18.700 JORDAN NORMAL FORM NOTES

These are some supplementary notes on how to find the Jordan normal form of a small matrix. First we recall some of the facts from lecture, next we give the general algorithm for finding the Jordan normal form of a linear operator, and then we will see how this works for small matrices.

1. Facts

Throughout we will work over the field $\mathbb{C}$ of complex numbers, but if you like you may replace this with any other algebraically closed field. Suppose that V is a $\mathbb{C}$-vector space of dimension n and suppose that $T : V \to V$ is a $\mathbb{C}$-linear operator. Then the characteristic polynomial of T factors into a product of linear terms, and the irreducible factorization has the form

$$c_T(X) = (X - \lambda_1)^{m_1}(X - \lambda_2)^{m_2} \dots (X - \lambda_r)^{m_r}, \tag{1}$$

for some distinct numbers $\lambda_1, \dots, \lambda_r \in \mathbb{C}$ and with each m_i an integer $m_1 \geq 1$ such that $m_1 + \cdots + m_r = n$.

Recall that for each eigenvalue λ_i, the eigenspace E_{λ_i} is the kernel of $T - \lambda_i I_V$. We generalized this by defining for each integer $k = 1, 2, \dots$ the vector subspace

$$E_{(X-\lambda_i)^k} = \ker(T - \lambda_i I_V)^k. \tag{2}$$

It is clear that we have inclusions

$$E_{\lambda_i} = E_{X-\lambda_i} \subset E_{(X-\lambda_i)^2} \subset \cdots \subset E_{(X-\lambda_i)^e} \subset \dots. \tag{3}$$

Since $\dim(V) = n$, it cannot happen that each $\dim(E_{(X-\lambda_i)^k}) < \dim(E_{(X-\lambda_i)^{k+1}})$, for each $k = 1, \dots, n$. Therefore there is some least integer $e_i \leq n$ such that $E_{(X-\lambda_i)^{e_i}} = E_{(X-\lambda_i)^{e_i+1}}$. As was proved in class, for each $k \geq e_i$ we have $E_{(X-\lambda_i)^k} = E_{(X-\lambda_i)^{e_i}}$, and we defined the *generalized eigenspace* $E^{\text{gen}}_{\lambda_i}$ to be $E_{(X-\lambda_i)^{e_i}}$.

It was proved in lecture that the subspaces $E^{\text{gen}}_{\lambda_1}, \dots, E^{\text{gen}}_{\lambda_r}$ give a direct sum decomposition of V. From this our criterion for diagonalizability of follows: T is diagonalizable iff for each $i = 1, \dots, r$, we have $E^{\text{gen}}_{\lambda_i} = E_{\lambda_i}$. Notice that in this case T acts on each $E^{\text{gen}}_{\lambda_i}$ as λ_i times the identity. This motivates the definition of the *semisimple part* of T as the unique $\mathbb{C}$-linear operator $S : V \to V$ such that for each $i = 1, \dots, r$ and for each $v \in E^{\text{gen}}_{\lambda_i}$ we have $S(v) = \lambda_i v$. We defined $N = T - S$ and observed that N preserves each $E^{\text{gen}}_{\lambda_i}$ and is *nilpotent*, i.e. there exists an integer $e \geq 1$ (really just the maximum of $e_1, \dots, e_r$) such that N^e is the zero linear operator. To summarize:

(A) The *generalized eigenspaces* $E^{\text{gen}}_{\lambda_1}, \dots, E^{\text{gen}}_{\lambda_r}$ defined by

$$E^{\text{gen}}_{\lambda_i} = \{v \in V | \exists e, (T - \lambda_i I_V)^e(v) = 0\}, \tag{4}$$

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give a direct sum decomposition of V. Moreover, we have $\dim(E^{\text{gen}}_{\lambda_i})$ equals the algebraic multiplicity of λ_i, m_i.

(B) The *semisimple part* S of T and the *nilpotent part* N of T defined to be the unique $\mathbb{C}$-linear operators $V \to V$ such that for each $i = 1, \dots, r$ and each $v \in E^{\text{gen}}_{\lambda_i}$ we have

$$S(v) = S^{(i)}(v) = \lambda_i v, N(v) = N^{(i)}(v) = T(v) - \lambda_i v, \tag{5}$$

satisfy the properties:

1. S is diagonalizable with $c_S(X) = c_T(X)$, and the λ_i-eigenspace of S is $E^{\text{gen}}_{\lambda_i}$ (for T).
2. N is nilpotent, N preserves each $E^{\text{gen}}_{\lambda_i}$ and if $N^{(i)} : E^{\text{gen}}_{\lambda_i} \to E^{\text{gen}}_{\lambda_i}$ is the unique linear operator with $N^{(i)}(v) = N(v)$, then $\left[N^{(i)}\right]^{e_i - 1}$ is nonzero but $\left[N^{(i)}\right]^{e_i} = 0$.
3. $T = S + N$.
4. $SN = NS$.
5. For any other $\mathbb{C}$-linear operator $T' : V \to V$, T' commutes with T ($T'T = TT'$) iff T' commutes with both S and N. Moreover T' commutes with S iff for each $i = 1, \dots, r$, we have $T'(E^{\text{gen}}_{\lambda_i}) \subset E^{\text{gen}}_{\lambda_i}$.
6. If (S', N') is any pair of a diagonalizable operator S' and a nilpotent operator N' such that $T = S' + N'$ and $S'N' = N'S'$, then $S' = S$ and $N' = N$. We call the unique pair (S, N) the *semisimple-nilpotent decomposition* of T.

