Basic identities of matrix/vector ops
$(A+B)^T = A^T + B^T$ $(AB)^T = B^T A^T$ $(A^{-1})^T = (A^T)^{-1}$
$(AB)^{-1} = B^{-1}A^{-1}$

For $A\in\mathbb{R}^{m\times n}$, A_{ij} is the i-th **ROW** then j-th **COLUMN**
$(A^T)_{ij} = A_{ji}$ $(AB)_{ij} = A_{i*}\cdot B_{*j} = \sum_k A_{ik}B_{kj}$
$(Ax)_i = A_{i*}\cdot x = \sum_j A_{ij}x_j$ $x^Ty = y^Tx = x\cdot y = \sum_i x_iy_i$
$x^TAx = \sum_i\sum_j A_{ij}x_ix_j$

Scalar-multiplication + addition distributes over:
∘**column-blocks** => $\lambda A + B = \lambda[A_1|\dots|A_c] + [B_1|\dots|B_c] = [\lambda A_1 + B_1|\dots|\lambda A_c + B_c]$
∘**row-blocks** => $\lambda A+B = \lambda[A_1;\dots;A_r] + [B_1;\dots;B_r] = [\lambda A_1+B_1;\dots;\lambda A_r+B_r]$
Matrix-multiplication distributes over:
∘**column-blocks** => $AB = A[B_1|\dots|B_p] = [AB_1|\dots|AB_p]$
∘**row-blocks** => $AB = [A_1;\dots;A_p]B = [A_1B;\dots;A_pB]$
∘**outer-product sum** => $AB = [A_1|\dots|A_p][B_1;\dots;B_p] = \sum_{i=1}^p A_iB_i$
–e.g. for $A = [a_1|\dots|a_n]$, $B = [b_1;\dots;b_n]$ => $AB = \sum_i a_ib_i$

Projection: definition & properties
•A **projection** $\pi: V\to V$ is a **endomorphism** such that $\pi\circ\pi = \pi$, i.e. it leaves its image unchanged (its idempotent)
•**A square matrix** P such that $P^2 = P$ is called a **projection matrix**
–It is called an **orthogonal projection matrix** if $P^2 = P = P^T$ (conjugate-transpose)
–Eigenvalues of a **projection matrix** must be 0 or 1
•Because $\pi: V\to V$ is a linear map, its **image space** $U = \text{im}(\pi)$ and **null space** $W = \ker(\pi)$ are **subspaces** of V
–π is the **identity operator** on U
–The **linear map** $\pi^* = I_V - \pi$ is **also** a projection with $W = \text{im}(\pi^*)$ and $U = \ker(\pi^*) = \text{im}(\pi)$, i.e. they swapped
⋆π is a projection **along** W **onto** U
⋆π^* is a projection **along** U **onto** W
⋆π^* is the **identity operator** on W
–V can be decomposed as $V = U\oplus W$ meaning every vector $x\in V$ can be uniquely written as $x = u + w$
⋆$u\in U$ and $u = \pi(x)$
⋆$w\in W$ and $w = x - \pi(x) = (I_V - \pi)(x) = \pi^*(x)$
•An **orthogonal projection** further satisfies $U\perp W$, i.e. the **image** and **kernel** of π are **orthogonal subspaces**
–infact they are eachother's **orthogonal compliments**, i.e. $U^\perp = W, W^\perp = U$ *(because finite-dimensional vectorspaces)*
–so we have $\pi(x)\cdot y = \pi(x)\cdot\pi(y) = x\cdot\pi(y)$
–or equivalently, $\pi(x)\cdot(y - \pi(y)) = (x-\pi(x))\cdot\pi(y) = 0$

•By Cauchy–Schwarz inequality we have $\|\pi(x)\|\le\|x\|$
•The **orthogonal projection on the line** containing vector u is $\text{proj}_u = \hat u\hat u^T$, i.e. $\text{proj}_u(v) = \frac{u\cdot v}{u\cdot u}u$; $\hat u = \frac{u}{\|u\|}$
•A special case of $\pi(x)\cdot(y-\pi(y)) = 0$ is $u\cdot(v - \text{proj}_u v) = 0$ since $\text{proj}_u(u) = u$
•If $U\subseteq\mathbb{R}^n$ is a k-dimensional subspace with **orthonormal basis (ONB)** $\langle u_1,\dots,u_k\rangle\in\mathbb{R}^m$
–Let $U = [u_1|\dots|u_k]\in\mathbb{R}^{m\times k}$ matrix
–**Orthogonal projection onto** U is $\pi_U = UU^T$
–Can be rewritten as $\pi_U(v) = \sum_i (u_i\cdot v)u_i$
–If $\langle u_1,\dots,u_k\rangle$ is **not orthonormal**, then "normalizing factor" $(U^TU)^{-1}$ is added => $\pi_U = U(U^TU)^{-1}U^T$
⋆For **line subspaces** $U = \text{span}\{u\}$ we have $(U^TU)^{-1} = (u^Tu)^{-1} = 1/(u\cdot u) = 1/\|u\|$

Gram-Schmidt (GS) to gen. ONB from lin. ind. vectors
•Gram-Schmidt is **iterative** projection => we use **current** j-**dim subspace**, to get **next** $(j+1)$-**dim subspace**
–Assume **orthonormal basis (ONB)** $\langle q_1,\dots,q_j\rangle\in\mathbb{R}^m$ for j-**dim subspace** $U_j\subset\mathbb{R}^m$
⋆Let $Q_j = [q_1|\dots|q_j]\in\mathbb{R}^{m\times j}$ be the matrix
⋆$P_j = Q_jQ_j^T$ is orthogonal projection **onto** U_j
⋆$P_{\perp j} = I_m - Q_jQ_j^T$ is orthogonal projection **onto** $(U_j)^\perp$ (orthogonal compliment)
–Uniquely decompose next $U_j\not\ni a_{j+1} = v_{j+1} + u_{j+1}$
⋆$v_{j+1} = P_j(a_{j+1})\in U_j$ => discard it!!
⋆$u_{j+1} = P_{\perp j}(a_{j+1})\in(U_j)^\perp$ => we're after this!!
–Let $q_{j+1} = \hat u_{j+1}$ => we have **next ONB** $\langle q_1,\dots,q_{j+1}\rangle$ for U_{j+1} => start next iteration
⋆$u_{j+1} = (I_m - Q_jQ_j^T)a_{j+1} = a_{j+1} - Q_jc_j$ where $c_j = [q_1\cdot a_{j+1},\dots,q_j\cdot a_{j+1}]^T$

⋆**Notice:** $Q_jc_j = \sum_{i=1}^j (q_i\cdot a_{j+1})q_i = \sum_{i=1}^j \text{proj}_{q_i}(a_{j+1})$, so rewrite as
$$u_{j+1} = a_{j+1} - \sum_{i=1}^j (q_i\cdot a_{j+1})q_i = a_{j+1} - \sum_{i=1}^j\text{proj}_{q_i}(a_{j+1})$$
•Let $a_1,\dots,a_n\in\mathbb{R}^m$ $(m\ge n)$ be linearly independent, i.e. basis of n-**dim subspace** $U_n = \text{span}\{a_1,\dots,a_n\}$
–We apply Gram-Schmidt to build **ONB** $\langle q_1,\dots,q_n\rangle\in\mathbb{R}^m$ for $U_n\subset\mathbb{R}^m$
–$j=1$ => $u_1 = a_1$ and $q_1 = \hat u_1$, i.e. ***start of iteration***
–$j=2$ => $u_2 = a_2 - (q_1\cdot a_2)q_1$ and $q_2 = \hat u_2$, **etc...**
–Linear independence ***guarantees*** that $a_{j+1}\notin U_j$
–**For exams**: compute $u_{j+1} = a_{j+1} - Q_jc_j$
1. Gather $Q_j = [q_1|\dots|q_j]\in\mathbb{R}^{m\times j}$
2. Compute $c_j = [q_1\cdot a_{j+1},\dots,q_j\cdot a_{j+1}]^T\in\mathbb{R}^j$
3. Compute $Q_jc_j\in\mathbb{R}^m$, and subtract from a_{j+1}

Properties: dot-product & norm
$x^Ty = y^Tx = x\cdot y = \sum_i x_iy_i$ $x\cdot y = \|a\|\|b\|\cos\widehat{xy}$
$x\cdot y = y\cdot x$ $x\cdot(y+z) = x\cdot y + x\cdot z$ $\alpha x\cdot y = \alpha(x\cdot y)$
$x\cdot x = \|x\|^2 = 0 \iff x = 0$
for $x\ne 0$, we have $x\cdot y = x\cdot z \implies x\cdot(y-z) = 0$
$|x\cdot y|\le\|x\|\|y\|$ (**Cauchy-Schwartz inequality**)
$\|u+v\|^2 + \|u-v\|^2 = 2\|u\|^2 + 2\|v\|^2$ (**parallelogram law**)
$\|u+v\|\le\|u\|+\|v\|$ (**triangle inequality**)
$u\perp v \iff \|u+v\|^2 = \|u\|^2+\|v\|^2$ (**pythagorean theorem**)
$\|c\|^2 = \|a\|^2+\|b\|^2 - 2\|a\|\|b\|\cos\widehat{ab}$ (**law of cosines**)

Transformation matrix & linear maps
For linear map $f:\mathbb{R}^n\to\mathbb{R}^m$, ordered bases $\langle b_1,\dots,b_n\rangle\in\mathbb{R}^n$ and $\langle c_1,\dots,c_m\rangle\in\mathbb{R}^m$
•$A = F_{CB}\in\mathbb{R}^{m\times n}$ is the **transformation-matrix** of f w.r.t to bases B and C
•$f(b_j) = \sum_{i=1}^m A_{ij}c_i$ => each b_j basis gets mapped to a linear combination of $\sum_i a_ic_i$ bases
•If f^{-1} exists *(i.e. its bijective and $m=n$)* then $(F_{CB})^{-1} = F^{-1}{}_{BC}$ *(where $F^{-1}{}_{BC}$ is the **transformation-matrix** of f^{-1})*

The transformation matrix of the identity map is called change-in-basis matrix
•The identity matrix I_m represents id_m w.r.t. the standard basis $E_m = \langle e_1,\dots,e_m\rangle$ => i.e. $I_m = I_{EE}$
•If $B = \langle b_1,\dots,b_m\rangle$ is a basis of $\mathbb{R}^m$, then $I_{EB} = [b_1|\dots|b_m]$ is the transformation matrix from B to E
•$I_{BE} = (I_{EB})^{-1}$, so => $F_{CB} = I_{CE}F_{EE}I_{EB}$

Dot-product uniquely determines a vector w.r.t. to basis
•If $a_j = x\cdot b_j; x = \sum_i a_ib_i$, we call a_j the coordinate-vector of x w.r.t. to B
Rank-nullity theorem:
$\dim(\text{im}(f)) + \dim(\ker(f)) = \text{rk}(A) + \dim(\ker(A)) = n$
f is injective/monomorphism **iff** $\ker(f) = \{0\}$ **iff** A is full-rank

Orthogonality concepts
•$u\perp v \iff u\cdot v = 0$, i.e. u and v are orthogonal
•u and v are orthonormal **iff** $u\perp v$, $\|u\|=1=\|v\|$
•$A\in\mathbb{R}^{n\times n}$ is orthogonal **iff** $A^{-1} = A^T$
–Columns of $A = [a_1|\dots|a_n]$ are orthonormal basis (ONB) $\langle a_1,\dots,a_n\rangle\in\mathbb{R}^n$, so $A = I_{EC}$ is change-in-basis matrix
–Orthogonal transformations preserve lengths/angles/distances => $\|Ax\|_2 = \|x\|_2$, $\widehat{AxAy} = \widehat{xy}$
⋆Therefore can be seen as a succession of reflections and planar rotations
–$\det(A) = 1$ or $\det(A) = -1$, and all **eigenvalues** of A are s.t. $|\lambda| = 1$
•$A\in\mathbb{R}^{m\times n}$ is semi-orthogonal **iff** $A^TA = I$ or $AA^T = I$
–If $n>m$ then **all** m **rows** are orthonormal vectors
–If $n<m$ then **all** n **columns** are orthonormal vectors
•$U\perp V\subset\mathbb{R}^n \iff u\cdot v = 0$ for all $u\in U, v\in V$, i.e. they are **orthogonal subspaces**
•**Orthogonal compliment** of $U\subset\mathbb{R}^n$ is the subspace
$$U^\perp = \{x\in\mathbb{R}^n \mid \forall y\in\mathbb{R}^n: x\perp y\} = \{x\in\mathbb{R}^n \mid \forall y\in\mathbb{R}^n: \|x\|\le\|x+y\|\}$$
–$\mathbb{R}^n = U\oplus U^\perp$ and $(U^\perp)^\perp = U$
–$U\perp V \iff U^\perp = V$ and vice-versa
–$Y\subseteq X \implies X^\perp\subseteq Y^\perp$ and $X\cap X^\perp = \{0\}$
–Any $x\in\mathbb{R}^n$ can be uniquely decomposed into $x = x_j + x_k$ where $x_j\in U$ and $x_k\in U^\perp$
•For matrix $A\in\mathbb{R}^{m\times n}$ and for row-space $R(A)$, column-space $C(A)$ and null space $\ker(A)$
–$R(A)^\perp = \ker(A)$ and $C(A)^\perp = \ker(A^T)$
–Any $b\in\mathbb{R}^m$ can be uniquely decomposed into
⋆$b = b_j + b_k$, where $b_j\in C(A)$ and $b_k\in\ker(A^T)$
⋆$b = b_j + b_k$, where $b_j\in R(A)$ and $b_k\in\ker(A)$

