

18.03 Problem Set 9

I encourage collaboration on homework in this course. However, if you do your homework in a group, be sure it works to your advantage rather than against you. Good grades for homework you have not thought through will translate to poor grades on exams. **You must turn in your own writeups of all problems, and, if you do collaborate, you must write on the front of your solution sheet the names of the students you worked with.**

Because the solutions will be available immediately after the problem sets are due, **no extensions will be possible.**

IV. First order systems

L34	F 30 Apr	Complex or repeated eigenvalues: EP 5.4, Notes LS.3.
L35	M 3 May	Qualitative behavior of linear systems; phase portrait: SN 26.
R23	T 4 May	Linear phase portraits.
L36	W 5 May	Normal modes and the matrix exponential: EP 5.7, Notes LS.6.
R24	Th 6 May	Matrix exponential.
L37	F 7 May	Nonlinear systems: EP 7.2, 7.3; Notes GS.

Part I. 34. (F 30 Apr) Notes 4D-2. EP 5.6: 1. (You might use **Linear Phase Portraits: Matrix Entry** to construct the phase portrait.)

35. (M 3 May) Notes 5B-4. (This can also be checked using the same applet.)

36. (W 5 May) EP 5.7: 1, 3.

Part II.

34. (F 30 Apr) [Complex and repeated eigenvalues]

(a) The population of long-tailed weasels and meadow voles on Nantucket Island has been studied by biologists. They measure the populations relative to a baseline, in hundreds of animals. So $x(2) = 5$ means that at $t = 2$ there are 500 more weasels than the baseline value, and $y(2) = -5$ means that at $t = 2$ there are 500 fewer voles than the baseline value.

Biologists from MIT have established the following relationship between $x(t)$ and $y(t)$:

$$\dot{x} = (0.5)x + y, \quad \dot{y} = -(2.25)x + (0.5)y$$

So the natural growth rate for each species is 0.5, and cross terms show that more voles are good for weasels but more weasels are very bad for voles.

Work out the population evolution predicted by this model. (**Linear Phase Portraits: Matrix Entry** may be useful to you in visualizing this.) What are the eigenvalues? For one eigenvalue, find the exponential solution of $\dot{\mathbf{u}} = \mathbf{A}\mathbf{u}$. Then take the real and imaginary parts to produce two real solutions. Suppose that at $t = 0$ there are 100 more weasels than baseline, and the vole population is the baseline value. What is the solution to this initial value problem? Is the number of weasels increasing at $t = 0$? How about the number of voles? When does the number of voles next equal its baseline value (if ever)? Please sketch the phase portrait and the graphs of $x(t)$ and $y(t)$ (for this initial condition) for t between about -2 and $+2$. Make it clear how these three pictures are related: indicate on the trajectory the position of $\begin{bmatrix} x(t) \\ y(t) \end{bmatrix}$ when $t = \frac{k\pi}{3}$ for $k = -2, -1, 0, 1, 2$.

(b) Invoke the Mathlet **Linear Phase Portraits: Matrix Entry**. Play with the tool for a while to get a feel of it. Notice that the eigenvalues can be displayed on the complex plane. Deselect the **[Companion Matrix]** option, so you can set all four entries in the matrix. Select the **[eigenvalues]** option, so the eigenvalues become visible by means of a plot of their location in the complex plane and also a read-out of their values.

Set the sliders so that $A = \begin{bmatrix} 1 & b \\ 0 & 1 \end{bmatrix}$. Watch what happens to the phase portrait as b varies from -4 to 4 . For each value of b , the applet suggests a pair of eigenvalues; verify what it claims. For each value of b , describe the collection of all eigenvectors for each eigenvalue. (This description will depend upon b .) For each value of b , write down all the normal mode solutions (i.e. all the solutions of the form $e^{\lambda t}\mathbf{v}$, where λ is a number and \mathbf{v} is a vector). If the system is defective, find a complementary solution. Take one value of b for which the system is complete and sketch the phase portrait. Take one value of b for which the system is defective and sketch the phase portrait.

