

# Stability

## Control Theory, Lecture 2

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Consider the following ODE:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, t) \quad (1)$$

Let  $\mathbf{x}_0$  be such a state that:

$$\mathbf{f}(\mathbf{x}_0, t) = 0 \quad (2)$$

Then such state  $\mathbf{x}_0$  is called a *node* or a *critical point*.

Node  $\mathbf{x}_0$  is called *stable* iff for any constant  $\delta$  there exists constant  $\varepsilon$  such that:

$$\|\mathbf{x}(0) - \mathbf{x}_0\| < \delta \longrightarrow \|\mathbf{x}(t) - \mathbf{x}_0\| < \varepsilon \quad (3)$$

Think of it as "for any initial point that lies at most  $\delta$  away from  $\mathbf{x}_0$ , the rest of the trajectory  $\mathbf{x}(t)$  will be at most  $\varepsilon$  away from  $\mathbf{x}_0$ ".

Or, more picturesque, think of it as "the solutions with different initial conditions do not diverge from the node"

Node  $\mathbf{x}_0$  is called *asymptotically stable* iff for any constant  $\delta$  it is true that:

$$\|\mathbf{x}(0) - \mathbf{x}_0\| < \delta \longrightarrow \lim_{t \rightarrow \infty} \mathbf{x}(t) = \mathbf{x}_0 \quad (4)$$

Think of it as "for any initial point that lies at most  $\delta$  away from  $\mathbf{x}_0$ , the trajectory  $\mathbf{x}(t)$  will asymptotically approach the point  $\mathbf{x}_0$ ".

Or, more picturesque, think of it as "the solutions with different initial conditions converge to the node"

# STABILITY VS ASYMPTOTIC STABILITY

## Example

Consider dynamical system  $\dot{x} = 0$ , and solution  $x = 7$ . This solution is stable, but not asymptotically stable (other solutions do not diverge from  $x = 7$ , but do not converge to it either).

## Example

Consider dynamical system  $\dot{x} = -x$ , and solution  $x = 0$ . This solution is stable and asymptotically stable (other solutions converge to  $x = 0$ ).

## Example

Consider dynamical system  $\dot{x} = x$ , and solution  $x = 0$ . This solution is unstable (other solutions diverge from  $x = 0$ ).

Consider the following linear ODE:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} \quad (5)$$

This is called a *linear time-invariant system*, or *LTI*.

Consider the following linear ODE:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} \quad (6)$$

This is also an LTI, but it is also called an *autonomous system*, since its evolution depends only on the state of the system.

# STABILITY OF AUTONOMOUS LTI

## Real eigenvalues

Consider autonomous LTI:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} \quad (7)$$

where  $\mathbf{A}$  can be decomposed via eigen-decomposition as  $\mathbf{A} = \mathbf{V}\mathbf{D}\mathbf{V}^{-1}$ , where  $\mathbf{D}$  is a diagonal matrix.

$$\dot{\mathbf{x}} = \mathbf{V}\mathbf{D}\mathbf{V}^{-1}\mathbf{x} \quad (8)$$

Multiply it by  $\mathbf{V}^{-1} \longrightarrow \mathbf{V}^{-1}\dot{\mathbf{x}} = \mathbf{V}^{-1}\mathbf{V}\mathbf{D}\mathbf{V}^{-1}\mathbf{x}$ .

Define  $\mathbf{z} = \mathbf{V}^{-1}\mathbf{x} \longrightarrow \dot{\mathbf{z}} = \mathbf{D}\mathbf{z}$ .

Since elements of  $\mathbf{D}$  are real, we can clearly see, that iff they are *all negative* will the system be asymptotically stable. If they are non-positive, the system is stable. And those elements are eigenvalues of  $\mathbf{A}$ .



# STABILITY OF AUTONOMOUS LTI

## Complex eigenvalues, 2-dimensional case (1)

Let us consider the following system:

$$\begin{bmatrix} \dot{\mathbf{x}}_1 \\ \dot{\mathbf{x}}_2 \end{bmatrix} = \begin{bmatrix} \alpha & -\beta \\ \beta & \alpha \end{bmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} \quad (9)$$

The eigenvalues of the system are  $\alpha \pm i\beta$ . We denote  $\begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} = \mathbf{x}$ .

