This document is an **exact transcript** of the lecture, with extra summary and vocabulary sections for your convenience. Due to time constraints, the lectures sometimes only contain limited illustrations, proofs, and examples. For a more thorough discussion of the course content, **consult the textbook**.

Summary

Quick summary of today's notes. Lecture starts on next page.

- Let A be an $n \times n$ matrix. Let $I = I_n$ be the $n \times n$ identity matrix.

  Let λ be a number and suppose $0 \neq v \in \mathbb{R}^n$.

  If $Av = \lambda v$ then we say that v is an *eigenvector* for A and that λ is an *eigenvalue* for A.

  More specifically, v is an *eigenvector with eigenvalue* λ for A.

- The eigenvalues of A are the solutions to the *characteristic equation* $\det(A - xI) = 0$.

  If λ is any number then $\mathrm{Nul}(A - \lambda I)$ is the *λ-eigenspace* of A.

  If λ is **not** an eigenvalue for A then the λ-eigenspace is the zero subspace $\{0\}$.

  If λ is an eigenvalue for A then the λ-eigenspace is a nonzero subspace.

  To find a basis for the λ-eigenspace, use our familiar algorithm for finding bases of null spaces.

- Suppose $v_1, v_2, \dots, v_r$ are eigenvectors for A.

  Let λ_i be the eigenvalue such that $Av_i = \lambda_i v_i$.

  If $\lambda_1, \lambda_2, \dots, \lambda_r$ are all distinct, then $v_1, v_2, \dots, v_r$ are linearly independent.

- If A and B are $n \times n$ matrices and there exists an invertible $n \times n$ matrix P with

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

  then we say that A is *similar* to B and that B is *similar* to A.

  Any matrix is similar to itself, and if A is similar to B and B is similar to C then A is similar to C.

- Similar matrices have the same characteristic equations and same eigenvalues.

- A is *diagonalizable* if A is similar to a diagonal matrix D.

  One useful property of diagonalizable matrices: if $A = PDP^{-1}$ where D is diagonal, then there are simple formulas for each entry in the matrix $A^n = PD^nP^{-1}$ for all positive integers n.

1 Eigenvector and eigenvalues

Everywhere is this lecture, n is a positive integer and A is an $n \times n$ matrix.

Let I denote the $n \times n$ identity matrix. Let λ be a number.

Definition. A vector $v \in \mathbb{R}^n$ is an *eigenvector* for A with *eigenvalue* λ if $v \neq 0$ and $Av = \lambda v$.

The set of $v \in \mathbb{R}^n$ with $Av = \lambda v$ is the *λ-eigenspace* of A for λ. This is equal to the nullspace of $A - \lambda I$.

Proposition. Let λ be a number. The following are equivalent:

1. There exists an eigenvector $v \in \mathbb{R}^n$ for A with eigenvalue λ.

   (Remember that eigenvectors must be nonzero.)
2. The matrix $A - \lambda I$ is not invertible.
3. $\det(A - \lambda I) = 0$.
4. The λ-eigenspace for A contains a nonzero vector.

As usual, a matrix is *triangular* if it is upper-triangular or lower-triangular.

The *characteristic polynomial* of a square matrix A is $\det(A - xI)$.

Theorem. The eigenvalues of a triangular square matrix A are its diagonal entries. If these numbers are $d_1, d_2, \dots, d_n$ then the characteristic polynomial of A is $(d_1 - x)(d_2 - x) \cdots (d_n - x)$.

The following is true for all square matrices, not just triangular ones.

Theorem. Suppose $\lambda_1, \lambda_2, \dots, \lambda_r$ are **distinct** eigenvalues for A, meaning $\lambda_i \neq \lambda_j$ for $i \neq j$.

Let $v_1, v_2, \dots, v_r \in \mathbb{R}^n$ be the corresponding eigenvectors, so that $Av_i = \lambda_i v_i$ for $i = 1, 2, \dots, r$.

Then the vectors $v_1, v_2, \dots v_r$ are linearly independent.

Proof. Suppose $v_1, v_2, \dots, v_r$ are linearly dependent. We argue that this leads to a logical contradiction.

There must exist an index $p > 0$ such that $v_1, v_2, \dots, v_p$ are linearly independent and v_{p+1} is a linear combination of $v_1, v_2, \dots, v_p$. (Otherwise, the vectors $v_1, v_2, \dots, v_r$ would be linearly independent.)

