Syllabus

0.1 Admin Info

Class Name: Linear Algebra 2 (E)
Class Time: Th 19:20-20:55
Class Location: 4-4106
Instructor: Yilong Yang (YMSC)
Email: yy26@mail.tsinghua.edu.cn
Office: Jinchunyuan West 137
Office Hours: Th 5PM-6PM
TA: Lovy Singhal
TA Office: TBD
TA Office Hour: TBD
Discussion Session Time: TBD
Discussion Session Location: TBD
Class Wechat Group: TBD

0.2 Prerequisite

You should have mastered the following materials and skills:

1. Linear Combination and Linear Dependency.
2. Gausssian Elimination and LU decomposition.
3. Row and Column Operations to find Reduced Row Echelon Forms, to solve Linear Systems, and to find Determinants.
4. Matrix Inversion and Multiplication.
5. The Fundamental Theorem of Linear Algebra (Rank-nullity theorem and orthogonality between the four fundamental subspaces of a matrix.)
6. Gram-Schmidt Orthogonalization and QR-Decomposition.
7. Projections and Orthogonal Projections.
8. Change of Basis and orthogonal change of basis.
9. Eigenvalues and Eigenvectors.
10. Criteria for Diagonalizability.
11. Spectral Theorem for Real Symmetric Matrices.
12. Singular Value Decomposition.

In the stuff listed above, I want to specifically stress that, even though we do NOT need singular value decomposition in this class, it is probably HIGHLY IMPORTANT that you know it. It has tons of applications and will likely show up in your future.

If you do not know about singular value decompositions, you can read Gilbert Strang's introduction to linear algebra, chapter seven. (There are also accompanying online videos from MIT open course if you like.)

0.3 Content of Class

Textbook:

[LN] My lecture notes. This year's will be updated as our class go along, but feel free to check last year's notes.

[OLN] My old lecture notes, written up in 2019 Spring.

[OV] Online videos from 2020 spring, made during the COVID-19 pandemic.

Optional Textbook:

[GS] Gilbert Strang, Introduction to Linear Algebra 5th edition. The linear algebra textbook used in MIT. (University bookstore) This is NOT the main textbook, but we shall use some sections of it.

[ST] Sergei Treil, Linear Algebra Done Wrong. The linear algebra textbook used in Brown University for honor linear algebra class, and the one I used when I was a freshman. (Author made it free online.) We shall use some sections from it.

[SA] Sheldon Axler, Linear Algebra Done Right. Great linear algebra textbooks for math majors. A bit too hardcore sometimes.

[NH] Nicholas J Higham, Functions of Matrices: Theory and Computation. The first two chapters are all we need.

[BW] Ray M. Bowen and C. C. Wang, Introduction to Vectors and Tensors. Good for the tensor portion of the class.

Content Structure:

1. Complex Matrices (GS Ch 9)
2. Jordan Normal Form (ST Ch 9, SA Ch 8)
3. Matrix Analysis (NH ch 1)
4. Dual and Tensor (LADW Ch 8 and Lecture notes)
5. (Optional) ??? if we have time.

0.4 Grading

30% Homework, 30% Midterm, 30% Final, and 10% Project.

Homework: The homeworks should usually due weekly. Tries to write in english, but we do not really test your english ability, and it is totally fine if you let slide some Chinese if you are really struggling to express yourself.

All answers must be supplimented with proofs unless specifically told not to. Proofs need not to be rigiorous, but it is your job to make your reasoning clear to the grader. The grader should not be banging his/her head trying to decipher your logic. You are welcome to come to me or the TA for grading disputes.

As far as deadlines go, I'm usually easygoing, but I reserve the right to refuse any late submission.

Midterm: You take it home, you do it for two weeks, and you hand them back. Sort of like a glorified homework, but you must hand them in on time. The problems will of course be very hard. You will likely lose some hair.

Final: Open book final on our last class. (The university do not assign standard final exam times for "special" classes such as ours.) The time is tentatively 7PM-10PM. It will be significantly easier and more standardized than the Midterm.

Project: TBD. Mostly this would be some self-learning projects.

Collaboration:
I think stress is detrimental to all learning endeavor, and competition is meaningless in a classroom setting since all of us have the same goal, to learn. As a general principle, I encourage collaboration of all sorts.

Ideally, I hope that you look at the problems as soon as I put them up, and think independently at first. You do NOT need to do them right away. Look them first, think a little bit, and maybe sleep on them for a day or two. As you can see from the grading policy, I tried my best to minimize your stress, so you can take your time and think them through. Some problems are DESIGNED so that you might need a few days to solve. After a day or two, if the answer still eludes you, feel free to ask your classmates for collaboration.

I encourage collaborations on homeworks, projects and even the takehome midterm. However, you must obey the following rule:

1. You MUST each hand in your own work individially in your own words.
2. You MUST understand everything you wrote. (Say you copied your friend's WRONG answer without thinking, and that will most likely be in violation of this rule.)
3. You need to write down the names of your collaborator.
4. Failure to comply rule 2 and rule 3 will be treated as plagiarism.
5. Collaboration with people not in this class (such as a math grad student) is not forbidden but not recommended. If you choose to, then write down their names as well.

0.5 Classroom Policy

1. You are allowed to sleep, eat, drink during class as long as no other classmate objects to it. (Unless a school official come to observe. Then please be on your best behavior wink wink wink.)
2. We do not record attendance, but coming to class is obviously highly recommended, especially since I do extra stuff all the time and they will be tested.
3. You may speak or interrupt me without raising your hand at all time during class. If my writing, speaking or explaining confuses you somehow, it is very admirable of you to speak up about it.
4. Respect your classmates. Which means turn your phone to vibrate in class; admire them rather than judge them when your classmates ask questions in class; and when asked to collaborate, assume that they are competent and want to learn, and explain and discuss patiently with them. Do not insult your classmate by just throwing your answers to them, as if they are not worthy of your time, or as if they are hopelessly stupid to figure things out.

0.6 Class Schedule

Contents

Part I

Complex Matrix Theory

Chapter 1

Some Examples of Complex Matrices

1.1 What is a complex linear combination?

We are entering into the second portion of your linear algebra education, and we are going to see more complex matrices. A complex matrix is, in a very nominal sense, a matrix with possibly complex entries, say $\begin{bmatrix} 1+\mathrm{i} & -\mathrm{i} \\ 2-\mathrm{i} & 3 \end{bmatrix}$. But this should NOT be satisfactory for you, because what does it even mean?

Let us do a little review first.

Recall that a matrix $A = \begin{bmatrix} 1 & 1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$ is representing a linear map. In particular, it represents some process that respect linear combinations. As a quick example, say we are playing a version of the famous board game "settlers of catan". If you want to build a road, you would need to spend one wood and one brick. If you want to build a ship, you would need to spend one wood and one wool. So if you want to build $\begin{bmatrix} x \text{ roads} \\ y \text{ ships} \end{bmatrix}$, then you would need $A \begin{bmatrix} x \text{ roads} \\ y \text{ ships} \end{bmatrix} = \begin{bmatrix} x+y \text{ woods} \\ x \text{ bricks} \\ y \text{ wools} \end{bmatrix}$. So A is the evaluation process that tells you how much your required building would cost. This process is LINEAR, because the total cost of "a linear combination of buildings" is the linear combination of the cost of each type of building. It RESPECTS the linear combination in the sense that $A(s\boldsymbol{v} + t\boldsymbol{w}) = s(A\boldsymbol{v}) + t(A\boldsymbol{w})$.

If you forget all about our class last quarter, at least I hope you would remember these. A vector is representing a linear combination, and a matrix is representing a linear map, which is a map that preserves linear combinations. (Personally I think this perspectives on linear combinations and linear maps is WHY we learn linear algebra in college. No other stuff is not important.)

Now, under this view, the idea of a complex matrix like $\begin{bmatrix} 1+\mathrm{i} & -\mathrm{i} \\ 2-\mathrm{i} & 3 \end{bmatrix}$ is very disturbing. This seems to be about COMPLEX linear combinations, in contrast the the real linear combinations that we are used to. It is very easy to imagine the likes of "two apples and three bananas", but what is the meaning of an imaginary apple? So before we move on, we need a little extra perspective on complex numbers and complex linear combinations.

First of all, why do we even need complex numbers? The answer is obvious: we want a degree n polynomial to have an n-th root. This is straightforward enough. Over the reals, $x^2 + 1 = 0$ has no solution, which is super annoying. For example, without complex numbers, $\begin{bmatrix} 1 & 2 \\ -1 & -1 \end{bmatrix}$ has NO eigenvector and no eigenvalues, which is annoying. But over complex numbers, it will have distinct eigenvalues $\pm\mathrm{i}$, and in fact it will be diagonalizable. Hooray!

So this establishes the necessity of complex numbers. But where can we go search for this? As you recall in your high school complex number class, to have the complex numbers, all we need is to find the imaginary i, which is a square root of -1. With this square root of minus one, we can then have all complex numbers.