Vector norms (beyond euclidean)
•**vector norms** are such that: $\|x\| = 0\iff x=0$
$|\lambda x| = |\lambda|\|x\|$, $\|x+y\|\le\|x\|+\|y\|$
•ℓ_p norms: $\|x\|_p = (\sum_{i=1}^n |x_i|^p)^{1/p}$
–$p=1$: $\|x\|_1 = \sum_{i=1}^n |x_i|$
–$p=2$: $\|x\|_2 = \sqrt{\sum_{i=1}^n x_i^2} = \sqrt{x\cdot x}$
–$p=\infty$: $\|x\|_\infty = \lim_{p\to\infty}\|x\|_p = \max_{1\le i\le n}|x_i|$
•Any two norms in $\mathbb{R}^n$ are equivalent, meaning there exist $r>0, s>0$ such that:
$\forall x\in\mathbb{R}^n, r\|x\|_a\le\|x\|_b\le s\|x\|_a$
–Equivalence of ℓ_1,ℓ_2 and ℓ_∞ => $\|x\|_\infty\le\|x\|_2\le\|x\|_1$; $\|x\|_2\le\sqrt{n}\|x\|_\infty$; $\|x\|_1\le\sqrt{n}\|x\|_2$
•Induce **metric** $d(x,y) = \|y-x\|$, has additional properties:
–Translation invariance: $d(x+w,y+w) = d(x,y)$
–Scaling: $d(\lambda x,\lambda y) = |\lambda|d(x,y)$

Matrix norms
•**Matrix norms** are such that: $\|A\| = 0 \iff A=0$, $|\lambda A| = |\lambda|\|A\|$, $\|A+B\|\le\|A\|+\|B\|$
–Matrices $\mathbb{F}^{m\times n}$ are a vector space so **matrix norms are vector norms**, all results apply
•**Sub-multiplicative matrix norm** (assumed by default) is also such that $\|AB\|\le\|A\|\|B\|$
•Common matrix norms, for some $A\in\mathbb{R}^{m\times n}$
–$\|A\|_1 = \max_j\|A_{*j}\|_1$
–$\|A\|_2 = \sigma_1(A)$, i.e. largest singular value of A *(square-root of largest eigenvalue of A^TA or AA^T)*
–$\|A\|_\infty = \max_i\|A_{i*}\|_1$, note that $\|A\|_1 = \|A^T\|_\infty$
–**Frobenius norm**: $\|A\|_F = \sqrt{\sum_{i=1}^m\sum_{j=1}^n |A_{ij}|^2}$
•A matrix norm $\|\cdot\|$ on $\mathbb{R}^{m\times n}$ is **consistent** with the vector norms $\|\cdot\|_a$ on $\mathbb{R}^n$ and $\|\cdot\|_b$ on $\mathbb{R}^m$ if
–for all $A\in\mathbb{R}^{m\times n}$ and $x\in\mathbb{R}^n$: $\|Ax\|_b\le\|A\|\|x\|_a$
–If $a=b$, $\|\cdot\|$ is **compatible** with $\|\cdot\|_a$
–Frobenius norm is **consistent** with ℓ_2 norm => $\|Av\|_2\le\|A\|_F\|v\|_2$
•For a vector norm $\|\cdot\|$ on $\mathbb{R}^n$, the **subordinate matrix norm** $\|\cdot\|$ on $\mathbb{R}^{m\times n}$ is
$\|A\| = \max\{\|Ax\| : x\in\mathbb{R}^n, \|x\| = 1\}$
$= \max\{\frac{\|Ax\|}{\|x\|} : x\in\mathbb{R}^n, x\ne0\}$
$= \max\{\|Ax\| : x\in\mathbb{R}^n, \|x\|\le1\}$
•Vector norms are **compatible** with their **subordinate matrix norms**
•For $p=1,2,\infty$ **matrix norm** $\|\cdot\|_p$ is **subordinate** to the vector norm $\|\cdot\|_p$ *(and thus **compatible** with)*

Properties of matrices
Consider $A\in\mathbb{R}^{m\times n}$
If $Ax = x$ for all x then $A = I$
For square A, the **trace** of A is the **sum** of its **diagonals**, i.e. $\text{tr}(A)$

A is symmetric **iff** $A = A^T$, A is Hermitian, iff $A = A^\dagger$, i.e.
•AA^T and A^TA are **symmetric** *(and **positive semi-definite**)*
•For real matrices, **Hermitian/symmetric** are equivalent conditions
•Every eigenvalue λ_j of **Hermitian** matrices is real
–geometric multiplicity of λ_j = geometric multiplicity of λ_j
–eigenvectors x_1, x_2 associated to distinct eigenvalues λ_1,λ_2 are **orthogonal**, i.e. $x_1\perp x_2$

A is triangular **iff** all entries above (***lower-triangular***) or below (***upper-triangular***) the main diagonal are **zero**
•**Determinant** => $|A| = \prod_i a_{ii}$, i.e. the product of diagonal elements

A is diagonal **iff** $A_{ij} = 0, i\ne j$, i.e. if all off-diagonal entries are zero
•Written as $\text{diag}_{m\times n}(a) = \text{diag}_{m\times n}(a_1,\dots,a_p)$, $p = \min(m,n)$, where $a = [a_1,\dots,a_p]^T\in\mathbb{R}^p$ diagonal entries of A
•For $x\in\mathbb{R}^n$, $Ax = \text{diag}_{m\times n}(a_1,\dots,a_p)[x_1\dots x_n]^T = [a_1x_1\dots a_px_p\ 0\dots0]^T$ *(if $p=m$ then those tail-zeros don't exist)*
•$\text{diag}_{m\times n}(a)+\text{diag}_{m\times n}(b) = \text{diag}_{m\times n}(a+b)$
•Consider $\text{diag}_{n\times k}(c_1,\dots,c_q)$, $q = \min(n,k)$, then
$\text{diag}_{m\times n}(a_1,\dots,a_p)\text{diag}_{n\times k}(c_1,\dots,c_q) = \text{diag}_{m\times k}(a_1c_1,\dots,a_rc_r,0,\dots,0) = \text{diag}(s)$
–Where $r = \min(p,q) = \min(m,n,k)$, and $s\in\mathbb{R}^S$, $S = \min(m,k)$
•**Inverse of square-diagonals** => $\text{diag}(a_1,\dots,a_n)^{-1} = \text{diag}(a_1^{-1},\dots,a_n^{-1})$, i.e. diagonals **cannot be zero** *(division by zero undefined)*
•**Determinant of square-diagonals** => $|\text{diag}(a_1,\dots,a_n)| = \prod_i a_i$ *(since they are technically triangular matrices)*

The **(column) rank** of A is number of linearly independent columns, i.e. $\text{rk}(A)$
•I.e. its the **number of pivots** in **row-echelon-form**
–I.e. its the **dimension** of the **column-space** $\text{rk}(A) = \dim(C(A))$
–I.e. its the **dimension** of the **image-space** $\text{rk}(A) = \dim(\text{im}(f_A))$ of linear map $f_A(x) = Ax$
•The **(row) rank** of A is number of linearly independent rows
•The **row/column ranks** are **always the same**, hence $\text{rk}(A) = \dim(C(A)) = \dim(R(A)) = \dim(C(A^T)) = \text{rk}(A^T)$
•A is full-rank **iff** $\text{rk}(A) = \min(m,n)$, i.e. its as linearly independent as possible

Two matrices $A,\tilde A\in\mathbb{R}^{m\times n}$ are **equivalent** if there exist two invertible matrices $P\in\mathbb{R}^{m\times m}$ and $Q\in\mathbb{R}^{n\times n}$ such that $A = P\tilde AQ^{-1}$
Two matrices $A,\tilde A\in\mathbb{R}^{n\times n}$ are **similar** if there exists an invertible matrix $P\in\mathbb{R}^{n\times n}$ such that $A = P\tilde AP^{-1}$
•**Similar** matrices are equivalent, with $Q = P$
A is diagonalisable **iff** A is similar to some diagonal matrix D

Properties of determinants
•Consider $A\in\mathbb{R}^{n\times n}$, then $A_{ij}{}'\in\mathbb{R}^{(n-1)\times(n-1)}$ the (i,j)-**minor matrix** of A, obtained by deleting i-**th row** and j-**th column** from A
•Then we define **determinant** of A, i.e. $\det(A) = |A|$, as
–$\det(A) = \sum_{k=1}^n(-1)^{i+k}A_{ik}\det(A_{ik}{}')$, i.e. expansion along i-**th row** *(for any i)
–$\det(A) = \sum_{k=1}^n(-1)^{k+j}A_{kj}\det(A_{kj}{}')$, i.e. expansion along j-**th column** *(for any j)*
•When $\det(A) = 0$ we call A a **singular matrix**
•Common determinants
–For $n=1$, $\det(A) = A_{11}$
–For $n=2$, $\det(A) = A_{11}A_{22} - A_{12}A_{21}$
–$\det(I_n) = 1$
•**Multi-linearity in columns/rows**: if
$A = [a_1|\dots|a_j|\dots|a_n] = [a_1|\dots|\lambda x_j + \mu y_j|\dots|a_n]$ then
$\det(A) = \lambda\det([a_1|\dots|x_j|\dots|a_n]) + \mu\det([a_1|\dots|y_j|\dots|a_n])$
–And the exact same linearity property for **rows**
–*Immediately* leads to: $|A| = |A^T|$, $|\lambda A| = \lambda^n|A|$, and $|AB| = |BA| = |A||B|$ *(for any $B\in\mathbb{R}^{n\times n}$)*
•**Alternating**: if any **two columns** of A are **equal** *(or any **two rows** of A are **equal**)*, then $|A| = 0$ (its singular)
–*Immediately* from this (and **multi-linearity**) => if **columns *(or rows)*** are linearly-dependent *(some are linear combinations of others)* then $|A| = 0$
–Stated in other terms => $\text{rk}(A)<n \iff |A| = 0 \iff \text{RREF}(A)\ne I_n \iff |A| = 0$ *(reduced row-echelon-form)* $\iff C(A)\ne\mathbb{R}^n \iff |A| = 0$ *(column-space)*
–For more equivalence to the above, see invertible matrix theorem
•Interaction with **EROs/ECOs**:
–**Swapping** rows/columns **flips the sign**
–**Scaling** a row/column by $\lambda\ne0$ will **scale the determinant** by λ *(by multi-linearity)*
⋆Remember to **scale by** λ^{-1} **to maintain equality**, i.e. $\det(A) = \lambda^{-1}\det([a_1|\dots|\lambda a_j|\dots|a_n])$
–Invariant under **addition** of rows/columns
•**Link to invertable matrices** => $|A^{-1}| = |A|^{-1}$ which means A is invertible $\iff |A|\ne0$, i.e. **singular matrices are not invertible**
•For block-matrices:
–$\det\begin{pmatrix}A&B\\0&D\end{pmatrix} = \det(A)\det(B) = \det\begin{pmatrix}A&0\\C&D\end{pmatrix}$
–$\det\begin{pmatrix}A&B\\C&D\end{pmatrix} = \det(A)\det(D - CA^{-1}B) = \det(D)\det(A - BD^{-1}C)$ if A or D are invertible, *respectively*
•**Sylvester's determinant theorem**: $\det(I_m + AB) = \det(I_n + BA)$
•**Matrix determinant lemma**:
–$\det(A + uv^T) = (1 + v^TA^{-1}u)\det(A)$
–$\det(A+UV^T) = \det(I_m + V^TA^{-1}U)\det(A)$
–$\det(A+UWV^T) = \det(W^{-1} + V^TA^{-1}U)\det(W)\det(A)$

Tricks for computing determinant
•If block-triangular matrix then apply $\det\begin{pmatrix}A&B\\0&D\end{pmatrix} = \det(A)\det(B)$
•If *close* to triangular matrix apply **EROs/ECOs** to get it there, then its just product of diagonals
•If **Cholesky/LU/QR** is possible and cheap then do it, then apply $|AB| = |A||B|$
•If all else fails, try to find row/column with **MOST** zeros
–Perform minimal **EROs/ECOs** to get that row/column to be **all-but-one** zeros
⋆Don't forget to keep track of sign-flipping & scaling-factors
–Do Laplace expansion along *that* row/column => notice **all-but-one** minor matrix determinants **go to zero**

