

## Announcements:

- PS 5 due now
- PS 5 solutions posted later today

# Econ 204 2011

## Lecture 15

### Outline

1. Second Order Linear Differential Equations
2. Inhomogeneous Linear Differential Equations
3. Nonlinear Differential Equations - Linearization
4. Nonlinear Differential Equations - Stability

- PS 6 due  

9AM Monday
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→ Olexsa's mailbox

- PS 6 solutions + 2010 exam solutions posted Monday morning

# Higher Order Differential Equations

A differential equation of order  $n$  is an equation of the form

$$y^{(n)}(t) = F(y(t), y'(t), \dots, y^{(n-1)}(t), t) \quad (*)$$

$$F: \mathbb{R}^n \times \mathbb{R} \rightarrow \mathbb{R}$$

We can always rewrite an  $n^{\text{th}}$  order equation as a system of  $n$  first-order equations by redefining variables.

Set

$$\bar{y} = \begin{pmatrix} y \\ y' \\ \vdots \\ y^{(n-1)} \end{pmatrix}$$

rewrite (\*) :  $\bar{y}'(t) = \bar{F}(\bar{y}(t), t)$  2

for appropriate  $\bar{F}: \mathbb{R}^n \times \mathbb{R} \rightarrow \mathbb{R}^n$

# Second Order Linear Differential Equations

Consider the second order differential equation  $y'' = cy + by'$  with  $b, c \in \mathbf{R}$ .

Rewrite this as a **first order** linear differential equation in two variables:

Define

$$\bar{y}(t) = \begin{pmatrix} y(t) \\ y'(t) \end{pmatrix}$$

$$y''(t) = cy(t) + by'(t)$$

Then

$$\begin{aligned}\bar{y}'(t) &= \begin{pmatrix} y'(t) \\ y''(t) \end{pmatrix} \\ &= \begin{pmatrix} 0 & 1 \\ c & b \end{pmatrix} \begin{pmatrix} y(t) \\ y'(t) \end{pmatrix} = \begin{pmatrix} y'(t) \\ cy(t) + by'(t) \end{pmatrix} \\ &= \begin{pmatrix} 0 & 1 \\ c & b \end{pmatrix} \bar{y}\end{aligned}$$

The eigenvalues are the roots of the equation  $\lambda^2 - b\lambda - c = 0$ , which are  $\frac{b \pm \sqrt{b^2 + 4c}}{2}$ .

The qualitative behavior of the solutions can be explicitly described from the coefficients  $b$  and  $c$ , by determining whether the eigenvalues are real or complex, and whether the real parts are negative, zero, or positive. (if coefficient matrix is diagonalizable)