So the meaning of complex numbers ultimately depends on the meaning of the imaginary unit i. What is the meaning of this i?

Example 1.1.1. We are searching for x such that $x^2 = -1$. But broaden our minds a little bit. Can we find a matrix A such that $A^2 = -I$?

Yes we can. Consider the 2×2 real matrices, which are linear transformations on $\mathbb{R}^2$, the plane. On the plane, what is $-I$? That is basically reflecting everything about the origin, i.e., rotation by 180 degree. So what operation A can we find, such that A^2 is rotation by 180 degree? The answer is rotation by 90 degree, easy.

I hope you still remembered how to find this matrix. The answer is (if we rotate counter-clockwise) $A = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$. Of course, $-A$ also satisfies $(-A)^2 = -I$, so we in fact have at least two solutions, $\pm A$, just like $x^2 = -1$ has two solutions, $\pm i$. (We in fact have infinitely many solutions to the matrix equations $A^2 = -I$. Can you find a way to describe them all?)

Now is time to witness magic. Lo and behold the wonders of algebra.

$$(2 + 3\mathrm{i})(4 + \mathrm{i}) = 5 + 14\mathrm{i}.$$

$$\begin{bmatrix} 2 & -3 \\ 3 & 2 \end{bmatrix} \begin{bmatrix} 4 & -1 \\ 1 & 4 \end{bmatrix} = \begin{bmatrix} 5 & -14 \\ 14 & 5 \end{bmatrix}.$$

Why is this even true? Let me explain this by rewriting the second equation, and then I'll leave the thinking to you.

$$\begin{bmatrix} 2 & -3 \\ 3 & 2 \end{bmatrix} \begin{bmatrix} 4 & -1 \\ 1 & 4 \end{bmatrix} = (2I + 3A)(4I + A) = 5I + 14A.$$

Let me end this exploration with one question for you to think. Suppose some $n \times n$ matrix A satisfies $A^2 = -I$, then would we have a similar structure? ☺

Example 1.1.2. Bonus foods for your thought. Compute the following two matrix multiplications. What would you get? How are the two following calculations related?

$$\begin{bmatrix} 1 & \mathrm{i} \\ 2\mathrm{i} & 1+\mathrm{i} \end{bmatrix} \begin{bmatrix} \mathrm{i} & 1-\mathrm{i} \\ 2 & \mathrm{i} \end{bmatrix} =?$$

$$\left[\begin{array}{cc|cc} 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ \hline 0 & -2 & 1 & -1 \\ 2 & 0 & 1 & 1 \end{array}\right] \left[\begin{array}{cc|cc} 0 & -1 & 1 & 1 \\ 1 & 0 & -1 & 1 \\ \hline 2 & 0 & 0 & -1 \\ 0 & 2 & 1 & 0 \end{array}\right] =?$$

Suppose some $n \times n$ matrix A satisfies $A^2 = -I$, then can you construct similar coincidences? ☺

Example 1.1.3. We have hinted that whenever $A^2 = -I$, then you can choose i as representing A, and use complex numbers. What are other possible A? Here is an exotic (but useful) example.

Let V be the space of functions of the form $a\sin(x) + b\cos(x)$. Let $A : V \to V$ be the linear map of taking derivatives. Then note that $A^2 = -I$ in this space. ☺

The above serves to point out that the imaginary unit i has very real meanings, and possibly many many meanings, and you should pick your own meaning depending on the application at hand. Luckily for us, most of the time, when people use complex numbers, they are usually interpreting the imaginary i as some sort of rotation, i.e., $\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$.

Under this interpretation, a complex number $a + b\mathrm{i}$ can be interpreted as $\begin{bmatrix} a & -b \\ b & a \end{bmatrix}$. So a pure real number is like a dilation operation on the plane, while a purely imaginary number is like a rotation operation on the plane. Here is a example copied from the book "One Two Three ... Infinity".

Example 1.1.4. A treasure is buried on an island. To find the treasure, we start at a location with a flag (location Z). We then first walk to a building (location A), say with a total distance of x, then we turn right and walk x. Let us call this location A'.

Next we go back to the flag (location Z). We then first walk to a statue (location B), say with a total distance of y, then we turn left and walk y. Let us call this location B'.

The treasure is at the midpoint between A' and B'.

Now some bad guy came and took away the flag (so Z is unknown). Can you still find the treasure? Yes we can.

Note that $A' - A$ is $A - Z$ rotated clockwise, so $A' - A = -\mathrm{i}(A - Z)$. Similarly, $B' - B$ is $B - Z$ rotated counter-clockwise, so $B' - B = \mathrm{i}(B - Z)$. So the treasure locatio $\frac{1}{2}(A' + B') = \frac{1}{2}(A + B) + \frac{1}{2}\mathrm{i}(B - A)$, and no Z is involved in this. So the flag position does not matter at all. I'll leave the interpretation of the final treasure location to yourself.

This is NOT showing you the power of complex numbers. Rather, this is showing you the power of linear algebra. At the center of the entire calculation is the fact that rotation is linear. The complex numbers such as i are merely names that we slap on the operations such as rotations.

So... linear algebra rules, and complex numbers are just names and labels for convenience. ☺

So, when we are dealing with objects that can be "rotated", it would make sense to talk about i times that object. In this sense, we can do complex-linear combinations. No wonder that quantum mechanics where using complex numbers.

All in all, for a complex vector such as $\boldsymbol{v} = \begin{bmatrix} 1 \\ \mathrm{i} \\ 1-\mathrm{i} \end{bmatrix}$, it is better to think of each coordinate as representing a point in the plane. And if we perform a complex scalar multiplication $(2+\mathrm{i})\boldsymbol{v}$, think of this as applying a planar operation $\begin{bmatrix} 2 & -1 \\ 1 & 2 \end{bmatrix}$ to each coordinate of $\boldsymbol{v}$.

Here are some other fun applications of complex numbers.

Example 1.1.5 (Complex romantic relation)**.** Suppose $f' = kf$, then I'm sure you know that the solution is $f(x) = \mathrm{e}^{kx} f(0)$. That is the prerequisite knowledge of this application.

Suppose two person A, B are in a romantic relation.Their love for each other is a function of time, say $A(t)$ and $B(t)$. Now A is a normal person. For normal people, the more you are loved, the more you love back. In particular, $A'(t) = B(t)$. However, B is an unappreciative person. If you love B, then B take you for granted, and treat you as garbage. If, however, you treat B badly, then B would all of a sudden thinks of you as super charming and attractive. In short, B enjoys things that are hard to get, and think little of the things that are easy to get. In Chinese, we say B is a Jian Ren. Anyway, we see that $B'(t) = -A(t)$.

Now, consider the real vector $\boldsymbol{v}(t) = \begin{bmatrix} A(t) \\ B(t) \end{bmatrix} \in \mathbb{R}^2$. Then for the matrix $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$, we see that $\boldsymbol{v}' = -J\boldsymbol{v}$. Now, think of $\mathbb{R}^2$ as simply $\mathbb{C}$, and v would be like some complex number, and J is the rotation counter-clockwise by 90 degree, i.e., multiplication by i. And we have $\boldsymbol{v}' = -\mathrm{i}\boldsymbol{v}$. So the solution is $\boldsymbol{v}(t) = \mathrm{e}^{-\mathrm{i}t}\boldsymbol{v}(0) = (\cos(t) - \mathrm{i}\sin(t))\boldsymbol{v}(0)$.

Then the solution should be $(\cos(t)I - \sin(t)J)\begin{bmatrix} A(0) \\ B(0) \end{bmatrix} = \begin{bmatrix} A(0)\cos(t) + B(0)\sin(t) \\ B(0)\cos(t) - A(0)\sin(t) \end{bmatrix}$. This is indeed the collection of all possible solutions of our system. We have solved the differential equation.

Note that the romantic relation of A and B are necessarily periodic. If you are ever trapped in a relationship which is periodic, (i.e., happy for a week, then fight for a week, and repeat), then maybe you should think about this model a bit more. ☺

1.2 Complex Orthogonality

Procedural-wise, complex linear algebra works in the same way as real linear algebra. The Gaussian elimination works the same way. The matrix multiplication formula, the trace formula and the determinant formula are all the same. Nothing new all in all. However, one thing is crucially different: inner product, and by extension, transpose.

For two real vectors $\begin{bmatrix}1\\2\end{bmatrix}$ and $\begin{bmatrix}2\\-1\end{bmatrix}$, it is very easy to understand that they are orthogonal to each other. We can draw it, or visualize it in our mind, and so on. But for two complex vectors, what does it mean to be orthogonal to each other?

Example 1.2.1. Consider $\begin{bmatrix}1\\\mathrm{i}\end{bmatrix}$ and $\begin{bmatrix}1\\\mathrm{i}\end{bmatrix}$. What would happen if we perform the "real dot-product" on these two vectors? We would have $1^2 + (\mathrm{i})^2 = 1 + (-1) = 0$. Huh, this vector is "orthogonal" to itself? How can it be?