Representing EROs/ECOs as transformation matrices
For $A\in\mathbb{R}^{m\times n}$, suppose a sequence of:
•**EROs** transform $A\rightsquigarrow_{\text{EROs}} A'$ => there is matrix R s.t. $RA = A'$
•**ECOs** transform $A\rightsquigarrow_{\text{ECOs}} A'$ => there is matrix C s.t. $AC = A'$
•Both transform $A\rightsquigarrow_{\text{EROs+ECOs}} A'$ => there are matrices R, C s.t. $RAC = A'$

FORWARD: to compute these **transformation matrices**:
•Start with $[I_m \mid A \mid I_n]$, i.e. A and identity matrices
•For every **ERO** on A, do the same to **LHS** (i.e. I_m)
•For every **ECO** on A, do the same to **RHS** (i.e. I_n)
•Once done, you should get $[I_m \mid A \mid I_n]\rightsquigarrow[R \mid A' \mid C]$ with $RAC = A'$

If the sequences of **EROs** and **ECOs** were $R_1,\dots,R_\lambda$ and $C_1,\dots,C_\mu$ *respectively*
•$R = R_\lambda\cdots R_1$ and $C = C_1\cdots C_\mu$, so $(R_\lambda\cdots R_1)A(C_1\cdots C_\mu) = A'$
•$R^{-1} = R_1^{-1}\cdots R_\lambda^{-1}$ and $C^{-1} = C_\mu^{-1}\cdots C_1^{-1}$, where R_i^{-1}, C_j^{-1} are **inverse EROs/ECOs** *respectively*

BACKWARD: once $R_1,\dots,R_\lambda$ and $C_1,\dots,C_\mu$ for which $RAC = A'$ are **known**, starting with $[I_m \mid A \mid I_n]$
•For $i = 1\to\lambda$ perform R_i on A, perform $R_{\lambda-i+1}^{-1}$ on **LHS** (i.e. I_m)
•For $j = 1\to\mu$ perform C_j on A, perform $C_{\mu-j+1}^{-1}$ on **RHS** (i.e. I_n)
•You should get $[I_m \mid A \mid I_n]\rightsquigarrow[R^{-1} \mid A' \mid C^{-1}]$ with $A = R^{-1}A'C^{-1}$

You can mix-and-match the **forward/backward** modes
•i.e. inverse operations in inverse order for one, and operations in normal order for the other
•e.g. you can do $[I_m \mid A \mid I_n]\rightsquigarrow[R^{-1} \mid A' \mid C]$ to get $AC = R^{-1}A'$ => useful for LU factorization

Eigen-values/vectors
•Consider $A\in\mathbb{R}^{n\times n}$, non-zero $x\in\mathbb{C}^n$ is an **eigenvector** with **eigenvalue** $\lambda\in\mathbb{C}$ for A if $Ax = \lambda x$
–If $Ax = \lambda x$ then $A(kx) = \lambda(kx)$ for $k\ne0$, i.e. kx is also an **eigenvector**
–A has at most n distinct **eigenvalues**
•The set of all eigenvectors associated with eigenvalue λ is called **eigenspace** E_λ of A
–$E_\lambda = \ker(A - \lambda I)$
–The **geometric multiplicity** of λ is $\dim(E_\lambda) = \dim(\ker(A-\lambda I))$
•The **spectrum** $Sp(A) = \{\lambda_1,\dots,\lambda_n\}$ of A is the set of all eigenvalues of A
•The **characteristic polynomial** of A is $P(\lambda) = |A - \lambda I| = \sum_{i=0}^n a_i\lambda^i$
–$a_0 = |A|$, $a_{n-1} = (-1)^{n-1}\text{tr}(A)$, $a_n = (-1)^n$
–$\lambda\in\mathbb{C}$ is eigenvalue of A **iff** λ is a root of $P(\lambda)$
–The **algebraic multiplicity** of λ is the **number of times** it is **repeated as root** of $P(\lambda)$
–$1\le$ geometric multiplicity of λ $\le$ algebraic multiplicity of λ
•Let $\lambda_1,\dots,\lambda_n\in\mathbb{C}$ be *(potentially non-distinct)* **eigenvalues** of A, with $x_1,\dots,x_n\in\mathbb{C}^n$ their **eigenvectors**
–$\text{tr}(A) = \sum_i\lambda_i$ and $\det(A) = \prod_i\lambda_{ij}$
–A is diagonalisable **iff** there exist a basis of $\mathbb{R}^n$ consisting of $x_1,\dots,x_n$
–A is diagonalisable **iff** $r_i = g_i$, where r_i = geometric multiplicity of λ_i and g_i = geometric multiplicity of λ_i
–**Eigenvalues** of A^k are $\lambda_1,\dots,\lambda_n$
•Let $P = [x_1|\dots|x_n]$, then
$AP = [\lambda_1x_1|\dots|\lambda_nx_n] = [x_1|\dots|x_n]\text{diag}(\lambda_1,\dots,\lambda_n) = PD$
=> if P^{-1} exists then
–$A = PDP^{-1}$, i.e. A is diagonalisable
–$P = I_{EB}$ is **change-in-basis** matrix for basis $B = \langle x_1,\dots,x_n\rangle$ of eigenvectors
–If $A = F_{EE}$ is transformation-matrix of linear map f, then $F_{EE} = I_{EB}F_{BB}I_{BE}$
•**Spectral theorem**: if A is Hermitian then P^{-1} exists:
–If x_i, x_j associated to different eigenvalues then $x_i\perp x_j$
–If associated to same eigenvalue λ then **eigenspace** E_λ has spanning-set $\{x_{\lambda_i},\dots\}$
⋆$x_1,\dots,x_n$ are linearly independent => apply Gram-Schmidt $q_{\lambda_i},\dots\leftarrow x_{\lambda_i},\dots$
⋆Then $\{q_{\lambda_i},\dots\}$ is orthonormal basis (ONB) of E_λ
–$Q = \langle q_1,\dots,q_n\rangle$ is an ONB of $\mathbb{R}^n$ => $Q = [q_1|\dots|q_n]$ is orthogonal matrix i.e. $Q^{-1} = Q^T$
–$q_1,\dots,q_n$ are still eigenvectors of A => $A = QDQ^T$ ***(spectral decomposition)***
–$A = QDQ^T$ can be interpreted as scaling in direction of its eigenvectors:
1. Perform a succession of reflections/planar rotations to change coordinate-system
2. Apply scaling by λ_i to each dimension q_i
3. Undo those reflections/planar rotations

Extension to $\mathbb{C}^n$
•Standard inner product: $\langle x,y\rangle = x^\dagger y = \sum_i\overline{x_i}y_i$
–**Conjugate-symmetric**: $\langle x,y\rangle = \overline{\langle y,x\rangle}$
•Standard *(induced)* norm: $\|x\| = \sqrt{\langle x,y\rangle} = \sqrt{x^\dagger y}$
•We can diagonalise real matrices in $\mathbb{C}$ which lets us diagonalise more matrices than before

Least Square Method
If we are solving $Ax = b$ and $b\notin C(A)$, *i.e. no solution*, then **Least Square Method** is:
•Finding x which **minimizes** $\|Ax - b\|_2$
•Recall for $A\in\mathbb{R}^{m\times n}$ we have unique decomposition for any $b\in\mathbb{R}^m$: $b = b_i + b_k$
–where $b_i\in C(A)$ and $b_k\in\ker(A^T)$
•$\|Ax - b\|_2$ is minimized $\iff \|Ax - b_i\|_2 = 0 \iff Ax = b_i$

$A^TAx = A^Tb$ is the **normal equation** which gives solution to least square problem:
$\|Ax - b\|_2$ is minimized $\iff Ax = b_i \iff A^TAx = A^Tb$

Linear Regression
•Let $y = f(t) = \sum_{j=1}^n s_jf_j(t)$ be a **mathematical model**, where f_j are **basis functions** and s_j are **parameters**
•Let (t_i, y_i), $1\le i\le m$, $m\gg n$ be a set of **observations**, and $t, y\in\mathbb{R}^m$ are vectors representing those **observations**
–$f_j(t) = [f_j(t_1),\dots,f_j(t_m)]^T$ is **transformed vector**
–$A = [f_1(t)|\dots|f_n(t)]\in\mathbb{R}^{m\times n}$ is a matrix of columns
–$z = [s_1,\dots,s_n]^T$ is vector of parameters
•Then we get equation $Az = y$ => **minimizing** $\|Az - y\|_2$ is the solution to Linear Regression
–So applying **LSM** to $Az = y$ is *precisely* what **Linear Regression** is
–We can use normal equations for this => $\|Az - y\|_2$ is minimized $\iff A^TAz = A^Ty$
•Solution to **normal equations** unique **iff** A is full-rank, i.e. it has linearly-independent columns

Positive (semi-)definite matrices
Consider symmetric $A\in\mathbb{R}^{n\times n}$, i.e. $A = A^T$
A is positive-definite **iff** $x^TAx>0$ for all $x\ne0$
•A is positive-definite **iff** all its eigenvalues are **strictly positive**
•A is positive-definite => all its diagonals are **strictly positive**
•A is positive-definite => $\max(A_{ii}, A_{jj}) > |A_{ij}|$, i.e. **strictly larger coefficient** on the diagonals
•A is positive-definite => all **upper-left submatrices** are *also* positive-definite
•**Sylvester's criterion**: A is positive-definite **iff** all **upper-left submatrices** have strictly positive determinant

A is positive semi-definite **iff** $x^TAx\ge0$ for all x
•A is positive semi-definite **iff** all its eigenvalues are **non-negative**
•A is positive semi-definite => all its diagonals are **non-negative**
•A is positive semi-definite => $\max(A_{ii}, A_{jj})\ge|A_{ij}|$, i.e. **no coefficient larger** than on the diagonals
•A is positive semi-definite => all **upper-left submatrices** are *also* positive semi-definite
•A is positive semi-definite => it has a Cholesky Decomposition

For any $M\in\mathbb{R}^{m\times n}$, MM^T and M^TM are symmetric and **positive semi-definite**

Singular Value Decomposition (SVD) & Singular Values
Singular Value Decomposition of $A\in\mathbb{R}^{m\times n}$ is *any decomposition of the form* $A = USV^T$, where
•Orthogonal $U = [u_1|\dots|u_m]\in\mathbb{R}^{m\times m}$ and $V = [v_1|\dots|v_n]\in\mathbb{R}^{n\times n}$
•$S = \text{diag}_{m\times n}(\sigma_1,\dots,\sigma_p)$ where $p = \min(m,n)$ and $\sigma_1\ge\dots\ge\sigma_p\ge0$
•$\sigma_1,\dots,\sigma_p$ are **singular values** of A,
–*(Positive)* **singular values** are *(positive)* **square-roots of eigenvalues** of AA^T or A^TA
–i.e. $\sigma_1^2,\dots,\sigma_p^2$ are **eigenvalues** of AA^T or A^TA
–$\|A\|_2 = \sigma_1$ *(link to matrix norms)*
Let $r = \text{rk}(A)$, then number of strictly positive **singular values** is r
•i.e. $\sigma_1\ge\dots\ge\sigma_r>0$ and $\sigma_{r+1} = \dots = \sigma_p = 0$
•$A = \sum_{i=1}^r\sigma_iu_iv_i^T$

SVD is *similar* to spectral decomposition, except it always exists
If $n\le m$ then work with $A^TA\in\mathbb{R}^{n\times n}$:
•Obtain eigenvalues $\sigma_1^2\ge\dots\ge\sigma_n^2\ge0$ of A^TA
•Obtain **orthonormal** eigenvectors $v_1,\dots,v_n\in\mathbb{R}^n$ of A^TA (apply **normalization** e.g. **Gram-Schmidt**!!!! to **eigenspaces** E_{σ_i})
•$V = [v_1|\dots|v_n]\in\mathbb{R}^{n\times n}$ is orthogonal so $V^T = V^{-1}$
•$r = \text{rk}(A)$ = no. of strictly +ve σ_i
•Let $u_i = \frac{1}{\sigma_i}Av_i$ then $u_1,\dots,u_r\in\mathbb{R}^m$ are **orthonormal** *(therefore linearly independent)*
–The orthogonal compliment of $\text{span}\{u_1,\dots,u_r\}$ => $\text{span}\{u_1,\dots,u_r\}^\perp = \text{span}\{u_{r+1},\dots,u_m\}$
⋆Solve for unit-vector u_{r+1} s.t. it is orthogonal to $u_1,\dots,u_r$
⋆Then solve for unit-vector u_{r+2} s.t. it is orthogonal to $u_1,\dots,u_{r+1}$
⋆And so on…
–$U = [u_1|\dots|u_m]\in\mathbb{R}^{m\times m}$ is orthogonal so $U^T = U^{-1}$
•$S = \text{diag}_{m\times n}(\sigma_1,\dots,\sigma_n)$, **AND DONE!!!**
If $m<n$ then let $B = A^T$
•apply above method to B => $B = A^T = USV^T$
•$A = B^T = VS^TU^T$

