ODE: Qualitative Theory (Spring 2022, Shaobo Gan)

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Contents

1 Basic Concepts

§1.1 Basic notions and results

Assume $f:\mathbb{R}\times\mathbb{R}^n\to\mathbb{R}^n, (t,x)\mapsto f(t,x)$ continuous, consider the **equation** (or **system**)

$$\dot{x}=\frac{\mathrm{d}x}{\mathrm{d}t}=f(t,x).$$

A differentiable function $\gamma:(a,b)\subset\mathbb{R}\to\mathbb{R}^n$ is said to be a **solution** (or **solution curve**), if for every $t\in(a,b)$,

$$\frac{\mathrm{d}\gamma(t)}{\mathrm{d}t}=f(t,\gamma(t)).$$

The **graph** of γ is

$$\{(t,\gamma(t)):t\in(a,b)\}\subset\mathbb{R}\times\mathbb{R}^n.$$

For $t_0\in(a,b)$, let $x_0=\gamma(t_0)$, then γ is called the solution of the **initial value problem**

$$\begin{cases}\dfrac{\mathrm{d}x}{\mathrm{d}t}=f(t,x)\\ x(t_0)=x_0\end{cases}.$$

The initial value problem has a unique solution: Let $\gamma_i:(a_i,b_i)\to\mathbb{R}^n$ be two solutions of the initial value problem. Then there exists $\delta>0$, $(t_0-\delta,t_0+\delta)\subset(a_1,b_1)\cap(a_2,b_2)$, such that $\gamma_1(t)=\gamma_2(t),\forall t\in(t_0-\delta,t_0+\delta)$,

Theorem 1.1.1 (Existence and Uniqueness Theorem)
$f:\mathbb{R}\times\mathbb{R}^n\to\mathbb{R}^n, f(t,x)$ continuous, given $t_0\in\mathbb{R}^n, x_0\in\mathbb{R}^n, a>0, b>0$, consider the region

$$R=R(t_0,x_0,a,b)=\{(t,x):|t-t_0|\leqslant a,|x-x_0|\leqslant b\}.$$

If f is Lipchitz in x on R, i.e. $\exists L>0$, $\forall(t,x_1),(t,x_2)\in R$,

$$|f(t,x_1)-f(t,x_2)|\leqslant L|x_1-x_2|,$$

then the initial value problem

$$\begin{cases}\dfrac{\mathrm{d}x}{\mathrm{d}t}=f(t,x)\\ x(t_0)=x_0\end{cases}$$

has a unique solution on $[t_0-h,t_0+h]$, where $h=\min\left\{a,\frac{b}{M}\right\}, M=\max_{(t,x)\in R}|f(t,x)|$.

Remark 1.1.2 — The solution is denoted as $\varphi(t;t_0,x_0)$.

Corollary 1.1.3

When $f \in C^1$, the existence and uniqueness theorem holds.

Denotes the **maximal interval** of $\begin{cases} \dot{x} = f(t,x) \\ x(t_0) = x_0 \end{cases}$ as $I(t_0, x_0)$, it is an open interval.

Corollary 1.1.4

Assume $f \in C^1$ and $|f(x)| \leqslant A(t)|x| + B(t)$, then the maximal interval of the initial value problem is $(-\infty, +\infty)$.

§1.2 Flows

Now we consider the **autonomous equation**

$$\dot{x} = f(x).$$

$\mathbb{R}^n$ is called the **phase space** and $\mathbb{R} \times \mathbb{R}^n$ is called the **generalized phase space**.

The solution of the initial value problem $\begin{cases} \dot{x} = f(x) \\ x(0) = x_0 \end{cases}$ is denoted as $\varphi(t, x_0)$, the set

$$\mathrm{Orb}(x_0) := \{\varphi(t, x_0) : t \in I(x_0)\} \subset \mathbb{R}^n$$

is called the **orbit** pass by x_0.

Corollary 1.2.1 (Continuous Dependence on the Initial Value)

Assume $f \in C^1$, then $U = \{(t, x) : t \in I(x)\}$ is open and $\varphi : U \to \mathbb{R}^n, (t, x) \mapsto \varphi(t, x)$ is continuous.

