

# Vector ODEs

Math and modeling for high school

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Fall 2022

# SCALAR AND VECTOR EQUATIONS

Consider two differential equations:

$$\begin{cases} \dot{x} = -10x - 3t \\ \dot{y} = -2y + t \end{cases} \quad (1)$$

Introducing a vector variable  $\mathbf{v} = [x, y]$  we can re-write the system as:

$$\dot{\mathbf{v}} = \begin{bmatrix} -10 & 0 \\ 0 & -2 \end{bmatrix} \mathbf{v} + \begin{bmatrix} -3t \\ t \end{bmatrix} \quad (2)$$

Notice that it is still two independent equations. But it doesn't have to be. Here is an example of a system of equations which are not interdependent:

$$\dot{\mathbf{v}} = \begin{bmatrix} -10 & 2 \\ 0 & -2 \end{bmatrix} \mathbf{v} + \begin{bmatrix} -3t \\ t \end{bmatrix} \quad (3)$$

In general, consider equation

$$\dot{\mathbf{v}} = \mathbf{A}\mathbf{v} + \mathbf{c} \quad (4)$$

As before, we can discuss how the derivative of a variable in a ratio between the increase in its value and the time interval over which the increase has taken place:

$$\dot{\mathbf{v}} \approx \frac{\mathbf{v}(t + \Delta t) - \mathbf{v}(t)}{\Delta t} \quad (5)$$

So, we can make it into an *integration scheme*:

$$\mathbf{v}(t + \Delta t) = \mathbf{v}(t) + (\mathbf{A}\mathbf{v}(t) + \mathbf{c})\Delta t \quad (6)$$

# SATELLITE PROBLEM

When do system of ODEs become important?

Consider a problem: given a satellite orbiting Earth at the velocity  $\mathbf{v}$ , at the height  $h$ . Find its orbit.

Sounds quite intimidating, doesn't it?

# SATELLITE PROBLEM

## Newton's law

First, let us remember the Newton's law:

$$m\dot{\mathbf{v}} = \mathbf{f} \tag{7}$$

where  $m$  is the mass of the satellite,  $\mathbf{v}$  is its velocity and  $\mathbf{f}$  is the sum of all external forces acting on the satellite.

Second, we assume that the only external force acting on the satellite is gravitational force.

# SATELLITE PROBLEM

## Gravity model

For us it will be insufficient to assume that the gravity force is given by  $mg$  directed towards the center of the Earth. Instead, we want to use a more precise model of gravitational force:

$$f = G \frac{mM}{h^2} \quad (8)$$

where  $f$  is the magnitude of the gravitational force,  $m$  is the mass of the satellite,  $M$  is the mass of the Earth and  $h$  is the distance between the center of the Earth and the satellite.

Here are some of these constants:

- $M = 5.972 \cdot 10^{24}$  kg
- $G = 6.673 \cdot 10^{-11}$  N m<sup>2</sup>/kg<sup>2</sup>
- radius of Earth is  $6.371 \cdot 10^6$  m

# SATELLITE PROBLEM

## Position and gravity

Let us assume that the position of the satellite relative to the center of the Earth, is given by the vector  $\mathbf{r}$ . How can we use this information to compute the magnitude of the gravity force?

Our strategy is to realize that  $h = \|\mathbf{r}\|$ , and use it in the formula:

$$f = G \frac{mM}{\|\mathbf{r}\|^2} \tag{9}$$

# SATELLITE PROBLEM

## Direction of gravity

But how do we give this force a direction? It always points towards Earth, so in the direction  $-\mathbf{r}$ . The gravity force should be pointing in the same direction.

The way to ensure it, is to multiply the magnitude  $f = G \frac{mM}{\|\mathbf{r}\|^2}$  by the direction unit vector  $-\mathbf{r}/\|\mathbf{r}\|$ :

$$f = -G \frac{mM}{\|\mathbf{r}\|^3} \mathbf{r} \quad (10)$$



# SATELLITE PROBLEM

## Model

Now we know the gravity force, and we can write the equations of motion for the satellite:

$$\begin{cases} \dot{\mathbf{r}} = \mathbf{v} \\ m\dot{\mathbf{v}} = -G \frac{mM}{\|\mathbf{r}\|^3} \mathbf{r} \end{cases} \quad (11)$$

Clearly we can divide the first equation by  $m$ , ridding us from this parameter - meaning the mass of the satellite does not play a role in this problem. This is true because we do not consider the effect of other forces than gravity, and we do not consider the effects the satellite has on the Earth.

# SATELLITE PROBLEM

## Code

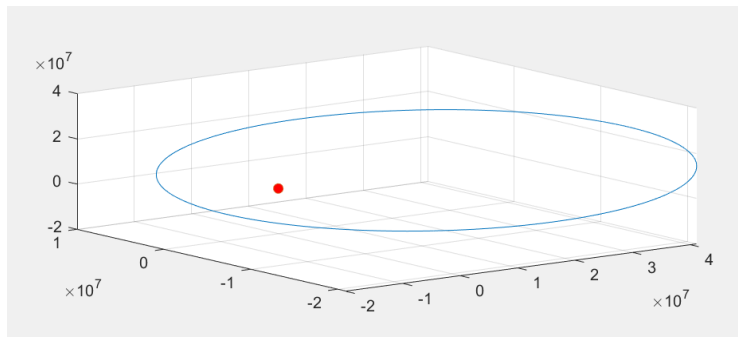
We can solve this system in MATLAB using the following code:

```
0      G = 6.673 * 10^(-11);
      M = 5.972 * 10^24;
2      r0 = randn(3, 1) * 7*10^6;
      v0 = randn(3, 1) * 1000;
4      tspan = linspace(0, 20^4, 10^5);
      x0 = [r0; v0];
6      odefun = @(t, x) [x(4:6); -G*M*x(1:3) / ...
      ((norm(x(1:3)))^3)];
8      opts = odeset('RelTol',1e-13,'AbsTol',1e-14,'
Stats','on');
      [t, x] = ode45(odefun, tspan, x0, opts);
10     plot3(x(:, 1), x(:, 2), x(:, 3));
```

# SATELLITE PROBLEM

## Graph

We plot the solution, and the result is shown below:



**Figure 1:** Orbit of a satellite, found by ode45; center of the Earth is given by a red dot

# THANK YOU!

Lecture slides are available via Moodle.

You can help improve these slides at:  
[github.com/SergeiSa/Extra-math-for-high-school](https://github.com/SergeiSa/Extra-math-for-high-school)

Check Moodle for additional links, videos, textbook suggestions.