Tricks: Computing orthonormal vector-set extensions
You have **orthonormal** vectors $u_1,\dots,u_r\in\mathbb{R}^m$ => need to **extend** to **orthonormal** vectors $u_1,\dots,u_m\in\mathbb{R}^m$
Special case => two 3D vectors => use **cross-product** => $a\times b\perp a, b$

Extension via standard basis $I_m = [e_1|\dots|e_m]$ using (tweaked) GS:
•**Choose candidate vector**: just work through $e_1,\dots,e_m$ sequentially starting from e_1 => denote the current candidate e_k
•**Orthogonalize**: Starting from $j = r$ going to $j = m$ with each iteration => with current orthonormal vectors $u_1,\dots,u_j$
–Compute $w_{j+1} = e_k - \sum_{i=1}^j(e_k\cdot u_i)u_i = e_k - \sum_{i=1}^j(u_i)_ku_i$
$= e_k - U_jc_j$
–Where $U_j = [u_1|\dots|u_j]$ and $c_j = [(u_1)_k,\dots,(u_j)_k]^T$
–**NOTE:** $e_k\cdot u_i = (u_i)_k$, i.e. k-th component of u_i
–If $w_{j+1} = 0$ then $e_k\in\text{span}\{u_1,\dots,u_j\}$ => discard w_{j+1}, choose next candidate e_{k+1}, try this step again
•**Normalize**: $w_{j+1}\ne0$ so compute unit vector $u_{j+1} = \hat w_{j+1}$
•**Repeat**: keep repeating the above steps, now with **new** orthonormal vectors $u_1,\dots,u_{j+1}$

SVD Application: Principal Component Analysis (PCA)
Assume $A_{\text{uncentered}}\in\mathbb{R}^{m\times n}$ represent m **samples** of n-**dimensional data** *(with $m\ge n$)*
•**Data centering**: subtract mean of each column from that column's elements
•Let the **resulting matrix** be $A\in\mathbb{R}^{m\times n}$, who's **columns** have **mean zero**
PCA is done on **centered** data-matrices like A:
•SVD exists i.e. $A = USV^T$ and $r = \text{rk}(A)$
•Let $A = [r_1;\dots;r_m]$ be rows $r_1,\dots,r_m\in\mathbb{R}^n$ => each row *corresponds to* a sample
•Let $A = [c_1|\dots|c_n]$ be columns $c_1,\dots,c_n\in\mathbb{R}^m$ => each column *corresponds to* one dimension of the data
Let $X_1,\dots,X_n$ be **random variables** where each X_i *corresponds* to column c_i
•i.e. each X_i *corresponds* to i-th component of data
•i.e. random vector $X = [X_1,\dots,X_n]^T$ models the data $r_1,\dots,r_m$
•**Co-variance matrix** of X is $\text{Cov}(A) = \frac{1}{m-1}A^TA$ => $(A^TA)_{ij} = (A^TA)_{ji} = \text{Cov}(X_i, X_j)$

$v_1,\dots,v_r$ *(columns of V)* are **principal axes** of A
Let $w\in\mathbb{R}^n$ be some unit-vector => let $\alpha_j = r_j\cdot w$ be the **projection/coordinate** of sample r_j onto w
•**Variance (Bessel's correction)** of $\alpha_1,\dots,\alpha_m$ is
$$\text{Var}_w = \frac{1}{m-1}\sum_j\alpha_j^2 = \frac{1}{m-1}w^T\left(\sum_j r_j^Tr_j\right)w = \frac{1}{m-1}w^TA^TAw$$
•**First (principal) axis defined** =>
$w_{(1)} = \arg\max_{\|w\|=1}w^TA^TAw$
$= \arg\max_{\|w\|=1}(m-1)\text{Var}_w = v_1$
•i.e. $w_{(1)}$ the direction that maximizes variance Var_w, i.e. maximizes variance of **projections on line** $\mathbb{R}w_{(1)}$
$\sigma_1u_1,\dots,\sigma_ru_r$ *(columns of US)* are **principal components/scores** of A
•Recall: $A = \sum_{i=1}^r\sigma_iu_iv_i^T$ with $\sigma_1\ge\dots\ge\sigma_r>0$, so that relates principal axes and principal components
•**Data compression**: If $\sigma_1\gg\sigma_2$ then **compress** A by projecting in direction of principal component => $A\approx\sigma_1u_1v_1^T$

Cholesky Decomposition
Consider **positive (semi-)definite** $A\in\mathbb{R}^{n\times n}$
Cholesky Decomposition is $A = LL^T$ where L is lower-triangular
•For positive semi-definite => **always exists**, but **non-unique**
•For positive-definite => **always *uniquely* exists** s.t. diagonals of L are positive

Finding a Cholesky Decomposition:
•Compute LL^T and solve $A = LL^T$ by matching terms
•For square roots always pick positive
•If there is **exact solution** then **positive-definite**
•If there are **free variables** at the end, then **positive semi-definite**
–i.e. the decomposition is a **solution-set** parameterized on **free variables**
–e.g. $\begin{bmatrix}1&1&1\\1&1&1\\1&1&2\end{bmatrix} = LL^T$ where $L = \begin{bmatrix}1&0&0\\1&0&0\\1&c&\sqrt{1-c^2}\end{bmatrix}$, $c\in[0,1]$

If $A = LL^T$ you can use forward/backward substitution to **solve equations**
•For $Ax = b$ => let $y = L^Tx$
•Solve $Ly = b$ by forward substitution to **find** y
•Solve $L^Tx = y$ by backward substitution to **find** x
For $n=3$ => $L = \begin{bmatrix}l_{11}&0&0\\l_{21}&l_{22}&0\\l_{31}&l_{32}&l_{33}\end{bmatrix}$,
$$LL^T = \begin{bmatrix}l_{11}^2 & l_{11}l_{21} & l_{11}l_{31}\\ l_{11}l_{21} & l_{21}^2+l_{22}^2 & l_{21}l_{31}+l_{22}l_{32}\\ l_{11}l_{31} & l_{21}l_{31}+l_{22}l_{32} & l_{31}^2+l_{32}^2+l_{33}^2\end{bmatrix}$$

Forward/backward substitution
•**Forward substitution**: for lower-triangular
$L = \begin{bmatrix}\ell_{1,1}&&0\\\vdots&\ddots&\\\ell_{n,1}&\cdots&\ell_{n,n}\end{bmatrix}$
–For $Lx = b$, just **solve** the first row
$\ell_{1,1}x_1 = b_1 \implies x_1 = \frac{b_1}{\ell_{1,1}}$ and **substitute down**
–Then **solve** the second row
$\ell_{2,1}x_1 + \ell_{2,2}x_2 = b_2 \implies x_2 = \frac{b_2 - \ell_{2,1}x_1}{\ell_{2,2}}$ and **substitute down**
–…and so on until all x_i are solved
•**Backward substitution**: for upper-triangular
$U = \begin{bmatrix}u_{1,1}&\cdots&u_{1,n}\\&\ddots&\vdots\\0&&u_{n,n}\end{bmatrix}$
–For $Ux = b$, just **solve** the last row
$u_{n,n}x_n = b_n \implies x_n = \frac{b_n}{u_{n,n}}$ and **substitute up**
–Then **solve** the second-to-last row
$u_{n-1,n-1}x_{n-1} + u_{n-1,n}x_n = b_{n-1} \implies x_{n-1} = \frac{b_{n-1} - u_{n-1,n-1}x_{n-1}}{u_{n-1,n}}$ and **substitute up**
–…and so on until all x_i are solved

Thin QR Decomposition w/ Gram-Schmidt (GS)
Consider **full-rank** $A = [a_1|\dots|a_n]\in\mathbb{R}^{m\times n}$ $(m\ge n)$, i.e. $a_1,\dots,a_n\in\mathbb{R}^m$ are linearly independent
•Apply GS $q_1,\dots,q_n\leftarrow\text{GS}(a_1,\dots,a_n)$ to build **ONB** $\langle q_1,\dots,q_n\rangle\in\mathbb{R}^m$ for $C(A)$
•**For exams**: more efficient to compute as $u_{j+1} = a_{j+1} - Q_jc_j$
1. Gather $Q_j = [q_1|\dots|q_j]\in\mathbb{R}^{m\times j}$ **all-at-once**
2. Compute $c_j = [q_1\cdot a_{j+1},\dots,q_j\cdot a_{j+1}]^T\in\mathbb{R}^j$ **all-at-once**
3. Compute $Q_jc_j\in\mathbb{R}^m$, and subtract from a_{j+1} **all-at-once**
•Can now rewrite $a_j = \sum_{i=1}^j(q_i\cdot a_j)q_i = Q_jc_j$

Choose $Q = Q_n = [q_1|\dots|q_n]\in\mathbb{R}^{m\times n}$, notice its semi-orthogonal since $Q^TQ = I_n$
•Notice => $a_j = Q_jc_j = Q[q_1\cdot a_j,\dots,q_j\cdot a_j,0,\dots,0]^T = Qr_j$
•Let $R = [r_1|\dots|r_n]\in\mathbb{R}^{n\times n}$ =>
$A = QR = Q\begin{bmatrix}q_1^Ta_1&\cdots&q_1^Ta_n\\&\ddots&\vdots\\0&&q_n^Ta_n\end{bmatrix}$, notice its upper-triangular

Full QR Decomposition
•Consider **full-rank** $A = [a_1|\dots|a_n]\in\mathbb{R}^{m\times n}$ $(m\ge n)$, i.e. $a_1,\dots,a_n\in\mathbb{R}^m$ are linearly independent
•Apply QR decomposition to obtain:
–ONB $\langle q_1,\dots,q_n\rangle\in\mathbb{R}^m$ for $C(A)$
–Semi-orthogonal $Q_1 = [q_1|\dots|q_n]\in\mathbb{R}^{m\times n}$ and

upper-triangular $R_1 \in \mathbb{R}^{n\times n}$, where $A = Q_1 R_1$
•Compute basis extension to obtain remaining $\mathbf{q}_{n+1},\dots,\mathbf{q}_m \in \mathbb{R}^m$, where $\langle \mathbf{q}_1,\dots,\mathbf{q}_m\rangle$ is **ONB** for $\mathbb{R}^m$
–Notice $\langle \mathbf{q}_{n+1},\dots,\mathbf{q}_m\rangle$ is **ONB** for $C(A)^\perp = \ker(A^T)$
–Let $Q_2 = [\mathbf{q}_{n+1} | \dots | \mathbf{q}_m] \in \mathbb{R}^{m\times(m-n)}$, let $Q = [Q_1 | Q_2] \in \mathbb{R}^{m\times m}$, let $R = [R_1; \mathbf{0}_{m-n}] \in \mathbb{R}^{m\times n}$
•Then **full QR decomposition** is

$$A = QR = [Q_1 | Q_2]\begin{bmatrix} R_1 \\ \mathbf{0}_{m-n}\end{bmatrix} = Q_1 R_1$$

–Q is **orthogonal**, i.e. $Q^{-1} = Q^T$, so its a basis transformation
–$\mathrm{proj}_{C(A)} = Q_1 Q_1^T$, $\mathrm{proj}_{C(A)^\perp} = Q_2 Q_2^T$ are orthogonal projections **onto** $C(A)$, $C(A)^\perp = \ker(A^T)$ *respectively*
–Notice: $QQ^T = \mathbf{I}_m = Q_1 Q_1^T + Q_2 Q_2^T$
•**Generalizable** to $A \in \mathbb{C}^{m\times n}$ by changing transpose to conjugate-transpose

Lines and hyperplanes in $\mathbb{E}^n (=\mathbb{R}^n)$

Consider **standard Euclidean space** $\mathbb{E}^n (=\mathbb{R}^n)$
•with standard basis $\langle \mathbf{e}_1,\dots,\mathbf{e}_n\rangle \in \mathbb{R}^n$
•with standard origin $\mathbf{0} \in \mathbb{R}^n$

A **line** $L = \mathbb{R}\mathbf{n} + \mathbf{c}$ is *characterized* by direction $\mathbf{n} \in \mathbb{R}^n$ ($\mathbf{n} \neq \mathbf{0}$) and offset from origin $\mathbf{c} \in L$
•It is customary that:
–$\mathbf{n}$ is a **unit vector**, i.e. $\|\mathbf{n}\| = \|\hat{\mathbf{n}}\| = 1$
–$\mathbf{c} \in L$ is **closest point to origin**, i.e. $\mathbf{c} \perp \mathbf{n}$
•If $\mathbf{c} \neq \lambda\mathbf{n}$ => L **not** vector-subspace of $\mathbb{R}^n$
–i.e. $\mathbf{0} \notin L$, i.e. L doesn't go through the origin
–L **is** affine-subspace of $\mathbb{R}^n$
•If $\mathbf{c} = \lambda\mathbf{n}$, i.e. $L = \mathbb{R}\mathbf{n}$ => L **is** vector-subspace of $\mathbb{R}^n$
–i.e. $\mathbf{0} \in L$, i.e. L goes through the origin
–L has $\dim(L) = 1$ and orthonormal basis (ONB) $\{\hat{\mathbf{n}}\}$

