

Analytic Geometry

DEF (*Dot Product*) The dot product between two vectors u and v is defined as

$$u^\top v = u_1 v_1 + u_2 v_2 + \dots + u_n v_n = \sum_{i=1}^n u_i v_i$$

DEF (*Bilinearity*) The dot product is bilinear, i.e. for any vectors u, v, w and scalar a ,

$$\begin{aligned} au^\top v &= au^\top v = u^\top av \\ u + v^\top w &= u^\top w + v^\top w \\ w^\top u + v &= w^\top u + w^\top v \end{aligned}$$

DEF (*Commutativity*) The dot product is commutative, i.e. $u^\top v = v^\top u$

DEF (*Inner Product*) The inner product between two vectors u and v is defined as

$$\langle u, v \rangle$$

Dot product is a special case of inner product.

DEF (ℓ_2 Norm) The ℓ_2 norm of a vector v is defined as

$$\|v\|_2 = \sqrt{v^\top v} = \sqrt{v_1^2 + v_2^2 + \dots + v_n^2}$$

Also called the Euclidean norm.

DEF (ℓ_2 properties) For all vectors u, v and scalar a ,

- The ℓ_2 norm is non-negative, i.e. $\|v\|_2 \geq 0$.
- $\|au\|_2 = |a| \|u\|_2$ for any scalar a .
- $\|u\|_2$ is zero if and only if u is the zero vector.
- The triangle inequality holds, i.e. $\|u + v\|_2 \leq \|u\|_2 + \|v\|_2$.
- $\|x - y\|_2 = \|y - x\|_2$, also called symmetry.
- $\|u + v\|_2^2 = \|u\|_2^2 + 2u^\top v + \|v\|_2^2$
- $\cos \theta = \frac{u^\top v}{\|u\|_2 \|v\|_2}$ (can be proved using the law of cosines)

THM (*Cauchy-Schwarz Inequality*) For any vectors u, v , the following inequality holds:

$$|\langle u, v \rangle| \leq \|u\|_2 \|v\|_2$$

DEF (*Line*) A line is a set of points

$$\{x : x = u + tv \text{ for some } t \in \mathbb{R}\}$$

where u is a point on the line and $v \neq 0$ is the direction vector.

DEF (*Plane*) A plane is a set of points

$$\{x : v^\top x - u = 0\}$$

where v is the normal vector to the plane and u is the shift from the origin.

DEF (*Projection*) The vector $\|u\|_2 \cos \theta \frac{v}{\|v\|_2}$ is a projection of u onto v .

DEF (*Distance between a point and a plane*) The distance between a point z and a plane $v^\top x - u = 0$ is given by

$$\frac{|v^\top z - u|}{\|v\|_2}$$

DEF (*Distance between a point and a line*) The distance between a point z and a line $x = u + tv$ is given by

$$\left\| z - u - \frac{z - u^\top v}{\|v\|_2^2} v \right\|_2$$

DEF (*Singular Value Decomposition (SVD)*) The SVD of a matrix X is $U\Sigma V^\top$, where $U^\top U = I, V^\top V = I$ and Σ is a diagonal matrix:

$$\Sigma = \begin{bmatrix} \sigma_1 & 0 & \dots & 0 \\ 0 & \sigma_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \sigma_n \end{bmatrix}$$

and $\sigma_1 \geq \sigma_2 \geq \dots \geq \sigma_n \geq 0$.

THM (*Eckart-Young Theorem*) Let $\Sigma_k = \text{diag}(\sigma_1, \dots, \sigma_k, 0, \dots, 0)$ where $k \leq d$. The matrix $U\Sigma_k V^\top$ is the optimal solution to the following problem:

$$\min_{\hat{X}} \|X - \hat{X}\|_F \text{ s.t. } \text{rank}(\hat{X}) \leq k$$

The matrices $Z = U\Sigma_k$ and $W = V^\top$ are the optimal solution to

$$\min_{Z, W} \|X - ZW\|_F \text{ s.t. } Z \in \mathbb{R}^{n \times k}, W \in \mathbb{R}^{k \times d}$$

Calculus

DEF (*Derivative*) The derivative of a function $f : \mathbb{R} \rightarrow \mathbb{R}$ at x_0 is defined as:

$$(D_x f)(x_0) = \left(\frac{d}{dx} f \right) (x_0) = \lim_{h \rightarrow 0} \frac{f(x_0 + h) - f(x_0)}{h}$$

