

This document is an **exact transcript** of the lecture, with extra summary and vocabulary sections. 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 $\text{Nul}(A - \lambda I)$ 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 in 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 $\text{Nul}(A - I)$.

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

This shows that $x \in \text{Nul}(A - I)$ 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 $\text{Nul}(A - I)$. 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 $\text{Nul}(A - 2I)$.

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

This shows that $x \in \text{Nul}(A - 2I)$ 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 $\text{Nul}(A - 2I)$. 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 $\text{Nul}(A - 3I)$.

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

This shows that $x \in \text{Nul}(A - 3I)$ 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 $\text{Nul}(A - 3I)$. 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 i th 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

$$\begin{aligned} P^{-1}APe_1 &= P^{-1}A \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = P^{-1} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} = e_1. \\ P^{-1}APe_2 &= P^{-1}A \begin{bmatrix} 5 \\ 1 \\ 0 \end{bmatrix} = 2P^{-1} \begin{bmatrix} 5 \\ 1 \\ 0 \end{bmatrix} = 2e_2. \\ P^{-1}APe_3 &= P^{-1}A \begin{bmatrix} 2 \\ 0 \\ 1 \end{bmatrix} = 3P^{-1} \begin{bmatrix} 2 \\ 0 \\ 1 \end{bmatrix} = 3e_3. \end{aligned}$$

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

In 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:

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

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 n th 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 $a_0, a_1, a_2, \dots$, $b_0, b_1, b_2, \dots$, and $c_0, c_1, c_2, \dots$ are sequences of numbers.

For each integer $n \geq 1$, suppose

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

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

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

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

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

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 $n \rightarrow \infty$.

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 $Y = P^{-1}XP$.

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 $A = RCR^{-1}$. $\square$

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.