A **hyperplane** $P = (\mathbb{R}\mathbf{n})^\perp + \mathbf{c} = \{x + \mathbf{c} \mid x \in \mathbb{R}^n, x \perp \mathbf{n}\} = \{x \in \mathbb{R}^n \mid x \cdot \mathbf{n} = \mathbf{c}\cdot\mathbf{n}\}$ is *characterized* by normal $\mathbf{n} \in \mathbb{R}^n$ ($\mathbf{n} \neq \mathbf{0}$) and offset from origin $\mathbf{c} \in P$
•It *represents* an $(n-1)$-**dimensional slice** of the n-**dimensional space**
•It is customary that:
–$\mathbf{n}$ is a **unit vector**, i.e. $\|\mathbf{n}\| = \|\hat{\mathbf{n}}\| = 1$
–$\mathbf{c} \in P$ is **closest point to origin**, i.e. $\mathbf{c} = \lambda\mathbf{n}$
–With those => $P = \{x \in \mathbb{R}^n \mid x \cdot \mathbf{n} = \lambda\}$
•If $\mathbf{c}\cdot\mathbf{n} \neq 0$ => P **not** vector-subspace of $\mathbb{R}^n$
–i.e. $\mathbf{0} \notin P$, i.e. P doesn't go through the origin
–P **is** affine-subspace of $\mathbb{R}^n$
•If $\mathbf{c}\cdot\mathbf{n} = 0$, i.e. $P = (\mathbb{R}\mathbf{n})^\perp$ => P **is** vector-subspace of $\mathbb{R}^n$
–i.e. $\mathbf{0} \in P$, i.e. P goes through the origin
–P has $\dim(P) = n-1$

Notice $L = \mathbb{R}\mathbf{n}$ and $P = (\mathbb{R}\mathbf{n})^\perp$ are orthogonal compliments, so:
•$\mathrm{proj}_L = \hat{\mathbf{n}}\hat{\mathbf{n}}^T$ is orthogonal projection **onto** L (*along* P)
•$\mathrm{proj}_P = \mathrm{id}_{\mathbb{R}^n} - \mathrm{proj}_L = \mathbf{I}_n - \hat{\mathbf{n}}\hat{\mathbf{n}}^T$ is orthogonal projection **onto** P *(**along** L)
•$L = \mathrm{im}(\mathrm{proj}_L) = \ker(\mathrm{proj}_P)$ and $P = \ker(\mathrm{proj}_L) = \mathrm{im}(\mathrm{proj}_P)$
•$\mathbb{R}^n = \mathbb{R}\mathbf{n} \oplus (\mathbb{R}\mathbf{n})^\perp$, i.e. all vectors $\mathbf{v} \in \mathbb{R}^n$ uniquely decomposed into $\mathbf{v} = \mathbf{v}_L + \mathbf{v}_P$

Householder Maps: reflections

•Two points $\mathbf{x}, \mathbf{y} \in \mathbb{E}^n$ are **reflections** w.r.t hyperplane $P = (\mathbb{R}\mathbf{n})^\perp + \mathbf{c}$ if:
1) The translation $\vec{\mathbf{xy}} = \mathbf{y} - \mathbf{x}$ is ***parallel*** to normal $\mathbf{n}$, i.e. $\vec{\mathbf{xy}} = \lambda\mathbf{n}$
2) Midpoint $m = 1/2(\mathbf{x}+\mathbf{y}) \in P$ ***lies*** on P, i.e. $m \cdot \mathbf{n} = \mathbf{c}\cdot\mathbf{n}$
•Suppose $P_{\boldsymbol{u}} = (\mathbb{R}\boldsymbol{u})^\perp$ goes through the origin with unit normal $\boldsymbol{u} \in \mathbb{R}^n$
–**Householder matrix** $H_{\boldsymbol{u}} = \mathbf{I}_n - 2\boldsymbol{u}\boldsymbol{u}^T$ is reflection w.r.t. hyperplane $P_{\boldsymbol{u}}$
–Recall: let $L_{\boldsymbol{u}} = \mathbb{R}\boldsymbol{u}$
⋆$\mathrm{proj}_{L_{\boldsymbol{u}}} = \boldsymbol{u}\boldsymbol{u}^T$ and $\mathrm{proj}_{P_{\boldsymbol{u}}} = \mathbf{I}_n - \boldsymbol{u}\boldsymbol{u}^T$ => $H_{\boldsymbol{u}} = \mathrm{proj}_{P_{\boldsymbol{u}}} - \mathrm{proj}_{L_{\boldsymbol{u}}}$
⋆**Visualize** as preserving component in $P_{\boldsymbol{u}}$, then flipping component in $L_{\boldsymbol{u}}$
–$H_{\boldsymbol{u}}$ is involutory, orthogonal and symmetric, i.e. $H_{\boldsymbol{u}} = H_{\boldsymbol{u}}^{-1} = H_{\boldsymbol{u}}^T$

Modified Gram-Schmidt

•Go check [[tutorial 1#Gram-Schmidt method to generate orthonormal basis from any linearly independent vectors|Classical GM]] first, as this is just an alternative computation method
•Let $\mathrm{P}_{\perp \mathbf{q}_j} = \mathbf{I}_m - \mathbf{q}_j\mathbf{q}_j^T$ be ***projector*** onto [[tutorial 5#Lines and hyperplanes in Euclidean space $ mathbb{E} {n}({=} mathbb{R} {n})$|hyperplane]] $(\mathbb{R}\mathbf{q}_j)^\perp$, i.e. [[tutorial 5#Lines and hyperplanes in Euclidean space $ mathbb{E} {n}({=} mathbb{R} {n})$|orthogonal compliment]] of line $\mathbb{R}\mathbf{q}_j$

–Notice: $\mathrm{P}_{\perp j} = \mathbf{I}_m - Q_j Q_j^T = \prod_{i=1}^{j}\left(\mathbf{I}_m - \mathbf{q}_i\mathbf{q}_i^T\right) = \prod_{i=1}^{j} \mathrm{P}_{\perp \mathbf{q}_i}$
⋆[[tutorial 1#Column-wise & row-wise matrix/vector ops|Outer-product sum equivalence]] =>

$$Q_j Q_j^T = [\mathbf{q}_1 | \dots | \mathbf{q}_j][\mathbf{q}_1^T; \dots; \mathbf{q}_j^T] = \sum_{i=1}^{j} \mathbf{q}_i\mathbf{q}_i^T$$

⋆For $i \neq k$, $\_$ =>

$$\prod_{i=1}^{j}\left(\mathbf{I}_m - \mathbf{q}_i\mathbf{q}_i^T\right) = \mathbf{I}_m - \sum_{i=1}^{j}\mathbf{q}_i\mathbf{q}_i^T = \mathbf{I}_m - Q_j Q_j^T$$

–Re-state: $\mathbf{u}_{j+1} = \left(\mathbf{I}_m - Q_j Q_j^T\right)\mathbf{a}_{j+1}$ =>

$$\mathbf{u}_{j+1} = \left(\prod_{i=1}^{j}\mathrm{P}_{\perp \mathbf{q}_i}\right)\mathbf{a}_{j+1} = \left(\mathrm{P}_{\perp \mathbf{q}_j} \cdots \mathrm{P}_{\perp \mathbf{q}_1}\right)\mathbf{a}_{j+1}$$

–**Projectors** $\mathrm{P}_{\perp \mathbf{q}_1}, \dots, \mathrm{P}_{\perp \mathbf{q}_j}$ are iteratively applied to $\mathbf{a}_{j+1}$, removing its components along $\mathbf{q}_1$, then along $\mathbf{q}_2$, *and so on…*
•Let $\mathbf{u}_k^{(j)} = \left(\prod_{i=1}^{j}\mathrm{P}_{\perp \mathbf{q}_i}\right)\mathbf{a}_k$, i.e. $\mathbf{a}_k$ ***without*** its components along $\mathbf{q}_1, \dots, \mathbf{q}_j$
–Notice: $\mathbf{u}_j = \mathbf{u}_j^{(j-1)}$, thus $\mathbf{q}_j = \hat{\mathbf{u}}_j = \mathbf{u}_j^{(j-1)}/r_{jj}$ where $r_{jj} = \left\|\mathbf{u}_j^{(j-1)}\right\|$
–Iterative step: $\mathbf{u}_k^{(j)} = \left(\mathrm{P}_{\perp \mathbf{q}_j}\right)\mathbf{u}_k^{(j-1)} = \mathbf{u}_k^{(j-1)} - \left(\mathbf{q}_j \cdot \mathbf{u}_k^{(j-1)}\right)\mathbf{q}_j$
–i.e. each **iteration** j of MGS computes $\mathrm{P}_{\perp \mathbf{q}_j}$ *(and projections under it)* **in one go**
•At ***start*** of iteration $j \in 1..n$ we have ONB $\mathbf{q}_1, \dots, \mathbf{q}_{j-1} \in \mathbb{R}^m$ and residual $\mathbf{u}_j^{(j-1)}, \dots, \mathbf{u}_n^{(j-1)} \in \mathbb{R}^m$
–Compute $r_{jj} = \left\|\mathbf{u}_j^{(j-1)}\right\|$ => $\mathbf{q}_j = \mathbf{u}_j^{(j-1)}/r_{jj}$
–For each $k \in (j+1)..n$, compute $r_{jk} = \mathbf{q}_j \cdot \mathbf{u}_k^{(j-1)}$ => $\mathbf{u}_k^{(j)} = \mathbf{u}_k^{(j-1)} - r_{jk}\mathbf{q}_j$
–We have **next ONB** $\langle \mathbf{q}_1, \dots, \mathbf{q}_j\rangle$ and **next residual** $\mathbf{u}_{j+1}^{(j)}, \dots, \mathbf{u}_n^{(j)}$
–NOTE: for $j = 1$ => $\mathbf{q}_1, \dots, \mathbf{q}_{j-1} = \varnothing$, i.e. we don't have any yet
•By ***end*** of iteration $j = n$, we have **ONB** $\langle \mathbf{q}_1, \dots, \mathbf{q}_n\rangle \in \mathbb{R}^m$ of n-**dim subspace** $U_n = \mathrm{span}\{\mathbf{a}_1, \dots, \mathbf{a}_n\}$

$$A = [\mathbf{a}_1 | \dots | \mathbf{a}_n] = [\mathbf{q}_1 | \dots | \mathbf{q}_n]\begin{bmatrix} r_{11} & \cdots & r_{1n} \\ & \ddots & \vdots \\ 0 & & r_{nn}\end{bmatrix} = QR$$

corresponds to [[tutorial 5#Thin QR Decomposition w/ Gram-Schmidt (GS)|thin QR decomposition]]
–Where $A \in \mathbb{R}^{m\times n}$ is full-rank, $Q \in \mathbb{R}^{m\times n}$ is semi-orthogonal, and $R \in \mathbb{R}^{n\times n}$ is upper-triangular

Classical vs. Modified Gram-Schmidt (for thin QR)

•These algorithms both compute [[tutorial 5#Thin QR Decomposition w/ Gram-Schmidt (GS)|thin QR decomposition]] ![[Pasted image 20250418034701.png|400]] ![[Pasted image 20250418034855.png|400]]
•Computes at j-th step:
–**Classical GS** => j-th column of Q and the j-th column of R
–**Modified GS** => j-th column of Q and the j-th row of R
•Both have **flop (floating-point operation)** count of $O(2mn^2)$
–NOTE: **Householder method** has $2\left(mn^2 - n^3/3\right)$ **flop** count, but better numerical properties
•Recall: $Q^\dagger Q = \mathbf{I}_n$ => check for loss of orthogonality with $\|\mathbf{I}_n - Q^\dagger Q\| = \text{loss}$
–**Classical GS** => $\|\mathbf{I}_n - Q^\dagger Q\| \approx \mathrm{Cond}(A)^2\epsilon_{\mathrm{mach}}$
–**Modified GS** => $\|\mathbf{I}_n - Q^\dagger Q\| \approx \mathrm{Cond}(A)\epsilon_{\mathrm{mach}}$
–NOTE: **Householder method** has $\|\mathbf{I}_n - Q^\dagger Q\| \approx \epsilon_{\mathrm{mach}}$

