Linear Algebra – brief review

Many good long textbooks

DO NOT CODE – use excellent free packages

Nonlinear fluids $\to$ many linear sub-problems,
e.g. Poisson problem, e.g. linear stability

Questions

- "matrix inversion": $Ax = b$
- eigenvalues: $Ae = \lambda e$

Matrices

- dense or sparse
- symmetric, positive definite, banded,...

LAPACK

Free packages. Download library.

Search engine to find correct routine for you

- linear equations or linear least squares,
  or eigenvalues, singular decomposition, generalised
- precision: single/double, real/complex
- matrix type: symmetric, SPD, banded

Driver routine, calls computational routines, calls auxiliary (BLAS)

Real, single, general matrix, linear equations
SGESV($N, Nrhs, A, LDA, IPIV, B, LBD, info$)
where matrix A is $N \times N$, with $Nrhs$ b's in B.

Solving linear simultaneous equations

1. Gaussian elimination

$$\begin{array}{ccccccccc} a_{11}x_1 & + & a_{12}x_2 & + & \dots & + & a_{1n}x_n & = & b_1 \\ a_{21}x_1 & + & a_{22}x_2 & + & \dots & + & a_{2n}x_n & = & b_2 \\ \vdots & & & & & & & & \vdots \\ a_{n1}x_1 & + & a_{n2}x_2 & + & \dots & + & a_{nn}x_n & = & b_n \end{array}$$

Divide 1st eqn by a_{11}, so coef x_1 is 1
Subtract 1st eqn $\times a_{k1}$ from kth eqn, so coef x_1 becomes 0
Repeat on $(n-1) \times (n-1)$ subsystem of eqn $2 \to n$
Repeat on even smaller subsystems

Finally back-solve

$$\begin{array}{rrcccc} & a_{nn}x_n & = b_n & \to & x_n \\ a_{n-1\,n-1}x_{n-1}+ & a_{n-1\,n}x_n & = b_{n-1} & \to & x_{n-1} \\ & \vdots & & & \\ & & & \to & x_1 \end{array}$$

LU decomposition – rephrase Gaussian elimination

Lower and Upper triangular

$$L = \begin{pmatrix} 1 & 0 & 0 & 0 \\ . & 1 & 0 & 0 \\ . & . & 1 & 0 \\ . & . & . & 1 \end{pmatrix} \qquad U = \begin{pmatrix} . & . & . & . \\ 0 & . & . & . \\ 0 & 0 & . & . \\ 0 & 0 & 0 & . \end{pmatrix}$$

Step $k = 1 \to n$:
$u_{kj} = a_{kj}$ for $j = k \to n$
$\ell_{ik} = a_{ik}/a_{kk}$ for $i = k \to n$
$a_{ij} \leftarrow a_{ij} - \ell_{ik}u_{kj}$ for $i = k+1 \to n$, for $j = k+1 \to n$

For a dense matrix $\frac{1}{3}n^3$ multiplies
For a tridiagonal matrix, avoiding zeros $2n$ multiplies

Solve $LUx = b$ by

Forward $Ly = b$

$$\begin{array}{ccccccc} \ell_{11}y_1 & & & = & b_1 & \rightarrow & y_1 \\ \ell_{21}y_1 & + & \ell_{22}y_2 & = & b_1 & \rightarrow & y-2 \\ & & & & & \vdots & \\ & & & & & \rightarrow & y_n \end{array}$$

Backward $Ux = y$

$$\begin{array}{ccccccc} & & u_{nn}x_n & = & y_n & \rightarrow & x_n \\ u_{n-1\,n-1}x_{n-1} & + & u_{n-1\,n}x_n & = & y_{n-1} & \rightarrow & x_{n-1} \\ & & & & & \vdots & \\ & & & & & \rightarrow & x_1 \end{array}$$

Finding LU is $O(n^3)$
but solving $LUx = b$ for a new b is only $O(n^2)$

LU: pivoting

Problem at step k if $a_{kk} = 0$
Find largest a_{jk} in $j = k \rightarrow n$, say at $j = \ell$
Swap rows k and ℓ – use index mapping (permutation matrix)

Partial pivoting = swapping rows
Full pivoting = swap rows and columns – rarely better

- Note $\det A = \Pi_i u_{ii}$
- Symmetric A: $A = LDL^T$ with diagonal D
- Sym & positive definite: $A = (LD^{1/2})(LD^{1/2})^T$ Cholesky
- Tridiagonal A: L diagonal and one under, U diagonal and one above.