(C) For each $i = 1, \dots, r$, choose an ordered basis $\mathcal{B}^{(i)} = (v^{(i)}_1, \dots, v^{(i)}_{m_i})$ of $E^{\text{gen}}_{\lambda_i}$ and let $\mathcal{B} = \left(\mathcal{B}^{(1)}, \dots, \mathcal{B}^{(r)}\right)$ be the concatenation, i.e.

$$\mathcal{B} = \left(v^{(1)}_1, \dots, v^{(1)}_{m_1}, v^{(2)}_1, \dots, v^{(2)}_{m_2}, \dots, v^{(r)}_1, \dots, v^{(r)}_{m_r}\right). \tag{6}$$

For each i let $S^{(i)}$, $N^{(i)}$ be as above and define the $m_i \times m_i$ matrices

$$D^{(i)} = \left[S^{(i)}\right]_{\mathcal{B}^{(i)},\mathcal{B}^{(i)}}, C^{(i)} = \left[N^{(i)}\right]_{\mathcal{B}^{(i)},\mathcal{B}^{(i)}}. \tag{7}$$

Then we have $D^{(i)} = \lambda_i I_{m_i}$ and $C^{(i)}$ is a nilpotent matrix of exponent e_i. Moreover we have the block forms of S and N:

$$[S]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} \lambda_1 I_{m_1} & 0_{m_1 \times m_2} & \dots & 0_{m_1 \times m_r} \\ 0_{m_2 \times m_1} & \lambda_2 I_{m_2} & \dots & 0_{m_2 \times m_r} \\ \vdots & \vdots & \ddots & \vdots \\ 0_{m_r \times m_1} & 0_{m_r \times m_1} & \dots & \lambda_r I_{m_r} \end{pmatrix}, \tag{8}$$

$$[N]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} C^{(1)} & 0_{m_1 \times m_2} & \dots & 0_{m_1 \times m_r} \\ 0_{m_2 \times m_1} & C^{(2)} & \dots & 0_{m_2 \times m_r} \\ \vdots & \vdots & \ddots & \vdots \\ 0_{m_r \times m_1} & 0_{m_r \times m_2} & \dots & C^{(r)} \end{pmatrix}. \tag{9}$$

Notice that $D^{(i)}$ has a nice form with respect to ANY basis $\mathcal{B}^{(i)}$ for $E^{\text{gen}}_{\lambda_i}$. But we might hope to improve $C^{(i)}$ by choosing a better basis.

A very simple kind of nilpotent linear transformation is the *nilpotent Jordan block*, i.e. $T_{J_a} : \mathbb{C}^a \to \mathbb{C}^a$ where J_a is the matrix

$$J_a = \begin{pmatrix} 0 & 0 & 0 & \dots & 0 & 0 \\ 1 & 0 & 0 & \dots & 0 & 0 \\ 0 & 1 & 0 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \dots & 0 & 0 \\ 0 & 0 & 0 & \dots & 1 & 0 \end{pmatrix}. \tag{10}$$

In other words,

$$J_a\mathbf{e}_1 = \mathbf{e}_2, J_a\mathbf{e}_2 = \mathbf{e}_3, \dots, J_a\mathbf{e}_{a-1} = \mathbf{e}_a, J_a\mathbf{e}_a = 0. \tag{11}$$

Notice that the powers of J_a are very easy to compute. In fact $J_a^a = 0_{a,a}$, and for $d = 1, \dots, a-1$, we have

$$J_a^d\mathbf{e}_1 = \mathbf{e}_{d+1}, J_a^d\mathbf{e}_2 = \mathbf{e}_{d+2}, \dots, J_a^d\mathbf{e}_{a-d} = \mathbf{e}_a, J_a^d\mathbf{e}_{a+1-d} = 0, \dots, J_a^d\mathbf{e}_a = 0. \tag{12}$$

Notice that we have $\ker(J_a^d) = \operatorname{span}(\mathbf{e}_{a+1-d}, \mathbf{e}_{a+2-d}, \dots, \mathbf{e}_a)$.

