists \mathbf{u} \neq 0, \mathbf{u}^T\mathbf{Au} < 0$
取 $\mathbf{B} = \mathbf{uu}^T$，则 $\langle \mathbf{A}, \mathbf{B}\rangle = trace(\mathbf{AB}^T) = trace(\mathbf{Auu}^T) = \langle \mathbf{Au}, \mathbf{u}\rangle = \mathbf{u}^T\mathbf{Au} < 0$
与条件矛盾，假设不成立.

原命题得证.

Q6: Define $f(\mathbf{x}) \triangleq \|\mathbf{Ax} - \mathbf{b}\|_2^2$. Compute $\nabla f(\mathbf{x})$ and $\nabla^2 f(\mathbf{x})$

记 $\mathbf{A} = (\mathbf{a}_1, \mathbf{a}_2, ..., \mathbf{a}_n))^T$, $\mathbf{a}_i \in \mathbb{R}^{1\times n}$

$(\nabla f(\mathbf{x}))_k = \frac{\partial}{\partial xk}((\mathbf{Ax})_1 - b_1)^2 + \frac{\partial}{\partial xk}((\mathbf{Ax})_2 - b_2)^2 + \cdots + \frac{\partial}{\partial xk}((\mathbf{Ax})_n - b_n)^2 = \frac{\partial}{\partial xk}(\mathbf{a}_1\mathbf{x} - b_1)^2 + \frac{\partial}{\partial xk}(\mathbf{a}_2\mathbf{x} - b_2)^2 + \cdots + \frac{\partial}{\partial xk}(\mathbf{a}_n\mathbf{x} - b_n)^2 = 2\mathbf{a}_{1k}(\mathbf{a}_1\mathbf{x} - b_1) + 2\mathbf{a}_{2k}(\mathbf{a}_2\mathbf{x} - b_2) + \cdots + 2\mathbf{a}_{nk}(\mathbf{a}_n\mathbf{x} - b_n) = 2\mathbf{a}_{1k}(\mathbf{Ax} - \mathbf{b})_1 + 2\mathbf{a}_{2k}(\mathbf{Ax} - \mathbf{b})_2 + \cdots + 2\mathbf{a}_{nk}(\mathbf{Ax} - \mathbf{b})_n = \sum_i 2\mathbf{a}_{ik}(\mathbf{Ax} - \mathbf{b})_i$

$\therefore \nabla f(\mathbf{x}) = 2\mathbf{A}^T(\mathbf{Ax} - \mathbf{b})$

$(\nabla^2 f(\mathbf{x}))_{ij} = \frac{\partial}{\partial xj}2\mathbf{a}_{1i}(\mathbf{a}_1\mathbf{x} - b_1) + \frac{\partial}{\partial xj}2\mathbf{a}_{2i}(\mathbf{a}_2\mathbf{x} - b_2) + \cdots + \frac{\partial}{\partial xj}2\mathbf{a}_{ni}(\mathbf{a}_n\mathbf{x} - b_n) = \sum_k 2\mathbf{a}_{ki}\mathbf{a}_{kj}$

$\therefore \nabla^2 f(\mathbf{x}) = 2\mathbf{A}^T\mathbf{A}$

Q7: Define $f(\mathbf{x}) \triangleq \|\mathbf{A} - \mathbf{xx}^T\|_F^2$. Compute $\nabla f(\mathbf{x})$ and $\nabla^2 f(\mathbf{x})$

假设 $\mathbf{x} \in \mathbb{R}^n$：

$(\nabla f(\mathbf{x}))_k = \frac{\partial}{\partial xk}\sum_{i,j}(A_{ij} - x_ix_j)^2 = \sum_{i,j} -2(A_{ij} - x_ix_j)\frac{\partial}{\partial xk}x_ix_j = -2(A_{kk} - x_k^2)2x_k - 2\sum_{i\neq k}(A_{ik} + A_{ki} - 2x_ix_k)x_i = -2\sum_i(A_{ik} + A_{ki} - 2x_ix_k)x_i = 4x_k\sum_i x_i^2 - 2\sum_i x_iA_{ik} - 2\sum_i x_iA_{ki}$

$\therefore \nabla f(\mathbf{x}) = 4\mathbf{xx}^T\mathbf{x} - 2\mathbf{Ax} - 2\mathbf{A}^T\mathbf{x}$