**Example** Consider the second order linear differential equation

$$y'' = 2y + y'$$

As above, let

$$\bar{y} = \begin{pmatrix} y \\ y' \end{pmatrix}$$

so the equation becomes

$$\bar{y}' = \begin{pmatrix} 0 & 1 \\ 2 & 1 \end{pmatrix} \bar{y}$$

The eigenvalues are the roots of the characteristic polynomial

$$\lambda^2 - \lambda - 2 = 0$$

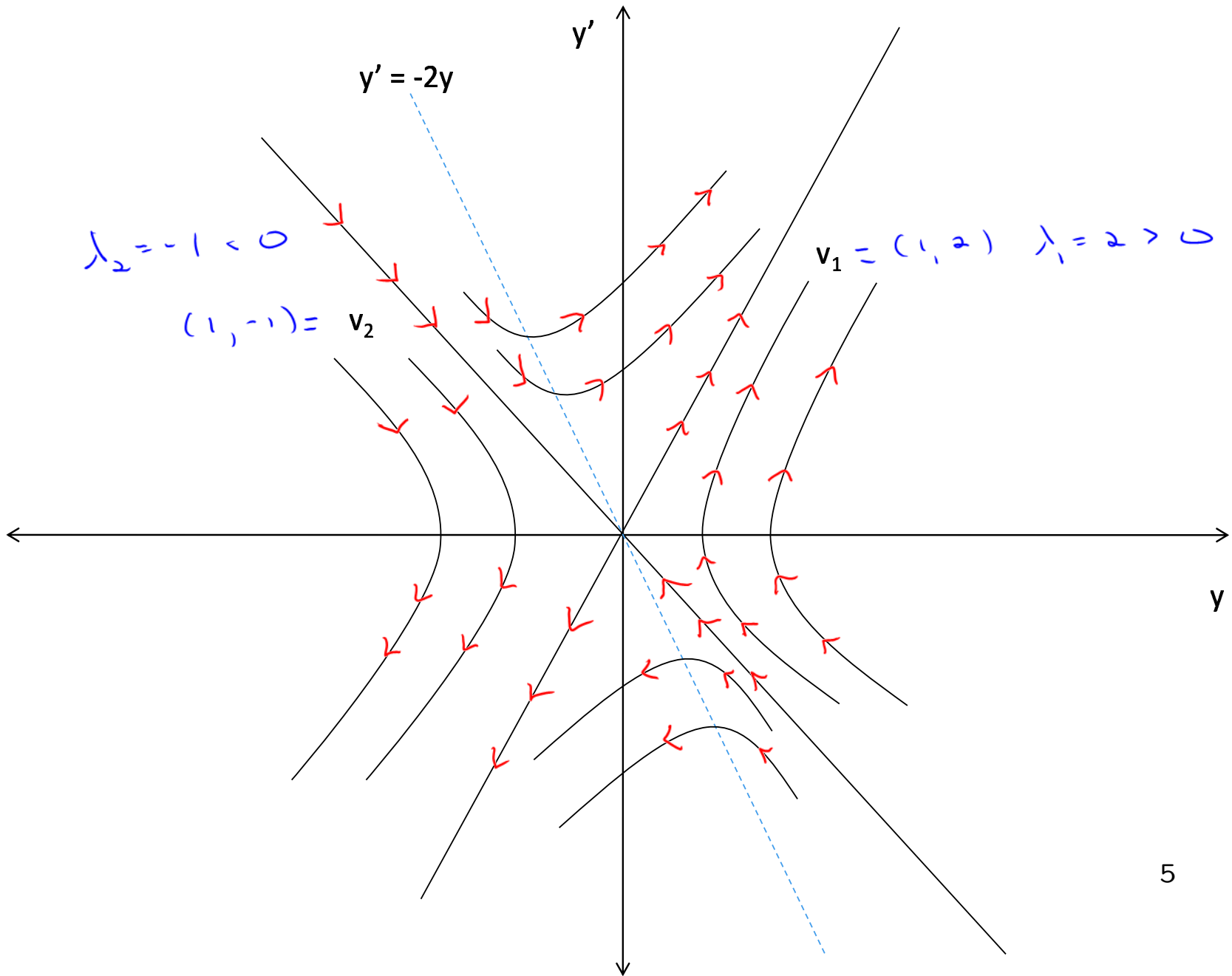
Eigenvalues and corresponding eigenvectors are given by

$$\begin{aligned} \lambda_1 &= 2 & v_1 &= (1, 2) \\ \lambda_2 &= -1 & v_2 &= (1, -1) \end{aligned}$$

$n (= 2)$  distinct eigenvalues  $\Rightarrow$  matrix diagonalizable!

From this information alone, we know the qualitative properties of the solutions are as given in the phase plane diagram

$$y'' = 2y + y'$$



- Solutions are roughly hyperbolic in shape with asymptotes along the eigenvectors. Along the eigenvector  $v_1$ , the solutions flow off to infinity; along the eigenvector  $v_2$ , the solutions converge to zero.
- Solutions flow in directions consistent with flows along asymptotes
- On the  $y$ -axis, we have  $y' = 0$ , which means that everywhere on the  $y$ -axis (except at the stationary point 0), the solution must have a vertical tangent.
- On the  $y'$ -axis, we have  $y = 0$ , so we have

$$y'' = 2y + y' = y'$$



Thus, above the  $y$ -axis,  $y'' = y' > 0$ , so  $y'$  is increasing along the direction of the solution; below the  $y$ -axis,  $y'' = y' < 0$ , so  $y'$  is decreasing along the direction of the solution.

- Along the line  $y' = -2y$ ,  $y'' = 2y - 2y = 0$ , so  $y'$  achieves a minimum or maximum where it crosses that line.