Theorem 1.2.2

$f(x) \in C^1$, then:

1. $\varphi_0(x) = x$ for every $x \in \mathbb{R}^n$.
2. $\varphi(t, \varphi(s, x)) = \varphi(t + s, x)$ for every $s \in I(x), t \in I(\varphi(s, x))$.

Definition 1.2.3. $\psi : \mathbb{R} \times \mathbb{R}^n \to \mathbb{R}^n$, continuous, is said to be a **(continuous) flow** if:

(i) $\psi(0, x) = x$,

(ii) $\psi(t, \psi(s, x)) = \psi(t + s, x)$.

Remark 1.2.4 — The solution of an autonomous equation is a **local flow.**

Corollary 1.2.5

Let $\psi : \mathbb{R} \times \mathbb{R}^n \to \mathbb{R}^n$ be a flow, then $\psi_t := \psi(t, \cdot) : \mathbb{R}^n \to \mathbb{R}^n$ are homeomorphisms.

Remark 1.2.6 — Consider the group of self-homeomorphisms of $\mathbb{R}^n$, denotes as $\mathrm{Homeo}(\mathbb{R}^n)$, then $\psi : \mathbb{R} \to \mathbb{R}^n$ is a group homomorphism. More generally, we can consider $G \to \mathrm{Homeo}(\mathbb{R}^n)$ for some group G.

Proposition 1.2.7

Assume f is a C^1 vector field, then the orbits of the flow generated by f are either coincide or disjoint.

$\bigcup_{x\in\mathbb{R}^n} \mathrm{Orb}(x)$ forms a partition of $\mathbb{R}^n$, is called the **orbit space**. For each orbit, orient it to indicate the direction of motion, the family of the oriented orbit $\varphi(t,x)/f(x)$ is called the **phase portrait**.

A point $x_0 \in \mathbb{R}^n$ with $f(x_0) = 0$ is called a **critical point** (or a **singularity**, **equilibrium**). The orbit $\mathrm{Orb}(x_0)$ is a single point $\{x_0\}$.

Example 1.2.8

$$\begin{cases} \dfrac{\mathrm{d}x}{\mathrm{d}t} = x \\ x(0) = x_0 \end{cases},$$

the solutions are $\varphi(t,x_0) = x_0 e^t$. There are three orbits $\mathbb{R}_+, \mathbb{R}_-, \{0\}$.

Example 1.2.9

$$\begin{cases} \dfrac{\mathrm{d}x}{\mathrm{d}t} = x^2 \\ x(0) = x_0 \end{cases},$$

the solutions are $\varphi(t,x_0) = \frac{x_0}{1-x_0 t}$. There are three orbits $\mathbb{R}_+, \mathbb{R}_-, \{0\}$. But the phase portrait is different from the former examples, because the orientations on $\mathbb{R}_-$ are different.

Theorem 1.2.10

Assume $f : \mathbb{R}^n \to \mathbb{R}^n$ is a C^1 vector field, $\beta(x) : \mathbb{R}^n \to \mathbb{R} \in C^1$ and $\beta(x) > 0$. Then the equations $\dot{x} = f(x)$ and $\dot{x} = \beta(x)f(x)$ have the same phase portraits.

Proof. $\varphi : I \to \mathbb{R}^n$ a solution of f. Find a C^1 diffeomorphism $h : J \to I$ such that $\varphi \circ h$ is the solution of $\dot{x} = \beta(x)f(x)$. It suffices that

$$\left.\frac{\mathrm{d}}{\mathrm{d}t}\right|_{t=h(s)} \varphi(t) \cdot \frac{\mathrm{d}h(s)}{\mathrm{d}s} = \beta(\varphi \circ h(s)) f(\varphi \circ h(s)),$$

i.e. $\frac{\mathrm{d}h(s)}{\mathrm{d}s} = \beta(\varphi \circ h(s)) > 0$, it is an initial value problem. It shows that the maximal solution curve of f is contain in some solution curve of βf. □

Theorem 1.2.11 (Differentiable Dependence on the Initial Value)
Assume $f \in C^1$, it generates the flow ϕ_t, then $\phi : \mathbb{R} \times \mathbb{R}^n \to \mathbb{R}^n$ is C^1.

