EIGENVALUE PROBLEMS

• Background on eigenvalues / eigenvectors / decompositions

• Perturbation analysis, condition numbers..

• Power method

• The QR algorithm

• Practical QR algorithms: use of Hessenberg form and shifts

• The symmetric eigenvalue problem.
Eigenvalue Problems. Introduction

Let $A$ an $n \times n$ real nonsymmetric matrix. The eigenvalue problem:

$$Ax = \lambda x$$

$\lambda \in \mathbb{C}$ : eigenvalue

$x \in \mathbb{C}^n$ : eigenvector

Types of Problems:

- Compute a few $\lambda_i$'s with smallest or largest real parts;
- Compute all $\lambda_i$'s in a certain region of $\mathbb{C}$;
- Compute a few of the dominant eigenvalues;
- Compute all $\lambda_i$'s.
Eigenvalue Problems. Their origins

- Structural Engineering \[ Ku = \lambda Mu \]
- Stability analysis [e.g., electrical networks, mechanical system,..]
- Bifurcation analysis [e.g., in fluid flow]
- Electronic structure calculations [Shrödinger equation..]
- Application of new era: page ranking on the world-wide web.
A complex scalar $\lambda$ is called an eigenvalue of a square matrix $A$ if there exists a nonzero vector $u$ in $\mathbb{C}^n$ such that $Au = \lambda u$. The vector $u$ is called an eigenvector of $A$ associated with $\lambda$. The set of all eigenvalues of $A$ is the ‘spectrum’ of $A$. Notation: $\Lambda(A)$.

- $\lambda$ is an eigenvalue iff the columns of $A - \lambda I$ are linearly dependent.
- ... equivalent to saying that its rows are linearly dependent. So: there is a nonzero vector $w$ such that $w^H(A - \lambda I) = 0$
- $w^H$ is a left eigenvector of $A$ ($u =$ right eigenvector)
- $\lambda$ is an eigenvalue iff $\det(A - \lambda I) = 0$
Basic definitions and properties (cont.)

An eigenvalue is a root of the Characteristic polynomial:

\[ p_A(\lambda) = \det(A - \lambda I) \]

So there are \( n \) eigenvalues (counted with their multiplicities).

The multiplicity of these eigenvalues as roots of \( p_A \) are called algebraic multiplicities.

The geometric multiplicity of an eigenvalue \( \lambda_i \) is the number of linearly independent eigenvectors associated with \( \lambda_i \).
➤ Geometric multiplicity is $\leq$ algebraic multiplicity.
➤ An eigenvalue is simple if its (algebraic) multiplicity is one.
➤ It is semi-simple if its geometric and algebraic multiplicities are equal.

Consider

$$A = \begin{pmatrix} 1 & 2 & -4 \\ 0 & 1 & 2 \\ 0 & 0 & 2 \end{pmatrix}$$

Eigenvalues of $A$? their algebraic multiplicities? their geometric multiplicities? Is one a semi-simple eigenvalue?

➤ Same questions if $a_{33}$ is replaced by one.
➤ Same questions if $a_{12}$ is replaced by zero.
Two matrices $A$ and $B$ are similar if there exists a nonsingular matrix $X$ such that

$$A = XBX^{-1}$$

**Definition:** $A$ is diagonalizable if it is similar to a diagonal matrix

**Theorem:** A matrix is diagonalizable iff it has $n$ linearly independent eigenvectors

... iff all its eigenvalues are semi-simple

... iff its eigenvectors form a basis of $\mathbb{R}^n$

$Av = \lambda v \iff B(X^{-1}v) = \lambda(X^{-1}v)$

eigenvalues remain the same, eigenvectors transformed.
**Other Transformations Preserving Eigenstructure**

**Shift**

\[ B = A - \sigma I: \quad Av = \lambda v \iff Bv = (\lambda - \sigma)v \]

eigenvalues move, eigenvectors remain the same.

**Poly-**

\[ B = p(A) = \alpha_0 I + \cdots + \alpha_n A^n: \quad Av = \lambda v \iff Bv = p(\lambda)v \]

eigenvalues transformed, eigenvectors remain the same.

**Invert**

\[ B = A^{-1}: \quad Av = \lambda v \iff Bv = \lambda^{-1}v \]

eigenvalues inverted, eigenvectors remain the same.