The general solution is given by

$$\begin{aligned}
 \begin{pmatrix} y(t) \\ y'(t) \end{pmatrix} &= Mtx_{UV}(id) \begin{pmatrix} e^{2(t-t_0)} & 0 \\ 0 & e^{-(t-t_0)} \end{pmatrix} Mtx_{V,U}(id) \begin{pmatrix} y(t_0) \\ y'(t_0) \end{pmatrix} \\
 &= \begin{pmatrix} \downarrow & \downarrow \\ 1 & 1 \\ 2 & -1 \end{pmatrix} \begin{pmatrix} e^{2(t-t_0)} & 0 \\ 0 & e^{-(t-t_0)} \end{pmatrix} \begin{pmatrix} \leftarrow & \leftarrow \\ 1/3 & 1/3 \\ 2/3 & -1/3 \end{pmatrix} \begin{pmatrix} y(t_0) \\ y'(t_0) \end{pmatrix} \\
 &= \begin{pmatrix} \frac{e^{2(t-t_0)} + 2e^{-(t-t_0)}}{3} & \frac{e^{2(t-t_0)} - e^{-(t-t_0)}}{3} \\ \frac{2e^{2(t-t_0)} - 2e^{-(t-t_0)}}{3} & \frac{2e^{2(t-t_0)} + e^{-(t-t_0)}}{3} \end{pmatrix} \begin{pmatrix} y(t_0) \\ y'(t_0) \end{pmatrix} \\
 &= \begin{pmatrix} \frac{y(t_0) + y'(t_0)}{3} e^{2(t-t_0)} + \frac{2y(t_0) - y'(t_0)}{3} e^{-(t-t_0)} \\ \frac{2y(t_0) + 2y'(t_0)}{3} e^{2(t-t_0)} + \frac{-2y(t_0) + y'(t_0)}{3} e^{-(t-t_0)} \end{pmatrix}
 \end{aligned}$$

The general solution has two real degrees of freedom; a specific solution is determined by specifying initial conditions  $y(t_0)$  and  $y'(t_0)$ .

Because

$$\bar{y} = \begin{pmatrix} y \\ y' \end{pmatrix}$$

it is easier to find the general solution by setting

$$y(t) = C_1 e^{2(t-t_0)} + C_2 e^{-(t-t_0)}$$

Then

$$\Rightarrow y'(t) = 2C_1 e^{2(t-t_0)} - C_2 e^{-(t-t_0)}$$

$$y(t_0) = C_1 + C_2$$

$$y'(t) = 2C_1 e^{2(t-t_0)} - C_2 e^{-(t-t_0)}$$

$$y'(t_0) = 2C_1 - C_2$$

$$C_1 = \frac{y(t_0) + y'(t_0)}{3}$$

$$\Rightarrow C_2 = \frac{2y(t_0) - y'(t_0)}{3}$$

$$y(t) = \frac{y(t_0) + y'(t_0)}{3} e^{2(t-t_0)} + \frac{2y(t_0) - y'(t_0)}{3} e^{-(t-t_0)}$$

# Inhomogeneous Linear Differential Equations with Nonconstant Coefficients

Consider the inhomogeneous linear differential equation

$$y' = M(t)y + H(t) \quad (1)$$

where  $M$  is continuous function from  $t$  to the set of  $n \times n$  matrices; and  $H$  is continuous function from  $t$  to  $\mathbf{R}^n$ .

There is a close relationship between solutions of the *inhomogeneous* linear differential equation (1) and the associated *homogeneous* linear differential equation

$$y' = M(t)y \quad (2)$$

Homogeneous : if  $y$  is a solution gives  $y_0$  then  
any  $c y$  is a solution gives  $c y_0$  for  
 $c \in \mathbb{R}$ .

# Inhomogeneous Linear Differential Equations with Nonconstant Coefficients

**Theorem 1.** *The general solution of the inhomogeneous linear differential equation (1) is*

$$y_h + y_p$$

where  $y_h$  is the general solution of the homogeneous linear differential equation (2) and  $y_p$  is any particular solution of the inhomogeneous linear differential equation (1).

*Proof.* Fix any particular solution  $y_p$  of inhomogeneous equation (1). Suppose  $y_h$  is any solution of the corresponding homoge-

neous equation (2). Let  $y_i(t) = y_h(t) + y_p(t)$ .

$$\begin{aligned}y_i'(t) &= y_h'(t) + y_p'(t) \\ &= M(t)y_h(t) + M(t)y_p(t) + H(t) \\ &= M(t)(y_h(t) + y_p(t)) + H(t) \\ &= M(t)y_i(t) + H(t)\end{aligned}$$

so  $y_i$  is solution of inhomogeneous equation (1).

