Chapter 7. **Systems of first order linear equations.**
Section 7.1 **Introduction**

1. **First-order system** of differential equations:

$$\begin{aligned} x_1' &= F_1(t, x_1, x_2, \ldots, x_n) \\ x_2' &= F_2(t, x_1, x_2, \ldots, x_n) \\ &\vdots \\ x_n' &= F_n(t, x_1, x_2, \ldots, x_n) \end{aligned} \tag{1}$$

2. A set of differentiable functions $x_1(t), x_2(t), \ldots, x_n(t)$ satisfying the system (1) is called a **solution** of the system (1).

3. System of ODE using a **vector notation**:

$$\mathbf{X} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}, \quad \mathbf{F} = \begin{pmatrix} F_1(t, x_1, x_2, \ldots, x_n) \\ F_2(t, x_1, x_2, \ldots, x_n) \\ \vdots \\ F_n(t, x_1, x_2, \ldots, x_n) \end{pmatrix}$$

   Then the system (1) can be written as

$$\mathbf{X}' = \mathbf{F}(t, \mathbf{X}). \tag{2}$$

   More generally, any differential equation of order n,

$$y^{(n)} = f(t, y, y', y'', \ldots, y^{(n-1)})$$

   can be transformed to a system of n differential equations of the first order by introducing derivatives up to order $n-1$ as new variables.

4. To transform the following n-th order IVP,

$$y^{(n)} = f(t, y, y', y'', \ldots, y^{(n-1)}),$$

$$(t_0) = \alpha_0, \quad y'(t_0) = \alpha_1, \ldots, \quad y^{(n-1)}(t_0) = \alpha_{n-1}$$

   into the system we set

$$\begin{aligned} x_1(t) &= y(t) \\ x_2(t) &= y'(t) \\ &\vdots \\ x_n(t) &= y^{(n-1)}(t) \end{aligned}$$

   to get

$$\begin{aligned} x_1' &= x_2 \\ x_2' &= x_3 \\ &\vdots \\ x_n' &= f(t, x_1, x_2, \ldots, x_n) \end{aligned}$$

   subject to

$$x_1(t_0) = \alpha_0, \quad x_2(t_0) = \alpha_1, \ldots, \quad x_n(t_0) = \alpha_{n-1}.$$

5. Note, if f depends on t then the system is called **non-autonomous** and the phase portrait (space) in this case is in $\mathbb{R}^{n+1}$. Otherwise (i.e. if f doesn't depend on t)the system is **autonomous** and the phase portrait (space) in this case is in $\mathbb{R}^n$.

6. Important: Not any system of n first order ODE comes from a scalar n-th order.

   Example 1. Transform the differential equation into a system of first order equations.

   (a) $y'' + 5y' - 2y = \sin t$

   (b) $y''' + 3y' + y = 4$

   Example 2. Transform the initial value problem

   $$y'' + .25y' + 4t = 2\cos 3t, \quad y(0) = 1, y'(0) = -2$$

   into a system of 2 first order differential equations.

7. **Existence and Uniqueness Theorem** for IVP defined by a system: Consider the IVP:

$$\begin{aligned}
x_1' &= F_1(t, x_1, x_2, \ldots, x_n) \\
x_2' &= F_2(t, x_1, x_2, \ldots, x_n) \\
&\vdots \\
x_n' &= F_n(t, x_1, x_2, \ldots, x_n) \\
x_1(t_0) &= x_1^0 \\
x_2(t_0) &= x_2^0 \\
&\vdots \\
x_n(t_0) &= x_n^0
\end{aligned} \tag{3}$$

If each of the functions $F_1, F_2, \ldots, F_n$ and the partial derivatives $\dfrac{\partial F_1}{\partial x_k}, \dfrac{\partial F_2}{\partial x_k}, \ldots, \dfrac{\partial F_n}{\partial x_k}$ $(1 \leq k \leq n)$ are continuous in a region

$$R = \{\alpha < t < \beta, \alpha_1 < x_1 < \beta_1, \alpha_2 < x_1 < \beta_2, \ldots, \alpha_n < x_n < \beta_n\}$$

and the point $(t_0, x_1^0, \ldots, x_n^0)$ belongs to R, then there is an interval $(t_0 - h, t_0 + h)$ in which there exists a unique solution of the IVP (3).

Linear Systems

8. When each of the functions $F_1, F_2, \ldots, F_n$ in (3) is linear in the dependent variables $x_1, \ldots, x_n$, we get a system of linear equations:

$$\begin{aligned}
x_1' &= p_{11}(t)x_1 + p_{12}(t)x_2 + \ldots + p_{1n}(t)x_n + g_1(t) \\
x_2' &= p_{21}(t)x_1 + p_{22}(t)x_2 + \ldots + p_{2n}(t)x_n + g_2(t) \\
&\vdots \\
x_n' &= p_{n1}(t)x_1 + p_{n2}(t)x_2 + \ldots + p_{nn}(t)x_n + g_n(t)
\end{aligned} \tag{4}$$

When $g_k(t) \equiv 0$ $(1 \leq k \leq n)$, the linear system (4) is said to be **homogeneous**; otherwise it is **nonhomogeneous.**

9. **Existence and Uniqueness Theorem** for linear IVP:

If the functions $p_{11}, p_{12}, \ldots, p_{nn}$ and $g_1, \ldots, g_n$ are continuous on an open interval $I = \{t : \alpha < t < \beta\}$, then there exists a unique solution of the system (4) that also satisfies the initial conditions $x_1(t_0) = x_1^0, x_2(t_0) = x_2^0, \ldots, x_n(t_0) = x_n^0$, where t_0 is any point of I. Moreover, the solution exists throughout the interval I.

Matrix Form of A Linear System

10. If X, $P(t)$, and $G(t)$ denote the respective matrices

$$X = \begin{pmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_n(t) \end{pmatrix}, \quad P(t) = \begin{pmatrix} p_{11}(t) & p_{12}(t) & \ldots & p_{1n}(t) \\ p_{21}(t) & p_{22}(t) & \ldots & p_{2n}(t) \\ \vdots & & & \vdots \\ p_{n1}(t) & p_{n2}(t) & \ldots & p_{nn}(t) \end{pmatrix}, \quad G(t) = \begin{pmatrix} g_1(t) \\ g_2(t) \\ \vdots \\ g_n(t) \end{pmatrix},$$

then the system of linear first-order DE (4) can be written as

$$X' = PX + G.$$

If the system is homogeneous, its matrix form is then

$$X' = PX.$$

11. **Example 3.** Express the given system in matrix form:

(a) $$\begin{aligned} x_1' &= x_2 \\ x_2' &= -x_1 \end{aligned}$$

(b) $$\begin{aligned} x_1' &= x_2 - x_1 + t \\ x_2' &= -x_1 + 7x_2 - x_3 - e^t \\ x_3' &= 2x_2 - x_3 + \sin t \end{aligned}$$