**Shift & Invert**

\[ B = (A - \sigma I)^{-1}: \quad Av = \lambda v \iff Bv = (\lambda - \sigma)^{-1}v \]
eigenvalues transformed, eigenvectors remain the same.

spacing between eigenvalues can be radically changed.
THEOREM (Schur form): Any matrix is unitarily similar to a triangular matrix, i.e., for any $A$ there exists a unitary matrix $Q$ and an upper triangular matrix $R$ such that

$$A = QRQ^H$$

Any Hermitian matrix is unitarily similar to a real diagonal matrix, (i.e. its Schur form is real diagonal).

It is easy to read off the eigenvalues (including all the multiplicities) from the triangular matrix $R$

Eigenvectors can be obtained by back-solving
Show that there is at least one eigenvalue and eigenvector of $A$: $Ax = \lambda x$, with $\|x\|_2 = 1$.

There is a unitary transformation $P$ such that $Px = e_1$. How do you define $P$?

Show that $PAP^H = \begin{pmatrix} \lambda & ** \\ 0 & A_2 \end{pmatrix}$.

Apply process recursively to $A_2$.

What happens if $A$ is Hermitian?

Another proof altogether: use Jordan form of $A$ and QR factorization.
Perturbation analysis

- General questions: If $A$ is perturbed how does an eigenvalue change? How about an eigenvector?
- Also: sensitivity of an eigenvalue to perturbations

**THEOREM [Gerschgorin]**

\[
\forall \lambda \in \Lambda(A), \quad \exists \ i \quad \text{such that} \quad |\lambda - a_{ii}| \leq \sum_{\substack{j=1\atop j \neq i}}^{\substack{j=n\atop j \neq i}} |a_{ij}|.
\]

- In words: eigenvalue $\lambda$ is located in one of the closed discs of the complex plane centered at $a_{ii}$ and with radius $\rho_i = \sum_{j \neq i} |a_{ij}|$. 
Proof: By contradiction. If contrary is true then there is one eigenvalue $\lambda$ that does not belong to any of the disks, i.e., such that $|\lambda - a_{ii}| > \rho_i$ for all $i$. Consider the matrix $A - \lambda I$ which we write as

$$A - \lambda I = D - F$$

where $D$ is the diagonal and $F = D - (A - \lambda I)$ is the matrix of off-diagonal entries. Now write $A = D(I - D^{-1}F)$. From assumptions we have $\|D^{-1}F\|_\infty < 1$. (Show this). The Lemma in P. 5-8 of notes would then show that $A - \lambda I$ is nonsingular – a contradiction $\square$
Find a region of the complex plane where the eigenvalues of the following matrix are located:

\[ A = \begin{pmatrix}
  1 & -1 & 0 & 0 \\
  0 & 2 & 0 & 1 \\
 -1 & -2 & -3 & 1 \\
 \frac{1}{2} & \frac{1}{2} & 0 & -4
\end{pmatrix} \]

Refinement: if disks are all disjoint then each of them contains one eigenvalue

Refinement: can combine row and column version of the theorem (column version: apply theorem to \( A^H \)).
Application: If $A$ is diagonalizable, $A = P \Lambda P^{-1}$, with $\Lambda$ = the diagonal matrix of eigenvalues & $P$ = the matrix of eigenvectors, then apply Gershgorin to $\Lambda + P^{-1}EP = P^{-1}(A + E)P$.

Can apply same to block diagonalizable matrix.
Bauer-Fike theorem

THEOREM [Bauer-Fike] Let $\tilde{\lambda}, \tilde{u}$ be an approximate eigenpair with $\|\tilde{u}\|_2 = 1$, and let $r = A\tilde{u} - \tilde{\lambda}\tilde{u}$ (‘residual vector’). Assume $A$ is diagonalizable: $A = XD X^{-1}$, with $D$ diagonal. Then

$$\exists \lambda \in \Lambda(A) \text{ such that } |\lambda - \tilde{\lambda}| \leq \text{cond}_2(X)\|r\|_2.$$ 

Very restrictive result - also not too sharp in general.

Alternative formulation. If $E$ is a perturbation to $A$ then for any eigenvalue $\tilde{\lambda}$ of $A + E$ there is an eigenvalue $\lambda$ of $A$ such that:

$$|\lambda - \tilde{\lambda}| \leq \text{cond}_2(X)\|E\|_2.$$ 

Prove this result from the previous one.
Conditioning of Eigenvalues

Assume that $\lambda$ is a simple eigenvalue with right and left eigenvectors $u$ and $w^H$ respectively. Consider the matrices:

$$A(t) = A + tE$$

Eigenvalue $\lambda(t)$, Eigenvector $u(t)$.