DEF (*Directional Derivative*) The directional derivative of a function $f : \mathbb{R}^d \rightarrow \mathbb{R}$ along the direction v at $x_0 \in \mathbb{R}^d$ is defined as:

$$(D_v f)(x_0) = \lim_{h \rightarrow 0} \frac{f(x_0 + hv) - f(x_0)}{h}$$

DEF (*Partial Derivative*) The partial derivative is a directional derivative along the direction of coordinate axes. For a function $f : \mathbb{R}^d \rightarrow \mathbb{R}$, the partial derivative with respect to the i -th coordinate is denoted as:

$$\frac{\partial f}{\partial x_i} = \lim_{h \rightarrow 0} \frac{f(x_1, \dots, x_i + h, \dots, x_d) - f(x_1, \dots, x_i, \dots, x_d)}{h}$$

DEF (*Gradient*) The gradient of a function is the vector consisting of all partial derivatives denoted by ∇f or $\frac{\partial f}{\partial x}$. For a function $f : \mathbb{R}^d \rightarrow \mathbb{R}$,

EX (*Gradient Identities*)

- Given a function $f(a) = b^\top a$, $(\nabla f)(a) = b$
- Given a function $f(a) = \|a\|_2^2$, $(\nabla f)(a) = 2a$

EX (Hessian) The Hessian of a function $f : \mathbb{R}^d \rightarrow \mathbb{R}$ is the matrix of second partial derivatives:

$$\nabla^2 f = \begin{bmatrix} \frac{\partial^2 f}{\partial x_1^2} & \frac{\partial^2 f}{\partial x_1 \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_1 \partial x_d} \\ \frac{\partial^2 f}{\partial x_2 \partial x_1} & \frac{\partial^2 f}{\partial x_2^2} & \cdots & \frac{\partial^2 f}{\partial x_2 \partial x_d} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f}{\partial x_d \partial x_1} & \frac{\partial^2 f}{\partial x_d \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_d^2} \end{bmatrix}$$

EX (Hessian Example) Given a function $f(x, y) = x^2 - y^2$, the Hessian is:

$$\nabla^2 f = \begin{bmatrix} 2 & 0 \\ 0 & -2 \end{bmatrix}$$

The 2 indicates that it looks like a cup along the x -axis and the -2 indicates that it looks like an upside-down cup along the y -axis.

Optimisation

DEF (Minimum) The minimum of a function $f : \mathbb{R}^d \rightarrow \mathbb{R}$ is written as $\min_x f(x)$, and has the property that $\min_x f(x) \leq f(y)$ for all $y \in \mathbb{R}^d$. The value x^* such that $f(x^*) = \min_x f(x)$ is called the minimizer.

DEF (Convexity) A function $f : \mathbb{R}^d \rightarrow \mathbb{R}$ is convex if for any $0 \leq \alpha \leq 1$, we have

$$f(\alpha x + (1 - \alpha)y) \leq \alpha f(x) + (1 - \alpha)f(y)$$

In general,

$$f\left(\sum_{i=1}^k \alpha_i x_i\right) \leq \sum_{i=1}^k \alpha_i f(x_i)$$

DEF (Concavity) A function f is concave if $-f$ is convex.

THM (First Order Condition (Convexity)) If f is convex then,

$$\bullet f(x) \geq f(y) + \nabla f(y)^\top (x - y)$$

DEF (Positive Semidefinite) A matrix A is positive semidefinite if for all vectors $v \neq 0$ we have $v^\top A v \geq 0$. Also written as $A \succeq 0$.

THM (Convex Function Implies Positive Semidefinite Hessian) If f is convex, then $\nabla^2 f(x) \succeq 0$.

DEF (Positive Definite) A matrix A is positive definite if for all vectors $v \neq 0$ we have $v^\top A v > 0$. Also written as $A \succ 0$.

DEF (Affine) A function f is affine if $f(x) = Ax + b$ for some matrix A and vector b .

THM (Affine Transform Preservation) If f is convex, then $g(x) = f(Ax + b)$ is also convex.

THM (Non-negative Weighted Sum) If f_1, f_2, \dots, f_k are convex functions, then $f(x) = \sum_{i=1}^k \beta_i f_i(x)$ is convex for all $\beta_i \geq 0$.