A nilpotent matrix $C \in M_{m\times m}(\mathbb{C})$ is said to be in *Jordan normal form* if it is of the form

$$C = \begin{pmatrix} J_{a_1} & 0_{a_1\times a_2} & \dots & 0_{a_1\times a_t} & 0_{a_1\times b} \\ 0_{a_2\times a_1} & J_{a_2} & \dots & 0_{a_2\times a_t} & 0_{a_2\times b} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0_{a_t\times a_1} & 0_{a_t\times a_1} & \dots & J_{a_t} & 0_{a_t\times b} \\ 0_{b\times a_1} & 0_{b\times a_1} & \dots & 0_{b\times a_t} & 0_{b\times b} \end{pmatrix}, \tag{13}$$

where $a_1 \geq a_2 \geq \dots \geq a_t \geq 2$ and $a_1 + \dots + a_t + b = m$.

We say that a basis $\mathcal{B}^{(i)}$ puts $T^{(i)}$ in *Jordan normal form* if $C^{(i)}$ is in Jordan normal form. We say that a basis $\mathcal{B} = \left(\mathcal{B}^{(1)}, \dots, \mathcal{B}^{(r)}\right)$ puts T in Jordan normal form if each $\mathcal{B}^{(i)}$ puts $T^{(i)}$ in Jordan normal form.

WARNING: Usually such a basis is not unique. For example, if T is diagonalizable, then ANY basis $\mathcal{B}^{(i)}$ puts $T^{(i)}$ in Jordan normal form.

2. Algorithm

In this section we present the general algorithm for finding bases $\mathcal{B}^{(i)}$ which put T in Jordan normal form.

Suppose that we already had such bases. How could we describe the basis vectors? One observation is that for each Jordan block J_a, we have that $\mathbf{e}_{d+1} = J_a^d(\mathbf{e}_1)$ and also that $\operatorname{span}\mathbf{e}_1$ and $\ker(J_a^{a-1})$ give a direct sum decomposition of $\mathbb{C}^a$.

What if we have two Jordan blocks, say

$$J = \begin{pmatrix} J_{a_1} & 0_{a_1\times a_2} \\ 0_{a_2\times a_1} & J_{a_2} \end{pmatrix}, a_1 \geq a_2. \tag{14}$$

This is the matrix such that

$$J\mathbf{e}_1 = \mathbf{e}_2, \ldots, J\mathbf{e}_{a_1-1} = \mathbf{e}_{a_1}, J\mathbf{e}_{a_1} = 0, J\mathbf{e}_{a_1+1} = \mathbf{e}_{a_1+2}, \ldots, J\mathbf{e}_{a_1+a_2-1} = \mathbf{e}_{a_1+a_2}, J\mathbf{e}_{a_1+a_2} = 0. \tag{15}$$

Again we have that $\mathbf{e}_{d+1} = J^d\mathbf{e}_1$ and $\mathbf{e}_{d+a_1+1} = J^d\mathbf{e}_{a_1+1}$. So if we wanted to reconstruct this basis, what we really need is just $\mathbf{e}_1$ and $\mathbf{e}_{a_1+1}$. We have already seen that a distinguishing feature of $\mathbf{e}_1$ is that it is an element of $\ker(J^{a_1})$ which is not in $\ker(J^{a_1-1})$. If $a_2 = a_1$, then this is also a distinguishing feature of $\mathbf{e}_{a_1+1}$. But if $a_2 < a_1$, this doesn't work. In this case it turns out that the distinguishing feature is that $\mathbf{e}_{a_1+1}$ is in $\ker(J^{a_2})$ but is not in $\ker(J^{a_2-1}) + J\left(\ker(J^{a_2+1})\right)$. This motivates the following definition:

Definition 1. *Suppose that $B \in M_{n\times n}(\mathbb{C})$ is a matrix such that $ker(B^e) = ker(B^{e+1})$. For each $k = 1, \ldots, e$, we say that a subspace $G_k \subset ker(B^k)$ is* primitive *(for k) if*

1. $G_k + ker(B^{k-1}) + B\left(ker(B^{k+1})\right) = ker(B^k)$, *and*
2. $G_k \cap \left(ker(B^{k-1}) + B\left(ker(B^{k+1})\right)\right) = \{0\}$.

Here we make the convention that $B^0 = I_n$.

It is clear that for each k we can find a primitive G_k: simply find a basis for $\ker(B^{k-1}) + B\left(\ker(B^{k+1})\right)$ and then extend it to a basis for all of $\ker(B^k)$. The new basis vectors will span a primitive G_k.

Now we are ready to state the algorithm. Suppose that T is as in the previous section. For each eigenvalue λ_i, choose any basis $\mathcal{C}$ for V and let $A = [T]_{\mathcal{C},\mathcal{C}}$. Define $B = A - \lambda_i I_n$. Let $1 \leq k_1 < \cdots < k_u \leq n$ be the distinct integers such that there exists a nontrivial primitive subspace G_{k_j}. For each $j = 1, \ldots, u$, choose a basis $\left(v[j]_1, \ldots, v[j]_{p_j}\right)$ for G_{k_j}. Then the desired basis is simply

$$\begin{aligned}\mathcal{B}^{(i)} = \big(&v[u]_1, Bv[u]_1, \ldots, B^{u-1}v[u]_1,\\ &v[u]_2, Bv[u]_2, \ldots, B^{k_u-1}v[u]_2, \ldots, v[u]_{p_u}, \ldots, B^{k_u-1}v[u]_{p_1}, \ldots,\\ &v[j]_i, Bv[j]_i, \ldots, B^{k_j-1}v[j]_i, \ldots, v[1]_1, \ldots, B^{k_1-1}v[1]_1, \ldots,\\ &v[1]_{p_1}, \ldots, B^{k_1-1}v[1]_{p_1}\big).\end{aligned}$$

When we perform this for each $i = 1, \ldots, r$, we get the desired basis for V.