Conditioning of $\lambda$ of $A$ relative to $E$ is

$$\frac{d\lambda(t)}{dt} \bigg|_{t=0}.$$

Write

$$A(t)u(t) = \lambda(t)u(t)$$

Then multiply both sides to the left by $w^H$

$$w^H(A + tE)u(t) = \lambda(t)w^H u(t) \rightarrow$$

$$\lambda(t)w^H u(t) = w^H Au(t) + tw^H Eu(t)$$

$$= \lambda w^H u(t) + tw^H Eu(t).$$
\[
\lambda(t) - \lambda \frac{w^H u(t)}{t} = w^H Eu(t)
\]

Take the limit at \( t = 0 \),

\[
\lambda'(0) = \frac{w^H Eu}{w^H u}
\]

Note: the left and right eigenvectors associated with a simple eigenvalue cannot be orthogonal to each other.

Actual conditioning of an eigenvalue, given a perturbation “in the direction of \( E \)” is \(|\lambda'(0)|\).

In practice only estimate of \( \|E\| \) is available, so

\[
|\lambda'(0)| \leq \frac{\|Eu\|_2 \|w\|_2}{|(u, w)|} \leq \|E\|_2 \|u\|_2 \|w\|_2 \frac{1}{|(u, w)|}
\]
**Definition.** The condition number of a simple eigenvalue $\lambda$ of an arbitrary matrix $A$ is defined by

$$\text{cond}(\lambda) = \frac{1}{\cos \theta(u, w)}$$

in which $u$ and $w^H$ are the right and left eigenvectors, respectively, associated with $\lambda$.

**Example:** Consider the matrix

$$A = \begin{pmatrix} -149 & -50 & -154 \\ 537 & 180 & 546 \\ -27 & -9 & -25 \end{pmatrix}$$
\[ \Lambda(A) = \{1, 2, 3\} \]. Right and left eigenvectors associated with \( \lambda_1 = 1 \):

\[
u = \begin{pmatrix} 0.3162 \\ -0.9487 \\ 0.0 \end{pmatrix} \quad \text{and} \quad w = \begin{pmatrix} 0.6810 \\ 0.2253 \\ 0.6967 \end{pmatrix}
\]

So:

\[ \text{cond}(\lambda_1) \approx 603.64 \]

Perturbing \( a_{11} \) to \(-149.01\) yields the spectrum:

\[ \{0.2287, 3.2878, 2.4735\} \]

as expected.

For Hermitian (also normal matrices) every simple eigenvalue is well-conditioned, since \( \text{cond}(\lambda) = 1 \).
Perturbations with Multiple Eigenvalues - Example

\[ A = \begin{pmatrix} 1 & 2 & 0 \\ 0 & 1 & 2 \\ 0 & 0 & 1 \end{pmatrix} = I_3 + \begin{pmatrix} 0 & 2 & 0 \\ 0 & 0 & 2 \\ 0 & 0 & 0 \end{pmatrix} = I + 2J \]

Worst case perturbation is in 3,1 position: set \( J_{31} = \epsilon \).

Eigenvalues of perturbed \( A \) are the roots of
\[ p(\mu) = (\mu - 1)^3 - 4 \cdot \epsilon. \]

Hence eigenvalues of perturbed \( A \) are \( 1 + O(\sqrt[3]{\epsilon}) \).

In general, if index of eigenvalue (dimension of largest Jordan block) is \( k \), then an \( O(\epsilon) \) perturbation to \( A \) can lead to \( O(\sqrt[3]{\epsilon}) \) change in eigenvalue. Simple eigenvalue case corresponds to \( k = 1 \).
The power method

Basic idea is to generate the sequence of vectors $A^k v_0$ where $v_0 \neq 0$ – then normalize.

Most commonly used normalization: ensure that the largest component of the approximation is equal to one.