Let $c_1, c_2, \dots, c_p \in \mathbb{R}$ be scalars such that $v_{p+1} = c_1 v_1 + c_2 v_2 + \cdots + c_p v_p$. Then

$$\lambda_{p+1} v_{p+1} = Av_{p+1} = A(c_1 v_1 + \cdots + c_p v_p) = c_1 Av_1 + \cdots + c_p Av_p = c_1 \lambda_1 v_1 + c_2 \lambda_2 v_2 + \cdots + c_p \lambda_p v_p.$$

On the other hand, multiplying both sides of $v_{p+1} = c_1 v_1 + c_2 v_2 + \cdots + c_p v_p$ by λ_{p+1} gives

$$\lambda_{p+1} v_{p+1} = c_1 \lambda_{p+1} v_1 + c_2 \lambda_{p+1} v_2 + \cdots + c_p \lambda_{p+1} v_p.$$

By subtracting the two equations, we get

$$0 = \lambda_{p+1} v_{p+1} - \lambda_{p+1} v_{p+1} = c_1(\lambda_1 - \lambda_{p+1}) v_1 + c_2(\lambda_2 - \lambda_{p+1}) v_2 + \cdots + c_p(\lambda_p - \lambda_{p+1}) v_p.$$

Since the vectors $v_1, v_2, \dots, v_p$ are linearly independent by assumption, we must have

$$c_1(\lambda_1 - \lambda_{p+1}) = c_2(\lambda_2 - \lambda_{p+1}) = \cdots = c_p(\lambda_p - \lambda_{p+1}) = 0.$$

But the differences $\lambda_i - \lambda_{p+1}$ for $i = 1, 2, \dots, p$ are all nonzero, so we must have $c_1 = c_2 = \cdots = c_p = 0$. This implies that $v_{p+1} = 0$, contradicting our assumption that v_{p+1} is a (necessarily nonzero) eigenvector.

We conclude from this contradiction that actually the vectors $v_1, v_2, \dots, v_r$ are linearly independent. $\square$

Let x be a variable. The eigenvalues of A are precisely the solutions to the equation $\det(A - xI) = 0$ which we call the *characteristic equation* for A.

Example. The matrix

$$A = \begin{bmatrix} 5 & -2 & 6 & -1 \\ 0 & 3 & -8 & 0 \\ 0 & 0 & 5 & 4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

has characteristic polynomial $\det(A - xI) = (5-x)(3-x)(5-x)(1-x) = (5-x)^2(3-x)(1-x)$.

Since $(5-x)^2$ divides $\det(A-xI)$ but $(5-x)^3$ does not divide $\det(A-xI)$, we say that 5 is an eigenvalue of A with *algebraic multiplicity* 2. The other eigenvalues 1 and 3 have *algebraic multiplicity* 1.

In general the *algebraic multiplicity* of an eigenvalue λ for a square matrix A is the unique integer $m \geq 1$ such that $(\lambda - x)^m$ divides $\det(A - xI)$ but $(\lambda - x)^{m+1}$ does not divide $\det(A - xI)$.

We consider the following example in more depth.

Example. Consider the matrix

$$A = \begin{bmatrix} 1 & 5 & 4 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix}.$$

Since A is triangular, its characteristic polynomial is $(1-x)(2-x)(3-x)$ and its eigenvalues are $1, 2, 3$.

Each eigenvalue in this example has algebraic multiplicity 1. We compute the corresponding eigenspaces:

1-eigenspace. The eigenvectors of A with eigenvalue 1 are the nonzero elements of $\mathrm{Nul}(A - I)$.

$$A - I = \begin{bmatrix} 0 & 5 & 4 \\ & 1 & 0 \\ & & 2 \end{bmatrix} \sim \begin{bmatrix} 0 & 1 & 0 \\ & 5 & 4 \\ & & 2 \end{bmatrix} \sim \begin{bmatrix} 0 & 1 & 0 \\ & 0 & 4 \\ & & 2 \end{bmatrix} \sim \begin{bmatrix} 0 & 1 & 0 \\ & 0 & 1 \\ & & 0 \end{bmatrix} = \mathsf{RREF}(A - I).$$

This shows that $x \in \mathrm{Nul}(A - I)$ if and only if $x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} x_1 \\ 0 \\ 0 \end{bmatrix} = x_1 \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$, so $\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$ is a basis for $\mathrm{Nul}(A - I)$. Therefore all eigenvectors of A with eigenvalue 1 are nonzero scalar multiples of $\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$.