Exercise 1.2.12.

$$\frac{\partial}{\partial t}\frac{\partial \phi(t,x)}{\partial x} = \frac{\partial}{\partial x}\frac{\partial \phi(t,x)}{\partial t}.$$

Let $\Phi(t,x) = \Phi_t(x) = \frac{\partial \phi(t,x)}{\partial t}$, then Φ is the solution of the equation

$$\begin{cases} \dfrac{\mathrm{d}y(t)}{\mathrm{d}t} = A(t)y(t), A(t) = Df(\phi_t(x)) \\ y(0) = \mathrm{Id} \end{cases}.$$

The equation is called the **variation equation** of $f(x)$ along $\phi_t(x)$.

Lemma 1.2.13
$f \in C^1$, $\Phi(t,x)$, then

$$\Phi_t(\phi_s(x))\Phi_s(x) = \Phi_{t+s}(x).$$

Remark 1.2.14 — This property is called the **cocycle** condition.

We already know that ϕ_t are self-homeomorphisms of $\mathbb{R}^n$, and lemma 1.2.13 shows that the differential is invertible, hence ϕ_t are diffeomorphisms. Define

$$\begin{aligned} \Phi : \mathbb{R} \times \mathbb{R}^n \times \mathbb{R}^n &\to \mathbb{R}^n \times \mathbb{R}^n \\ (t,x,v) &\mapsto (\phi_t(x), \Phi_t(x)v). \end{aligned}$$

Proposition 1.2.15
$\Phi : \mathbb{R} \times \mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}^n \times \mathbb{R}^n$ is a flow.

Remark 1.2.16 — We call Φ_t is a skew product flow of ϕ_t.

Theorem 1.2.17

$$\Phi_t(x)f(x) = f(\phi_t(x)).$$

If ψ is a C^1 flow, let

$$g(x) = \left.\frac{\partial \psi(t,x)}{\partial t}\right|_{t=0},$$

then $\psi(t,x_0)$ solve the initial value problem $\begin{cases} \dot{x} = g(x) \\ x(0) = x_0 \end{cases}$. Because

$$\frac{\partial \psi(t,x_0)}{\partial t} = \left.\frac{\partial \psi(t+s,x_0)}{\partial s}\right|_{s=0} = \left.\frac{\partial \psi(s,\psi(t,x_0))}{\partial s}\right|_{s=0} = g(\psi(t,x_0)).$$

§1.3 Equations on manifolds

Let M be a closed smooth manifold, X is a C^1 vector field on M. Then X is bounded, hence the maximal intervals are $(-\infty, +\infty)$. Consider the equation

$$\begin{cases} \dfrac{\mathrm{d}x}{\mathrm{d}t} = X(x) \\ x(0) = x_0 \end{cases},$$

then the solution $\varphi(t, x)$ generates a flow.

2 Linear Systems

§2.1 Plane linear sigularities

Consider the equation

$$\begin{cases} \dot{x} = f(x,y) \\ \dot{y} = g(x,y) \end{cases}, \quad (x,y) \in \mathbb{R}^2.$$

It is said to be a **plane linear system** if f, g both linear functions of x, y, i.e.

$$\begin{cases} \dot{x} = ax + by \\ \dot{y} = cx + dy \end{cases}, \quad a,b,c,d \in \mathbb{R}.$$

If $\begin{vmatrix} a & b \\ c & d \end{vmatrix} \neq 0$, then $(0,0)$ is the only sigularity of the vector field, elementary singularity.