We start by claiming that the system will be stable iff the  $\dot{\mathbf{x}}^\top \mathbf{x} < 0$ . Indeed, vector  $\dot{\mathbf{x}}$  can always be decomposed into two components,  $\dot{\mathbf{x}}_{\parallel}$  parallel to  $\mathbf{x}$ , and  $\dot{\mathbf{x}}_{\perp}$  perpendicular to  $\mathbf{x}$ . By definition  $\dot{\mathbf{x}}_{\perp}^\top \mathbf{x} = 0$ , and is responsible for the change in orientation of  $\mathbf{x}$ . The value of  $\dot{\mathbf{x}}_{\parallel}$  is responsible for the change in the length of  $\mathbf{x}$ ; the length would shrink iff  $\dot{\mathbf{x}}_{\parallel}$  is of opposite direction to  $\mathbf{x}$ , giving negative value of the dot product  $\dot{\mathbf{x}}^\top \mathbf{x}$ .

# STABILITY OF AUTONOMOUS LTI

## Complex eigenvalues, 2-dimensional case (2)

Let us compute  $\dot{\mathbf{x}}^\top \mathbf{x}$ :

$$\dot{\mathbf{x}}^\top \mathbf{x} = \begin{bmatrix} \mathbf{x}_1 & \mathbf{x}_2 \end{bmatrix} \begin{bmatrix} \alpha & -\beta \\ \beta & \alpha \end{bmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix} \quad (10)$$

$$\dot{\mathbf{x}}^\top \mathbf{x} = \alpha(\mathbf{x}_1^2 + \mathbf{x}_2^2) \quad (11)$$

From this it is clear that the product  $\dot{\mathbf{x}}^\top \mathbf{x} < 0$  is negative iff  $\alpha < 0$ .

### Definition

As long as the *real parts of the eigenvalues* of the system are *strictly negative*, the system is *asymptotically stable*. If the real parts of the eigenvalues of the system are zero, the system is *marginally stable*.

# STABILITY OF AUTONOMOUS LTI

## Complex eigenvalues, 2-dimensional case (3)

Vector field of  $\begin{bmatrix} \dot{\mathbf{x}}_1 \\ \dot{\mathbf{x}}_2 \end{bmatrix} = \begin{bmatrix} \alpha & -\beta \\ \beta & \alpha \end{bmatrix} \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{bmatrix}$  is shown below:



# STABILITY OF AUTONOMOUS LTI

## General case (1)

Given  $\dot{\mathbf{x}} = \mathbf{A}\mathbf{x}$ , where  $\mathbf{A}$  can be decomposed via eigen-decomposition as  $\mathbf{A} = \mathbf{U}\mathbf{C}\mathbf{U}^{-1}$ , where  $\mathbf{C}$  is a complex-valued diagonal matrix and  $\mathbf{U}$  is a complex-valued invertible matrix.

We multiply both sides by  $\mathbf{U}^{-1}$ , then define  $\mathbf{z} = \mathbf{U}^{-1}\mathbf{x}$  to arrive at:

$$\dot{\mathbf{z}} = \mathbf{C}\mathbf{z} \quad (12)$$

which falls into a set of independent equations, with complex coefficients  $c_j$ :

$$\dot{z}_j = c_j z_j \quad (13)$$

# STABILITY OF AUTONOMOUS LTI

## General case (2)

Expanding  $c_j = \alpha + i\beta$ , and  $z_j = u + iv$  (we dismiss subscripts for clarity), we find that  $\dot{z}_j = c_j z_j$  can be expanded as:

$$\dot{u} + i\dot{v} = \dot{z}_j = c_j z_j = (\alpha + i\beta)(u + iv) \quad (14)$$

$$\dot{u} + i\dot{v} = \alpha u + i\beta u + i\alpha v - \beta v \quad (15)$$

$$\begin{bmatrix} \dot{u} \\ \dot{v} \end{bmatrix} = \begin{bmatrix} \alpha & -\beta \\ \beta & \alpha \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} \quad (16)$$