It simply cannot be. Quoting Sherlock Holmes, when you have eliminated the impossible, whatever remains, however improbable, must be the truth: we used the wrong "dot product"!

There is a lesson we can learn from this. Blindly apply analogous procedures will usually lead you astray. It is always to guide your scientific exploration with proper intuitions.

What is $\begin{bmatrix}1\\\mathrm{i}\end{bmatrix}$? Recall that previously, we have talked about the relation between $a + b\mathrm{i}$ and $\begin{bmatrix}a & -b\\ b & a\end{bmatrix}$. Using this interpretation, let us think of $\begin{bmatrix}1\\\mathrm{i}\end{bmatrix}$ as $\begin{bmatrix}1 & 0\\ 0 & 1\\ 0 & -1\\ 1 & 0\end{bmatrix}$. So instead of one vector, it is in fact two vectors!

So what is orthogonal to $\begin{bmatrix}1\\\mathrm{i}\end{bmatrix}$? Well, let us consider $\begin{bmatrix}1\\-\mathrm{i}\end{bmatrix}$. Then the two vectors can be thought of as $\begin{bmatrix}1 & 0\\ 0 & 1\\ 0 & -1\\ 1 & 0\end{bmatrix}$ and $\begin{bmatrix}1 & 0\\ 0 & 1\\ 0 & 1\\ -1 & 0\end{bmatrix}$. Did you see that? ALL FOUR column vectors are mutually orthogonal to each other. So we conclude that $\begin{bmatrix}1\\\mathrm{i}\end{bmatrix}$ and $\begin{bmatrix}1\\-\mathrm{i}\end{bmatrix}$ are orthogonal to each other.

What does this mean? It means that if n-dimensional complex vectors $\boldsymbol{v}, \boldsymbol{w}$ corresponds to $2n \times 2$ real matrices A, B, then we say $\boldsymbol{v} \perp \boldsymbol{w}$ if and only if $A^{\mathrm{T}}B$ has all four entries zero.

Something funny is going on here. Note that, by interpreting i as $\begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix}$, we are interpreting $\boldsymbol{v} = \begin{bmatrix}1\\\mathrm{i}\end{bmatrix}$ as $A = \begin{bmatrix}1 & 0\\ 0 & 1\\ 0 & -1\\ 1 & 0\end{bmatrix}$. Then $A^{\mathrm{T}} = \begin{bmatrix}1 & 0 & 0 & 1\\ 0 & 1 & -1 & 0\end{bmatrix}$, and it does NOT represent $\boldsymbol{v}^{\mathrm{T}}$. Rather, it represents $\overline{\boldsymbol{v}}^{\mathrm{T}}$. Here the line means complex conjugates on each coordinate.

In particular, the fact that $A^{\mathrm{T}}B$ is the 2×2 zero meatrix corresponds to the fact that $\overline{\boldsymbol{v}}^{\mathrm{T}}\boldsymbol{w}$ is the complex number zero. ☺

Definition 1.2.2. *For two complex vectors $\boldsymbol{v}, \boldsymbol{w} \in \mathbb{C}^n$, then we define their complex dot product to be $\langle \boldsymbol{v}, \boldsymbol{w}\rangle = \overline{\boldsymbol{v}}^{\mathrm{T}}\boldsymbol{w}$.*

A generic guideline is that, whenever you take transpose for a real matrix, in the corresponding world of complex matrices, you probably would like to take a transpose conjugate. Think of this as a generalization of the following fact: if $\begin{bmatrix}a & -b\\ b & a\end{bmatrix}$ represents $a + b\mathrm{i}$, then its transpose actually represents $a - b\mathrm{i}$. For convenience, we shall use the "star" as a shorthand for conjugate transpose, i.e., we define A^* as $\overline{A}^{\mathrm{T}}$.

For example, we have the following result.

Theorem 1.2.3. *For a complex $m \times n$ matrix A, then $\mathrm{Ran}(A)$ and $\mathrm{Ker}(A^*)$ are orthogonal complements, and $\mathrm{Ran}(A^*)$ and $\mathrm{Ker}(A)$ are orthogonal complements. Oh, and $\mathrm{Ran}(A)$ and $\mathrm{Ran}(A^*)$ and $\mathrm{Ran}(A^{\mathrm{T}})$ have the same complex dimension, i.e., the rank of A.*

Familar yes? We have a bunch of similar results here. Note that ultimately, everything here involves an orthogonal structure, which is why conjugate transpose is used throughout. Review or read up about their real conterparts if needed.

1. A complex matrix is ***Hermitian*** if $A = A^*$. In this case, it is diagonalizable with real eigenvalues, and the underlying space has an orthogonal basis made of eigenvectors of A.
2. A complex matrix is ***skew-Hermitian*** if $-A = A^*$. In this case, it is diagonalizable with purely-imaginary eigenvalues, and the underlying space has an orthogonal basis made of eigenvectors of A.
3. A complex matrix is ***unitary*** if $A^{-1} = A^*$. In this case, it is diagonalizable with unit complex eigenvalues (complex numbers with absolute value one), and the underlying space has an orthogonal basis made of eigenvectors of A. Note that in particular, such a map would preserve the complex dot product, i.e., $\langle \boldsymbol{v}, \boldsymbol{w}\rangle = \langle A\boldsymbol{v}, A\boldsymbol{w}\rangle$.
4. A complex matrix is ***normal*** if $AA^* = A^*A$. In this case, it is diagonalizable, and the underlying space has an orthogonal basis made of eigenvectors of A.

1.3 Fourier Matrix

Here is a family of matrices that is both super cool, extremely useful in practice, and also illustrates some funny situations mentioned above. It is the famous Fourier matrix.

For any n, let ω be the ***primitive** n**-th root of unity***, i.e., it is the complex number $\omega = \cos(2\pi/n) + \mathrm{i}\sin(2\pi/n)$. Then as you can check, $1, \omega, ..., \omega^{n-1}$ are all distinct complex numbers, and $\omega^n = 1$. In fact, by thinking of complex numbers as dilations and rotations, it is easy to see that $1, \omega, ..., \omega^{n-1}$ are ALL solutions to the equation $x^n = 1$ over the complex numbers.

We start by looking at the fourier matrix F_n whose (i, j) entry is $\omega^{(i-1)(j-1)}$. For a typical example, we have $F_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & \omega & \omega^2 & \omega^3 \\ 1 & \omega^2 & \omega^4 & \omega^6 \\ 1 & \omega^3 & \omega^6 & \omega^9 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & i & -1 & -i \\ 1 & -1 & 1 & -1 \\ 1 & -i & -1 & i \end{bmatrix}$.

As you can see, it appears that $F_n^{\mathrm{T}} = F_n$. However, it is NOT Hermitian. (For example, its diagonal is not real.) In fact, it is the opposite of Hermitian: it is a multiple of a unitary matrix. Feel free to perform $F_4F_4^*$ to verify the case when $n = 4$. In particular, you can also check that $\frac{1}{n}\overline{F_n} = F_n^{-1}$.

The fourier matrix is closely related to the Fourier series and Fourier Transforms. In Calculus we learned that Fourier series is very important. For a periodic function $f(x)$ with period 2π, you can try to decompose it into different frequencies via fourier series, and write it as a linear combination of sines and cosines. Say we have maybe $f(x) = \sum c_k \mathrm{e}^{k\mathrm{i}x}$. Here note that $\mathrm{e}^{\mathrm{i}x} = \cos x + \mathrm{i}\sin x$, so $\mathrm{e}^{\mathrm{i}x}$ is just a lazy way to write sine and cosine simultaneously.

Suppose we have a decomposition $f(x) = c_0 + c_1\mathrm{e}^{\mathrm{i}x} + c_2\mathrm{e}^{2\mathrm{i}x} + c_3\mathrm{e}^{3\mathrm{i}x}$. Given c_0, c_1, c_2, c_3, what do we know about the function $f(x)$? Well, if you apply F_4 to the vector $\begin{bmatrix} c_0 \\ c_1 \\ c_2 \\ c_3 \end{bmatrix}$, then you can verify that you have $\begin{bmatrix} f(0) \\ f(\pi/2) \\ f(\pi) \\ f(3\pi/2) \end{bmatrix}$. As you can see, you get four points on the graph of $f(x)$. By using more fourier coefficients, and larger Fourier matrix, you will get more detailed points on your graph for $f(x)$. This is the forward direction.

But consider the backward direction as well. In pratical cases, we usually have the graph of $f(x)$ by some data gathering. How can we work out the Fourier coefficients? Suppose we have $f(x) = c_0 +$

$c_1 e^{ix} + c_2 e^{2ix} + c_3 e^{3ix}$ where the c_i are unknown. How to find the fourier coefficient of $f(x)$? We could evaluate $f(0), f(\pi/2), f(\pi), f(3\pi/2)$ empirically or experimentially, and then compute $F_4^{-1}\begin{bmatrix} f(0) \\ f(\pi/2) \\ f(\pi) \\ f(3\pi/2) \end{bmatrix} = \frac{1}{n}\overline{F_4}\begin{bmatrix} f(0) \\ f(\pi/2) \\ f(\pi) \\ f(3\pi/2) \end{bmatrix}$. As you can see, by evaluating at merely a few points and apply $\frac{1}{n}\overline{F_n}$, we can conveniently obtain the (approximate) Fourier coefficients. The approximation will get better as we use more data points and larger Fourier matrix.