Multivariate Calculus

•Consider $f : \mathbb{R}^n \to \mathbb{R}$ => **when clear** write i-**th component** of input as i instead of $\mathbf{x}_i$
•**Level curve** w.r.t. to $c \in \mathbb{R}$ is all points s.t. $f(\mathbf{x}) = c$
–Projecting level curves onto $\mathbb{R}^n$ gives **contour-map** of f
•n_k-**th order partial derivative** w.r.t i_k, of …, of n_1-**th order partial derivative** w.r.t i_1 of f is:

$$\frac{\partial^{n_k+\dots+n_1}}{\partial \mathbf{x}_{i_k}^{n_k}\cdots\partial \mathbf{x}_{i_1}^{n_1}} f = \partial_{i_k}^{n_k}\cdots\partial_{i_1}^{n_1} f = f_{i_1\cdots i_k}^{(n_1,\dots,n_k)} = \left(f_{i_1\cdots i_{k-1}}^{(n_1,\dots,n_{k-1})}\right)_{i_k}^{(n_k)}$$

–Overall, its an N-**th order partial derivative** where $N = \sum_k n_k$
•$\nabla f = \left[\partial_1 f, \dots, \partial_n f\right]^T$ is gradient of f => $(\nabla f)_i = \dfrac{\partial f}{\partial \mathbf{x}_i}$
–$\nabla^T f = (\nabla f)^T$ is transpose of ∇f, i.e. $\nabla^T f$ is row vector

•$D_{\mathbf{u}} f(\mathbf{x}) = \lim_{\delta\to 0}\dfrac{f(\mathbf{x}+\delta\mathbf{u}) - f(\mathbf{x})}{\delta}$ ***directional-derivative*** of f
–It is rate-of-change in direction $\mathbf{u}$, where $\mathbf{u} \in \mathbb{R}^n$ is unit-vector
–$D_{\mathbf{u}} f(\mathbf{x}) = \nabla f(\mathbf{x}) \cdot \mathbf{u} = \|\nabla f(\mathbf{x})\|\|\mathbf{u}\|\cos(\theta)$ => $D_{\mathbf{u}} f(\mathbf{x})$ **maximized** when $\cos\theta = 1$
–i.e. when $\mathbf{x}, \mathbf{u}$ are parallel => hence $\nabla f(\mathbf{x})$ is direction of **max.** rate-of-change
•$\mathbf{H}(f) = \nabla^2 f = \mathbf{J}(\nabla f)^T$ is the ***Hessian*** of f => $\mathbf{H}(f)_{ij} = \dfrac{\partial^2 f}{\partial \mathbf{x}_i\partial \mathbf{x}_j}$
•f has **local minimum** at $\mathbf{x}_{\mathrm{loc}}$ if there's radius $r > 0$ s.t. $\forall \mathbf{x} \in B[r; \mathbf{x}_{\mathrm{loc}}]$ we have $f(\mathbf{x}_{\mathrm{loc}}) \le f(\mathbf{x})$
–f has **global minimum** $\mathbf{x}_{\mathrm{glob}}$ if $\forall \mathbf{x} \in \mathbb{R}^n$ we have $f(\mathbf{x}_{\mathrm{glob}}) \le f(\mathbf{x})$
–A local minimum satisfies optimality conditions:
⋆$\nabla f(\mathbf{x}) = \mathbf{0}$, e.g. for $n = 1$ its $f'(x) = 0$
⋆$\nabla^2 f(\mathbf{x})$ is positive-definite, e.g. for $n = 2$ its $f''(x) > 0$
•Interpret $F : \mathbb{R}^n \to \mathbb{R}^m$ as m functions $F_i : \mathbb{R}^n \to \mathbb{R}$ *(one per output-component)*
–$\mathbf{J}(F) = \left[\nabla^T F_1; \dots; \nabla^T F_m\right]$ is ***Jacobian matrix*** of F => $\mathbf{J}(F)_{ij} = \dfrac{\partial F_i}{\partial \mathbf{x}_j}$

Conditioning

•A ***problem*** is some $f : X \to Y$ where X, Y are normed vector-spaces
–A problem ***instance*** is f with fixed input $x \in X$, shortened to ***just*** "problem" *(with $x \in X$ implied)
–δx is **small perturbation** of x => $\delta f = f(x + \delta x) - f(x)$
–A problem (instance) is:
⋆**Well-conditioned** if all **small** δx lead to **small** δf, i.e. if κ is **small** *(e.g. 1, 10, 10^2)*
⋆**Ill-conditioned** if some **small** δx lead to **large** δf, i.e. if κ is **large** *(e.g. 10^6, 10^{16})
•***Absolute* condition number** $\mathrm{cond}(x) = \hat{\kappa}(x) = \hat{\kappa}$ of f **at** x is
–$\hat{\kappa} = \lim_{\delta\to 0}\sup_{\|\delta x\|\le\delta}\dfrac{\|\delta f\|}{\|\delta x\|}$ => for most problems simplified to $\hat{\kappa} = \sup_{\delta x}\dfrac{\|\delta f\|}{\|\delta x\|}$
–If Jacobian $\mathbf{J}_f(x)$ exists then $\hat{\kappa} = \|\mathbf{J}_f(x)\|$, where matrix norm $\|-\|$ induced by norms on X and Y
•***Relative* condition number** $\kappa(x) = \kappa$ of f **at** x is
–$\kappa = \lim_{\delta\to 0}\sup_{\|\delta x\|\le\delta}\left(\dfrac{\|\delta f\|}{\|f(x)\|} \Big/ \dfrac{\|\delta x\|}{\|x\|}\right)$ => for most problems simplified to $\kappa = \sup_{\delta x}\left(\dfrac{\|\delta f\|}{\|f(x)\|} \Big/ \dfrac{\|\delta x\|}{\|x\|}\right)$
–If Jacobian $\mathbf{J}_f(x)$ exists then $\kappa = \dfrac{\|\mathbf{J}_f(x)\|}{\|f(x)\|/\|x\|}$
–More important than $\hat{\kappa}$ for *numerical analysis*
•***Matrix* condition number** $\mathrm{Cond}(A) = \kappa(A) = \|A\|\|A^{-1}\|$ => comes up so often that has its own name
–$A \in \mathbb{C}^{m\times m}$ is well-conditioned if $\kappa(A)$ is **small**, ill-conditioned if **large**
–$\kappa(A) = \kappa(A^{-1})$ and $\kappa(A) = \kappa(\gamma A)$
–If $\|\cdot\| = \|\cdot\|_2$ then $\kappa(A) = \dfrac{\sigma_1}{\sigma_m}$
•For $A \in \mathbb{C}^{m\times n}$, the problem $f_A(x) = Ax$ has $\kappa = \|A\|\dfrac{\|x\|}{\|Ax\|}$ => if A^{-1} exists then $\kappa \le \mathrm{Cond}(A)$
–If $Ax = b$, problem of finding x given b is just $f_{A^{-1}}(b) = A^{-1}b$ => $\kappa = \left\|A^{-1}\right\|\dfrac{\|b\|}{\|x\|} \le \mathrm{Cond}(A)$
•For $\mathbf{b} \in \mathbb{C}^m$, the problem $f_{\mathbf{b}}(A) = A^{-1}\mathbf{b}$ *(i.e. finding x in $Ax = \mathbf{b}$)* has $\kappa = \|A\|\left\|A^{-1}\right\| = \mathrm{Cond}(A)$

Stability

•Given a problem $f : X \to Y$, an **algorithm** for f is $\tilde{f} : X \to Y$
–$\tilde{f}$ is **computer implementation**, so inputs/outputs are **FP**
–Input $x \in X$ is first rounded to $\mathrm{fl}(x)$, i.e. $\tilde{f}(x) = \tilde{f}(\mathrm{fl}(x))$
–$\tilde{f}$ cannot be **continuous** *(for the most part)*
–**Absolute error** => $\|\tilde{f}(x) - f(x)\|$; **relative error** => $\dfrac{\|\tilde{f}(x) - f(x)\|}{\|f(x)\|}$
•$\tilde{f}$ is **accurate** if $\forall x \in X$, $\dfrac{\|\tilde{f}(x) - f(x)\|}{\|f(x)\|} = O(\epsilon_{\mathrm{mach}})$
•$\tilde{f}$ is **stable** if $\forall x \in X$, $\exists \tilde{x} \in X$ s.t. $\dfrac{\|\tilde{f}(x) - f(\tilde{x})\|}{\|f(\tilde{x})\|} = O(\epsilon_{\mathrm{mach}})$ and $\dfrac{\|\tilde{x} - x\|}{\|x\|} = O(\epsilon_{\mathrm{mach}})$
–i.e. nearly the right answer to nearly the right question
–**outer-product** is stable
•$\tilde{f}$ is **backwards stable** if $\forall x \in X$, $\exists \tilde{x} \in X$ s.t. $\tilde{f}(x) = f(\tilde{x})$ and $\dfrac{\|\tilde{x} - x\|}{\|x\|} = O(\epsilon_{\mathrm{mach}})$
–i.e. exactly the right answer to nearly the right question, a **subset of stability**
–$\oplus, \ominus, \otimes, \oslash$, **inner-product**, back-substitution w/ triangular systems, are backwards stable
–If **backwards stable** $\tilde{f}$ and f has condition number $\kappa(x)$ then relative error $\dfrac{\|\tilde{f}(x) - f(x)\|}{\|f(x)\|} = O(\kappa(x)\epsilon_{\mathrm{mach}})$

•Accuracy, stability, backwards stability are **norm-independent** for fin-dim X, Y

Big-O meaning for numerical analysis

•In complexity analysis $f(n) = O(g(n))$ as $n \to \infty$
•But in numerical analysis $f(\epsilon) = O(g(\epsilon))$ as $\epsilon \to 0$, i.e. $\limsup_{\epsilon\to 0}\ \|f(\epsilon)\| / \|g(\epsilon)\| < \infty$
–i.e. $\exists C, \delta > 0$ s.t. $\forall \epsilon$, we have $0 < \|\epsilon\| < \delta \implies \|f(\epsilon)\| \le C\|g(\epsilon)\|$
–$O(g)$ is set of functions $\left\{f\ :\ \limsup_{\epsilon\to 0}\ \|f(\epsilon)\| / \|g(\epsilon)\| < \infty\right\}$
•**Smallness** partial order $O(g_1) \preceq O(g_2)$ defined by set-inclusion $O(g_1) \subseteq O(g_2)$
–i.e. as $\epsilon \to 0$, $g_1(\epsilon)$ goes to zero ***faster*** than $g_2(\epsilon)$
–*Roughly* same hierarchy as complexity analysis but **flipped** *(some break pattern)*
⋆e.g. $\dots, O(\epsilon^3) < O(\epsilon^2) < O(\epsilon) < O(1)$
–**Maximum**: $O(\max(|g_1|, |g_2|)) = O(g_2) \iff O(g_1) \preceq O(g_2)$
⋆e.g. $O(\max(\epsilon^k, \epsilon)) = O(\epsilon)$
•Using functions $f_1, \dots, f_n$, let $\square(f_1, \dots, f_n)$ be formula **defining some function**
–Then $\square(O(g_1), \dots, O(g_n))$ is the class of functions $\{\square(f_1, \dots, f_n)\ :\ f_1 \in O(g_1), \dots, f_n \in O(g_n)\}$
⋆e.g. $\epsilon^{O(1)} = \{\epsilon^{f(\epsilon)} : f \in O(1)\}$
–General case: $\square_1(O(f_1), \dots, O(f_m)) = \square_2(O(g_1), \dots, O(g_n))$ means $\square_1(O(f_1), \dots, O(f_m)) \subseteq \square_2(O(g_1), \dots, O(g_n))$
⋆e.g. $\epsilon^{O(1)} = O(k^\epsilon)$ means $\{\epsilon^{f(\epsilon)} : f \in O(1)\} \subseteq O(k^\epsilon)$; *not necessarily true*
–Special case: $f = \square(O(g_1), \dots, O(g_n))$ means $f \in \square(O(g_1), \dots, O(g_n))$
⋆e.g. $(\epsilon+1)^2 = \epsilon^2 + O(\epsilon)$ means $\epsilon \mapsto (\epsilon+1)^2 \in \{\epsilon^2 + f(\epsilon) : f \in O(\epsilon)\}$; *not necessarily true*
•Let $f_1 = O(g_1)$, $f_2 = O(g_2)$ and let $k \neq 0$ be a constant
–$f_1 f_2 = O(g_1 g_2)$ and $f \cdot O(g) = O(fg)$
–$f_1 + f_2 = O(\max(|g_1|, |g_2|))$ => **if** $g_1 = g = g_2$ **then** $f_1 + f_2 = O(g)$
–$O(|k| \cdot g) = O(g)$