2-eigenspace. The eigenvectors of A with eigenvalue 2 are the nonzero elements of $\mathrm{Nul}(A - 2I)$.

$$A - 2I = \begin{bmatrix} -1 & 5 & 4 \\ & 0 & 0 \\ & & 1 \end{bmatrix} \sim \begin{bmatrix} 1 & -5 & 0 \\ & 0 & 1 \\ & & 0 \end{bmatrix} = \mathsf{RREF}(A - 2I).$$

This shows that $x \in \mathrm{Nul}(A - 2I)$ if and only if $x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 5x_2 \\ x_2 \\ 0 \end{bmatrix} = x_2 \begin{bmatrix} 5 \\ 1 \\ 0 \end{bmatrix}$, so $\begin{bmatrix} 5 \\ 1 \\ 0 \end{bmatrix}$ is a basis for $\mathrm{Nul}(A - 2I)$. All eigenvectors of A with eigenvalue 2 are nonzero scalar multiples of $\begin{bmatrix} 5 \\ 1 \\ 0 \end{bmatrix}$.

3-eigenspace. The eigenvectors of A with eigenvalue 3 are the nonzero elements of $\mathrm{Nul}(A-3I)$.

$$A-3I=\begin{bmatrix}-2&5&4\\&-1&0\\0&0&0\end{bmatrix}\sim\begin{bmatrix}-2&0&4\\&1&0\\&&0\end{bmatrix}\sim\begin{bmatrix}1&0&-2\\&1&0\\&&0\end{bmatrix}=\mathsf{RREF}(A-3I).$$

This shows that $x\in\mathrm{Nul}(A-3I)$ if and only if $x=\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}=\begin{bmatrix}2x_3\\0\\x_3\end{bmatrix}=x_3\begin{bmatrix}2\\0\\1\end{bmatrix}$ so $\begin{bmatrix}2\\0\\1\end{bmatrix}$ is a basis for $\mathrm{Nul}(A-3I)$. All eigenvectors of A with eigenvalue 3 are nonzero scalar multiples of $\begin{bmatrix}2\\0\\1\end{bmatrix}$.

Since the eigenvalues 1, 2, 3, are distinct, the eigenvectors $\begin{bmatrix}1\\0\\0\end{bmatrix},\begin{bmatrix}5\\1\\0\end{bmatrix},\begin{bmatrix}2\\0\\1\end{bmatrix}$ are linearly independent.

Consider the **invertible** matrix whose columns are given by these linearly independent vectors:

$$P=\begin{bmatrix}1&5&2\\0&1&0\\0&0&1\end{bmatrix}.$$

As usual, let $e_1=\begin{bmatrix}1\\0\\0\end{bmatrix}$, $e_2=\begin{bmatrix}0\\1\\0\end{bmatrix}$, and $e_3=\begin{bmatrix}0\\0\\1\end{bmatrix}$. The product Pe_i is the ith column of P, so

$$Pe_1=\begin{bmatrix}1\\0\\0\end{bmatrix}\quad\text{and}\quad Pe_2=\begin{bmatrix}5\\1\\0\end{bmatrix}\quad\text{and}\quad Pe_3=\begin{bmatrix}2\\0\\1\end{bmatrix}.$$

Since $Px=y$ means that $P^{-1}y=P^{-1}Px=Ix=x$, it follows that

$$P^{-1}\begin{bmatrix}1\\0\\0\end{bmatrix}=e_1\quad\text{and}\quad P^{-1}\begin{bmatrix}5\\1\\0\end{bmatrix}=e_2\quad\text{and}\quad P^{-1}\begin{bmatrix}2\\0\\1\end{bmatrix}=e_3.$$

Combining these identities shows that

$$P^{-1}APe_1=P^{-1}A\begin{bmatrix}1\\0\\0\end{bmatrix}=P^{-1}\begin{bmatrix}1\\0\\0\end{bmatrix}=e_1.$$

$$P^{-1}APe_2=P^{-1}A\begin{bmatrix}5\\1\\0\end{bmatrix}=2P^{-1}\begin{bmatrix}5\\1\\0\end{bmatrix}=2e_2.$$

$$P^{-1}APe_3=P^{-1}A\begin{bmatrix}2\\0\\1\end{bmatrix}=3P^{-1}\begin{bmatrix}2\\0\\1\end{bmatrix}=3e_3.$$

These calculations determine the columns of the matrix $P^{-1}AP$.