Conversely, suppose  $y_i$  is any solution of inhomogeneous equation (1). Let  $y_h(t) = y_i(t) - y_p(t)$ .

$$\begin{aligned}y_h'(t) &= y_i'(t) - y_p'(t) \\ &= M(t)y_i(t) + H(t) - M(t)y_p(t) - H(t) \\ &= M(t)(y_i(t) - y_p(t)) \\ &= M(t)y_h(t)\end{aligned}$$

so  $y_h$  is solution of homogeneous equation (2) and  $y_i = y_h + y_p$ .  
□

**Remark:** To find general solution of inhomogeneous equation:

1. Find general solution of homogeneous equation;
2. Find a particular solution of inhomogeneous equation;
3. Add these to get general solution of inhomogeneous equation

One nice case in which we can easily  
give closed form expression: 10



$$z'(t) = c z(t) \quad c \in \mathbb{R}$$

$$z(t) = e^{c(t-t_0)} z_0$$

**Theorem 2.** Consider the inhomogeneous linear differential equation (1), and suppose that  $M(t)$  is a constant matrix  $M$ , independent of  $t$ . A particular solution of the inhomogeneous linear differential equation (1), satisfying the initial condition  $y_p(t_0) = y_0$ , is given by

$$y_p(t) = e^{(t-t_0)M} y_0 + \int_{t_0}^t e^{(t-s)M} H(s) ds \quad (3)$$

The general solution to the corresponding homogeneous equation is

$$y_h(t) = e^{(t-t_0)M} y_0, \quad y_0 \in \mathbb{R}^n$$

$$x \in \mathbb{R} \text{ or } \mathbb{C} : e^x = \sum_{k=0}^{\infty} \frac{x^k}{k!}$$

## Matrix Exponentials

Here for an  $n \times n$  matrix  $M$ , we define

$$e^M = \sum_{k=0}^{\infty} \frac{M^k}{k!} = I + M + \frac{M^2}{2} + \dots$$

and

$$e^{tM} = \sum_{k=0}^{\infty} \frac{t^k M^k}{k!}$$

- if  $D$  is a diagonal matrix with diagonal  $d_1, \dots, d_n$ ,

$$e^D = \begin{pmatrix} e^{d_1} & 0 & \dots & 0 \\ 0 & e^{d_2} & \dots & 0 \\ \vdots & \vdots & \dots & \vdots \\ 0 & 0 & \dots & e^{d_n} \end{pmatrix}$$

•  $e^{A+B} = e^A e^B$  if  $AB = BA$  (not necessarily if  $A$  &  $B$  do not commute)

•  $e^{P^{-1}AP} = P^{-1}e^A P$

•  $g(t) = e^{tM}$  is differentiable and  $g'(t) = M e^{tM}$   
( $C^\infty$ )

Proof. We verify that  $y_p$  solves (5):

$$\begin{aligned}
 y_p(t) &= e^{(t-t_0)M} y_0 + \int_{t_0}^t e^{(t-s)M} H(s) ds \\
 &= e^{(t-t_0)M} y_0 + \int_{t_0}^t e^{(t-t_0)M} e^{-(s-t_0)M} H(s) ds \\
 &= e^{(t-t_0)M} \left( y_0 + \int_{t_0}^t e^{-(s-t_0)M} H(s) ds \right) \quad \leftarrow \text{pull out } e^{(t-t_0)M} \\
 y_p'(t) &= M e^{(t-t_0)M} \left( y_0 + \int_{t_0}^t e^{-(s-t_0)M} H(s) ds \right) \\
 &\quad + e^{(t-t_0)M} \left( e^{-(t-t_0)M} H(t) \right) \quad \leftarrow \text{chain rule} \\
 &= M y_p(t) + H(t) \quad \leftarrow \text{Fund. Thm of calculus} \\
 y_p(t_0) &= e^{(t_0-t_0)M} y_0 + \int_{t_0}^{t_0} e^{(s-t_0)M} H(s) ds \\
 &= y_0
 \end{aligned}$$