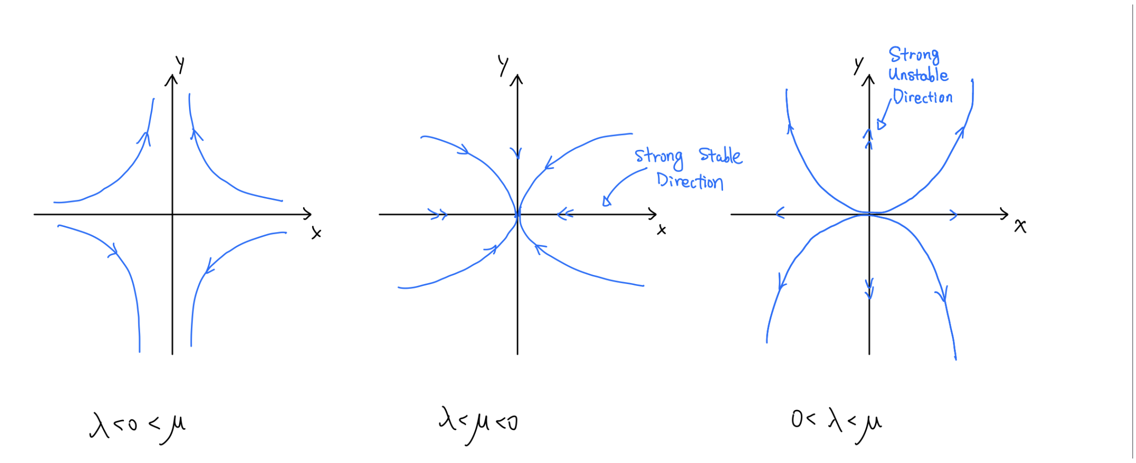
Let $A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$, consider the Jordan form of A. There are four cases:

I. Two different real eigenvalues: $\begin{bmatrix} \lambda & 0 \\ 0 & \mu \end{bmatrix}$, then $\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} x_0 e^{\lambda t} \\ y_0 e^{\mu t} \end{bmatrix}$.

   i. $\lambda < 0 < \mu$: the origin is called a **saddle point**.

   ii. $\lambda < \mu < 0$: the origin is called a **stable node**.

   iii. $0 < \lambda < \mu$: the origin is called a **unstable node**.



II. Conjugated imaginary eigenvalues: $\begin{bmatrix} \alpha & -\beta \\ \beta & \alpha \end{bmatrix}, \beta > 0$, then $\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = e^{\alpha t} \begin{bmatrix} \cos \beta t & -\sin \beta t \\ \sin \beta t & \cos \beta t \end{bmatrix} \begin{bmatrix} x_0 \\ y_0 \end{bmatrix}$.

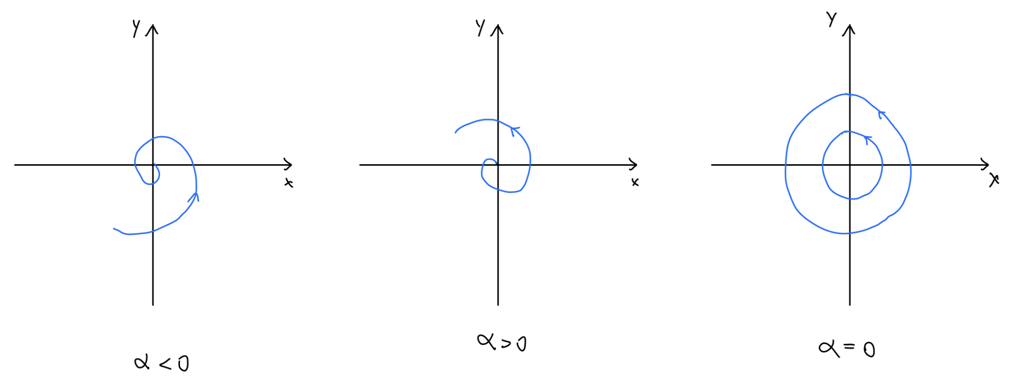
   If we consider this equation in the polar coordinates, it turns $\begin{cases} \dot{r} = \alpha r \\ \dot{\theta} = \beta \end{cases}$.

   i. $\alpha < 0$, the origin is called a **stable focus**.

   ii. $\alpha > 0$, the origin is called a **unstable focus**.

   iii. $\alpha = 0$, the origin is called a **center**.