As we can see,  $\dot{z}_j = c_j z_j$  is asymptotically stable iff  $\text{Re}(c_j) < 0$ , and marginally stable if  $\alpha = \text{Re}(c_j) = 0$ . Same is true for  $\dot{\mathbf{z}} = \mathbf{C}\mathbf{z}$  and hence, for  $\dot{\mathbf{x}} = \mathbf{A}\mathbf{x}$ , as  $\mathbf{U}$  is invertible.

# STABILITY OF AUTONOMOUS LTI

## Condition

Consider an autonomous LTI:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} \quad (17)$$

### Definition

Eq. (17) is stable iff real parts of eigenvalues of  $\mathbf{A}$  are non-positive.

### Definition

Eq. (17) is asymptotically stable iff real parts of eigenvalues of  $\mathbf{A}$  are negative.

# STABILITY OF AUTONOMOUS LTI

## Illustration

Here is an illustration of *phase portraits* of two-dimensional LTIs with different types of stability:

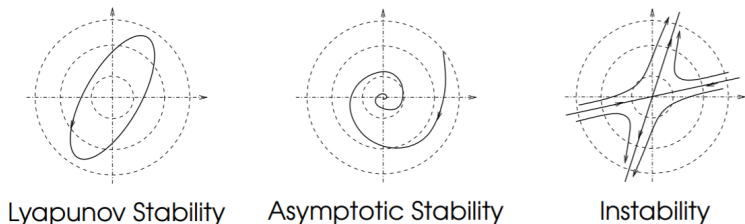
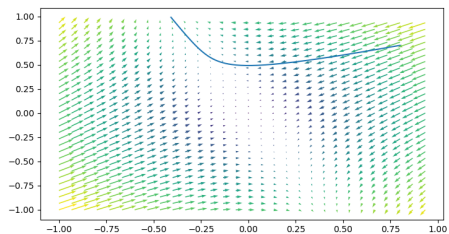
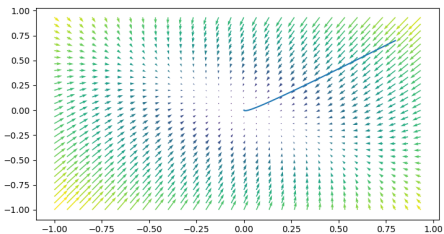
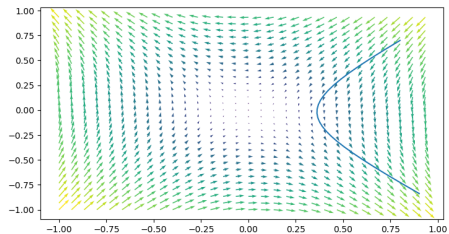
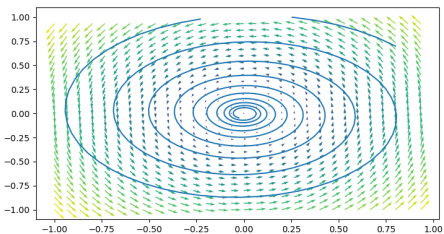


Figure 1: phase portraits for different types of stability

Credit: [staff.uz.zgora.pl/wpaszke/materialy/spc/Lec13.pdf](http://staff.uz.zgora.pl/wpaszke/materialy/spc/Lec13.pdf)





- Control Systems Design, by Julio H. Braslavsky  
[staff.uz.zgora.pl/wpaszke/materialy/spc/Lec13.pdf](http://staff.uz.zgora.pl/wpaszke/materialy/spc/Lec13.pdf)

# THANK YOU!

Lecture slides are available via Moodle.

You can help improve these slides at:

[github.com/SergeiSa/Control-Theory-Slides-Spring-2022](https://github.com/SergeiSa/Control-Theory-Slides-Spring-2022)

Check Moodle for additional links, videos, textbook suggestions.