Floating-point numbers

•Consider **base/radix** $\beta \ge 2$ *(typically 2)* and **precision** $t \ge 1$ *(24 or 53 for IEEE single/double precisions)*
•**Floating-point numbers** are discrete subset $\mathbf{F} = \left\{(-1)^s\left(m/\beta^t\right)\beta^e \mid 1 \le m \le \beta^t,\ s \in \mathbb{B}, m, e \in \mathbb{Z}\right\}$
–s is **sign-bit**, m/β^t is **mantissa**, e is **exponent** *(8-bit for single, 11-bit for double)*
–Equivalently, can restrict to $\beta^{t-1} \le m \le \beta^t - 1$ for unique m and e
–$\mathbf{F} \subset \mathbb{R}$ is idealized *(ignores over/underflow)*, so is countably infinite and self-similar *(i.e. $\mathbf{F} = \beta\mathbf{F}$)*
–For all $x \in \mathbb{R}$ there exists $\mathrm{fl}(x) \in \mathbf{F}$ s.t. $|x - \mathrm{fl}(x)| \le \epsilon_{\mathrm{mach}}|x|$
⋆Equivalently $\mathrm{fl}(x) = x(1+\delta)$, $|\delta| \le \epsilon_{\mathrm{mach}}$
•**Machine epsilon** $\epsilon_{\mathrm{machine}} = \epsilon_{\mathrm{mach}} = \frac{1}{2}\beta^{1-t}$ is maximum relative gap between FPs
–Half the gap between 1 and next largest FP
–$2^{-24} \approx 5.96\times 10^{-8}$ and $2^{-53} \approx 10^{-16}$ for single/double
•**FP arithmetic**: let $*, \circledast$ be real and floating counterparts of arithmetic operation
–For $x, y \in \mathbf{F}$ we have $x \circledast y = \mathrm{fl}(x * y) = (x * y)(1+\epsilon)$, $|\delta| \le \epsilon_{\mathrm{mach}}$
⋆Holds for ***any*** arithmetic operation $\circledast = \oplus, \ominus, \otimes, \oslash$
–Complex floats implemented pairs of real floats, so above applies complex ops as-well
⋆Caveat: $\epsilon_{\mathrm{mach}} = \frac{1}{2}\beta^{1-t}$ must be scaled by factors on the order of $2^{3/2}, 2^{5/2}$ for $\otimes, \oslash$ *respectively*
–$(x_1 \oplus \dots \oplus x_n) \approx (x_1 + \dots + x_n) + \sum_{i=1}^{n} x_i\left(\sum_{j=i}^{n}\delta_j\right)$, $|\delta_j| \le \epsilon_{\mathrm{mach}}$
–$(x_1 \otimes \dots \otimes x_n) \approx (x_1 \times \dots \times x_n)(1+\epsilon)$, $\epsilon \le 1.06(n-1)\epsilon_{\mathrm{mach}}$
–$\mathrm{fl}\left(\sum x_i y_i\right) = \sum x_i y_i (1+\epsilon_i)$ where $1+\epsilon_i = (1+\delta_i)\times(1+\eta_i)\cdots(1+\eta_n)$ and $|\delta_j|, |\eta_j| \le \epsilon_{\mathrm{mach}}$
⋆$1+\epsilon_i \approx 1+\delta_i+(\eta_i+\dots+\eta_n)$
⋆$|\mathrm{fl}(x^T y) - x^T y| \le \sum|x_i y_i||\epsilon_i|$
⋆Assuming $n\epsilon_{\mathrm{mach}} \le 0.1$ => $|\mathrm{fl}(x^T y) - x^T y| \le \phi(n)\epsilon_{\mathrm{mach}}|x|^T|y|$, where $|x|_i = |x_i|$ is vector and $\phi(n)$ is small function of n
–**Summing a series** is more stable if terms added in order of increasing magnitude
•For **FP matrices**, let $|M|_{ij} = |M_{ij}|$, i.e. matrix $|M|$ of absolute values of M
–$\mathrm{fl}(\lambda\mathbf{A}) = \lambda\mathbf{A} + E$, $|E|_{ij} \le |\lambda\mathbf{A}|_{ij}\epsilon_{\mathrm{mach}}$
–$\mathrm{fl}(\mathbf{A}+\mathbf{B}) = (\mathbf{A}+\mathbf{B}) + E$, $|E|_{ij} \le |\mathbf{A}+\mathbf{B}|_{ij}\epsilon_{\mathrm{mach}}$
–$\mathrm{fl}(\mathbf{AB}) = \mathbf{AB} + E$, $|E|_{ij} \le n\epsilon_{\mathrm{mach}}(|\mathbf{A}||\mathbf{B}|)_{ij} + O\left(\epsilon_{\mathrm{mach}}^2\right)$
•***Taylor series*** about $a \in \mathbb{R}$ is $f(x) = \sum_{k=0}^{n}\dfrac{f^{(k)}(a)}{k!}(x-a)^k + O\left((x-a)^{n+1}\right)$ as $x \to a$
–Need $a = 0$ => $f(x) = \sum_{k=0}^{n}\dfrac{f^{(k)}(0)}{k!}x^k + O\left(x^{n+1}\right)$ as $x \to 0$
–e.g. $(1+\epsilon)^p = \sum_{k=0}^{n}\binom{p}{k}\epsilon^k + O\left(\epsilon^{n+1}\right) = \sum_{k=0}^{n}\dfrac{p!}{k!(p-k)!}\epsilon^k + O\left(\epsilon^{n+1}\right)$ as $\epsilon \to 0$

Elementary Matrices

•Identity $\mathbf{I}_n = [\mathbf{e}_1 | \dots | \mathbf{e}_n] = [\mathbf{e}_1; \dots; \mathbf{e}_n]$ has elementary vectors $\mathbf{e}_1, \dots, \mathbf{e}_n$ for rows/columns
•**Row/column switching**: permutation matrix P_{ij} obtained by switching $\mathbf{e}_i$ and $\mathbf{e}_j$ in $\mathbf{I}_n$ *(same for rows/columns)*
–Applying P_{ij} **from left** will switch rows, **from right** will swap columns
–$P_{ij} = P_{ij}^T = P_{ij}^{-1}$, i.e. applying twice will **undo** it
•**Row/column scaling**: $D_i(\lambda)$ obtained by scaling $\mathbf{e}_i$ by λ in $\mathbf{I}_n$ *(same for rows/columns)*
–Applying P_{ij} **from left** will scale rows, **from right** will scale columns
–$D_i(\lambda) = \mathrm{diag}(1, \dots, \lambda, \dots, 1)$ so all **diagonal** properties apply, e.g. $D_i(\lambda)^{-1} = D_i(\lambda^{-1})$
•**Row addition**: $L_{ij}(\lambda) = \mathbf{I}_n + \lambda\mathbf{e}_i\mathbf{e}_j^T$ performs $R_i \leftarrow R_i + \lambda R_j$ when applying **from left**
–$\lambda\mathbf{e}_i\mathbf{e}_j^T$ is zeros except for λ **in** (i, j)-**th entry**
–$L_{ij}(\lambda)^{-1} = L_{ij}(-\lambda)$ both triangular matrices

LU factorization w/ Gaussian elimination

•[[tutorial 1#Representing EROs/ECOs as transformation matrices|Recall that]] you can represent **EROs** and **ECOs** as transformation matrices R, C *respectively*
•LU **factorization** => finds $A = LU$ where L, U are lower/upper triangular *respectively*
•**Naive Gaussian Elimination** performs $[I_m \mid A \mid I_n] \rightsquigarrow [R^{-1} \mid U \mid I_n]$ to get $AI_n = R^{-1}U$ using only row addition
–R^{-1}, i.e. **inverse EROs** in reversed order, is **lower-triangular** so $L = R^{-1}$
–![[Pasted image 20250419051217.png|400]]
–The **pivot element** is simply diagonal entry $u_{kk}^{(k-1)}$; fails if $u_{kk}^{(k-1)} \approx 0$
–$\tilde{L}\tilde{U} = A + \delta A$, $\dfrac{\|\delta A\|}{\|L\| \cdot \|U\|} = O(\epsilon_{\mathrm{mach}})$; only **backwards stable** if $\|L\| \cdot \|U\| \approx \|A\|$
–Work required: $\sim\frac{2}{3}m^3$ flops $\sim O(m^3)$
–Solving $Ax = LUx$ is $\sim\frac{2}{3}m^3$ flops *(back substitution is $O(m^2)$)*
–**NOTE:** Householder triangularisation requires $\sim\frac{4}{3}m^3$
•**Partial pivoting** computes $PA = LU$ where P is a permutation matrix => $PP^T = I$, i.e. its orthogonal
–For each column j, finds largest entry and row-swaps to make it new pivot => P_j
–Then performs normal elimination on that column => L_j
–Result is $L_{m-1}P_{m-1}\dots L_2P_2L_1P_1A = U$, where $L_{m-1}P_{m-1}\dots L_2P_2L_1P_1 = L'_{m-1}\dots L'_1P_{m-1}\dots P_1$
–Setting $L = \left(L'_{m-1}\dots L'_1\right)^{-1}$, $P = P_{m-1}\dots P_1$ gives $PA = LU$
–![[Pasted image 20250420092322.png|450]]
–Work required: $\sim\frac{2}{3}m^3$ flops $\sim O(m^3)$; results in $L_{ij} \le 1$ so $\|L\| = O(1)$
–Stability depends on **growth-factor** $\rho = \dfrac{\max_{i,j}|u_{i,j}|}{\max_{i,j}|a_{i,j}|}$ => for partial pivoting $\rho \le 2^{m-1}$
–$\|U\| = O(\rho\|A\|)$ => $\tilde{L}\tilde{U} = \tilde{P}A + \delta A$, $\dfrac{\|\delta A\|}{\|A\|} = O(\rho\epsilon_{\mathrm{machine}})$ => only **backwards stable** if $\rho = O(1)$
•**Full pivoting** is $PAQ = LU$ finds largest entry in **bottom-right submatrix**
–Makes it **pivot** with row/column swaps before normal elimination
–Very expensive $O(m^3)$ search-ops, **partial pivoting** only needs $O(m^2)$

Systems of Equations: Iterative Techniques

•Let $A, R, G \in \mathbb{R}^{n\times n}$ where G^{-1} exists => **splitting** $A = G + R$ helps iteration
–$A\mathbf{x} = \mathbf{b}$ rewritten as $\mathbf{x} = M\mathbf{x} + \mathbf{c}$ where $M = -G^{-1}R$; $\mathbf{c} = -G^{-1}\mathbf{b}$
–Define $f(\mathbf{x}) = M\mathbf{x} + \mathbf{c}$ and sequence $\mathbf{x}^{(k+1)} = f(\mathbf{x}^{(k)}) = M\mathbf{x}^{(k)} + \mathbf{c}$ with starting point $\mathbf{x}^{(0)}$
–**Limit** of $\langle \mathbf{x}_k\rangle$ is fixed point of f => unique fixed point of f is **solution** to $A\mathbf{x} = \mathbf{b}$
–If $\|-\|$ is consistent norm and $\|M\| < 1$ then $\langle \mathbf{x}_k\rangle$ converges for any $\mathbf{x}^{(0)}$ *(because Cauchy-completeness)*
⋆For splitting, we want $\|M\| < 1$ and easy to compute M; $\mathbf{c}$
⋆**Stopping criterion** usually the relative residual $\dfrac{\left\|\mathbf{b} - A\mathbf{x}^{(k)}\right\|}{\|\mathbf{b}\|} \le \epsilon$
•Assume A's **diagonal is non-zero** *(w.l.o.g. permute/change basis if isn't)* then $A = D + L + U$
–Where D is **diagonal** of A, L, U are strict **lower/upper triangular** parts of A
•**Jacobi Method**: $G = D$; $R = L + U$ => $M = -D^{-1}(L+U)$; $\mathbf{c} = D^{-1}\mathbf{b}$
–$\mathbf{x}_i^{(k+1)} = \dfrac{1}{A_{ii}}\left(\mathbf{b}_i - \sum_{j\neq i}A_{ij}\mathbf{x}_j^{(k)}\right)$ => $\mathbf{x}_i^{(k+1)}$ only needs $\mathbf{b}_i$; $\mathbf{x}^{(k)}$; A_{i*} => row-wise parallelization
•**Gauss-Seidel (G-S) Method**: $G = D + L$; $R = U$ => $M = -(D+L)^{-1}U$; $\mathbf{c} = (D+L)^{-1}\mathbf{b}$
–$\mathbf{x}_i^{(k+1)} = \dfrac{1}{A_{ii}}\left(\mathbf{b}_i - \sum_{j=1}^{i-1}A_{ij}\mathbf{x}_j^{(k+1)} - \sum_{j=i+1}^{n}A_{ij}\mathbf{x}_j^{(k)}\right)$
–Computing $\mathbf{x}_i^{(k+1)}$ needs $\mathbf{b}_i$; $\mathbf{x}^{(k)}$; A_{i*} and $\mathbf{x}_j^{(k+1)}$ for $j < i$ => lower storage requirements
•**Successive over-relaxation (SOR)**: $G = \omega^{-1}D + L$; $R = (1-\omega^{-1})D + U$ => $M = -(\omega^{-1}D + L)^{-1}((1-\omega^{-1})D + U)$; $\mathbf{c} = -(\omega^{-1}D + L)^{-1}\mathbf{b}$
–$\mathbf{x}_i^{(k+1)} = \dfrac{\omega}{A_{ii}}\left(\mathbf{b}_i - \sum_{j=1}^{i-1}A_{ij}\mathbf{x}_j^{(k+1)} - \sum_{j=i+1}^{n}A_{ij}\mathbf{x}_j^{(k)}\right) + (1-\omega)\mathbf{x}_i^{(k)}$ for **relaxation factor** $\omega > 1$
•If A is **strictly row diagonally dominant** then Jacobi/Gauss-Seidel methods converge
–A is **strictly row diagonally dominant** if $|A_{ii}| > \sum_{j\neq i}|A_{ij}|$
•If A is positive-definite then **G-S** and **SOR** ($\omega \in (0, 2)$) converge

