January 11 Math 2306 sec. 54 Spring 2019

Section 1: Concepts and Terminology

We define solutions of the nth order ODE $F(x, y, y', \dots, y^{(n)}) = 0$ (*)

Definition: A function ϕ defined on an interval[1] I and possessing at least n continuous derivatives on I is a **solution** of (*) on I if upon substitution (i.e. setting $y = \phi(x)$) the equation reduces to an identity.

Definition: An **implicit solution** of (*) is a relation $G(x, y) = 0$ provided there exists at least one function $y = \phi$ that satisfies both the differential equation (*) and this relation.

[1] The interval is called the *domain of the solution* or the *interval of definition*.

An Implicit Solution

Verify that the relation(left) defines and implicit solution of the differential equation (right).

$$y^2 - 2x^2y = 1, \qquad \frac{dy}{dx} = \frac{2xy}{y - x^2}$$

we'll show that when x and y satisfy the relation, the ODE is also true. We start with the relation $y^2 - 2x^2y = 1$ and use implicit differentiation.

$$2y\frac{dy}{dx} - 2\left(2xy + x^2\frac{dy}{dx}\right) = 0$$

It may not be possible to clearly identify the domain of definition of an implicit solution.

we'll isolate $\frac{dy}{dx}$.

$$y\frac{dy}{dx} - 2xy - x^2\frac{dy}{dx} = 0$$

$$(y - x^2)\frac{dy}{dx} = 2xy$$

$$\frac{dy}{dx} = \frac{2xy}{y - x^2}$$

So the relation does define a solution (implicitly) to the ODE.

Function vs Solution

The interval of defintion has to be an interval.

Example: Consider the ODE $y' = -y^2$. A solution is $y = \dfrac{1}{x}$.

The interval of defintion can be

$$(-\infty, 0) \quad \text{or} \quad (0, \infty)$$

or any interval that doesn't contain the origin.

But it CAN't be $(-\infty, 0) \cup (0, \infty)$ because this isn't an interval!

Depending on other available information, we often assume I is the largest (or one of the largest) possible intervals.

Function vs Solution

The graph of an ODE solution[2] will not have disconnected pieces.

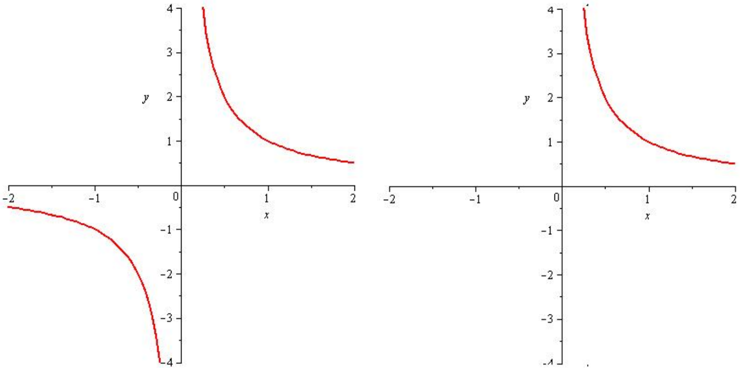


Figure: Left: Plot of $f(x) = \frac{1}{x}$ as a **function**. Right: Plot of $f(x) = \frac{1}{x}$ as a possible **solution** of an ODE.

[2]This is known as a *classical solution*.

Unspecified Constants in a Function

Show that for any choice of constants c_1 and c_2, $y = c_1 x + \frac{c_2}{x}$ is a solution of the differential equation

$$x^2 y'' + xy' - y = 0$$

we'll show that $y = c_1 x + \frac{c_2}{x}$ solves the ODE without putting any conditions on the numbers c_1 and c_2.

We substitute:

$$y = c_1 x + c_2 x^{-1}$$

$$y' = c_1 - c_2 x^{-2}$$

$$y'' = 0 + 2c_2 x^{-3}$$

$$x^2y'' + xy' - y =$$

$$x^2(2c_2x^{-3}) + x(c_1 - c_2x^{-2}) - (c_1x + c_2x^{-1}) =$$

$$2c_2x^{-1} + c_1x - c_2x^{-1} - c_1x - c_2x^{-1} =$$

$$x^{-1}(2c_2 - c_2 - c_2) + x(c_1 - c_1) =$$

$$x^{-1}(0) + x(0) = 0$$

$$0 = 0$$

So $y = c_1x + \frac{c_2}{x}$ solves the ODE for any pair of numbers c_1, c_2.

Some Terms

- A **parameter** is an unspecified constant such as c_1 and c_2 in the last example.
- A **family of solutions** is a collection of solution functions that only differ by a parameter.
- An ***n*-parameter family of solutions** is one containing n parameters (e.g. $c_1x + \frac{c_2}{x}$ is a 2 parameter family).
- A **particular solution** is one with no arbitrary constants in it.
- The **trivial solution** is the simple constant function $y = 0$.
- An **integral curve** is the graph of one solution (perhaps from a family).