3. Small cases

The algorithm above sounds more complicated than it is. To illustrate this, we will present a step-by-step algorithm in the 2×2 and 3×3 cases and illustrate with some examples.

3.1. **Two-by-two matrices.**

First we consider the two-by-two case. If $A \in M_{2\times 2}(\mathbb{C})$ is a matrix, its characteristic polynomial $c_A(X)$ is a quadratic polynomial. The first dichotomy is whether $c_A(X)$ has two distinct roots or one repeated root.

Two distinct roots Suppose that $c_A(X) = (X - \lambda_1)(X - \lambda_2)$ with $\lambda_1 \neq \lambda_2$. Then for each $i = 1, 2$ we form the matrix $B_i = A - \lambda_i I_2$. By performing Gauss-Jordan elimination we may find a basis for $\ker(B_i)$. In fact each kernel will be one-dimensional, so let v_1 be a basis for $\ker(B_1)$ and let v_2 be a basis for $\ker(B_2)$. Then with respect to the basis $\mathcal{B} = (v_1, v_2)$, we will have

$$[A]_{\mathcal{B}} = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix}. \tag{16}$$

Said a different way, if we form the matrix $P = (v_1|v_2)$ whose first column is v_1 and whose second column is v_2, then we have

$$A = P \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix} P^{-1}. \tag{17}$$

To summarize:

$$\mathrm{span}(v_1) = E_{\lambda_1} = \ker(A - \lambda_1 I_2) = \ker(A - \lambda_1 I_2)^2 = \cdots = E^{\mathrm{gen}}_{\lambda_1}, \tag{18}$$

$$\mathrm{span}(v_2) = E_{\lambda_2} = \ker(A - \lambda_2 I_1) = \ker(A - \lambda_2 I_2)^2 = \cdots = E^{\mathrm{gen}}_{\lambda_2}. \tag{19}$$

Setting $\mathcal{B} = (v_1, v_2)$ and $P = (v_1|v_2)$, We also have

$$[A]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix}, A = P \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix} P^{-1}. \tag{20}$$

Also $S = A$ and $N = 0_{2\times 2}$.

Now we consider an example. Consider the matrix

$$A = \begin{pmatrix} 38 & -70 \\ 21 & -39 \end{pmatrix}. \tag{21}$$

The characteristic polynomial is $X^2 - \mathrm{trace}(A)X + \det(A)$, which is $X^2 + X - 12$. This factors as $(X+4)(X-3)$, so we are in the case discussed above. The two eigenvalues are -4 and 3.

First we consider the eigenvalue $\lambda_1 = -4$. Then we have

$$B_1 = A + 4I_2 = \begin{pmatrix} 42 & -70 \\ 21 - 35 & \end{pmatrix}. \tag{22}$$

Performing Gauss-Jordan elimination on this matrix gives a basis of the kernel: $v_1 = (5, 3)^\dagger$.

Next we consider the eigenvalue $\lambda_2 = 3$. Then we have

$$B_2 = A - 3I_2 = \begin{pmatrix} 35 & -70 \\ 21 & -42 \end{pmatrix}. \tag{23}$$

Performing Gauss-Jordan elimination on this matrix gives a basis of the kernel: $v_2 = (2, 1)^\dagger$.

We conclude that:

$$E_{-4} = \mathrm{span}\left(\begin{pmatrix} 5 \\ 3 \end{pmatrix}\right), E_3 = \mathrm{span}\left(\begin{pmatrix} 2 \\ 1 \end{pmatrix}\right). \tag{24}$$

and that

$$A = P \begin{pmatrix} -4 & 0 \\ 0 & 3 \end{pmatrix} P^{-1}, P = \begin{pmatrix} 5 & 2 \\ 3 & 1 \end{pmatrix}. \tag{25}$$

One repeated root: Next suppose that $c_A(X)$ has one repeated root: $c_A(X) = (X-\lambda_1)^2$. Again we form the matrix $B_1 = A - \lambda_1 I_2$. There are two cases depending on the dimension of $E_{\lambda_1} = \ker(B_1)$. The first case is that $\dim(E_{\lambda_1}) = 2$. In this case A is diagonalizable. In fact, with respect to some basis $\mathcal{B}$ we have

$$[A]_{\mathcal{B},\mathcal{B}} = \left(\begin{array}{cc} \lambda_1 & 0 \\ 0 & \lambda_1 \end{array} \right). \tag{26}$$

But, if you think about it, this means that A has the above form with respect to ANY basis. In other words, our original matrix, expressed with respect to any basis, is simply $\lambda_1 I_2$. This case is readily identified, so if A is not already in diagonal form at the beginning of the problem, we are in the second case.