Break up matrices into (uneven blocks)

•e.g. symmetric $A \in \mathbb{R}^{n\times n}$ can become $A = \left[\begin{array}{c|c} a_{1,1} & b \\ \hline b^T & C\end{array}\right]$, then perform proofs on that

Catchup: metric spaces and limits

•Metrics obey these axioms
–$d(x, x) = 0$
–$x \neq y \implies d(x, y) > 0$
–$d(x, y) = d(y, x)$
–$d(x, z) \le d(x, y) + d(y, z)$
•For metric spaces, **mix-and-match** these infinite/finite limit definitions:
–$\lim_{x\to+\infty} f(x) = +\infty \iff \forall r \in \mathbb{R}, \exists N \in \mathbb{N}, \forall x > N :\ f(x) > r$
–$\lim_{x\to p} f(x) = L \iff \forall\varepsilon > 0, \exists\delta > 0, \forall x \in A :\ 0 < d_X(x, p) < \delta \implies d_Y(f(x), L) < \varepsilon$
–**Cauchy sequences**, i.e. $\forall\varepsilon > 0, \exists N \in \mathbb{N}, \forall m, n \ge N :\ d(a_m, a_n) < \varepsilon$, converge in **complete spaces**
•You can manipulate matrix limits much **like in real analysis**, e.g. $\lim_{n\to\infty}(A^nB + C) = \left(\lim_{n\to\infty}A^n\right)B + C$
•Turn **metric limit** $\lim_{n\to\infty}x_n = L$ into **real limit** $\lim_{n\to\infty}d(x_n, L) = 0$ to leverage real analysis
–Bounded **monotone sequences** converge in $\mathbb{R}$
–Sandwich theorem for limits in $\mathbb{R}$ => pick easy upper/lower bounds
–$\lim_{n\to\infty}r^n = 0 \iff |r| < 1$ and $\lim_{n\to\infty}\sum_{i=0}^{n}ar^i = \dfrac{a}{1-r} \iff |r| < 1$

Eigenvalue Problems: Iterative Techniques

•If A is [[tutorial 1#Properties of matrices|diagonalizable]] then [[tutorial 1#Eigen-values/vectors|eigen-decomposition]] $A = X\Lambda X^{-1}$
–**Dominant** $\lambda_1; \mathbf{x}_1$ are such that $|\lambda_1|$ is strictly largest for which $A\mathbf{x} = \lambda\mathbf{x}$
–**Rayleigh quotient** for Hermitian $A = A^\dagger$ is $R_A(\mathbf{x}) = \dfrac{\mathbf{x}^\dagger A\mathbf{x}}{\mathbf{x}^\dagger\mathbf{x}}$
⋆Eigenvectors are stationary points of R_A
⋆$R_A(\mathbf{x})$ is closest to being like eigenvalue of $\mathbf{x}$, i.e. $R_A(\mathbf{x}) = \mathrm{argmin}_\alpha\|A\mathbf{x} - \alpha\mathbf{x}\|_2$
⋆$R_A(\mathbf{x}) - R_A(\mathbf{v}) = O(\|\mathbf{x} - \mathbf{v}\|^2)$ as $\mathbf{x} \to \mathbf{v}$ where $\mathbf{v}$ is eigenvector
•**Power iteration**: define sequence $\mathbf{b}^{(k+1)} = \dfrac{A\mathbf{b}^{(k)}}{\left\|A\mathbf{b}^{(k)}\right\|}$ with initial $\mathbf{b}^{(0)}$ s.t. $\left\|\mathbf{b}^{(0)}\right\| = 1$
–Assume **dominant** $\lambda_1; \mathbf{x}_1$ exist for A, and that $\mathrm{proj}_{\mathbf{x}_1}\left(\mathbf{b}^{(0)}\right) \neq 0$
–Under above assumptions, $\mu_k = R_A\left(\mathbf{b}^{(k)}\right) = \dfrac{\mathbf{b}^{(k)\dagger}A\mathbf{b}^{(k)}}{\mathbf{b}^{(k)\dagger}\mathbf{b}^{(k)}}$ converges to **dominant** λ_1
–$\langle \mathbf{b}_k\rangle$ converges to some **dominant** $\mathbf{x}_1$ associated with λ_1 => $\left\|A\mathbf{b}^{(k)}\right\|$ converges to $|\lambda_1|$
–If $\mathrm{proj}_{\mathbf{x}_1}\left(\mathbf{b}^{(0)}\right) = \mathbf{0}$ then $\langle \mathbf{b}_k\rangle$; $\langle \square_k\rangle$ converge to second **dominant** $\lambda_2; \mathbf{x}_2$ instead
–If **no dominant** λ *(i.e. multiple eigenvalues of maximum $|\lambda|$)* then $\langle \mathbf{b}_k\rangle$ will converge to linear combination of their corresponding eigenvectors
–Slow convergence if **dominant** λ_1 not "very dominant"
–$\left\|\mathbf{b}^{(k)} - \alpha_k\mathbf{x}_1\right\| = O\left(\left|\dfrac{\lambda_2}{\lambda_1}\right|^k\right)$ for **phase factor** $\alpha_k \in \{-1, 1\}$ it may alternate if $\lambda_1 < 0$
⋆$\alpha_k = \dfrac{(\lambda_1)^k c_1}{|\lambda_1|^k|c_1|}$ where $c_1 = \mathbf{x}_1^\dagger\mathbf{b}^{(0)}$ and assuming $\mathbf{b}^{(k)}; \mathbf{x}_1$ are normalized
–$(A - \sigma I)$ has **eigenvalues** $\lambda - \sigma$ => power-iteration on $(A - \sigma I)$ has $\dfrac{\lambda_2 - \sigma}{\lambda_1 - \sigma}$
–Eigenvector guess => estimated eigenvalue
•**Inverse (power-)iteration**: perform power iteration on $(A - \sigma I)^{-1}$ to get $\lambda_{1,\sigma}$ **closest** to σ
–$(A - \sigma I)^{-1}$ has eigenvalues $(\lambda - \sigma)^{-1}$ so power iteration will yield **largest** $(\lambda_{1,\sigma} - \sigma)^{-1}$
i.e. will yield **smallest** $\lambda_{1,\sigma} - \sigma$, i.e. will yield $\lambda_{1,\sigma}$ **closest** to σ
–$\left\|\mathbf{b}^{(k)} - \alpha_k\mathbf{x}_{1,\sigma}\right\| = O\left(\left|\dfrac{\lambda_{1,\sigma} - \sigma}{\lambda_{2,\sigma} - \sigma}\right|^k\right)$ where $\mathbf{x}_{1,\sigma}$ corresponds to $\lambda_{1,\sigma}$ and $\lambda_{2,\sigma}$ is 2nd-closest to σ
–Efficiently compute eigenvectors for **known eigenvalues** σ
–Eigenvalue guess => estimated eigenvector
–![[Pasted image 20250420131643.png|300]]
–Can reduce matrix inversion $O(m^3)$ to $O(m^2)$ by pre-factorization

Nonlinear Systems of Equations: Iterative Techniques

•[[tutorial 6#Multivariate Calculus|Recall]] that $\nabla f(\mathbf{x})$ is direction of **max.** rate-of-change $|\nabla f(\mathbf{x})|$
•Search for stationary point by **gradient descent**: $\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} - \alpha\nabla f(\mathbf{x}^{(k)})$ for step length α
•A is positive-definite solving $A\mathbf{x} = \mathbf{b}$ and $\min_{\mathbf{x}} f(\mathbf{x}) = \frac{1}{2}\mathbf{x}^TA\mathbf{x} - \mathbf{x}^T\mathbf{b}$ are equivalent
–Get iterative methods $\mathbf{x}^{(k+1)} = \mathbf{x}^{(k)} - \alpha^{(k)}\mathbf{p}^{(k)}$ for step length $\alpha^{(k)}$ and directions $\mathbf{p}^{(k)}$
•**Conjugate gradient (CG) method**: if $A \in \mathbb{R}^{n\times n}$ also symmetric then $\langle \mathbf{u}, \mathbf{v}\rangle_A = \mathbf{u}^TA\mathbf{v}$ is an inner-product
–**GC** chooses $\mathbf{p}^{(k)}$ that are conjugate w.r.t. A, i.e. $\langle \mathbf{p}^{(i)}, \mathbf{p}^{(j)}\rangle_A = 0$ for $i \neq j$
–And chooses $\alpha^{(k)}$ s.t. **residuals** $\mathbf{r}^{(k)} = -\nabla f(\mathbf{x}^{(k)}) = \mathbf{b} - A\mathbf{x}^{(k)}$ are orthogonal
⋆$k = 0$ => $\mathbf{p}^{(0)} = -\nabla f(\mathbf{x}^{(0)}) = \mathbf{r}^{(0)}$
⋆$k \ge 1$ => $\mathbf{p}^{(k)} = \mathbf{r}^{(k)} - \sum_{i<k}\dfrac{\langle \mathbf{p}^{(i)}, \mathbf{r}^{(k)}\rangle_A}{\langle \mathbf{p}^{(i)}, \mathbf{p}^{(i)}\rangle_A}\mathbf{p}^{(i)}$
⋆$\alpha^{(k)} = \mathrm{argmin}_\alpha f(\mathbf{x}^{(k)} + \alpha^{(k)}\mathbf{p}^{(k)}) = \dfrac{\mathbf{p}^{(k)} \cdot \mathbf{r}^{(k)}}{\langle \mathbf{p}^{(k)}, \mathbf{p}^{(k)}\rangle_A}$
–Without rounding errors, **CG** converges in $\le n$ iterations
⋆Similar to to [[tutorial 1#Gram-Schmidt method to generate orthonormal basis from any linearly independent vectors|Gram-Schmidt]] *(different inner-product)*
⋆$\langle \mathbf{p}^{(0)}, \dots, \mathbf{p}^{(n-1)}\rangle$ and $\langle \mathbf{r}^{(0)}, \dots, \mathbf{r}^{(n-1)}\rangle$ are bases for $\mathbb{R}^n$

QR Algorithm to find Schur decomposition $A = QUQ^\dagger$

•Any $A \in \mathbb{C}^{m\times m}$ has **Schur decomposition** $A = QUQ^\dagger$
–Q is unitary, i.e. $Q^\dagger = Q^{-1}$ and upper-triangular U
–Diagonal of U contains **eigenvalues** of A
•![[Pasted image 20250420135506.png|300]]
•For $A \in \mathbb{R}^{m\times m}$ each iteration $A^{(k)} = Q^{(k)}R^{(k)}$ produces orthogonal $Q^{(k)T} = Q^{(k)-1}$
•So $A^{(k+1)} = R^{(k)}Q^{(k)} = (Q^{(k)T}Q^{(k)})R^{(k)}Q^{(k)} = Q^{(k)T}A^{(k)}Q^{(k)}$ means $A^{(k+1)}$ is **similar** to $A^{(k)}$
–Setting $A^{(0)} = A$ we get $A^{(k)} = \tilde{Q}^{(k)T}A\tilde{Q}^{(k)}$ where $\tilde{Q}^{(k)} = Q^{(0)}\dots Q^{(k-1)}$
•Under certain conditions **QR algorithm** converges to **Schur decomposition**
•We can **apply shift** $\mu^{(k)}$ at iteration k => $A^{(k)} - \mu^{(k)}I = Q^{(k)}R^{(k)}$; $A^{(k+1)} = R^{(k)}Q^{(k)} + \mu^{(k)}I$
–If **shifts** are good eigenvalue estimates then last column of $\tilde{Q}^{(k)}$ converges quickly to an **eigenvector**
–Estimate $\mu^{(k)}$ with Rayleigh quotient => $\mu^{(k)} = (A_k)_{mm} = \tilde{q}_m^{(k)T}A\tilde{q}_m^{(k)}$ where $\tilde{q}_m^{(k)}$ is m-th column of $\tilde{Q}^{(k)}$