Suppose you want to compute the first 1000 fourier coefficients (say you know the rest are probably noises or measurement errors). In effect, you want to quickly multiply F_{1000} to a known vector. Wow, that is pretty big! How should you do it? By brute force, this is a 1000 by 1000 matrix, and calculating with it needs millions of calculations. That would take forever. So a better approach is the Fast Fourier Transfour. We start by looking at F_{1024}, reduce it to F_{512}, then reduce it to F_{256}, and so forth, until we reach $F_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$. So in 10 steps, we reduce the problem to a much smaller one. In the end, one million calculations will be reduced to merely 5000 calculations. Imagine the gain in speed in signal processing and etc. This is ranked as the top 10 algorithms of the 20-th centry by the IEEE journal Computing in Science and Engineering.

Example 1.3.1. Consider $F_4 = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & i & -1 & -i \\ 1 & -1 & 1 & -1 \\ 1 & -i & -1 & i \end{bmatrix}$. Observe the relation between its first and third column, and between its second and forth column. You can see that the first and third coordinates of corresponding columns are the same, and the second and forth coordinates are negated.

Let us now swap the columns to bring the original first and third column togehter, and the original second and forth column together. Then we have $F_4 P_{23} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & i & -i \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -i & i \end{bmatrix}$. Hey, note that the upper left corner and lower left corner is exactly $\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} = F_2$! In fact, let $D_2 = diag(1, i)$, we have $F_4 P_{23} = \begin{bmatrix} F_2 & D_2 F_2 \\ F_2 & D_2 F_2 \end{bmatrix} = \begin{bmatrix} I_2 & D_2 \\ I_2 & -D_2 \end{bmatrix}\begin{bmatrix} F_2 & 0 \\ 0 & F_2 \end{bmatrix}$. So step by step, we have extracted F_2 out of F_4! ☺

Theorem 1.3.2 (Fast Fourier Transform)**.** *We have the following decomposition, where $D_n = (1, \omega, ..., \omega^{n-1})$ where $\omega = \cos(\pi/n) + i\sin(\pi/n)$, and P is a matrix permuting all odd columns to the left and all even columns to the right.*

$$F_{2n} = \begin{bmatrix} I_n & D_n \\ I_n & -D_n \end{bmatrix}\begin{bmatrix} F_n & 0 \\ 0 & F_n \end{bmatrix} P.$$

Proof. Do it yourself. Same idea as Example 1.3.1. □

Example 1.3.3. Here's what happen after a recursion. You will have

$$F_{4n} = \begin{bmatrix} I_{2n} & D_{2n} \\ I_{2n} & -D_{2n} \end{bmatrix}\begin{bmatrix} I_n & D_n & 0 & 0 \\ I_n & -D_n & 0 & 0 \\ 0 & 0 & I_n & D_n \\ 0 & 0 & I_n & -D_n \end{bmatrix}\begin{bmatrix} F_n & 0 & 0 & 0 \\ 0 & F_n & 0 & 0 \\ 0 & 0 & F_n & 0 \\ 0 & 0 & 0 & F_n \end{bmatrix} P.$$

Here P is a permutation matrix that put all (1 mod 4) columns to the left, followed by the (3 mod 4) columns, followed by the (2 mod 4) columns, and followed by the (4 mod 4) columns. ☺

Proof. Do it yourself. ∎

Example 1.3.4. What would happen to F_{3n}? Can you do something similar? I'll leave this to yourself. ☺

Chapter 2

Jordan Canonical Form

2.1 Generalized Eigenstuff

We are moving towards Jordan canonical form. For a square matrix A, sometimes it is diagonalizable. And by doing so, we shall find all the eigenvalues and eigenvectors and so on, so that we can completely understand the behavior of this matrix. But what if we cannot diagonalize a matrix?

Well, first let us strive for a block-diagonalization.

2.1.1 (Review) Block Matrices in $\mathbb{R}^n$ or $\mathbb{C}^n$

We use block matrices a lot, and we know that they can be multiplied like regular matrices and so on. But let us be reminded here about their meaning. Block matrices are NOT just a formality in grouping entries. Each individual block is in fact a linear "submap" in some sense.

Example 2.1.1. Consider a map sending foods to nutrients. Say we have foods: apples, bananas, meat. And we have nutrients: fibers, proteins, suger. Then this map is a matrix A, such that if we have $\begin{bmatrix} x \\ y \\ z \end{bmatrix}$ apples, bananas and meat, then we have $A\begin{bmatrix} x \\ y \\ z \end{bmatrix}$ fibers, proteins and suger. Obviously A is a 3 by 3 matrix.

Now consider the block form $A = \left[\begin{array}{cc|c} a & b & c \\ \hline d & e & f \\ g & h & i \end{array}\right] = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$, where A_{ij} represent the corresponding blocks.

What does A_{11} do? It sends fruits to the low calory nutrients they contain. What does A_{12} do? It send fruits to the high calory nutrients they contain. What does A_{21} do? It sends meat to the low calory nutrients it contains. What does A_{22} do? It send meat to the high calory nutrients it contains.

$$\begin{tikzcd} \text{fruits} \arrow[r, "A_{11}"] \arrow[dr, "A_{21}"] & \text{low calory} \\ \text{meat} \arrow[r, "A_{22}"] \arrow[ur, "A_{12}"] & \text{high calory} \end{tikzcd}.$$

And what is A? A as a linear map is simply the collection of these four linear maps. ☺

Intuitively, when we have a block matrix, we are grouping input coordinates and output coordinates. The block A_{ij} records how the i-th group of inputing coordinates effect the j-th group of outputing coordinates.

Example 2.1.2. Consider $\left[\begin{array}{cc|c} 1 & 1 & 1 \\ 1 & 1 & 2 \\ \hline 0 & 0 & 1 \end{array}\right]$. Note that the lower left block is zero. This means the first two input coodinates does NOT effect the third output coordiante.

Indeed we have $\left[\begin{array}{cc|c} 1 & 1 & 1 \\ 1 & 1 & 2 \\ \hline 0 & 0 & 1 \end{array}\right] \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x+y+z \\ x+y+2z \\ z \end{bmatrix}$.

$$\begin{tikzcd} \mathbb{R}^2 \arrow[r, "A_{11}"] & \mathbb{R}^2 \\ \mathbb{R} \arrow[ur, "A_{12}"] \arrow[r, "A_{22}"] & \mathbb{R} \end{tikzcd}.$$

This is a ***block upper triangular matrix***.

In particular, block diagonal means each groups of coordinates only effect themselves. In particular, instead of one system, it is more like many separate independent systems, one for each diagonal block. Here is a picture for $\left[\begin{array}{cc|c} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ \hline 0 & 0 & 2 \end{array}\right]$, which is a ***block diagonal matrix***.

$$\begin{tikzcd} \mathbb{R}^2 \arrow[r, "A_{11}"] & \mathbb{R}^2 \\ \mathbb{R} \arrow[r, "A_{22}"] & \mathbb{R} \end{tikzcd}.$$

As you can see, a block diagonal matrix happens exactly when the two "linear submaps" are independent of each other. ☺

So here is how one can think about block matrices. For example, for the block matrix $\begin{bmatrix} A \\ B \end{bmatrix}$ where A is $m_1 \times n$ and B is $m_2 \times n$, we can think of it as this:

$$\begin{tikzcd} \mathbb{R}^n \arrow[r, "A"] \arrow[dr, "B"] & \mathbb{R}^{m_1} \\ & \mathbb{R}^{m_2} \end{tikzcd}.$$

And for the block matrix $\begin{bmatrix} A & B \end{bmatrix}$ where A is $m \times n_1$ and B is $m \times n_2$, we can think of it as this:

$$\begin{tikzcd} \mathbb{R}^{n_1} \arrow[r, "A"] & \mathbb{R}^m \\ \mathbb{R}^{n_2} \arrow[ur, "B"] & \end{tikzcd}.$$

Now, why would the block matrices multiply exactly as regular matrices? Let us reprove this via more diagrams. We have $\begin{bmatrix} A_1 & A_2 \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} = A_1B_1 + A_2B_2$ because of this:

$$\begin{tikzcd} \mathbb{R}^n \arrow[r, bend left, "B_1"] \arrow[rrr, bend left, "B_2"] & \mathbb{R}^a \arrow[rrr, bend right, "A_1"'] & \oplus & \mathbb{R}^b \arrow[r, bend right, "A_2"'] & \mathbb{R}^m \end{tikzcd}$$

And we have $\begin{bmatrix} A_1 \\ A_2 \end{bmatrix} \begin{bmatrix} B_1 & B_2 \end{bmatrix} = \begin{bmatrix} A_1B_1 & A_1B_2 \\ A_2B_1 & A_2B_2 \end{bmatrix}$ because of this:

$$
\begin{tikzcd}
\mathbb{R}^{n_1} \arrow[dr, "B_1"] & & \mathbb{R}^{m_1} \\
& \mathbb{R}^d \arrow[ur, "A_1"] \arrow[dr, "A_2"] & \\
\mathbb{R}^{n_2} \arrow[ur, "B_2"] & & \mathbb{R}^{m_2}
\end{tikzcd}
.
$$

Example 2.1.3. Consider a rotation in $\mathbb{R}^3$ around the line $x = y = z$ that sends the positive x-axis to the positive y-axis, and the positive y-axis to the positive z-axis, and the positive z-axis to the positive x-axis. How to find the matrix R of this linear map?