In the second case E_{λ_1} has dimension 1. According to our algorithm, we must find a primitive subspace $G_2 \subset \ker(B_1^2) = \mathbb{C}^2$. Such a subspace necessarily has dimension 1, i.e. it is of the form $\mathrm{span}(v_1)$ for some v_1. And the condition that G_2 be primitive is precisely that $v_1 \notin \ker(B_1)$. In other words, we begin by choosing ANY vector $v_1 \notin \ker(B_1)$. Then we define $v_2 = B(v_1)$. We form the basis $\mathcal{B} = (v_1, v_2)$, and the transition matrix $P = (v_1|v_2)$. Then we have $E_{\lambda_1} = \mathrm{span}(v_2)$ and also

$$[A]_{\mathcal{B},\mathcal{B}} = \left(\begin{array}{cc} \lambda & 0 \\ 1 & \lambda \end{array} \right), A = P \left(\begin{array}{cc} \lambda & 0 \\ 1 & \lambda \end{array} \right) P^{-1}. \tag{27}$$

This is the one case where we have nontrivial nilpotent part:

$$S = \lambda_1 I_2 = \left(\begin{array}{cc} \lambda & 0 \\ 0 & \lambda \end{array} \right), N = A - \lambda_1 I_2 = B_1 = P \left(\begin{array}{cc} 0 & 0 \\ 1 & 0 \end{array} \right) P^{-1}. \tag{28}$$

Let's see how this works in an example. Consider the matrix from the practice problems:

$$A = \left(\begin{array}{cc} -5 & -4 \\ 1 & -1 \end{array} \right). \tag{29}$$

The trace of A is -6 and the determinant is $(-5)(-1) - (-4)(1) = 9$. So $c_A(X) = X^2 + 6X + 9 = (X+3)^2$. So the characteristic polynomial has a repeated root of $\lambda_1 = -3$. We form the matrix $B_1 = A + 3I_2$,

$$B_1 = A + 3I_2 = \left(\begin{array}{cc} -2 & -4 \\ 1 & 2 \end{array} \right). \tag{30}$$

Performing Gauss-Jordan elimination (or just by inspection) a basis for the kernel is given by $(2,-1)^\dagger$. So for v_1 we choose ANY vector which is not a multiple of this vector, for example $v_1 = \mathbf{e}_1 = (1,0)^\dagger$. Then we find that $v_2 = B_1 v_1 = (-2,1)^\dagger$. So we define

$$\mathcal{B} = \left(\left(\begin{array}{c} 1 \\ 0 \end{array} \right), \left(\begin{array}{c} -2 \\ 1 \end{array} \right) \right), P = \left(\begin{array}{cc} 1 & -2 \\ 0 & 1 \end{array} \right). \tag{31}$$

Then we have

$$[A]_{\mathcal{B},\mathcal{B}} = \left(\begin{array}{cc} -3 & 0 \\ 1 & -3 \end{array} \right), A = P \left(\begin{array}{cc} -3 & 0 \\ 1 & -3 \end{array} \right) P^{-1}. \tag{32}$$

The semisimple part is just $S = -3I_2$, and the nilpotent part is:

$$N = B_1 = P \left(\begin{array}{cc} 0 & 0 \\ 1 & 0 \end{array} \right) P^{-1}. \tag{33}$$

3.2. **Three-by-three matrices.** This is basically as in the last subsection, except now there are more possible types of A. The first question to answer is: what is the characteristic polynomial of A. Of course we know this is $c_A(X) = \det(XI_3 - A)$. But a faster way of calculating this is as follows. We know that the characteristic polynomial has the form

$$c_A(X) = X^3 - \mathrm{trace}(A)X^2 + tX - \det(A), \tag{34}$$

for some complex number $t \in \mathbb{C}$. Usually $\mathrm{trace}(A)$ and $\det(A)$ are not hard to find. So it only remains to determine t. This can be done by choosing any convenient number $c \in \mathbb{C}$ other than $c = 0$, computing $\det(cI_2 - A)$ (here it is often useful to choose c equal to one of the diagonal entries to reduce the number of computations), and then solving the one linear equation

$$ct + (c^3 - \mathrm{trace}(A)c^2 - \det(A)) = \det(cI_2 - A), \tag{35}$$

to find t. Let's see an example of this:

$$D = \begin{pmatrix} 2 & 1 & -1 \\ -1 & 1 & 2 \\ 0 & -1 & 3 \end{pmatrix}. \tag{36}$$

Here we easily compute $\mathrm{trace}(D) = 6$ and $\det(D) = 8$. Finally to compute the coefficient t, we set $c = 2$ and we get

$$\det(2I_2 - A) = \det \begin{pmatrix} 0 & -1 & 1 \\ -1 & 1 & -2 \\ 0 & 1 & -1 \end{pmatrix} = 0. \tag{37}$$

Plugging this in, we get

$$(2)^3 - 6(2)^2 + t(2) - 8 = 0 \tag{38}$$

or $t = 12$, i.e. $c_A(X) = X^3 - 6X^2 + 12X - 8$. Notice from above that 2 is a root of this polynomial (since $\det(2I_3 - A) = 0$). In fact it is easy to see that $c_A(X) = (X-2)^3$.