□

**Example** Consider the inhomogeneous linear differential equation

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix}' = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} y_1 \\ y_2 \end{pmatrix} + \begin{pmatrix} \sin t \\ \cos t \end{pmatrix}$$

$$t_0 = 0$$

$$y_0 = \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

By Theorem 2, a particular solution is given by

$$\begin{aligned}
 y_p(t) &= e^{(t-t_0)M} y_0 + \int_{t_0}^t e^{(t-s)M} H(s) ds \\
 &= \begin{pmatrix} e^t & 0 \\ 0 & e^{-t} \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix} + \int_0^t \begin{pmatrix} e^{(t-s)} & 0 \\ 0 & e^{-(t-s)} \end{pmatrix} \begin{pmatrix} \sin s \\ \cos s \end{pmatrix} ds \\
 &= \begin{pmatrix} e^t \\ e^{-t} \end{pmatrix} + \int_0^t \begin{pmatrix} e^{t-s} \sin s \\ e^{s-t} \cos s \end{pmatrix} ds \\
 &= \begin{pmatrix} e^t \left( 1 + \int_0^t e^{-s} \sin s ds \right) \\ e^{-t} \left( 1 + \int_0^t e^s \cos s ds \right) \end{pmatrix}
 \end{aligned}$$

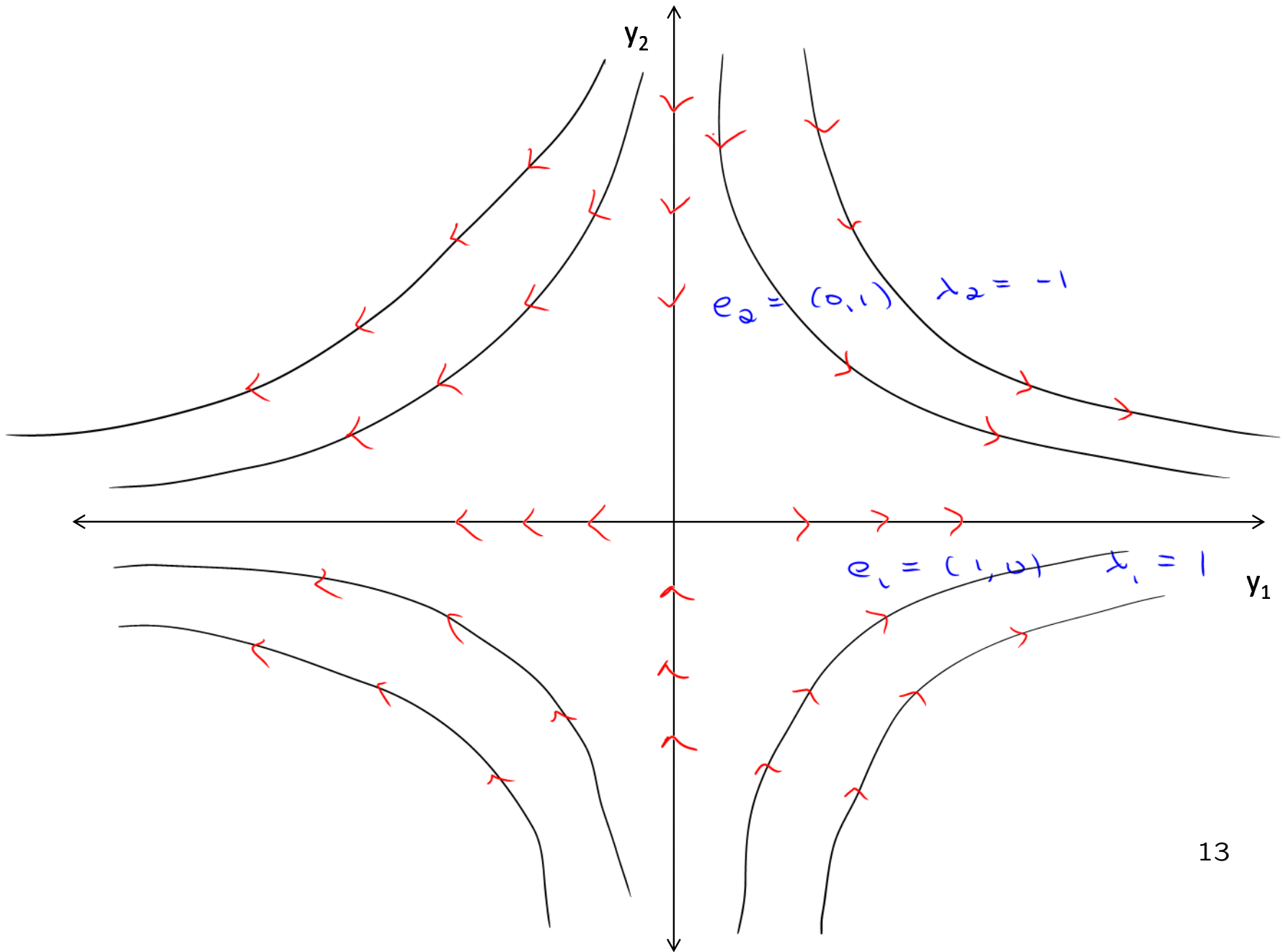
*Handwritten notes:*  $e^{tm}$  (with an arrow pointing to the matrix in the second line),  $H(s)$  (with an arrow pointing to the vector in the second line).

