## The Lorenz equations

$\sigma, r, b > 0$

$$\dot{x} = \sigma(y - x)$$
$$\dot{y} = rx - y - \underline{xz}$$
$$\dot{z} = \underline{xy} - bz$$

Simplified model of atmospheric convection.

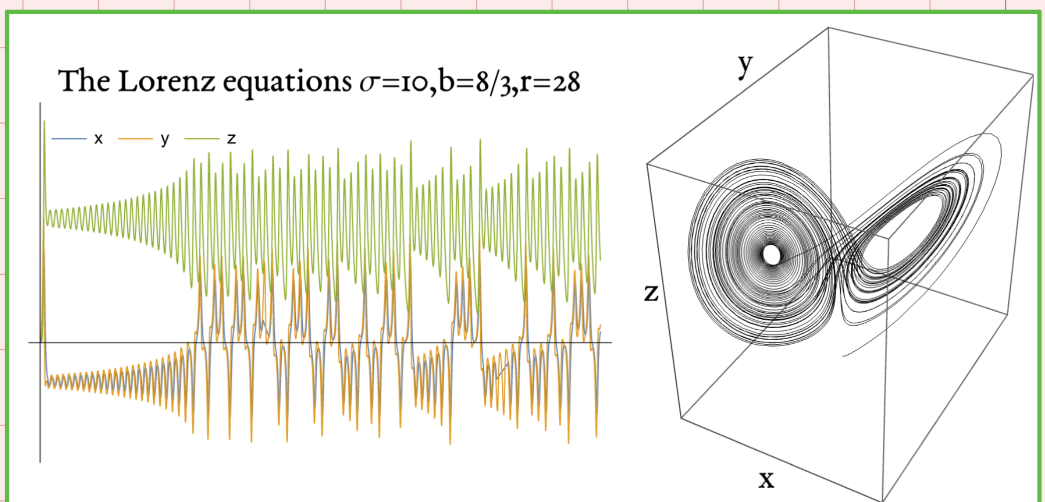
→ Nonlinear

→ 3-dimensional phase space

→ Symmetric : $(x, y, z) \longmapsto (-x, -y, z)$

tinyurl.com/E91lorenz1
tinyurl.com/E91lorenz2

Wed, Apr 2 Lecture 18



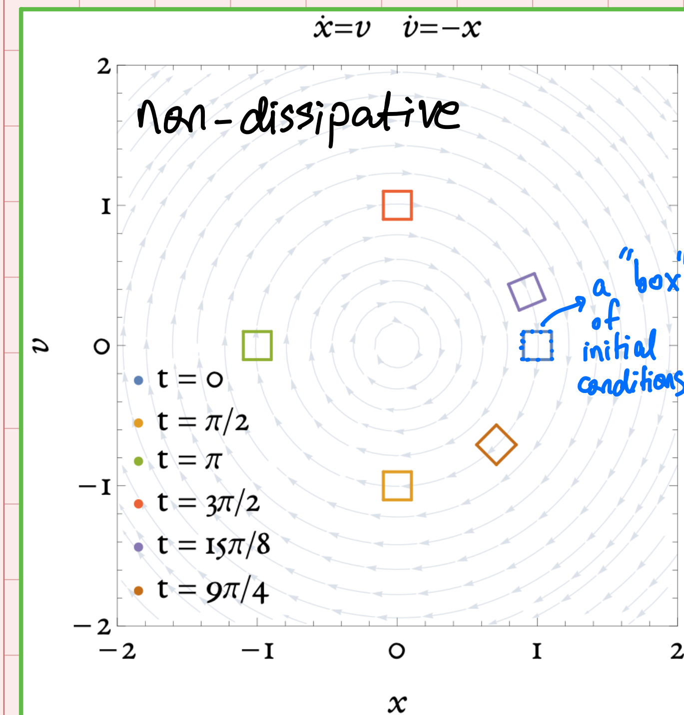

→ Dissipative : "Volumes in phase space" shrink exponentially with time

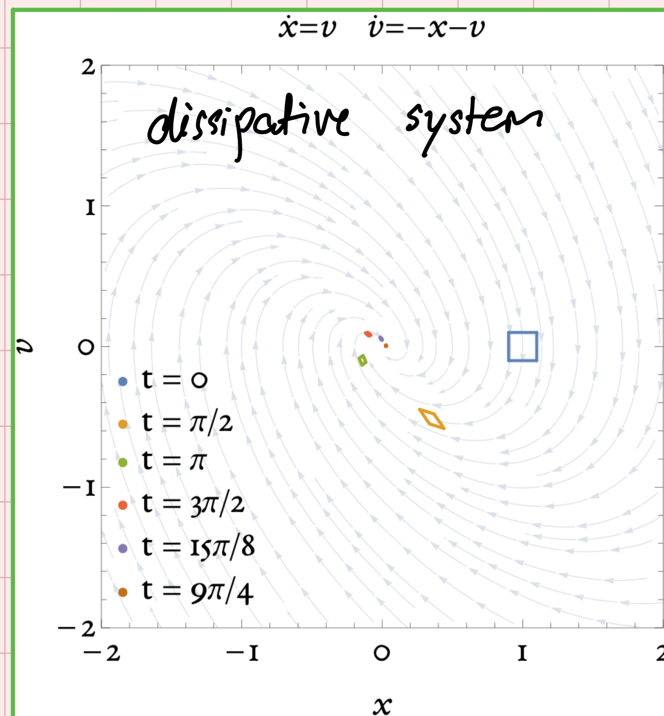
i.e. $\underset{\sim}{\dot{x}} = \underset{\sim}{f}(\underset{\sim}{x})$, $\nabla \cdot \underset{\sim}{f} < 0$ for dissipative systems.

$$\nabla = \begin{bmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{bmatrix}$$

If $\nabla \cdot \underset{\sim}{f} > 0$ in some region, volumes expand

If $\nabla \cdot \underset{\sim}{f} < 0$ " " " , volumes shrink




The rate of change of volumes is $\dot{V} = \int_V (\nabla \cdot \underset{\sim}{f})\, dV$