Errors $Ax = b$

Small ϵ error in b could become $\epsilon/\lambda_{\min}$ error in solution,
while worst solution is $b/\lambda_{\max}$
Thus relative error in solution could increase by factor

$$K = \frac{\lambda_{\max}}{\lambda_{\min}} = \text{condition number of } A$$

Theoretically LU decomposition gives bigger errors, but not often

QR decomposition

$$A = QR$$

- R upper triangular
- Q orthogonal, $QQ^T = I$, i.e. columns orthonormal
  So at no cost $Q^{-1} = Q^T$
- May not stretch/increase errors like LU
- Used for eigenvalues
- $\det A = \Pi_i r_{ii}$

Q not unique

3 methods: Gram-Schmidt, Givens, Householder

QR Gram-Schmidt

Columns of A $\quad \mathbf{a}_1, \mathbf{a}_2, \ldots, \mathbf{a}_n$

$$\begin{array}{llll}
\mathbf{q}_1' = \mathbf{a}_1 & & & \mathbf{q}_1 = \mathbf{q}_1'/|\mathbf{q}_1'| \\
\mathbf{q}_2' = \mathbf{a}_2 & -(\mathbf{a}_2\cdot\mathbf{q}_1)\mathbf{q}_1 & & \mathbf{q}_2 = \mathbf{q}_2'/|\mathbf{q}_2'| \\
\mathbf{q}_3' = \mathbf{a}_3 & -(\mathbf{a}_3\cdot\mathbf{q}_1)\mathbf{q}_1 & -(\mathbf{a}_3\cdot\mathbf{q}_2)\mathbf{q}_2 & \mathbf{q}_3 = \mathbf{q}_3'/|\mathbf{q}_3'| \\
\vdots & & &
\end{array}$$

$Q =$ matrix with columns $\mathbf{q}_1, \mathbf{q}_2, \ldots, \mathbf{q}_n$

Let

$$r_{ii} = |\mathbf{q}_i'|, \quad \text{and} \quad r_{ij} = \mathbf{a}_j\cdot\mathbf{q}_i, \quad i<j$$

Then

$$\mathbf{a}_j = \sum_{i=1}^{j} \mathbf{q}_j r_{ij} \qquad \text{i.e.} \quad A = QR$$

Better: when produce $\mathbf{q}_i$ project it out of $\mathbf{a}_j$ $j>i$

QR Givens rotation

$Q =$ product of many rotations

$$G_{ij} = \begin{array}{c} \\ \\ \\ i \\ \\ \\ j \\ \\ \\ \end{array}\begin{array}{c}\begin{array}{cccccccc} & & i & & & j & & \end{array}\\ \begin{pmatrix}
1 & & & & & & & \\
 & 1 & & & & & & \\
 & & \cos\theta & & & \sin\theta & & \\
 & & & 1 & & & & \\
 & & & & 1 & & & \\
 & & -\sin\theta & & & \cos\theta & & \\
 & & & & & & 1 & \\
 & & & & & & & 1
\end{pmatrix}\end{array}$$

$G_{ij}A$ alters rows and columns i and j

Choose θ to zero an off-diagonal

Strategy to avoid filling previous zeros

Can parallelise

QR Householder

$Q =$ product of many reflections

$$H = \left(I - 2\frac{\mathbf{h}\mathbf{h}^T}{\mathbf{h}\cdot\mathbf{h}}\right)$$

Take $\quad \mathbf{h}_1 = \mathbf{a}_1 + (\alpha_1, 0, \ldots, 0)^T$ with $\alpha_1 = |\mathbf{a}_1| sign(a_{11})$