Thus, the general solution of the original inhomogeneous equation is given by

$$\begin{aligned} \begin{pmatrix} y_1 \\ y_2 \end{pmatrix} &= \begin{pmatrix} C_1 e^t \\ C_2 e^{-t} \end{pmatrix} + \begin{pmatrix} e^t \left( 1 + \int_0^t e^{-s} \sin s \, ds \right) \\ e^{-t} \left( 1 + \int_0^t e^s \cos s \, ds \right) \end{pmatrix} \\ &= \begin{pmatrix} D_1 e^t - \frac{\sin t + \cos t}{2} \\ D_2 e^{-t} + \frac{\sin t + \cos t}{2} \end{pmatrix} \quad (\text{after much simplification}) \end{aligned}$$

where  $D_1$  and  $D_2$  are arbitrary real constants.

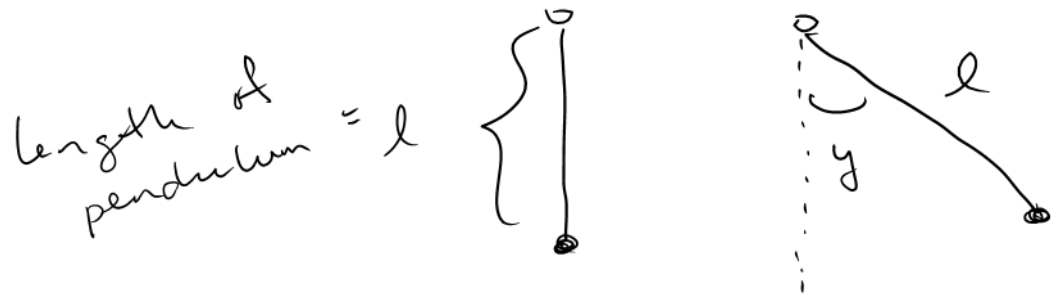
phase diagram for solutions to homogeneous equation  $y_1(t) = C_1 e^t$ ,  $y_2(t) = C_2 e^{-t}$



# Nonlinear Differential Equations - Linearization

- Nonlinear differential equations are very difficult to solve in closed form.
- Specific techniques solve special classes of equations.
- Numerical methods compute numerical solutions of any ordinary differential equation.
- Linearization can provide qualitative information about the solutions of nonlinear autonomous equations.





**Example: Pendulum** The equation of motion of a frictionless pendulum is a nonlinear autonomous differential equation

$$y'' = -\alpha^2 \sin y, \alpha > 0$$

Here,  $y$  is the angle between the pendulum and a vertical line. The fact that the motion follows this differential equation is obtained by resolving the downward force of gravity into two components, one tangent to the curve the pendulum follows and one which is parallel to the pendulum; the latter component is canceled by the pendulum rod.

This has much in common with all cyclical processes, including processes such as business cycles. This equation very difficult to solve exactly because of nonlinearity.

$$y'' = -\alpha^2 \sin y$$

Transform to first-order equation:

Define

$$\bar{y}(t) = \begin{pmatrix} y(t) \\ y'(t) \end{pmatrix} = \begin{pmatrix} y_1(t) \\ y_2(t) \end{pmatrix}$$

so differential equation becomes

$$\bar{y}'(t) = \begin{pmatrix} y_2(t) \\ -\alpha^2 \sin y_1(t) \end{pmatrix}$$

Let

$$F(\bar{y}) = \begin{pmatrix} y_2 \\ -\alpha^2 \sin y_1 \end{pmatrix}$$

$$F: \mathbb{R}^2 \rightarrow \mathbb{R}^2$$

Solve for stationary points: points  $\bar{y}$  such that  $F(\bar{y}) = 0$ :

$$\begin{aligned} F(\bar{y}) = 0 &\Rightarrow \begin{pmatrix} y_2 \\ -\alpha^2 \sin y_1 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \\ &\Rightarrow \sin y_1 = 0 \text{ and } y_2 = 0 \\ &\Rightarrow y_1 = n\pi \text{ and } y_2 = 0 \end{aligned}$$