If fact, we see that $P^{-1}AP=D$ where $D=\begin{bmatrix}e_1&2e_2&3e_3\end{bmatrix}=\begin{bmatrix}1&0&0\\0&2&0\\0&0&3\end{bmatrix}$.

This means that $A = P(P^{-1}AP)P^{-1} = PDP^{-1}$, so

$$\begin{bmatrix} 1 & 5 & 4 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix} = \begin{bmatrix} 1 & 5 & 2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix} \begin{bmatrix} 1 & 5 & 2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-1}.$$

One application of this decomposition: we can derive a simple formula for an arbitrary power A^n of A.

Define $A^0 = I$, $A^1 = A$, $A^2 = AA$, $A^3 = AAA$, and so on.

Lemma. For any integer $n \geq 0$ we have $A^n = (PDP^{-1})^n = PD^nP^{-1}$.

Proof. Do some small examples and convince yourself that the pattern continues:

$$A^2 = AA = PDP^{-1}PDP^{-1} = PDIDP^{-1} = PD^2P^{-1}$$
$$A^3 = A^2A = PD^2P^{-1}PDP^{-1} = PD^2IDP^{-1} = PD^3P^{-1}$$
$$A^4 = A^3A = PD^3P^{-1}PDP^{-1} = PD^3IDP^{-1} = PD^4P^{-1}$$
$$\vdots$$

and so on. □

Lemma. For any integer $n \geq 0$ we have

$$D^n = \begin{bmatrix} 1^n & 0 & 0 \\ 0 & 2^n & 0 \\ 0 & 0 & 3^n \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 2^n & 0 \\ 0 & 0 & 3^n \end{bmatrix}.$$

Proof. To multiply diagonal matrices we just multiply the entries in the corresponding diagonal positions:

$$\begin{bmatrix} x_1 & & & \\ & x_2 & & \\ & & \ddots & \\ & & & x_k \end{bmatrix} \begin{bmatrix} y_1 & & & \\ & y_2 & & \\ & & \ddots & \\ & & & y_k \end{bmatrix} = \begin{bmatrix} x_1y_1 & & & \\ & x_2y_2 & & \\ & & \ddots & \\ & & & x_ky_k \end{bmatrix}.$$

Therefore to evaluate $D^n = DD\cdots D$, we just raise each diagonal entry to the nth power. □

Finally, by the usual algorithm we can compute $P^{-1} = \begin{bmatrix} 1 & -5 & -2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$.

(Check that this is the correct inverse of P!)

Putting everything together gives the identity

$$\begin{aligned} A^n = PD^nP^{-1} &= \begin{bmatrix} 1 & 5 & 2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 2^n & 0 \\ 0 & 0 & 3^n \end{bmatrix} \begin{bmatrix} 1 & -5 & -2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} 1 & 5 \cdot 2^n & 2 \cdot 3^n \\ 0 & 2^n & 0 \\ 0 & 0 & 3^n \end{bmatrix} \begin{bmatrix} 1 & -5 & -2 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 & 5(2^n - 1) & 2(3^n - 1) \\ 0 & 2^n & 0 \\ 0 & 0 & 3^n \end{bmatrix}. \end{aligned}$$

Remark. We've done all these calculations in detail as a means of illustrating some key concepts. But these calculations would also come up in the solution of the following discrete dynamical system. Suppose $a_0, a_1, a_2, \ldots$, $b_0, b_1, b_2, \ldots$, and $c_0, c_1, c_2, \ldots$ are sequences of numbers.

For each integer $n \geq 1$, suppose

$$a_n = a_{n-1} + 5b_{n-1} + 4c_{n-1} \qquad \text{and} \qquad b_n = 2b_{n-1} \qquad \text{and} \qquad c_n = 3c_{n-1}. \tag{*}$$

How could we find a formula for a_n, b_n, and c_n in terms of n and the sequences' initial values a_0, b_0, c_0?

The system of formulas (*) is equivalent to

$$\begin{bmatrix} a_n \\ b_n \\ c_n \end{bmatrix} = \begin{bmatrix} 1 & 5 & 4 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix} \begin{bmatrix} a_{n-1} \\ b_{n-1} \\ c_{n-1} \end{bmatrix} = A \begin{bmatrix} a_{n-1} \\ b_{n-1} \\ c_{n-1} \end{bmatrix} = A^2 \begin{bmatrix} a_{n-2} \\ b_{n-2} \\ c_{n-2} \end{bmatrix} = \cdots = A^n \begin{bmatrix} a_0 \\ b_0 \\ c_0 \end{bmatrix}.$$