For Lorenz: $\nabla \cdot f = \begin{bmatrix} \partial/\partial x \\ \partial/\partial y \\ \partial/\partial z \end{bmatrix} \cdot \begin{bmatrix} \sigma(y-x) \\ rx - y - xz \\ xy - bz \end{bmatrix}$

$\rightsquigarrow \nabla \cdot \underset{\sim}{f} = -\sigma - 1 - b$. It happens to not be a function of $(x, y, z)$. Const. everywhere.

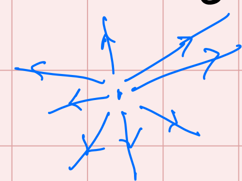
$\dot{V} = -(\sigma + 1 + b) V$

$V(t) = V(0) e^{-(\sigma+1+b)t}$

## Because of dissipation

→ Quasiperiodicity is not allowed because q.p. flow occurs on the surface of a fixed torus in phase space. But if volumes in phase space are always shrinking, you can't have such an invariant torus.

→ No repelling fixed points or repelling closed orbits are allowed.



## Fixed Points of Lorenz system

$(x,y,z) = \underline{0}$ is always a fixed pt.

$(x,y,z) = \left(\pm\sqrt{b(r-1)}, \pm\sqrt{b(r-1)}, r-1\right)$ $(C^+, C^-)$ are fixed pts if $r > 1$

Linear Stability of origin:

linearized Lorenz equations:

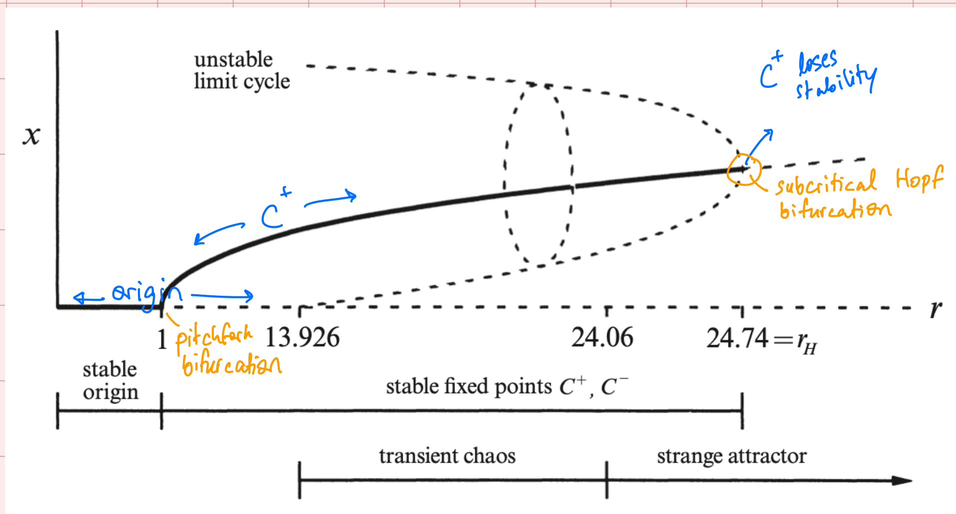
$$\dot{x} = \sigma(y-x)$$
$$\dot{y} = rx - y$$
$$\dot{z} = -bz$$

contracting direction

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} -\sigma & \sigma \\ r & -1 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

$$\left.\begin{aligned} \tau &= -(\sigma+1) \\ \Delta &= \sigma - \sigma r = \sigma(1-r) \end{aligned}\right\} \quad \begin{aligned} r > 1 &: \text{saddle pt} \\ r < 1 &: \text{stable node} \end{aligned}$$

$C^+$ and $C^-$ are stable for $1 < r < r_H = \dfrac{\sigma(\sigma+b+3)}{\sigma-b-1}$




so what exists after $r = r_H$ ?

- trajectories don't go out to infinity
- (it can be shown) there are no stable limit cycles
- no attracting fixed pts.
- but phase space is dissipative

<E91lorenz3>

$\rightsquigarrow$ A strange attractor

<u>Attractor</u> :

if "A" is an attractor, it has these properties $\longrightarrow$

1. $A$ is an *invariant set:* any trajectory $\mathbf{x}(t)$ that starts in $A$ stays in $A$ for all time.
2. *$A$ attracts an open set of initial conditions*: there is an open set $U$ containing $A$ such that if $\mathbf{x}(0) \in U$, then the distance from $\mathbf{x}(t)$ to $A$ tends to zero as $t \to \infty$. This means that $A$ attracts all trajectories that start sufficiently close to it. The largest such $U$ is called the *basin of attraction of $A$.*
3. $A$ is *minimal:* there is no proper subset of $A$ that satisfies conditions 1 and 2.

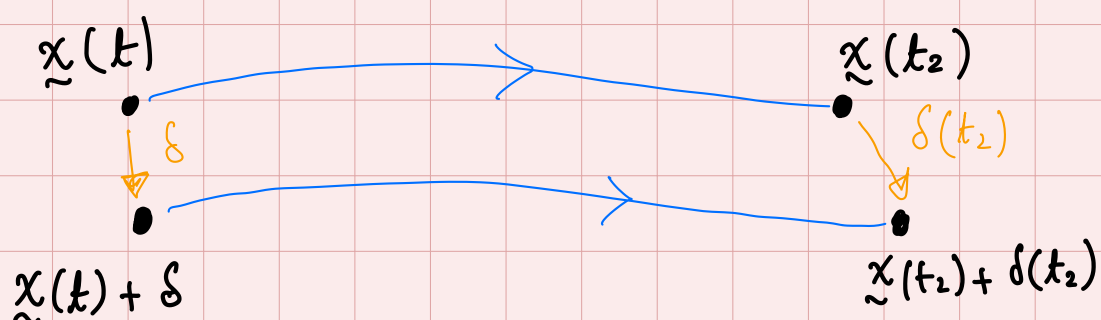
An attractor has a certain shape — what is the shape of the Lorenz attractor?

- dimension "2.05"

tinyurl.com/E91lorenz3

For Lorenz's parameters $\sigma = 10$, $b = 8/3$, $r = 28$, the system exhibits chaos. Strange attractors are chaotic ones.

Strogatz: Chaos is aperiodic long-term behaviour in a deterministic system that shows sensitive dependence on initial conditions.




$\delta(t)$: how far apart are the two trajectories

use both as independent as initial conditions. $\longrightarrow$ See how $\delta$ evolves