so set of stationary points is

$$\{(n\pi, 0) : n \in \mathbf{Z}\}$$

Linearize the equation around each of the stationary points:

$$F(y_1, y_2) = \begin{pmatrix} y_2 \\ -\alpha^2 \sin y_1 \end{pmatrix}$$

Take the first order Taylor polynomial for  $F$ : at  $(n\pi, 0)$ : evaluated at  $(n\pi, 0)$

$$\begin{aligned} F(n\pi + h, 0 + k) + o(|h| + |k|) &= F(n\pi, 0) + \begin{pmatrix} \frac{\partial F_1}{\partial y_1} & \frac{\partial F_1}{\partial y_2} \\ \frac{\partial F_2}{\partial y_1} & \frac{\partial F_2}{\partial y_2} \end{pmatrix} \begin{pmatrix} h \\ k \end{pmatrix} \\ &= \begin{pmatrix} 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 & 1 \\ -\alpha^2 \cos n\pi & 0 \end{pmatrix} \begin{pmatrix} h \\ k \end{pmatrix} \\ &= \begin{pmatrix} 0 & 1 \\ \underbrace{(-1)^{n+1} \alpha^2}_{\cos n\pi = (-1)^n} & 0 \end{pmatrix} \begin{pmatrix} h \\ k \end{pmatrix} \end{aligned}$$

- For  $n$  even, the eigenvalues are solutions to

$$\lambda^2 + \alpha^2 = 0$$

$$\text{so } \lambda_1 = i\alpha, \lambda_2 = -i\alpha$$

- $n=2$  distinct eigenvalues  $\Rightarrow$  diagonalizable!
- all real parts of eigenvalues = 0  
 $\Rightarrow$  solutions spiral around stationary points

Close to  $(n\pi, 0)$  for  $n$  even, the solutions spiral around the stationary point. For  $y_2 = y_1' > 0$ ,  $y_1$  is increasing, so the solutions move in a clockwise direction.

- For  $n$  odd, the eigenvalues solve  $\lambda^2 - \alpha^2 = 0$ , so the eigenvalues and eigenvectors are

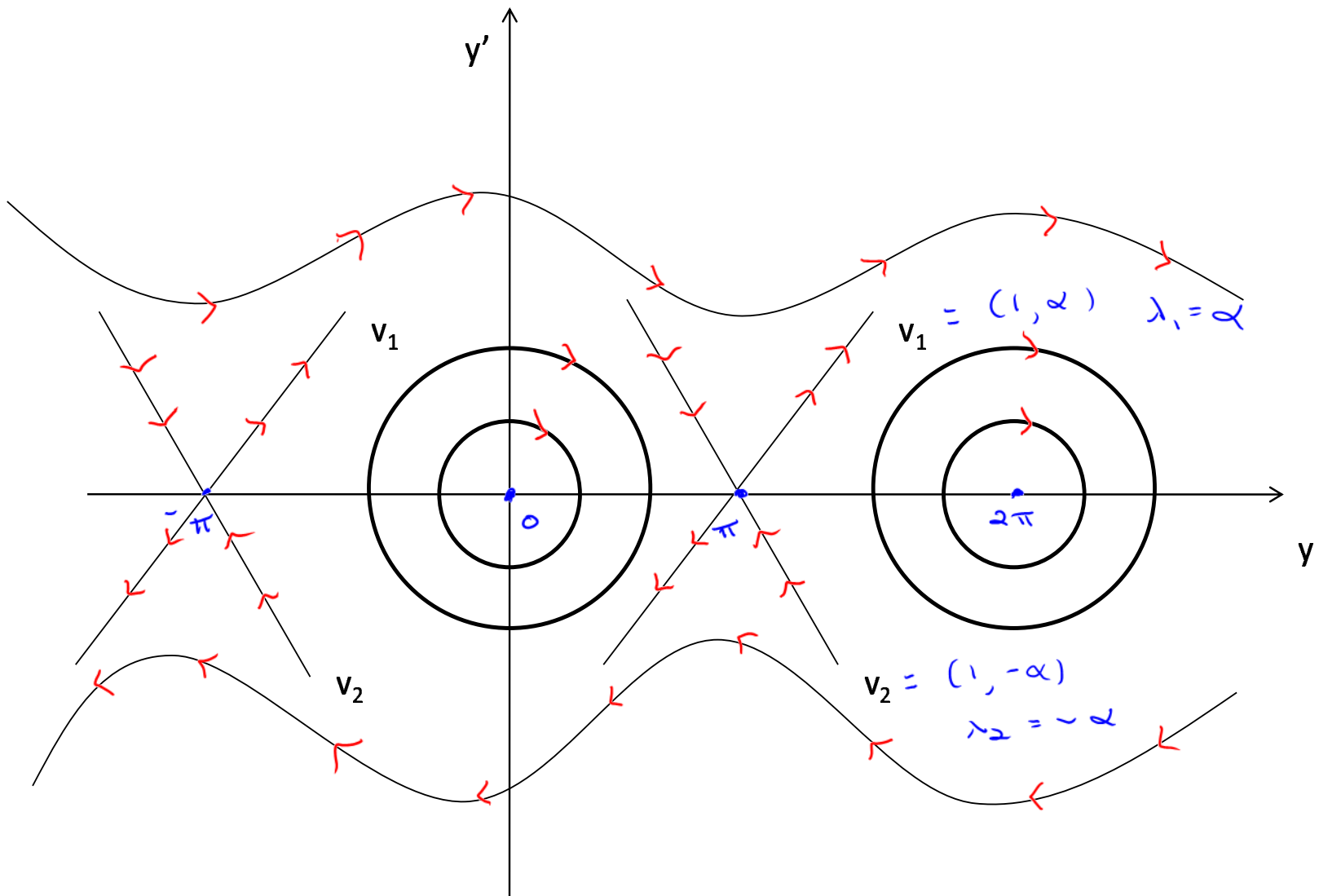
$$\begin{aligned}\lambda_1 &= \alpha, \lambda_2 = -\alpha \\ v_1 &= (1, \alpha), v_2 = (1, -\alpha)\end{aligned}$$