So

$$\mathbf{h}_1\cdot\mathbf{a}_1 = |\mathbf{a}_1|^2 + |a_{11}||\mathbf{a}_1| \quad \text{and} \quad \mathbf{h}_1\cdot\mathbf{h}_1 = \text{twice}$$

Hence

$$H_1\mathbf{a}_1 = (-\alpha_1, 0, \ldots, 0)^T$$

Now work on $(n-1)\times(n-1)$ subsystem in same way

Note $H\mathbf{x}$ is $O(n)$ operations, not $O(n^3)$

Hence forming Q is $O(n^3)$

Sparse matrices

Do not store all A, just non-zero elements in "packed" form

Evaluating $A\mathbf{x}$ cheaper than $O(n^2)$

e.g. Poisson on $N\times N$ grid, A is $N^2\times N^2$ with $5N^2$ non-zero,

so $A\mathbf{x}$ is $5N^2$ not N^4

LU and QR "direct methods" for dense (faster if banded)

Use iterative method for sparse A

i.e.

$$A = B + C \quad \to \quad \mathbf{x}_{n+1} = B^{-1}(\mathbf{b} - C\mathbf{x}_n)$$

converges if $|B^{-1}C| < 1$, e.g. SOR

Conjugate gradients – A symmetric, positive definite

– actually a direct method, but usually converges well before n steps

Solve $Ax = b$ by minimising quadratic

$$f(x) = \tfrac{1}{2}(Ax-b)^T A^{-1}(Ax-b) = \tfrac{1}{2}x^T Ax - x^T b + \tfrac{1}{2}b^T Ab$$

with

$$\nabla f = Ax - b$$

From $\mathbf{x}_n$ look in direction $\mathbf{u}$ for minimum

$$f(\mathbf{x}_n + \alpha\mathbf{u}) = f(\mathbf{x}_n) + \alpha\mathbf{u}\cdot\nabla f_n + \tfrac{1}{2}\alpha^2\mathbf{u}^T A\mathbf{u}$$

i.e. minimum at $\alpha = -\mathbf{u}\cdot\nabla f_n/\mathbf{u}^A\mathbf{u}$

Choose $\mathbf{u}$? steepest descent $\mathbf{u} = \nabla f$? NO

Conjugate Gradient Algorithm

Start x_0 and u_0
Residual $r_n = Ax_n - b = \nabla f_n$
Iterate

$$x_{n+1} = x_n + \alpha u_n \qquad \text{Minimising} \quad \alpha = -\frac{u_n^T r_n}{u_n^T A u_n}$$
$$r_{n+1} = r_n + \alpha A u_n$$
$$u_{n+1} = r_{n+1} + \beta u_n \qquad \text{Conj grad} \quad \beta = -\frac{r_{n+1}^T A u_n}{u_n^T A u_n}$$

Note only one matrix evaluation per iteration – good sparse

Can show u_{n+1} conjugate all u_i $i = 1, 2, \ldots, n$

Can show $\alpha = \dfrac{r_n^T r_n}{u_n^T A u_n}$, $\qquad \beta = \dfrac{r_{n+1}^T r_{n+1}}{r_n^T r_n}$

GC not steepest descent ∇f

Steepest descent $\to$ rattle from side to side across steep valley
with no movement along the valley floor

Need new direction $\mathbf{v}$ which does not reset $\mathbf{u}$ minimisation

$$f(\mathbf{x}_n + \alpha\mathbf{u} + \beta\mathbf{v}) = f(\mathbf{x}_n) + \alpha\mathbf{u}\cdot\nabla f_n + \tfrac{1}{2}\alpha^2\mathbf{u}^T A\mathbf{u}$$
$$+\alpha\beta\mathbf{u}^T A\mathbf{v} + \beta\mathbf{v}\cdot\nabla f_n + \tfrac{1}{2}\beta^2\mathbf{v}^T A\mathbf{v}$$

Hence need $\mathbf{u}^T A\mathbf{v} = 0$ "conjugate directions"