Section 2: Initial Value Problems

An initial value problem consists of an ODE with a certain type of additional conditions.

Solve the equation [3]

$$\frac{d^n y}{dx^n} = f(x, y, y', \ldots, y^{(n-1)}) \tag{1}$$

subject to the *initial conditions*

$$y(x_0) = y_0, \quad y'(x_0) = y_1, \quad \ldots, y^{(n-1)}(x_0) = y_{n-1}. \tag{2}$$

The problem (1)–(2) is called an *initial value problem* (IVP).

[3] on some interval I containing x_0.

IVPs

First order case:

1st order

one initial condition (IC)

$$\frac{dy}{dx} = f(x,y), \quad y(x_0) = y_0$$

If y solves this problem, the ODE part tells use the shape of y's graph (via its slope). The condition $y(x_0)=y_0$ tells use the curve passes through the point (x_0,y_0).

Second order case:

2nd order

2 conditions

$$\frac{d^2y}{dx^2} = f(x,y,y'), \quad y(x_0) = y_0, \quad y'(x_0) = y_1$$

If y is the position of a particle at time x, the ODE gives the particle's acceleration

y_0 = initial position and y_1 = initial velocity.

Example

Given that $y = c_1 x + \frac{c_2}{x}$ is a 2-parameter family of solutions of $x^2 y'' + xy' - y = 0$, solve the IVP

$$x^2 y'' + xy' - y = 0, \quad y(1) = 1, \quad y'(1) = 3$$

We know that the solutions look like $y = c_1 x + \frac{c_2}{x}$.

We must find c_1, c_2 so that $y(1) = 1$ and $y'(1) = 3$.

$$y(x) = c_1 x + \frac{c_2}{x} \qquad y(1) = c_1(1) + \frac{c_2}{1} = 1$$

$$y'(x) = c_1 - \frac{c_2}{x^2} \qquad y'(1) = c_1 - \frac{c_2}{1^2} = 3$$

We solve

$$c_1 + c_2 = 1$$

$$c_1 - c_2 = 3$$

add the equations

$$2c_1 = 4 \Rightarrow c_1 = 2$$

$$c_1 + c_2 = 1 \Rightarrow c_2 = 1 - c_1 = 1 - 2 = -1$$

The solution to the IVP is

$$\boxed{y = 2x - \frac{1}{x}}$$

Example

Part 1

Show that for any constant c the relation $x^2 + y^2 = c$ is an implicit solution of the ODE

$$\frac{dy}{dx} = -\frac{x}{y}$$

Assuming $x^2 + y^2 = c$ for some number c

$2x + 2y\frac{dy}{dx} = 0$ solve for $\frac{dy}{dx}$

$2y\frac{dy}{dx} = -2x$

$\frac{dy}{dx} = \frac{-2x}{2y} = \frac{-x}{y}$ (for $y \neq 0$)

Example

Part 2

Use the preceding results to find an explicit solution of the IVP

$$\frac{dy}{dx} = -\frac{x}{y}, \quad y(0) = -2$$

We know solutions to the ODE look like

$$x^2 + y^2 = C.$$

Since $y(0) = -2$, $0^2 + (-2)^2 = C \Rightarrow C = 4$

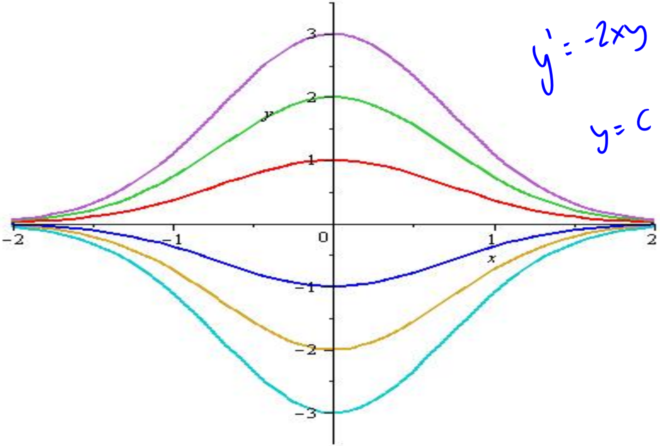
So $x^2 + y^2 = 4$ is an implicit solution to the IVP.

Solving for y

$$y^2 = 4 - x^2 \quad \Longrightarrow \quad y = \sqrt{4 - x^2} \quad \text{or} \quad y = -\sqrt{4 - x^2}$$

Since $y(0) = -2$, the explicit solution is $y = -\sqrt{4 - x^2}$.

Graphical Interpretation



$y' = -2xy$

$y = c e^{-x^2}$

Figure: Each curve solves $y' + 2xy = 0$, $y(0) = y_0$. Each colored curve corresponds to a different value of y_0