By looking at the standard basis, we obviously have $R = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$. If we break down the domain and codomain as a sum of three one-dimensional subspaces, i.e., the coordinate-axes, then we have a diagram:

$$
\begin{tikzcd}
\mathbb{R}_x \arrow[dr] & \mathbb{R}_x \\
\mathbb{R}_y \arrow[dr] & \mathbb{R}_y \\
\mathbb{R}_z \arrow[uur] & \mathbb{R}_z
\end{tikzcd}
.
$$

The arrows here are identity maps. And the arrows NOT DRWAN are zero maps.

Let us try a different decomposition of the domain and the codomain. What if we think of the domain and codomain as the sum of the xy-plane and the z-axis? Then we shall have a block structure $R = \begin{bmatrix} R_1 & R_2 \\ R_3 & R_4 \end{bmatrix}$ where R_1 is a 2×2 matrix, and R_2 is 1×2, and R_3 is 2×1, and R_4 is 1×1.

To find R_1, we want to understand the action of R on the xy-plane, ignoring the z-axis. So we want to look at the projection of $R\boldsymbol{e}_1, R\boldsymbol{e}_2$ back to the xy-plane. Since the positive x-axis goes to the positive y-axis, and the positive y-axis goes to the positive z-axis (which is projected to the origin), we see that $R_1 = \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix}$. You can work out the others similarly, and you shall have $R = \left[\begin{array}{cc|c} 0 & 0 & 1 \\ 1 & 0 & 0 \\ \hline 0 & 1 & 0 \end{array}\right]$. ☺

We use mostly $\mathbb{R}^n$ here, but it does not really matter. Replace them all by $\mathbb{C}^n$ if you like.

2.1.2 (Review) Spatial Decompositions and invariant decompositions

We are now going to reformulate everything in the last section in an abstract manner.

Example 2.1.4. Recall that we say V is the direct sum of its subspaces V_1, V_2 if $V_1 \cap V_2 = \{0\}$, and $V_1 + V_2 = V$. We also write $V = V_1 \oplus V_2$, and call this a decomposition of V into subspaces. Now, there are four linear maps involved in this structure.

First of all, we have an inclusion map $\iota_1 : V_1 \to V$ and $\iota_2 : V_2 \to V$. These maps don't change the input at all, but their codomain is larger than the domain. They tell us how the smaller spaces (the domains) is included in the bigger space (the codomain).

Now since $V = V_1 \oplus V_2$, by our knowledge in the last semester, each vector $\boldsymbol{v} \in V$ has a UNIQUE decomposition $\boldsymbol{v} = \boldsymbol{v}_1 + \boldsymbol{v}_2$ such that $\boldsymbol{v}_i \in V_i$. So we also have two projection maps $p_1 : V \to V_1$ and $p_2 : V \to V_2$ such that $p_i(\boldsymbol{v}) = \boldsymbol{v}_i$. These are INDEED projection maps. For example, note that for any $\boldsymbol{v}_1 \in V_1$, then $\boldsymbol{v}_1 = \boldsymbol{v}_1 + \boldsymbol{0}$ must be the unique decomposition according to $V = V_1 \oplus V_2$. Therefore $p_1(\boldsymbol{v}_1) = \boldsymbol{v}_1$. In particular, $p_i^2 = p_i$. (This is the defining algebraic property for projections in any mathematical context.) However, these are NOT necessarily orthogonal projections. They could be oblique projections. See last semester's note for oblique projections. (They are only orthogonal projections when $V_1 \perp V_2$. Otherwise they are oblique projections, where p_i preserves V_i and kills V_j for $j \neq i$.)

Now if we have a linear map $L : V \to W$, and decompositions $V = V_1 \oplus V_2$ and $W = W_1 \oplus W_2$. Then there are four possible linear maps induced from these structures. We can restrict the domain of L to V_i and project the codomain to W_j, and obtain $L_{ij} = p_j \circ L \circ \iota_i : V_i \to W_j$. Then we can write $L = \begin{bmatrix} L_{11} & L_{21} \\ L_{12} & L_{22} \end{bmatrix}$. For each $\boldsymbol{v} \in V$, if the unique decomposition according to $V = V_1 \oplus V_2$ is $\boldsymbol{v} = \boldsymbol{v}_1 + \boldsymbol{v}_2$, then let us write it as $\begin{bmatrix} \boldsymbol{v}_1 \\ \boldsymbol{v}_2 \end{bmatrix}$, and and we do similar things in W. Then we shall see that $\begin{bmatrix} L_{11} & L_{21} \\ L_{12} & L_{22} \end{bmatrix} \begin{bmatrix} \boldsymbol{v}_1 \\ \boldsymbol{v}_2 \end{bmatrix} = \begin{bmatrix} (L\boldsymbol{v})_1 \\ (L\boldsymbol{v})_2 \end{bmatrix}$. ☺

These whole venture is purely philosophical, and you need to feel no pressure to master these abstract computations. My goal is to address the following question: What is the idea behind a block matrix? It means that as we decompose domain and codomain into subspaces, the linear map is decomposed into submaps. The "blocks" are actually "submaps", or restrictions of the original linear map to corresponding subspaces.

Now we go back to our task of block diagonalizing matrices.

Why are diagonal matrices neat? Consider $\begin{bmatrix} d_1 & & \\ & d_2 & \\ & & d_3 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix} = \begin{bmatrix} d_1 a_1 \\ d_2 a_2 \\ d_3 a_3 \end{bmatrix}$. As you can see, for a diagonal matrix, treated as a linear map, it acts on each coordinate independently. The i-th coordinate of the output depends only on the i-th coordinate of the input, and vice versa, the i-th coordinate of the input will influence only the i-th coordinate of the output. Coordinates will NOT cross-influence each other, they just each do their own thing during this linear map.

Given a diagonalizable matrix, how would we diagonalize it? We need to find eigenvectors. Each eigenvector is like an invariant direction that the matrix must preserve. Now our matrix acts on each invaraint direction independently, so if we pick a basis made of eigenvectors, then our matrix after a corresponding change of basis will be diagonal.

Now, invariant directions are like one dimensional invariant subspaces. In general, we can define the following:

Definition 2.1.5. *We say a subspace W of a space V is an* ***invariant subspace*** *of the linear transformation $L : V \to V$ if $L(W) \subseteq W$. (We do NOT require them to be equal. The point is such that L can be restricted to a linear transformation on W.)*

We say a decomposition $V = V_1 \oplus V_2$ is an invariant decomposition for the linear transformation $L : V \to V$ if both V_1 and V_2 are invariant subspaces.

Proposition 2.1.6. *Given an invariant decomposition $V = V_1 \oplus V_2$ for the linear transformation $L : V \to V$, then the corresponding block structure for L is block diagonal. (I only used two subspaces here, but the case for more subspaces is identical.)*

Proof. Since $L(V_i) \subseteq V_i$, therefore for $i \neq j$, $p_j \circ L$ will kill V_i. So $L_{ij} = p_j \circ L \circ \iota_i = 0$. □

An eigen-direction is essentially a one-dimensional invariant subspace for our matrix. Since one dimensional subspace are spanned by a single vector, we sometimes just study eigenvectors. Finding a basis made of eigenvectors is essentially the same as finding a decomposition of V into invaraint one-dimensional subspaces. In particular, to block diagonalize a matrix is exactly the same as to find invariant decompositions of the domain.

Let us see a concrete example of this, using the same example as before.

Example 2.1.7. Consider a rotation in $\mathbb{R}^3$ around the line $x = y = z$ that sends the positive x-axis to the positive y-axis, and the positive y-axis to the positive z-axis, and the positive z-axis to the positive x-axis. We know its linear map has matrix $R = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$. This matrix has non-real eigenvalues, so there is NO REAL diagonalizations. However, maybe we can find a REAL block-diagonalization?

There are two invariant subspaces that R must act on. One is the axis of rotation, the line $x = y = z$. This is a one-dimensional subspace V_1 spanned by $\begin{bmatrix}1\\1\\1\end{bmatrix}$. R acts on V_1 by simply fixing everyone, i.e., via the 1×1 matrix $R_{11} = \begin{bmatrix}1\end{bmatrix}$.