EX (Gradient of Quadratic Form) $\nabla_x(x^\top A x) = (A + A^\top)x$

DEF (Strictly Convex) A function $f : \mathbb{R}^d \rightarrow \mathbb{R}$ is called strictly convex if for $0 \leq \alpha \leq 1$ we have

$$f(\alpha x + (1 - \alpha)y) < \alpha f(x) + (1 - \alpha)f(y)$$

for any $x \neq y$.

DEF (First Order Condition (Strict Convexity)) If f is strictly convex then,

$$\bullet f(x) > f(y) + \nabla f(y)^\top (x - y)$$

THM (Unique Minimizer) If f is strictly convex, then f has a unique minimizer.

THM (Jensen's Inequality) If a function f is convex,

$$f(\mathbb{E}_{x \sim p}[x]) \leq \mathbb{E}_{x \sim p}[f(x)]$$

DEF (Subgradient) A subgradient at x is a vector g that satisfies

$$f(y) \geq f(x) + g^\top (y - x)$$

for any y , and the set of subgradients at x is denoted as $\partial f(x)$. $\nabla f(x) \in \partial f(x)$ if f is differentiable at x . In other words subgradients are tangents that are below the function.

EX (Constrained Optimisation Problem) An example of a constrained optimisation problem is

$$\min_x x^2 \text{ s.t. } -2.5 \leq x \leq -0.5$$

DEF (Feasible Solution) A feasible solution is a point that satisfies all the constraints.

DEF (Lagrangian) If you have an optimisation problem of the form

$$\min_x f(x) \text{ s.t. } h(x) \leq 0$$

the **Lagrangian** is defined as

$$f(x) + \lambda h(x)$$

for some $\lambda \geq 0$ (Lagrange multiplier).

ALG (Solving the Lagrangian)

- Solve $g(\lambda) = \min_x [f(x) + \lambda h(x)]$
- Find $\hat{\lambda}$ such that $\min_x [f(x) + \hat{\lambda} h(x)]$ gives a feasible solution
- Suppose \hat{x} is the solution to the above, and $x^* = \arg \min_{x: h(x) \leq 0} f(x)$ (the optimal solution), then

$$f(\hat{x}) = f(\hat{x}) + \hat{\lambda} h(\hat{x}) \leq f(x^*) + \hat{\lambda} h(x^*) \leq f(x^*)$$

Probability

DEF (Gaussian Distribution) We write $x \sim \mathcal{N}(\mu, \Sigma)$ to denote that x is a random variable with mean μ and covariance Σ . It means that the probability density function of x is given by

$$p(x) = \frac{1}{2\pi^{d/2}|\Sigma|^{1/2}} \exp\left(-\frac{1}{2}(x - \mu)^T \Sigma^{-1}(x - \mu)\right)$$

DEF (Statistical Independence) Two variables x and y are independent if

$$p(x, y) = p(x)p(y)$$

Equivalently,

$$p(x|y) = p(x)$$

. The independence of x and y is denoted by $x \perp y$.

DEF (Statistical Independence [general]) If $\{x_1, \dots, x_n\} \perp \{y_1, \dots, y_m\}$ then

$$p(x_1, \dots, x_n, y_1, \dots, y_m) = p(x_1, \dots, x_n)p(y_1, \dots, y_m)$$

EX (Factorisation of a joint distribution) Suppose $x \in \mathcal{X}, y \in \mathcal{Y}, z \in \mathcal{Z}$. If $\{x, y\} \perp z$ then

$$p(x, y, z) = p(x, y)p(z)$$

The original joint distribution (of size $|\mathcal{X}| \times |\mathcal{Y}| \times |\mathcal{Z}|$) can be factorised into two distributions of size $|\mathcal{X}| \times |\mathcal{Y}|$ and $|\mathcal{Z}|$.

DEF (Mutual Independence) A set of variables $\{x_1, \dots, x_n\}$ are mutually independent if

$$p(x_1, \dots, x_n) = \prod_{i=1}^n p(x_i)$$

DEF (Pairwise Independence) A set of variables $\{x_1, \dots, x_n\}$ are pairwise independent if

$$p(x_i, x_j) = p(x_i)p(x_j)$$

for all $i \neq j$.

THM (Mutual Independence implies Pairwise Independence) If a set of variables $\{x_1, \dots, x_n\}$ are mutually independent, then they are pairwise independent. Converse is not true!

DEF (Conditional Independence) The variables x and y are conditionally independent given z if

$$p(x, y|z) = p(x|z)p(y|z)$$

This is denoted by $x \perp y|z$.