Now that we know how to compute $c_A(X)$ in a more efficient way, we can begin our analysis. There are three cases depending on whether $c_A(X)$ has three distinct roots, two distinct roots, or only one root.

Three roots: Suppose that $c_A(X) = (X - \lambda_1)(X - \lambda_2)(X - \lambda_3)$ where $\lambda_1, \lambda_2, \lambda_3$ are distinct. For each $i = 1, 2, 3$ define $B_i = \lambda_1 I_3 - A$. By Gauss-Jordan elimination, for each B_i we can compute a basis for $\ker(B_i)$. In fact each $\ker(B_i)$ has dimension 1, so we can find a vector v_i such that $E_{\lambda_1} = \ker(B_i) = \mathrm{span}(v_i)$. We form a basis $\mathbf{B} = (v_1, v_2, v_3)$ and the transition matrix $P = (v_1|v_2|v_3)$. Then we have

$$[A]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_2 \end{pmatrix}, A = P \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_2 \end{pmatrix} P^{-1}. \tag{39}$$

We also have $S = A$ and $N = 0$.

Let's see how this works in an example. Consider the matrix

$$A = \begin{pmatrix} 7 & -7 & 2 \\ 8 & -8 & 2 \\ 4 & -4 & 1 \end{pmatrix}. \tag{40}$$

It is easy to see that $\mathrm{trace}(A) = 0$ and also $\det(A) = 0$. Finally we consider the determinant of $I_3 - A$. Using cofactor expansion along the third column, this is:

$$\det \begin{pmatrix} -6 & 7 & -2 \\ -8 & 9 & -2 \\ -4 & 4 & 0 \end{pmatrix} = -2((-8)4 - 9(-4)) - (-2)((-6)4 - 7(-4)) = -2(4) + 2(4) = 0. \tag{41}$$

So we have the linear equation

$$1^3 - 0 * 1^2 + t * 1 - 0 = 0, t = -1. \tag{42}$$

Thus $c_A(X) = X^3 - X = (X+1)X(X-1)$. So A has the three eigenvalues $\lambda_1 = -1, \lambda_2 = 0, \lambda_3 = 1$. We define $B_1 = A - (-1)I_3, B_2 = A, B_3 = A - I_3$. By Gauss-Jordan elimination we find

$$E_{-1} = \ker(B_1) = \mathrm{span}\left(\begin{pmatrix} 3 \\ 4 \\ 2 \end{pmatrix}\right), E_0 = \ker(B_2) = \mathrm{span}\left(\begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}\right),$$
$$E_1 = \ker(B_3) = \mathrm{span}\left(\begin{pmatrix} 2 \\ 2 \\ 1 \end{pmatrix}\right).$$

We define

$$\mathcal{B} = \left(\begin{pmatrix} 3 \\ 4 \\ 2 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 2 \\ 2 \\ 1 \end{pmatrix}\right), P = \begin{pmatrix} 3 & 1 & 2 \\ 4 & 1 & 2 \\ 2 & 0 & 1 \end{pmatrix}. \tag{43}$$

Then we have

$$[A]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, A = P \begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} P^{-1}. \tag{44}$$

Two roots: Suppose that $c_A(X)$ has two distinct roots, say $c_A(X) = (X - \lambda_1)^2(X - \lambda_2)$. Then we form $B_1 = A - \lambda_1 I_3$ and $B_2 = A - \lambda_2 I_3$. By performing Gauss-Jordan elimination, we find bases for $E_{\lambda_1} = \ker(B_1)$ and for $E_{\lambda_2} = \ker(B_2)$. There are two cases depending on the dimension of E_{λ_1}.

The first case is when E_{λ_1} has dimension 2. Then we have a basis (v_1, v_2) for E_{λ_1} and a basis v_3 for E_{λ_2}. With respect to the basis $\mathcal{B} = (v_1, v_2, v_3)$ and defining $P = (v_1|v_2|v_3)$, we have

$$[A]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_1 & 0 \\ 0 & 0 & \lambda_2 \end{pmatrix}, A = P \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_1 & 0 \\ 0 & 0 & \lambda_2 \end{pmatrix} P^{-1}. \tag{45}$$

In this case $S = A$ and $N = 0$.