The other is the orthogonal complement of V_1, the subspace V_2 of all vectors $\begin{bmatrix}x\\y\\z\end{bmatrix}$ such that $x+y+z = 0$. Say we pick basis $\begin{bmatrix}1\\-1\\0\end{bmatrix}$ and $\begin{bmatrix}1\\0\\-1\end{bmatrix}$. Our linear map acts on V_2 as a rotation of $\frac{2\pi}{3}$, i.e., via some 2×2 matrix R_{22}. To find the matrix $R_{22} : V_2 \to V_2$, note that it depends on the basis we have chosen for V_2!!! So this is NOT going to be the standard rotation matrix, because we forgot to pick an orthonormal basis. Oops. Nevermind, let us just keep going forward.

Using the basis $\boldsymbol{v}_1 = \begin{bmatrix}1\\-1\\0\end{bmatrix}$ and $\boldsymbol{v}_2 = \begin{bmatrix}1\\0\\-1\end{bmatrix}$ for V_2, note that $R\boldsymbol{v}_1 = \begin{bmatrix}0\\1\\-1\end{bmatrix} = \boldsymbol{v}_2 - \boldsymbol{v}_1$, and $R\boldsymbol{v}_2 = \begin{bmatrix}-1\\1\\0\end{bmatrix} = -\boldsymbol{v}_1$. So $R_{22} = \begin{bmatrix}-1 & -1\\1 & 0\end{bmatrix}$.

So, under the basis $\begin{bmatrix}1\\1\\1\end{bmatrix}$, $\begin{bmatrix}1\\-1\\0\end{bmatrix}$ and $\begin{bmatrix}1\\0\\-1\end{bmatrix}$, our matrix will change into $\begin{bmatrix}R_{11} & \\ & R_{22}\end{bmatrix} = \begin{bmatrix}1 & & \\ & -1 & -1\\ & 1 & 0\end{bmatrix}$, which is block diagonal.

So we have $R = \begin{bmatrix}1 & 1 & 1\\1 & -1 & 0\\1 & 0 & -1\end{bmatrix}\begin{bmatrix}1 & & \\ & -1 & -1\\ & 1 & 0\end{bmatrix}\begin{bmatrix}1 & 1 & 1\\1 & -1 & 0\\1 & 0 & -1\end{bmatrix}^{-1}$.

Of course, as we can see in hind-sight, we can also find an orthonormal basis for V_2, say $\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\\0\end{bmatrix}$ and $\frac{1}{\sqrt{6}}\begin{bmatrix}1\\1\\-2\end{bmatrix}$. Then R_{22} will be the standard rotation matrix $\begin{bmatrix}\cos\frac{2\pi}{3} & -\sin\frac{2\pi}{3}\\ \sin\frac{2\pi}{3} & \cos\frac{2\pi}{3}\end{bmatrix} = \begin{bmatrix}-\frac{1}{2} & -\frac{\sqrt{3}}{2}\\ \frac{\sqrt{3}}{2} & -\frac{1}{2}\end{bmatrix}$.

So we have$R = \begin{bmatrix}\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{6}}\\ \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{6}}\\ \frac{1}{\sqrt{3}} & 0 & -\frac{2}{\sqrt{6}}\end{bmatrix}\begin{bmatrix}1 & & \\ & -\frac{1}{2} & -\frac{\sqrt{3}}{2}\\ & \frac{\sqrt{3}}{2} & -\frac{1}{2}\end{bmatrix}\begin{bmatrix}\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{6}}\\ \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{6}}\\ \frac{1}{\sqrt{3}} & 0 & -\frac{2}{\sqrt{6}}\end{bmatrix}^{-1}$. We saved a bit of calculations but the numbers are uglier. Also note that the inverse here is also easy to calculate, because that matrix is now an orthogonal matrix, courtesy of picking an orthonormal basis. So the inverse here is just a transpose. In practise, this alone will make this better than the previous calculation, despite the ugly entries. ☺

Now, before we move on, let us consider the decompositions with more than two subspaces. These are mostly quoted from my linear algebra notes last semester.

Proposition 2.1.8. *For subspaces $V_1, \dots, V_k$ of a vector space V, the following are equivalent:*

1. *Pick any non-zero $\boldsymbol{v}_i \in V_i$ for each i, then $\boldsymbol{v}_1, \dots, \boldsymbol{v}_n$ is linearly independent.*
2. $\dim(\sum V_i) = \sum \dim V_i$.

Proof. Pick a basis for each subspace, and put them together. This collection is obviously spanning. So if $\dim(\sum V_i) = \sum \dim V_i$, then this collection also has exactly the right number of vectors, so it is a basis. So it is linearly independent, and the first statement is true.

Conversely, if the first statement is true, then by standard arguments it is easy to verify that this collection is linearly independent. So this collection is a basis, and we have $\dim(\sum V_i) = \sum \dim V_i$. $\square$

If either of these two conditions is satisfied, then we say the subspaces $V_1, \ldots, V_k$ are linearly independent. Keep in mind that pairwise independence does NOT imply collective independence. Consider the following example.

Example 2.1.9. Let U, V, W be three subspaces of $\mathbb{R}^2$ such that U is the x-axis, V is the y-axis, and W is the line defined by the equation $x = y$. Then note that U, V, W are pairwise independent, but collectively, they are NOT linearly independent.

This counter example is important to keep in mind. For example, subset algebra satisfies the law of distribution. (I.e., in set theory, $S_1 \cap (S_2 \cup S_3) = (S_1 \cap S_2) \cup (S_1 \cap S_3)$ and $S_1 \cup (S_2 \cap S_3) = (S_1 \cup S_2) \cap (S_1 \cup S_3)$ for any three subsets.) However, subspace algebra does NOT have the law of distribution. You can verify that, in our example, $U \cap (V + W) \neq (U + V) \cap (U + W)$ and similarly $U + (V \cap W) \neq (U + V) \cap (U + W)$.

This is also closely related to probability theory. For many random variables, pairwise independently distributed does NOT imply collectively independently distributed. And the counter example there is essentially a modified version of our example here. (Just change our field $\mathbb{R}$ into any finite field, and build variables X, Y, Z whose distribution is defined via the subspaces U, V, W.) ☺

In a similar manner as before, block diagonalizations are related to invariant decomposition of the domain $\mathbb{R}^n$ into a direct sum of linearly independent subspaces.

We end this with a quick lemma for future use.

2.1.3 Searching for good invariant decomposition

So this is it. How can we find a good invariant decomposition? Let us first see what kinds of invariant subspaces we have.

Example 2.1.10. Given any matrix A, consider the zero space $\mathrm{Ker}(A)$. obviosuly $A(\mathrm{Ker}(A)) = \{0\} \subseteq \mathrm{Ker}(A)$. So this is indeed an invariant subspace!

Dually, since A sends everything into $\mathrm{Ran}(A)$ by definition, we have $A(\mathrm{Ran}(A)) \subseteq \mathrm{Ran}(A)$ as well. Hooray! Another invariant subspace!

In fact, for $n \times n$ matrices A, we also have $\dim \mathrm{Ker}(A) + \dim \mathrm{Ran}(A) = n$. This is a really good omen. In fact, consider say $A = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{bmatrix}$. Then $\mathrm{Ker}(A)$ and $\mathrm{Ran}(A)$ are both invaraint subspaces, and in fact we have $\mathbb{R}^3 = \mathrm{Ker}(A) \oplus \mathrm{Ran}(A)$ in this case, a perfect decomposition into invariant subspaces!

Unfortunately, we do not always have this. Consider $A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$. Then $\mathrm{Ker}(A) = \mathrm{Ran}(A)$. So we failed in this case.

In fact, the best complement subspace for $\mathrm{Ker}(A)$ is actually $\mathrm{Ran}(A^{\mathrm{T}})$ (or $\mathrm{Ran}(A^*)$ in the complex case), and we always have $\mathbb{R}^n = \mathrm{Ker}(A) \oplus \mathrm{Ran}(A^{\mathrm{T}})$. However, again consider $A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$, you shall see that $\mathrm{Ran}(A^{\mathrm{T}})$ is usually not an invaraint subspace!

We are screwed either way. ☺

What can we do then? Well, recall our original motivation of doing diagonalization. What started us on this path about eigenstuff and diagonalization? The original motivation is to understand iterated applications of the same matrix, i.e., the eventual behavior of the sequence $\boldsymbol{v}, A\boldsymbol{v}, \ldots, A^n\boldsymbol{v}, \ldots$. Diagonalization gives us a quick way to calculate A^n for large n.

As a result, maybe we shouldn't focus on the *immediate* kernel and range of A. Rather, we should focus on the *eventual* kernel and range of A.