DEF (Marginalisation) The marginal distribution of x is obtained by summing out all other variables.

$$p(x) = \sum_y p(x, y)$$

$$p(x|z) = \sum_y p(x, y|z)$$

$$p(x, y|z) = p(x|z)p(y|z)$$

DEF (Bayes Rule) Bayes rule is a way to invert conditional probabilities.

$$p(x|y) = \frac{p(y|x)p(x)}{p(y)}$$

DEF (Chain Rule) Any joint distribution can be factorised into a product of conditional distributions.

$$p(x_1, \dots, x_n) = p(x_1)p(x_2|x_1)p(x_3|x_1, x_2) \cdots p(x_n|x_1, \dots, x_{n-1})$$

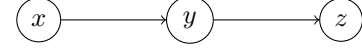
DEF ((directed) Graph Representation) A directed graph is a set of nodes connected by edges. Each vertex is a random

variable and each edge represents a direct dependency. It is directed and acyclic (DAG). A distribution factorises according to the graph if

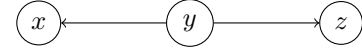
$$p(x_1, \dots, x_n) = \prod_{i=1}^n p(x_i | \text{parents}(x_i))$$

DEF (Graph structures)

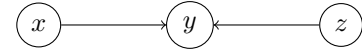
- Chain $x \perp z|y$



- Common cause $x \perp z|y$



- v-structure $x \perp z$ but $x \not\perp z|y$



Training

DEF (Loss Function) Given a predicted output \hat{y} and observed output y , the loss function measures how close the model's prediction is

DEF (Zero-One Loss) $L(y, \hat{y}) = \mathbb{I}_{\{y \neq \hat{y}\}}$

DEF (Mean Squared Error (MSE)) $L(y, \hat{y}) = (y - \hat{y})^2$

DEF (Hinge Loss) $L(y, \hat{y}) = \max(0, 1 - y \cdot \hat{y})$

DEF (Gradient Descent) The gradient descent algorithm is given by

$$x_{t+1} = x_t - \eta \nabla f(x_t)$$

where η is the learning rate/step size.

DEF (Convergence) Given $\epsilon > 0$, we say that an algorithm converges to a point x^* if

$$f(x_t) - f(x^*) \leq \epsilon$$

DEF (Convergence Rate) The convergence rate of an algorithm is the rate at which the algorithm converges to the optimal point. There are three types of convergence rates:

- Sublinear: $f(x_t) - f(x^*) \leq \frac{c}{t^2}$ ($\epsilon = O(\frac{1}{t^2}), t = O(\frac{1}{\sqrt{\epsilon}})$)
- Linear: $f(x_t) - f(x^*) \leq cr^t$ ($\epsilon = O(r^t), t = O(\log \frac{1}{\epsilon})$)
- Quadratic: $f(x_t) - f(x^*) \leq cr^{2^t}$

ALG (Stochastic Gradient Descent (SGD)) Sample a random point x_t, y_t from the dataset and compute the gradient at that point. Repeat until solution is satisfactory.

ALG (Mini-batch Gradient Descent) Sample a mini-batch of points x_t, y_t from the dataset and compute the gradient at that point. Repeat until solution is satisfactory.

DEF (Training) The act of minimising the loss function by adjusting the model's parameters is known as training.

Regression

DEF (Regression) The learning of relationships between input variables x and a numerical output y

DEF (Feature Transformation) We call ϕ a feature transformation. It transforms the input space X into a new space Z .

DEF (Linear Regression) Given a dataset $S = \{(\phi(x_1), y_1), \dots, (\phi(x_n), y_n)\}$, minimise the MSE loss function

$$L = \frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2$$

where $\hat{y}_i = w^T \phi(x_i)$

DEF (*Closed-form Solution*) The closed-form solution to linear regression is given by

$$w = (\Phi \Phi^T)^{-1} \Phi y$$

DEF (*Probabilistic Interpretation*) The probabilistic interpretation of linear regression is that

$$y = w^T \phi(x) + \epsilon_i$$

where $\epsilon_i \sim \mathcal{N}(0, 1)$ which implies $y_i \sim \mathcal{N}(w^T \phi(x_i), 1)$. So the log likelihood (L) of the data is

$$L = \sum_{i=1}^N \left[\frac{1}{2} \log(2\pi) - \frac{1}{2} (y_i - w^T \phi(x_i))^2 \right]$$

Classification

DEF (*Classification*) Given a dataset S , the goal is to learn a function h that maps input variables x to y , where y is a class label.