The Power Method

1. Choose a nonzero initial vector $v^{(0)}$.
2. For $k = 1, 2, \ldots$, until convergence, Do:
3. $v^{(k)} = \frac{1}{\alpha_k} A v^{(k-1)}$ where
4. $\alpha_k = \arg\max_{i=1, \ldots, n} |(A v^{(k-1)})_i|$
5. EndDo

$\arg\max_{i=1, \ldots, n} |x_i| \equiv$ the component $x_i$ with largest modulus
**Convergence of the power method**

**THEOREM** Assume there is one eigenvalue $\lambda_1$ of $A$, s.t. $\lambda_1 = \max_j |\lambda_j|$, and that $\lambda_1$ is semi-simple. Then either the initial vector $v^{(0)}$ has no component in $\text{Null}(A - \lambda_1 I)$ or $v^{(k)}$ converges to an eigenvector associated with $\lambda_1$ and $\alpha_k \to \lambda_1$.

Proof in the diagonalizable case.

- $v^{(k)}$ is $=$ vector $A^k v^{(0)}$ normalized by a certain scalar $\hat{\alpha}_k$ in such a way that its largest component is 1.

- Decompose initial vector $v^{(0)}$ in the eigenbasis as:

$$v^{(0)} = \sum_{i=1}^{n} \gamma_i u_i$$

- Each $u_i$ is an eigenvector associated with $\lambda_i$.
Note that \( A^k u_i = \lambda_i^k u_i \)

\[
v^{(k)} = \frac{1}{\text{scaling}} \times \sum_{i=1}^{n} \lambda_i^k \gamma_i u_i
\]

\[
= \frac{1}{\text{scaling}} \times \left[ \lambda_1^k \gamma_1 u_1 + \sum_{i=2}^{n} \lambda_i^k \gamma_i u_i \right]
\]

\[
= \frac{1}{\text{scaling}'} \times \left[ u_1 + \sum_{i=2}^{n} \left( \frac{\lambda_i}{\lambda_1} \right)^k \gamma_i u_i \right]
\]

Second term inside bracket converges to zero. QED

Proof suggests that the convergence factor is given by

\[
\rho_D = \frac{|\lambda_2|}{|\lambda_1|}
\]

where \( \lambda_2 \) is the second largest eigenvalue in modulus.
Example: Consider a ‘Markov Chain’ matrix of size \( n = 55 \). Dominant eigenvalues are \( \lambda = 1 \) and \( \lambda = -1 \). The power method applied directly to \( A \) fails. (Why?)

We can consider instead the matrix \( I + A \). The eigenvalue \( \lambda = 1 \) is then transformed into the (only) dominant eigenvalue \( \lambda = 2 \)

<table>
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<tr>
<th>Iteration</th>
<th>Norm of diff.</th>
<th>Res. norm</th>
<th>Eigenvalue</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.639D-01</td>
<td>0.276D-01</td>
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<td>161</td>
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<td>0.430D-07</td>
<td>1.00000005</td>
</tr>
</tbody>
</table>
In previous example shifted $A$ into $B = A + I$ before applying power method. We could also iterate with $B(\sigma) = A + \sigma I$ for any positive $\sigma$

**Example:** With $\sigma = 0.1$ we get the following improvement.

<table>
<thead>
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<th>Norm of diff.</th>
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<th>Eigenvalue</th>
</tr>
</thead>
<tbody>
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<td>88</td>
<td>0.971D-07</td>
<td>0.261D-07</td>
<td>1.00000002</td>
</tr>
</tbody>
</table>
Question: What is the best shift-of-origin $\sigma$ to use?

Easy to answer the question when all eigenvalues are real.

Assume all eigenvalues are real and labeled decreasingly:

$$\lambda_1 > \lambda_2 \geq \lambda_2 \geq \cdots \geq \lambda_n,$$

Then:

The shift $\sigma$ that yields the best convergence factor is:

$$\sigma_{opt} = \frac{\lambda_2 + \lambda_n}{2}$$

Plot a typical function $\phi(\sigma) = \rho(A - \sigma I)$ as a function of $\sigma$. Determine the minimum value and prove the above result.
**Inverse Iteration**

**Observation:** The eigenvectors of $A$ and $A^{-1}$ are identical.

- Idea: use the power method on $A^{-1}$.
- Will compute the eigenvalues closest to zero.
- **Shift-and-invert** Use power method on $(A - \sigma I)^{-1}$.
- will compute eigenvalues closest to $\sigma$.
- **Rayleigh-Quotient Iteration:** use $\sigma = \frac{v^T Av}{v^T v}$ (best approximation to $\lambda$ given $v$).
- Advantages: fast convergence in general.
- **Drawbacks:** need to factor $A$ (or $A - \sigma I$) into LU.