Example 2.1.11. Consider $A = \begin{bmatrix} 0 & 1 & & \\ & 0 & 1 & \\ & & 0 & \\ & & & 1 \end{bmatrix}$. Then applying A repeatedly, we have:

$$\begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix} \stackrel{A}{\longmapsto} \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \stackrel{A}{\longmapsto} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \stackrel{A}{\longmapsto} \mathbf{0}.$$

Then we say $\begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$ is *eventually* killed by A. Let N_∞ be the subspace of all vectors eventually killed by A.

Also note that $A^2 = \begin{bmatrix} 0 & 0 & 1 & \\ & 0 & 0 & \\ & & 0 & \\ & & & 1 \end{bmatrix}$ and $A^n = \begin{bmatrix} 0 & 0 & 0 & \\ & 0 & 0 & \\ & & 0 & \\ & & & 1 \end{bmatrix}$ for all $n \geq 3$. So eventually, $A^n\boldsymbol{v}$ will be a multiple of $\boldsymbol{e}_4$ for large enough n. So we say the *eventual* range of A is the subspace R_∞ spanned by $\boldsymbol{e}_4$.

Check yourself that in fact $\mathbb{R}^4 = N_\infty \oplus R_\infty$ is an invariant decomposition. ☺

Definition 2.1.12. *Given a linear map or a matrix A, we define $N_\infty(A) = \cup_{k=1}^\infty \operatorname{Ker}(A^k)$ and $R_\infty(A) = \cap_{k=1}^\infty \operatorname{Ran}(A^k)$.*

In particular, $\boldsymbol{v} \in N_\infty(A)$ if and only if some powers of A will kill $\boldsymbol{v}$. And $\boldsymbol{v} \in R_\infty(A)$ if and only if $\boldsymbol{v}$ is in the range of ALL powers of A.

It turns out that we don't really have to look at all powers of A. Whatever A kills, then A^2 must kill as well. So as k grows, the subspace $\operatorname{Ker}(A^k)$ will be non-decreasing. However, its dimension is at most n (the dimension of the domain). So it cannot grow forever, and eventually it must stabilize. So we see that $N_\infty(A) = \operatorname{Ker}(A^k)$ for some k. We in fact have more. It turns out that k does not need to be too large.

Proposition 2.1.13. *For any $n \times n$ matrix A, we have $N_\infty(A) = \operatorname{Ker}(A^k)$ for some $k \leq n$. (In particular, we always have $N_\infty(A) = \operatorname{Ker}(A^n)$.)*

Proof. Let k be the smallest integer such that $A^k\boldsymbol{v} = \mathbf{0}$. Then by the lemma below, $\boldsymbol{v}, A\boldsymbol{v}, \ldots, A^{k-1}\boldsymbol{v}$ are linearly independent. But now we have k linearly independent vectors in $\mathbb{R}^n$, so $k \leq n$. □

Let us prove this lemma here. It claims that for a killing chain $\boldsymbol{v} \stackrel{A}{\longmapsto} A\boldsymbol{v} \stackrel{A}{\longmapsto} \ldots \stackrel{A}{\longmapsto} A^{k-1}\boldsymbol{v} \stackrel{A}{\longmapsto} \mathbf{0}$, everything will be independent before $\boldsymbol{v}$ is finally killed.

Lemma 2.1.14. *For any $n \times n$ matrix A, and any $\boldsymbol{v} \in N_\infty(A)$, let k be the smallest integer such that $A^k\boldsymbol{v} = \mathbf{0}$. Then $\boldsymbol{v}, A\boldsymbol{v}, \ldots, A^{k-1}\boldsymbol{v}$ are linearly independent.*

Proof. (As an illustrative example, say wehave $k = 4$, so $A^4\boldsymbol{v} = \mathbf{0}$. Suppose for contradiction, say we have a linear relation $3A\boldsymbol{v} + 2A^2\boldsymbol{v} + 4A^3\boldsymbol{v} = \mathbf{0}$. Then multiply A^2 to both sides, we have $\mathbf{0} = 3A^3\boldsymbol{v} + 2A^4\boldsymbol{v} + 4A^5\boldsymbol{v} = 3A^3\boldsymbol{v}$. So $A^3\boldsymbol{v} = \mathbf{0}$. Contradiction indeed.)

Suppose we have a nontrivial relation $\sum_{i=0}^{k-1} a_i A^i \boldsymbol{v} = \mathbf{0}$.Let j be the smallest natural number such that $a_j \neq 0$. Then multiply A^{k-j-1} on both sides of $\sum_{i=0}^{k-1} a_i A^i \boldsymbol{v} = \mathbf{0}$, and use the fact that $A^k\boldsymbol{v} = \mathbf{0}$, we see that $a_j A^{k-1}\boldsymbol{v} = \mathbf{0}$. Then since $a_j \neq 0$, we see that $A^{k-1}\boldsymbol{v} = \mathbf{0}$. Contradiction.

So all linear relations among $\boldsymbol{v}, A\boldsymbol{v}, \ldots, A^{k-1}\boldsymbol{v}$ are trivial. These vectors are linearly independent. □

As you can see, vectors should be your role models. I hope that after college, you shall grow into an independent person until you die, like these vectors here.

We also have a similar result for the "eventual range" of A.

Proposition 2.1.15. *$N_\infty(A) = \operatorname{Ker}(A^k)$ if and only if $R_\infty(A) = \operatorname{Ran}(A^k)$.*

Proof. Note that as k increases, $\operatorname{Ran}(A^k)$ is a non-increasing chain of subspaces. But since $\dim \operatorname{Ran}(A^k) = n - \dim \operatorname{Ker}(A^k)$, we see that $\dim \operatorname{Ran}(A^k)$ must stabilize as soon as $\dim \operatorname{Ker}(A^k)$ stabilizes, and hence that $\operatorname{Ran}(A^k)$ must stabilize as soon as $\operatorname{Ker}(A^k)$ stabilizes. □

Let us now show that we indeed have invariant subspaces.

Proposition 2.1.16. *For any polynomial $p(x)$, then $\operatorname{Ker}(p(A))$ and $\operatorname{Ran}(p(A))$ are A-invariant.*

Proof. The key is the fact that $xp(x) = p(x)x$ as polynomials. As a result, $Ap(A) = p(A)A$ as matrices because they are the same polynomial of A.

Suppose $p(A)\boldsymbol{v} = \mathbf{0}$. Then $p(A)(A\boldsymbol{v}) = p(A)A\boldsymbol{v} = Ap(A)\boldsymbol{v} = A(\mathbf{0}) = \mathbf{0}$. So $\operatorname{Ker}(p(A))$ is A-invariant.

Suppose $\boldsymbol{v} = p(A)\boldsymbol{w}$ for some $\boldsymbol{w}$. Then $A\boldsymbol{v} = Ap(A)\boldsymbol{w} = p(A)(A\boldsymbol{w})$. So $\operatorname{Ran}(p(A))$ is A-invariant. □

Corollary 2.1.17. *$N_\infty(A)$ and $R_\infty(A)$ are A-invariant.*

Theorem 2.1.18 (The Ultimate Invariant Decomposition)**.** *For any $n \times n$ matrix A, we have an invariant decomposition $\mathbb{R}^n = N_\infty(A) \oplus R_\infty(A)$.*

Proof. We already know that these two are invariant subspaces. Also, since for some $k \leq n$ we have $N_\infty(A) = \operatorname{Ker}(A^k)$ and $R_\infty(A) = \operatorname{Ran}(A^k)$, therefore we have $\dim N_\infty(A) + \dim R_\infty(A) = n$. So we only need to show that they have zero intersection.

(Remark: For a collection of vectors, having n vectors, linearly independent, spanning, any two of these three conditions would imlpy that we have a basis. In a comparative manner, dimensions add up to n, zero intersection, sum space is the whole space, any two of these three conditions would imlpy that we have a direct sum.)

Suppose $\boldsymbol{v} \in N_\infty(A) \cap R_\infty(A)$. Since $\boldsymbol{v} \in N_\infty(A)$, we have some $k \leq n$ such that $A^k\boldsymbol{v} = \mathbf{0}$. But since $\boldsymbol{v} \in R_\infty(A) \subseteq \operatorname{Ran}(A^n)$, we have $\boldsymbol{v} = A^n\boldsymbol{w}$ for some $\boldsymbol{w}$. Then $A^{k+n}\boldsymbol{w} = \mathbf{0}$, so $\boldsymbol{w} \in N_\infty(A)$ as well. But this implies that $\boldsymbol{w} \in \operatorname{Ker}(A^n)$, and hence $\boldsymbol{v} = A^n\boldsymbol{w} = \mathbf{0}$. Oops. So we are done.

(Essentially, the key idea is that $N_\infty(A)$ stabilizes after finitely many steps, while $\boldsymbol{v} \in R_\infty(A)$ means we can realize $\boldsymbol{v}$ after arbitrarily many steps, which forces $\boldsymbol{v} \in N_\infty(A)$ to be zero.) □

2.1.4 Generalized Eigenspace

In our previous sections, we have been doing linear algebra over $\mathbb{R}$. But it is just the same over $\mathbb{C}$. For the rest of the section, we are restricting our attention to $\mathbb{C}$ because we need those eigenvalues.