*n=2 distinct  
eigenvalues  
=> diagonalizable!*

Close to  $(n\pi, 0)$  for  $n$  odd, the solutions are roughly hyperbolic in shape; along  $v_2$ , they converge to the stationary point, while along  $v_1$ , they diverge from the stationary point. The solutions of the linearized equation tend to infinity along  $v_1$ . The stationary point  $(n\pi, 0)$  with  $n$  odd corresponds to the pendulum pointing vertically upwards.

- From this information alone, we know the qualitative properties of the solutions of the linearized equation are as given in the phase plane diagram in Figure 2; the solutions of the original equation will closely follow these near the ~~stable~~ stationary points:
  - On the  $y$ -axis, we have  $y' = 0$ , which means that everywhere on the  $y$ -axis (except at the stationary points), the solution must have a vertical tangent.
  - Solve  $y'' = -\alpha^2 \sin y = 0$ , so  $y = n\pi$ ; thus, at  $y = n\pi$ , the derivative of  $y'$  is zero, so the tangent to the curve is horizontal.
- If the initial value of  $|y_2|$  is sufficiently large, the solutions of the linearized equation no longer follow closed curves; this

corresponds to the pendulum going “over the top” rather than oscillating back and forth. From the physical properties of the pendulum, we can see this is also true for the solutions of the nonlinear equation, but this is probably a coincidence; there is no guarantee that a nonlinear equation will behave like its linearization far from the stationary points.





# Nonlinear Differential Equations - Stability

Linearization provides information about qualitative properties of solutions of nonlinear differential equations near the stationary points. Suppose  $y_s$  is a stationary point:

- If eigenvalues of linearized equation at  $y_s$  all have strictly negative real parts, there exists  $\varepsilon > 0$  such that  $|y(0) - y_s| < \varepsilon \Rightarrow \lim_{t \rightarrow \infty} y(t) = y_s$ . All solutions of the original nonlinear equation which start sufficiently close to the stationary point  $y_s$  converge to  $y_s$ .
- If eigenvalues of the linearized equation at  $y_s$  all have strictly positive real parts, no solution of the original nonlinear equation converges to  $y_s$ .

- If eigenvalues of the linearized equation at  $y_s$  all have real part zero, then the solutions of linearized equation are closed curves around  $y_s$ . This tells us little about the solutions of nonlinear equation. They may
  - follow closed curves around  $y_s$
  - converge to  $y_s$
  - converge to a limit closed curve around  $y_s$
  - diverge from  $y_s$
  - converge to  $y_s$  along certain directions and diverge from  $y_s$  along other directions.