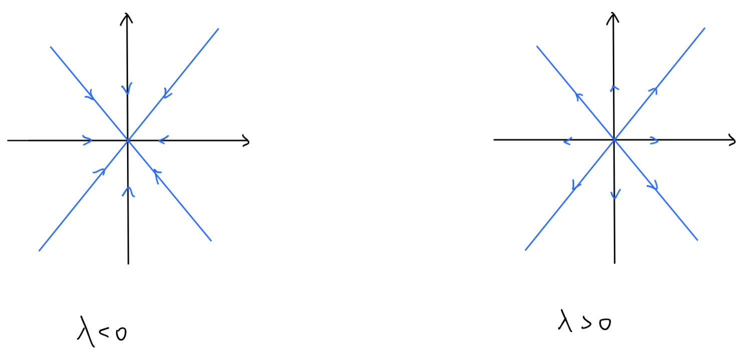
Definition 2.1.1. φ_t a flow. If p is not a singularity and $\exists T > 0$, such that $\varphi_T(p) = p$. Then p is called a **periodic point**, $\text{Orb}(p)$ is called a **periodic orbit**. If p is a periodic point, the smallest $T > 0$ is called the **minimum positive period**.



III. Two same real eigenvalues, diagonalizable: $\begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix}$, then $\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} x_0 e^{\lambda t} \\ y_0 e^{\lambda t} \end{bmatrix}$.

i. $\lambda < 0$, the origin is called a **stable critical node**.

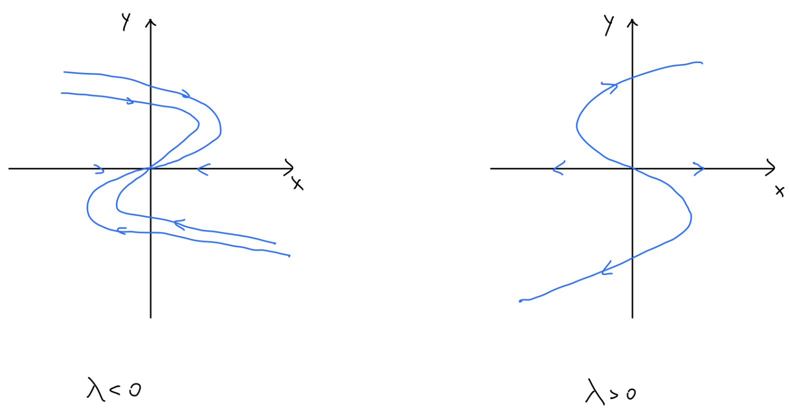
ii. $\lambda > 0$, the origin is called a **unstable critical node**.



IV. Two same real eigenvalues, not diagonalizable: $\begin{bmatrix} \lambda & 1 \\ 0 & \lambda \end{bmatrix}$, then $\begin{bmatrix} x(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} e^{\lambda t}(x_0 + t y_0) \\ e^{\lambda t} \end{bmatrix} y_0$, or $x(t) = \frac{x_0}{y_0} y(t) + \frac{y(t)}{\lambda} \ln \frac{y(t)}{y_0}$.

i. $\lambda < 0$, the origin is called a **stable unidirectional node**.

ii. $\lambda > 0$, the origin is called a **unstable unidirectional node**.



Exercise 2.1.2. Draw the phase portraits of non-elementary plane systems (i.e. the determinant is 0).

§2.2 Topological conjugacies between linear systems

Definition 2.2.1. Let $f, g : \mathbb{R}^n \to \mathbb{R}^n$ homeomorphisms. f and g are said to be **topologically conjugate** if there exists $h : \mathbb{R}^n \to \mathbb{R}^n$ such that $h \circ f = g \circ h$.

Remark 2.2.2 — Conjugacy is a equivalence relation.

Definition 2.2.3. Let $\varphi_t, \psi_t : \mathbb{R}^n \to \mathbb{R}^n$ be two flows, we call φ_t and ψ_t are conjugate if there is a homeomorphism $h : \mathbb{R}^n \to \mathbb{R}^n$ such that $h \circ \varphi_t = \psi_t \circ h$. Let X, Y be two C^1 vector fields on $\mathbb{R}^n$, we call X, Y are conjugate if the flows generated by them, respectively, are conjugate.

Example 2.2.4

$A, B \in M(n, \mathbb{R})$ are similar, then $\dot{x} = Ax$ and $\dot{y} = By$ are conjugate.