Thus, our formula for A^n gives

$$a_n = a_0 + 5(2^n - 1)b_0 + 2(3^n - 1)c_0 \qquad \text{and} \qquad b_n = 2^n b_0 \qquad \text{and} \qquad c_n = 3^n c_0.$$

If $a_0 = b_0 = c_0 = 1$ then $a_{10} = 123212$ and $b_{10} = 1024$ and $c_{10} = 59049$. Moreover,

$$\lim_{n\to\infty} \frac{a_n}{3^n} = \lim_{n\to\infty} \frac{a_0 + 5(2^n - 1)b_0 + 2(3^n - 1)c_0}{3^n} = 2c_0.$$

So being able to compute the matrix decomposition $A = PDP^{-1}$ lets us determine the asymptotic growth rate of the quantities in our discrete dynamical system as $n \to \infty$.

2 Similar matrices

When do square matrices have the same eigenvalues? Here is one condition that guarantees this to occur:

Definition. Two $n \times n$ matrices X and Y are *similar* if there exists an invertible $n \times n$ matrix P with

$$X = PYP^{-1}.$$

In this case it also holds that $Y = P^{-1}PYP^{-1}P = P^{-1}XP$.

If X and Y are similar, then we say that "X is *similar to* Y" and "Y is *similar to* X."

In the previous example we showed that $A = \begin{bmatrix} 1 & 5 & 4 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix}$ and $D = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix}$ are similar matrices.

There is a special name for this kind of similarity:

Definition. A square matrix X is *diagonalizable* if X is similar to a diagonal matrix

Proposition. An $n \times n$ matrix A is always similar to itself.

(This means that similarity is a *reflexive* relation on square matrices.)

Proof. Since $I = I^{-1}$ we have $A = PAP^{-1}$ for $P = I$. □

Proposition. Suppose A, B, C are $n \times n$ matrices.

Assume A and B are similar. Assume B and C are also similar. Then A and C are similar.

(This means that similarity is a *transitive* relation on square matrices.)

Proof. If $A = PBP^{-1}$ and $B = QCQ^{-1}$ then $R = PQ$ is invertible and $A = RCR^{-1}$. □

Theorem. If A and B are similar $n \times n$ matrices then A and B have the same characteristic polynomial and so they have the same eigenvalues.

(Similar matrices usually have different eigenvectors, however.)

Proof. Recall that $\det(XY) = \det(X)\det(Y)$. Assume $A = PBP^{-1}$. Then

$$A - xI = P(B - xI)P^{-1} \quad \text{and} \quad \det(A - xI) = \det(P(B - xI)P^{-1}) = \det(P)\det(B - xI)\det(P^{-1}).$$

But $\det(P)\det(P^{-1}) = \det(PP^{-1}) = \det(I) = 1$, so $\det(A - xI) = \det(B - xI)$. $\square$

3 Vocabulary

Keywords from today's lecture:

1. **Characteristic equation** of a square matrix A.

   The equation $\det(A - xI) = 0$, where I is the identity matrix with the same size as A.

   The solutions x for this equation give all eigenvalues of A.

   Example: If $A = \begin{bmatrix} 0 & 2 & 0 \\ 2 & 0 & 0 \\ 0 & 0 & 2 \end{bmatrix}$ then

   $$\det(A - xI) = \det \begin{bmatrix} -x & 2 & 0 \\ 2 & -x & 0 \\ 0 & 0 & 2-x \end{bmatrix} = (2-x)(x^2-4) = (2-x)^2(-2-x) = 0$$

   has solutions $x = 2$ and $x = -2$. These solutions are the eigenvalues for A.

2. **Algebraic multiplicity** of an eigenvalue λ of square matrix A.

   The number of times the factor $(\lambda - x)$ divides the characteristic polynomial $\det(A - xI)$.

   If $A = \begin{bmatrix} 0 & 2 & 0 \\ 2 & 0 & 0 \\ 0 & 0 & 2 \end{bmatrix}$ then 2 has algebraic multiplicity 2 and -2 has algebraic multiplicity 1.

3. **Similar matrices**.

   Two $n \times n$ matrices A and B are similar if there exists an invertible $n \times n$ matrix M with

   $$A = MBM^{-1}.$$

   If A and B are similar and B and C are similar, then A and C are similar.

   Example: $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix}$ is similar to $\begin{bmatrix} 3 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix} \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}^{-1}$.

4. **Diagonalizable matrix**.

   A matrix that is similar to a diagonal matrix.