$(\nabla^2 f(\mathbf{x}))_{ij} = -\frac{\partial}{\partial x_j} 2 \sum_k (A_{ki} + A_{ik} - 2x_k x_i) x_k = \begin{cases} \sum_k 4x_k^2 + 8x_i^2 - 4A_{ii}, i = j \\ 8x_i x_j - 2A_{ij} - 2A_{ji}, i \neq j \end{cases}$

$\therefore \nabla^2 f(\mathbf{x}) = 8\mathbf{x}\mathbf{x}^T + 4\mathbf{x}^T\mathbf{x}\mathbf{I} - 2\mathbf{A} - 2\mathbf{A}^T$

Q8: For the logistic regression example in lecture notes, compute $\nabla^2 E(\mathbf{w})$

Q9: Define $f(\mathbf{x}) \triangleq \log \sum_{k=1}^n (\exp(x_k))$. Prove $\nabla^2 f(\mathbf{x}) \succeq 0$

$\nabla^2 f(\mathbf{x}) =$
$$\begin{pmatrix} \frac{\exp(x1)\left(\sum_{k=1}^n \exp(xk)\right) - \exp(x1)^2}{\left(\sum_{k=1}^n \exp(xk)\right)^2} & \frac{-\exp(x1)\exp(x2)}{\left(\sum_{k=1}^n \exp(xk)\right)^2} & \cdots & \frac{-\exp(x1)\exp(xn)}{\left(\sum_{k=1}^n \exp(xk)\right)^2} \\ \frac{-\exp(x2)\exp(x1)}{\left(\sum_{k=1}^n \exp(xk)\right)^2} & \frac{\exp(x2)\left(\sum_{k=1}^n \exp(xk)\right) - \exp(x2)^2}{\left(\sum_{k=1}^n \exp(xk)\right)^2} & \cdots & \frac{-\exp(x2)\exp(xn)}{\left(\sum_{k=1}^n \exp(xk)\right)^2} \\ \vdots & \vdots & & \vdots \\ \frac{-\exp(xn)\exp(x1)}{\left(\sum_{k=1}^n \exp(xk)\right)^2} & \frac{-\exp(xn)\exp(x2)}{\left(\sum_{k=1}^n \exp(xk)\right)^2} & \cdots & \frac{\exp(xn)\left(\sum_{k=1}^n \exp(xk)\right) - \exp(xn)^2}{\left(\sum_{k=1}^n \exp(xk)\right)^2} \end{pmatrix}$$

对于任意 $\mathbf{z} \in \mathbb{R}^n$，$\mathbf{z}^T \nabla^2 f(\mathbf{x}) \mathbf{z} = \sum_i \sum_j \nabla^2 f(\mathbf{x}) z_i z_j =$
$\frac{\sum_i \sum_j \exp(x_i)\exp(x_j) z_i^2 - \sum_i \exp(x_i)^2 z_i^2 - \sum_i \sum_{j \neq i} \exp(x_i)\exp(x_j) z_i z_j}{\left(\sum_{k=1}^n \exp(xk)\right)^2} = \frac{\sum_i \sum_j \exp(x_i)\exp(x_j)(z_i^2 - z_i z_j)}{\left(\sum_{k=1}^n \exp(xk)\right)^2} =$
$\frac{\sum_i \sum_j \exp(x_i)\exp(x_j)(z_i^2 - 2z_i z_j + z_j^2)}{2\left(\sum_{k=1}^n \exp(xk)\right)^2} = \frac{\sum_i \sum_j \exp(x_i)\exp(x_j)(z_i - z_j)^2}{2\left(\sum_{k=1}^n \exp(xk)\right)^2} \geq 0$

故 $\nabla^2 f(\mathbf{x}) \succeq 0$.

Q10: Find at least one example in either of the following two fields that can be formulated as an optimization problem and show how to formulate it: 1.EDA software 2.cluster scheduling for data centers

问题：针对一个电路板和一种电路设计，找到电子元件在电路板上的最佳放置位置使得电线总长度最小

$$\begin{aligned} \text{minimize } & \sum_i \sum_j \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \\ \text{subject to } & (x_i - x_j)^2 + (y_i - y_j)^2 \geq (r_i + r_j)^2, \forall i \neq j \\ & d_{min} \leq \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \leq d_{max}, \forall i \neq j \end{aligned}$$