DEF (*Linear Separability*) A dataset is linearly separable if there exists a hyperplane that can separate the data points

DEF (*Training of Classification*) Find parameters θ such that the zero-one loss is minimised

DEF (*Logistic Regression*) A linear classifier that models the probability of a class label. The model is given by

$$p(y|x, \theta) = \sigma(-y\theta^T x) = \frac{1}{1 + \exp(-y(w^T x + b))}$$

where σ is the sigmoid function.

DEF (*Maximum Likelihood Estimation (MLE)*) The MLE of the parameters θ is given by

$$\hat{\theta} = \underset{\theta}{\operatorname{argmax}} \prod_{i=1}^n p(y_i|x_i, \theta)$$

DEF (*Log Likelihood*) The log likelihood is applying log to the MLE to obtain a more numerically stable solution:

$$L = \sum_{i=1}^n \log p(y_i|x_i, \theta)$$

ALG (*Training of Logistic Regression*) The training of logistic regression is done by maximising the log likelihood L of w and b .

$$L = \sum_{i=1}^n \log p(y_i|x_i, \theta)$$

There are no closed-form solutions to this problem, so iterative methods like gradient ascent are used which is equivalent to minimising the negative log likelihood.

DEF (*Multiclass Classification*) Using the softmax function, we can extend logistic regression to multiclass classification. Softmax is defined as

$$\operatorname{softmax} \left(\begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_k \end{bmatrix} \right) = \begin{bmatrix} \frac{e^{z_1}}{\sum_{i=1}^k e^{z_i}} \\ \frac{e^{z_2}}{\sum_{i=1}^k e^{z_i}} \\ \vdots \\ \frac{e^{z_k}}{\sum_{i=1}^k e^{z_i}} \end{bmatrix}$$

Neural Networks

DEF (*Perceptron (Single-layer Neural Network)*) A simple linear classifier that learns a weight vector w to classify data points. The perceptron training algorithm can be used to learn the weights. Can model logical functions like AND, OR and NOT.

THM (*Universal Approximation Theorem*) A single-output node NN with a single hidden layer with finite neurons can approximate finite continuous (and discontinuous) functions

DEF (*Multi-layer Perceptron (MLP) / Feedforward Neural Network (FNN)*) A neural network with multiple layers of perceptrons. The network is feedforward as there are no cycles in the network. It can model complex decision boundaries (piecewise linear) [XOR, etc] The perceptron training algorithm can not be used to learn the weights.

DEF (*Activation Function*) Allows for non-linear decision boundaries. They should be differentiable. Also controls the output range to a specific range. Common activation functions are:

- Sigmoid: $\sigma(x) = \frac{1}{1+e^{-x}}$
- Hyperbolic Tangent (tanh): $\tanh(x) = \frac{1-\exp(-2x)}{1+\exp(-2x)}$
- ReLU: $f(x) = \max(0, x)$ (faster than tanh)
- Leaky ReLU solves the 'dying ReLU' problem

DEF (*Computation Graph*) Represents computation as a directed graph comprising of simple operations on vectors and matrices which allows for automatic differentiation.

Expectation Maximisation

DEF (*K-means Distortion*)

$$J = \sum_{n=1}^N \sum_{k=1}^K r_{nk} \|x_n - \mu_k\|^2$$

DEF (*K-means Steps*) Randomly initialise $\mu_{k=1, \dots, K} \rightarrow$ Minimise J with respect to $r_{nk} \rightarrow$ Minimise J with respect to $\mu_k \rightarrow$ Repeat

DEF (*K-means Solutions*)

$$\mu_k = \frac{\sum_n r_{nk} x_n}{\sum_n r_{nk}}, r_{nk} = \mathbb{I}(k = \arg \min_j \|x_n - \mu_j\|^2)$$

DEF (*GMM Probabilities*)

$$p(z_k = 1) = \pi_k, p(\mathbf{z}) = \prod_{k=1}^K \pi_k^{z_k}, p(\mathbf{x}|\mathbf{z}) = \prod_{k=1}^K \mathcal{N}(x|\mu_k, \Sigma_k)^{z_k}$$

DEF (*Kullback-Leibler Divergence*)

$$KL(p||q) = \mathbb{E}_{x \sim p} \left[\log \frac{p(x)}{q(x)} \right] = \sum_{x \in X} p(x) \log \frac{p(x)}{q(x)}$$