35. (M 3 May) [Qualitative behavior of linear systems]

We will use **Linear Phase Portraits: Matrix Entry** to investigate the phase portraits of the homogeneous linear equation $\dot{\mathbf{u}} = \mathbf{A}\mathbf{u}$, where $A = \begin{bmatrix} a & -3 \\ 1 & -1 \end{bmatrix}$, as a varies. The focus is now on the colorful diagram at the upper left. To start with, set the matrix to $A = \begin{bmatrix} -4 & -3 \\ 1 & -1 \end{bmatrix}$. Then move the a slider up to $a = 4$, and watch (1) the movement of the mark on the (Tr,Det) plane; (2) the movement of the eigenvalues in the complex plane; and (3) the variation of the phase portrait.

(a) Compute the trace and determinant of A . (They will depend upon a , of course.) Find an equation for the curve (or line) traced out by the mark on the (Tr,Det) plane.

(b) You notice that the curve in the (Tr,Det) plane enters a number of different regions. When the cursor crosses a red boundary, the trajectories and the eigenvalue indicators turn red. Work out what the values of a are at those crossings. (So this is: where $\det A = 0$, where $\det A = (\text{tr}A/2)^2$ (twice, once not represented on the Mathlet), and where $\text{tr}A = 0$.)

(c) There are nine phase portrait types represented as a varies (five regions and four walls). Draw an interval from -5 to $+4$. On it, mark the four values of a at which the

matrix crosses one of the walls. Indicate the type of phase portrait you have at each of the marked points and along the intervals between them. That is, classify the phase portrait into one of the following types, as in the Supplementary Notes, §25: spiral (stable/unstable, clockwise/counterclockwise), node (stable/unstable); saddle; center (clockwise/counterclockwise); star (stable/unstable); defective node (stable/unstable; clockwise/counterclockwise); degenerate (comb (stable/unstable), constant, parallel lines). (The applet uses the alternative terms “source” and “sink” for “unstable” and “stable.”)

(d) For each of the four special values, and for your choice of one value in each of the five regions, make a sketch of the phase portrait. Be sure to include and mark as such any eigenlines, and the direction of time.

36. (W 5 May) [Exponential matrix]

(a) Following Recitation 21, Problem 4, a complex number $z = a + bi$ determines a matrix $A(z)$ in the following way: $A(a + bi) = \begin{bmatrix} a & -b \\ b & a \end{bmatrix}$. This matrix represents the operation

of multiplication by z , in the sense that if $z(x + yi) = v + wi$ then $A(z) \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} v \\ w \end{bmatrix}$.

What is $e^{A(z)t}$? What is $A(e^{zt})$?

(b) Say that a pair of solutions $x_1(t), x_2(t)$ of the equation $m\ddot{x} + b\dot{x} + kx = 0$ is *normalized* at $t = 0$ if:

$$\begin{aligned} x_1(0) &= 1, & \dot{x}_1(0) &= 0 \\ x_2(0) &= 0, & \dot{x}_2(0) &= 1 \end{aligned}$$

For example, find the normalized pair of solutions to $\ddot{x} + 2\dot{x} + 2x = 0$. Then find e^{At} where A is the companion matrix for the operator $D^2 + 2D + 2I$. Please comment.

(c) Suppose that $e^{3t} \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ and $e^{2t} \begin{bmatrix} 1 \\ 2 \end{bmatrix}$ satisfy the equation $\dot{\mathbf{u}} = A\mathbf{u}$.

(i) Find solutions $\mathbf{u}_1(t)$ and $\mathbf{u}_2(t)$ such that $\mathbf{u}_1(0) = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ and $\mathbf{u}_2(0) = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$.

(ii) Find e^{At} .

(iii) Find A .

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18.03 Differential Equations
Spring 2010

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