Precondition
$Ax = b$ same solution as $B^{-1}Ax = B^{-1}b$
Choose B with easy inverse and $B^{-1}A$ sparse
Typical ILU = incomplete LU, few large elements

Non-symmetric A
GMRES minimises $(Ax-b)^T(Ax-b)$
– but condition number K^2
GMRES(n) restart after n – avoids large storage

If tough, then SVD = singular value decomposition

$$A = USV = \sum_i u_i^T \lambda_i v_i$$

with v and u eigenvalues and adjoints, λ_i eigenvalues

Eigenproblems $Ae = \lambda e$ and generalised $Ae = \lambda Be$

- No finite/direct method – must iterate
- A real & symmetric – nice orthogonal evectors
- A not symmetric – possible degenerate cases
  also non-normal modes (& pseud-spectra...)

$$\frac{d}{dt}\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} -1 & k^2 \\ 0 & -1-k \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix} \quad \text{IC} \quad x(0) = 0 y(0) = 1$$

has solution $x = k(e^{-t} - e^{(1+k)t})$
which eventually decays but before is k larger than IC.

Henceforth A real and symmetric

Power iteration – for largest evalue

Start random x_0
Iterate a few times $x_{n+1} = Ax_n = A^n x_0$

x_n becomes dominated by evector with largest evalue, so

$$\lambda_{\text{approx}} = |Ax_x|/|x_n|, \qquad e_{\text{approx}} = Ax_x/|Ax_n|$$

With this crude approximation invert

$$(A - \lambda_{\text{approx}} I)^{-1}$$

which has one very large evalue $1/(\lambda_{\text{correct}} - \lambda_{\text{approx}})$,
so power iteration on this converges very rapidly

Find other evalues with μ-shifts $(A - \mu I)^{-1}$

Jacobi – small A only

Find maximum off-diagonal a_{ij}

Givens rotation G_{ij} with θ to zero a_{ij}, and a_{ji} by symmetry

$$A' = GAG^T \quad \text{has same evalues}$$

Does fill in previous zeros,
but sum of off-diagonals squared decreases by a_{ij}^2

Hence converges to diagonal (=evalues) form

Main method

Step 1: reduce to Hessenberg H, upper triangular plus one below diagonal

Arnoldi (GS on Kyrlov space $q_1, Aq_1, A^2q_1, \ldots$)
Given unit q_1, step $k = 1 \to n-1$

$$v = Aq_k$$
$$\text{for } j = 1 \to k \;\; H_{jk} = q_j \cdot v, \; v \leftarrow v - H_{jk} q_j$$
$$H_{kk} = |v|$$
$$q_{k+1} = v/H_{k+1\,k}$$

Hence

original $v = Aq_k = H_{k+1\,k} q_{k+1} + H_{kk} q_k + \ldots + H_{1k} q_1$

i.e. $A(q_1, q_2, \ldots, q_n) = (q_1, q_2, \ldots, q_n)\, H$

i.e. $AQ = QH$ or $H = Q^T AQ$ with same evalues as A

Cost $O(n^2)$ if dense

$$H = Q^T AQ \quad \text{Hessenberg}$$

A symmetric $\rightarrow$ H symmetric, hence tridiagonal

Hence reduce 'for $j = 1 \rightarrow k$' to 'for $j = k-1, k$',

Cost $\rightarrow O(n^2)$ (Lanzcos)

NB: making q_{k+1} orthogonal to q_k & q_{k-1}

gives q_{k+1} orthogonal to q_j $j = k, k-1, k-2, \dots, 1$

cf conjugate gradient

Main method, step 2

a. QR Find QR decomposition of H

Set $H' = RQ = Q^T AQ$

– remains Hessenberg/Tridiagonal

– off-diagonals reduced by λ_i/λ_j

$\rightarrow$ converges to diagonal, of evalues

b. Power iteration – quick when tridiagonal

c. Root solve $\det(A - \lambda I) = 0$ – quick if tridiagonal

BUT USE PACKAGES