The second case is when E_{λ_1} has dimension 2. Using Gauss-Jordan elimination we find a basis for $E^{\text{gen}}_{\lambda_1} = \ker(B_1^2)$. Choose any vector $v_1 \in E^{\text{gen}}_{\lambda_1}$ which is not in E_{λ_1} and define $v_2 = B_1 v_1$. Also using Gauss-Jordan elimination we may find a vector v_3 which forms a basis for E_{λ_2}. Then with respect to the basis $\mathcal{B} = (v_1, v_2, v_3)$ and forming the transition matrix $P = (v_1|v_2|v_3)$, we have

$$[A]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 1 & \lambda_1 & 0 \\ 0 & 0 & \lambda_2 \end{pmatrix}, A = P \begin{pmatrix} \lambda_1 & 0 & 0 \\ 1 & \lambda_1 & 0 \\ 0 & 0 & \lambda_2 \end{pmatrix} P^{-1}. \tag{46}$$

Also we have

$$[S]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_1 & 0 \\ 0 & 0 & \lambda_2 \end{pmatrix}, S = P \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_1 & 0 \\ 0 & 0 & \lambda_2 \end{pmatrix} P^{-1}, \tag{47}$$

and

$$[N]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, A = P \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} P^{-1}. \tag{48}$$

Let's see how this works in an example. Consider the matrix

$$A = \begin{pmatrix} 3 & 0 & 0 \\ 0 & 3 & -1 \\ -1 & 0 & 2 \end{pmatrix}. \tag{49}$$

It isn't hard to show that $c_A(X) = (X-3)^2(X-2)$. So the two eigenvalues are $\lambda_1 = 3$ and $\lambda_2 = 2$. We define the two matrices

$$B_1 = A - 3I_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -1 \\ -1 & 0 & -1 \end{pmatrix}, B_2 = A - 2I_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 0 \end{pmatrix}. \tag{50}$$

By Gauss-Jordan elimination we calculate that $E_2 = \ker(B_2)$ has a basis consisting of $v_3 = (0,1,1)^\dagger$. By Gauss-Jordan elimination, we find that $E_3 = \ker(B_1)$ has a basis consisting of $(0,1,0)^\dagger$. In particular it has dimension 1, so we have to keep going. We have

$$B_1^2 = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 1 \\ 1 & 0 & 1 \end{pmatrix}. \tag{51}$$

By Gauss-Jordan elimination (or inspection), we conclude that a basis consists of $(1,0,-1)^\dagger, (0,1,0)^\dagger$. A vector in $E^{\text{gen}}_3 = \ker(B_1^2)$ which isn't in E_3 is $v_1 = (1,0,-1)^\dagger$. We define $v_2 = B_1 v_1 = (0,1,0)^\dagger$. Then with respect to the basis

$$\mathcal{B} = \left(\begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} \right), P = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ -1 & 0 & 1 \end{pmatrix}. \tag{52}$$

we have

$$[A]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} 3 & 0 & 0 \\ 1 & 3 & 0 \\ 0 & 0 & 2 \end{pmatrix}, A = P \begin{pmatrix} 3 & 0 & 0 \\ 1 & 3 & 0 \\ 0 & 0 & 2 \end{pmatrix} P^{-1}. \tag{53}$$

We also have that

$$[S]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} 3 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 2 \end{pmatrix}, S = P \begin{pmatrix} 3 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 2 \end{pmatrix} P^{-1} = \begin{pmatrix} 3 & 0 & 0 \\ -1 & 3 & -1 \\ -1 & 0 & 2 \end{pmatrix}, \tag{54}$$

$$[N]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, N = P \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} P^{-1} = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}. \tag{55}$$

One root: The final case is when there is only a single root of $c_A(X)$, say $c_A(X) = (X - \lambda_1)^3$. Again we form $B_1 = A_1 - \lambda_1 I_3$. This case breaks up further depending on the dimension of $E_{\lambda_1} = \ker(B_1)$. The simplest case is when E_{λ_1} is three-dimensional, because in this case A is diagonal with respect to ANY basis and there is nothing more to do.

Dimension 2 Suppose that E_{λ_1} is two-dimensional. This is a case in which both G_1 and G_2 are nontrivial. We begin by finding a basis (w_1, w_2) for E_{λ_1}. Choose any vector v_1 which is not in E_{λ_1} and define $v_2 = B_1 v_1$. Then find a vector v_3 in E_{λ_1} which is NOT in the span of v_2 . Define the basis $\mathcal{B} = (v_1, v_2, v_3)$ and the transition matrix $P = (v_1|v_2|v_3)$. Then we have

$$[A]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 1 & \lambda_1 & 0 \\ 0 & 0 & \lambda_1 \end{pmatrix}, A = P \begin{pmatrix} \lambda_1 & 0 & 0 \\ 1 & \lambda_1 & 0 \\ 0 & 0 & \lambda_1 \end{pmatrix} P^{-1}. \tag{56}$$

Notice that there is a Jordan block of size 2 and a Jordan block of size 1. Also, $S = \lambda_1 I_3$ and we have $N = B_1$.

