QUESTION 4

ABHAY SHANKAR K: CS21BTECH11001 & KARTHEEK TAMMANA: CS21BTECH11028

(I) Knowing the maximum likelihood function,

$$p\left(\mathbf{t}|\mathbf{w}\right) = \prod_{n=1}^{N} y_n^{t_n} \left(1 - y_n\right)^{t_n}$$

we can obtain the cross-entropy error function by taking negative logarithm:

$$E(\mathbf{w}) = -\sum_{n=1}^{N} \left(t_n \ln y_n + (1 - t_n) \ln(1 - y_n)\right) \tag{1}$$

Taking gradients of 1 with respect to $\mathbf{w}$, we have

- Gradient of the error:

$$\nabla E(\mathbf{w}) = \sum_{n=1}^{N} \left(y_n - t_n\right) \phi_n = \mathbf{\Phi^T}(\mathbf{y} - \mathbf{t})$$

- The Hessian:

$$\nabla\nabla E(\mathbf{w}) = \sum_{n=1}^{N} y_n(1 - y_n)\phi_n\phi_n^T = \mathbf{\Phi^T R \Phi}$$

  where R is the diagonal matrix given by $R_{nn} = y_n(1 - y_n)$

- Update function:

$$\mathbf{w}^{(new)} = \mathbf{w}^{(old)} - \mathbf{H}^{-1}\nabla E(\mathbf{w}) =$$

$$\begin{aligned} \mathbf{w}^{(new)} &= \mathbf{w}^{(old)} - \mathbf{H}^{-1}\nabla E(\mathbf{w}) \\ &= \mathbf{w}^{(old)} - (\mathbf{\Phi^T R \Phi})^{-1}\mathbf{\Phi^T}(\mathbf{y} - \mathbf{t}) \\ &= (\mathbf{\Phi^T R \Phi})^{-1}\left(\mathbf{\Phi^T R \Phi w}^{(old)} - \mathbf{\Phi^T}(\mathbf{y} - \mathbf{t})\right) \\ &= (\mathbf{\Phi^T R \Phi})^{-1}\mathbf{\Phi^T R z} \end{aligned} \tag{2}$$

  with

$$\mathbf{z} = \mathbf{\Phi w}^{(old)} - \mathbf{R^{-1}}(\mathbf{y} - \mathbf{t})$$

where $\mathbf{\Phi}$ is the N $\times$ M design matrix, whose n'th row is given by ϕ_n^T, and $y_n = \sigma(\mathbf{w}^T\phi_n)$.

The algorithm for update, implemented in python:

```python
import numpy as np
def update(w, Phi, t):
    y =  mp.array([sigmoid(p @ w) for p in Phi])
    R = np.diag(y * (1 - y))
    z = Phi @ w - np.linalg.inv(R) @ (y - t)
    return np.linalg.inv(Phi.T @ R @ Phi) @ Phi.T @ R @ z
```

(II)
- Modifying 2, we get

$$(\mathbf{\Phi^T R \Phi})\mathbf{w} = \mathbf{\Phi^T R z}$$

  which is the normal equation for weighted least squares. Thus, the new weight vector $\mathbf{w}^{(new)}$ is the solution to the weighted least squares problem with $\mathbf{z}$ and the weighing matrix $\mathbf{R}$.

- The weighing matrix R is not constant, but depends on the parameter vector $\mathbf{w}$.

  Thus, we must apply the normal equations iteratively, each time using the new weight vector $\mathbf{w}$ to compute a revised weighing matrix R. So, the algorithm is known as iterative reweighted least squares (IRLS).

(III) With the Hessian:

$$\mathbf{H} = \mathbf{\Phi^T R \Phi}$$

We know that a function is concave if it's Hessian is positive definite. Thus, it is sufficient to prove positive-definiteness of the Hessian.

Expanding $u^T\mathbf{H}u$, we can prove positive-definiteness

$$\begin{aligned} u^T\mathbf{H}u &= u^T\mathbf{\Phi^T R \Phi}u \\ &= (u^T\mathbf{\Phi^T})\mathbf{R}(\mathbf{\Phi u}) \\ &= \sum_{n=1}^{N} u^T {\phi_\mathbf{n}}^T R_{nn} \phi_\mathbf{n} \mathbf{u} \\ &= \sum_{n=1}^{N} R_{nn} \left(\phi_\mathbf{n}\mathbf{u}\right)^2 \\ &> 0 \end{aligned} \tag{3}$$