Remark 2.1.19. *Usually, things done in $\mathbb{R}$ are easily true over $\mathbb{C}$ (as long as no inner product is involved), but things done in $\mathbb{C}$ might NOT be true over $\mathbb{R}$. For example, any $n \times n$ matrix over $\mathbb{C}$ has n eigenvalues in $\mathbb{C}$ counting algebraic multiplicity. But the statement is NOT true if we replace $\mathbb{C}$ by $\mathbb{R}$.*

Our goal here is the following. For any matrix A, we aim to block diagonalize it, such that each diagonal block is a matrix with all eigenvalues the same. For example, something like this: $\begin{bmatrix} 1 & 2 & 3 & 0 & 0 \\ 0 & 1 & 4 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 2 & 5 \\ 0 & 0 & 0 & 0 & 2 \end{bmatrix}$. Here there are two diagonal blocks, the first one has all eigenvalues 1, and the second one has all eigenvalues 2.

In essense, we are looking for an invariant decomposition $\mathbb{C}^n = V_1 \oplus \cdots \oplus V_k$ such that A retricted to each V_i will be a matrix with all eigenvalues the same.

Our previous ultimate invariant decomposition is already in this direction. Suppose $\begin{bmatrix} A_N & O \\ O & A_R \end{bmatrix}$ as the corresponding block-diagonalization of A for the invariant decomposition $\mathbb{C}^n = N_\infty(A) \oplus R_\infty(A)$. Now, A_N is the restriction of A to a linear transformation on $N_\infty(A)$, and it will eventually kill everything in this domain, so A_N can only have zero eigenvalues.

In contrast, Since $\mathrm{Ker}(A) \subseteq N_\infty(A)$ and $N_\infty(A) \cap R_\infty(A) = \{\mathbf{0}\}$, it turns out that A restricted to a linear transformation on $R_\infty(A)$ will have zero kernel, i.e., A_R is an invertible matrix! So it has no zero eigenvalue.

In particular, the invariant decomposition $\mathbb{C}^n = N_\infty(A) \oplus R_\infty(A)$ has successfully isolated all the zero-eigenvalue behaviors of A in $N_\infty(A)$, and all the non-zero-eigenvalue behaviors of A to $R_\infty(A)$.

Recall that the eigenspace of a matrix A for the eigenvalue λ is simply $\mathrm{Ker}(A - \lambda I)$. We now define the following.

Definition 2.1.20. *The generalized eigenspace of a matrix A for the eigenvalue λ is the subspace $N_\infty(A-\lambda I)$.*

Let us first show pairwise-independence

Lemma 2.1.21. $N_\infty(A - \lambda I) \cap N_\infty(A - \mu I) = \{\mathbf{0}\}$ *if* $\lambda \neq \mu$.

Proof. Replace A by $A - \mu I$ if needed, it is enough to prove that $N_\infty(A - \lambda I) \cap N_\infty(A) = \{\mathbf{0}\}$ whenever $\lambda \neq 0$. And to do this, it is enough to show that $N_\infty(A - \lambda I) \subseteq R_\infty(A)$.

Pick any $\boldsymbol{v} \in N_\infty(A - \lambda I) = \mathrm{Ker}(A - \lambda I)^n$. Our goal is to show that $\boldsymbol{v} \in \mathrm{Ran}(A^k)$ for all k. We have $(A - \lambda I)^n \boldsymbol{v} = \mathbf{0}$. Expanding this, since $\lambda \neq 0$, on the left hand side we have something like $A(\text{stuff})\boldsymbol{v} + (\text{non-zero constant})\boldsymbol{v} = \mathbf{0}$, which can be rearranged into $\boldsymbol{v} = A(\text{stuff})\boldsymbol{v}$, and its iteration shall give us the result. And we are done.

More formally, let $(x - \lambda)^n = xp(x) + (-\lambda)^n$ for some polynomial $p(x)$. So $\mathbf{0} = (A - \lambda I)^n \boldsymbol{v} = Ap(A)\boldsymbol{v} + (-\lambda)^n \boldsymbol{v}$. Let $B = -\frac{1}{(-\lambda)^n} p(A)$, we see that $\boldsymbol{v} = AB\boldsymbol{v}$ where $AB = BA$. Then it is easy to see that $\boldsymbol{v} = ABAB\boldsymbol{v} = A^2B^2\boldsymbol{v}$ and so on. So $\boldsymbol{v} = A^kB^k\boldsymbol{v} \in \mathrm{Ran}(A^k)$ for all k. So $\boldsymbol{v} \in \cap \mathrm{Ran}(A^k) = R_\infty(A)$. $\square$

Corollary 2.1.22. *If $\boldsymbol{v} \in N_\infty(A - \lambda I)$, then for any $\mu \neq \lambda$, $(A - \mu I)\boldsymbol{v} = \mathbf{0}$ if and only if $\boldsymbol{v} = \mathbf{0}$.*

Corollary 2.1.23. *If $\boldsymbol{v} \in N_\infty(A-\lambda I)$, then for any polynomial $p(x)$ without λ as a root, we have $p(A)\boldsymbol{v} = \mathbf{0}$ if and only if $\boldsymbol{v} = \mathbf{0}$.*

Of course, pairwise independence is not enough. We need collective independence.

Proposition 2.1.24. *Let $\lambda_1, \ldots, \lambda_k$ be the eigenvalues of A (NOT counting algebraic multiplicity, i.e., they are distinct complex numbers). Let $V_i = N_\infty(A - \lambda_i I)$ be the generalized eigenspace for each i. Then $V_1, \ldots, V_k$ are linearly independent subspaces ,and they are invariant under A.*

Proof. Note that for each i, $V_i = N_\infty(A - \lambda_i I) = \mathrm{Ker}(A - \lambda_i I)^n$, so it is indeed invariant under A.

We prove linear independence by giving you an example, and you can feel free to fledge it out into a formal proof by yourself. Suppose A only has eigenvalues $1, 2, 3$ NOT counting algebraic multiplicity. Pick non-zero $\boldsymbol{v}_i \in V_i$ for each i. Suppose $a\boldsymbol{v}_1 + b\boldsymbol{v}_2 + c\boldsymbol{v}_3 = \mathbf{0}$.

Now apply $(A - I)^n(A - 2I)^n$ on both sides. Then $\boldsymbol{v}_1, \boldsymbol{v}_2$ will be killed by definition. Yet the $\boldsymbol{v}_3$ term shall remain. (Since $v_3 \in N_\infty(A - 3I)$ and it is non-zero, therefore $(A - I)^n(A - 2I)^n\boldsymbol{v}_3$ is a non-zero vector by Corollary 2.1.23.) So we have $c(A - I)^n(A - 2I)^n\boldsymbol{v}_3 = \mathbf{0}$.

Similarly, $a = b = 0$ as well. So we are done. $\square$

They are not only independent. They in fact gives us the desired invariant decomposition of the whole domain.

Proposition 2.1.25 (Geometric meaning of algebraic multiplicity)**.** *Let λ be an eigenvalue of a square matrix A with algebraic multiplicity m, and let $V_\lambda = N_\infty(A - \lambda I)$ be the generalized eigenspace. Then $\dim V_\lambda = m$.*

Proof. Replacing A by $A - \lambda I$ if necessary, we can assume that $\lambda = 0$.

Now let $\begin{bmatrix} A_N & O \\ O & A_R \end{bmatrix}$ be the corresponding block diagonalization of A after a change of basis according to the invariant decomposition $\mathbb{C}^n = N_\infty(A) \oplus R_\infty(A)$. As we have discussed before, A_N will only have eigenvalue zero, while A_R has no zero eigenvalue. But their characteristic polynomials must satisfy $p_A(x) = p_{A_N}(x)p_{A_R}(x)$. So the algebraic multiplicity of 0 in p_A is exactly the same as the degree of p_{A_N}, whcih is $\dim N_\infty(A)$. $\square$

Theorem 2.1.26. *Let $\lambda_1, \ldots, \lambda_k$ be the eigenvalues of A (NOT counting algebraic multiplicity, i.e., they are distinct complex numbers). Let $V_i = N_\infty(A - \lambda_i I)$ be the generalized eigenspace for each i. Then we have an invariant decomposition $\mathbb{C}^n = \bigoplus_{i=1}^k V_i$.*

Recall that previously, we see that all eigenvalues of A_N must be zero in the block diagonalization $\begin{bmatrix} A_N & O \\ O & A_R \end{bmatrix}$ corresponding to the invariant decomposition $\mathbb{C}^n = N_\infty(A) \oplus R_\infty(A)$. Similarly, given a block diagonalization of A, say $\begin{bmatrix} A_1 & & \\ & \ddots & \\ & & A_k \end{bmatrix}$ according to the generalized eigenspaces, then each A_i is the restriction of A to V_i, so all eigenvalues of A_i must be λ_i.

2.2 Nilpotent Matrices

2.3 Jordan Canonical Form

2.4 Functions of Matrices

2.5 Applications