Let's see how this works in an example. Consider the matrix

$$A = \begin{pmatrix} -1 & -1 & 0 \\ 1 & -3 & 0 \\ 0 & 0 & -2 \end{pmatrix}. \tag{57}$$

It is easy to compute $c_A(X) = (X + 2)^3$. So the only eigenvalue of A is $\lambda_1 = -2$. We define $B_1 = A - (-2)I_3$, and we have

$$B_1 = \begin{pmatrix} 1 & -1 & 0 \\ 1 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \tag{58}$$

By Gauss-Jordan elimination, or by inspection, we see that $E_{-2} = \ker(B_1)$ has a basis $((1,1,0)^\dagger, (0,0,1)^\dagger)$. Since this is 2-dimensional, we are in the case above. So we choose any vector not in E_{-2}, say $v_1 = (1,0,0)^\dagger$. We define $v_2 = B_1 v_1 = (1,1,0)^\dagger$. Finally, we choose a vector in E_{λ_1} which is not in the span of v_2, say $v_3 = (0,0,1)^\dagger$. Then we define

$$\mathcal{B} = \left(\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \right), P = \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}. \tag{59}$$

We have

$$[A]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} -2 & 0 & 0 \\ 1 & -2 & 0 \\ 0 & 0 & -2 \end{pmatrix}, A = P \begin{pmatrix} -2 & 0 & 0 \\ 1 & -2 & 0 \\ 0 & 0 & -2 \end{pmatrix} P^{-1}. \tag{60}$$

We also have $S = -2I_3$ and $N = B_1$.

Dimension One In the final case for three by three matrices, we could have that $c_A(X) = (X - \lambda_1)^3$ and $E_{\lambda_1} = \ker(B_1)$ is one-dimensional. In this case we must also have $\ker(B_1^2)$ is two-dimensional. By Gauss-Jordan we compute a basis for $\ker(B_1^2)$ and then choose ANY vector v_1 which is not contained in $\ker(B_1^2)$. We define $v_2 = B_1 v_1$ and $v_3 = B_1 v_2 = B_1^2 v_1$. Then with respect to the basis $\mathcal{B} = (v_1, v_2, v_3)$ and the transition matrix $P = (v_1|v_2|v_3)$, we have

$$[A]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 1 & \lambda_1 & 0 \\ 0 & 1 & \lambda_1 \end{pmatrix}, A = P \begin{pmatrix} \lambda_1 & 0 & 0 \\ 1 & \lambda_1 & 0 \\ 0 & 1 & \lambda_1 \end{pmatrix} P^{-1}. \tag{61}$$

We also have $S = \lambda_1 I_3$ and $N = B_1$.

Let's see how this works in an example. Consider the matrix

$$A = \begin{pmatrix} 5 & -4 & 0 \\ 1 & 1 & 0 \\ 2 & -3 & 3 \end{pmatrix}. \tag{62}$$

The trace is visibly 9. Using cofactor expansion along the third column, the determinant is $+3(5 * 1 - 1(-4)) = 27$. Finally, we compute $\det(3I_3 - A) = 0$ since $3I_3 - A$ has the zero vector for its third column. Plugging in this gives the linear relation

$$(3)^3 - 9(3)^2 + t(3) - 27 = 0, t = 27. \tag{63}$$

So we have $c_A(X) = X^3 - 9X^2 + 27X - 27$. Also we see from the above that $X = 3$ is a root. In fact it is easy to see that $c_A(X) = (X - 3)^3$. So A has the single eigenvalue $\lambda_1 = 3$.

We define $B_1 = A_1 - 3I_3$, which is

$$B_1 = \begin{pmatrix} 2 & -4 & 0 \\ 1 & -2 & 0 \\ 2 & -3 & 0 \end{pmatrix}. \tag{64}$$

By Gauss-Jordan elimination we see that $E_3 = \ker(B_1)$ has basis $(0, 0, 1)^\dagger$. Thus we are in the case above. Now we compute

$$B_1^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & -2 & 0 \end{pmatrix}. \tag{65}$$

Either by Gauss-Jordan elimination or by inspection, we see that $\ker(B_1^2)$ has basis $((2, 1, 0)^\dagger, (0, 0, 1)^\dagger))$. So for v_1 we choose any vector not in the span of these vectors, say $v_1 = (1, 0, 0)^\dagger$. Then we define $v_2 = B_1 v_1 = (2, 1, 2)^\dagger$ and we define $v_3 = B_1 v_2 = B_1^2 v_1 = (0, 0, 1)^\dagger$. So with respect to the basis and transition matrix

$$\mathcal{B} = \left(\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \begin{pmatrix} 2 \\ 1 \\ 2 \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \right), P = \begin{pmatrix} 1 & 2 & 0 \\ 0 & 1 & 0 \\ 0 & 2 & 1 \end{pmatrix}, \tag{66}$$

we have

$$[A]_{\mathcal{B},\mathcal{B}} = \begin{pmatrix} 3 & 0 & 0 \\ 1 & 3 & 0 \\ 0 & 1 & 3 \end{pmatrix}, A = P \begin{pmatrix} 3 & 0 & 0 \\ 1 & 3 & 0 \\ 0 & 1 & 3 \end{pmatrix} P^{-1}. \tag{67}$$

We also have $S = 3I_3$ and $N = B_1$.