$f, g : \mathbb{R}^n \to \mathbb{R}^n$ C^1 vector fields, generate flows ϕ_t, ψ_t. Let $x = h(y) : \mathbb{R}^n \to \mathbb{R}^n$ be a C^1 diffeomorphism gives the conjugate, i.e., $h\psi_t(y) = \phi_t h(y)$. Then

$$\frac{\mathrm{d}}{\mathrm{d}t} h(y) = f(h(y)) \implies D_{h(y)} g(y) = D_{h(y)} \frac{\mathrm{d}y}{\mathrm{d}t} = f(h(y)).$$

If there exists a C^1 diffeomorphism conjugate $e^{Bt}y$ to $e^{At}x$ via $x = h(y)$, i.e. $h(e^{Bt}y) = e^{At}h(y)$. Then $Dh_0 e^{Bt} = e^{At} Dh_0$, hence $Dh_0 B = ADh_0$. It shows that C^1 conjugate generically not hold even if topologically conjugate.

Proposition 2.2.5

Assume f, g C^1 vector fields generate ϕ_t, ψ_t, let h be a conjugate between ϕ_t and ψ_t. Then:

1. $h(\mathrm{Orb}(x, \phi)) = \mathrm{Orb}(hx, \psi)$.
2. h maps the singularities of f to the singularities of g.
3. h maps the periodic orbits of f to the periodic orbits of g. Moreover, it preserves the minimum positive period.

Example 2.2.6

$\dot{x} = -2x$ and $\dot{y} = -4y$ are conjugate.

Let $h : \mathbb{R} \to \mathbb{R}, h(0) = 0$. Take $x_0, y_0 > 0$, let $h(x_0) = y_0$, then $h(e^{-2t}x_0) = e^{-4t}y_0$ or $h(x) = \left(\frac{x}{x_0}\right)^2 y_0$. The construction for the negative part is similar.

Exercise 2.2.7. $\lambda\mu \neq 0$, show that $\dot{x} = \lambda x$ is conjugate to $\dot{y} = \mu y$ if and only if $\lambda\mu > 0$.

Proposition 2.2.8

$\phi_t^i, \psi_t^i : \mathbb{R}^{n_i} \to \mathbb{R}^{n_i}$ are topologically conjugate by $h_i, i = 1, 2$. Then $\phi_t^1 \times \phi_t^2$ and $\psi_t^1 \times \psi_t^2$ are topologically conjugate by $h_1 \times h_2$.

Example 2.2.9

$\begin{cases} \dot{x} = -x \\ \dot{y} = -y \end{cases}$ and $\begin{cases} \dot{x} = -x - y \\ \dot{y} = x - y \end{cases}$ are conjugate.

Proof. $\phi_t(x, y) = e^{-t}(x, y)$ and $\psi_t(x, y) = e^{-t}\begin{bmatrix} \cos t & -\sin t \\ \sin t & \cos t \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix}$. For every $(x, y) \neq (0, 0)$, there exists unique $t = t(x, y)$ such that $\phi_t(x, y) \in \mathbb{S}^1$. Let $h(x, y) := \psi_{-t}\phi_t(x, y)$, where $t = t(x, y)$, then h gives the conjugate. $\square$

Exercise 2.2.10. Show that $\begin{cases} \dot{x} = -x \\ \dot{y} = -y \end{cases}$ and $\begin{cases} \dot{x} = -x - y \\ \dot{y} = -y \end{cases}$ are conjugate.

Classification of elementary plane linear systems:

(I) Stable: node, critical node, unidirectional node, focus.

(II) Unstable: node, critical node, unidirectional node, focus.

(III) Saddle point.

(IV) Center.

Definition 2.2.11. The linear system $\dot{x} = Ax$ in $\mathbb{R}^n$ is called **hyperbolic** if the real parts of eigenvalues of A are nonzero. The **(stable) index** of A is the number of eigenvalues with negative real parts, denoted by $\operatorname{Ind} A$.

Theorem 2.2.12

Two plane hyperbolic linear system $\dot{x} = Ax, \dot{y} = By$ are topologically conjugate if and only if $\operatorname{Ind} A = \operatorname{Ind} B$.

Proof. "$\implies$": Let $W_A^s = \left\{x : e^{tA}x \to 0, t \to \infty\right\}$, $W_B^s = \left\{x : e^{tB}x \to 0, t \to \infty\right\}$, then h and h^{-1} preserves the stable manifolds. Then $\operatorname{Ind} A = \dim W_A^s = \dim W_B^s = \operatorname{Ind} B$. $\square$

Example 2.2.13

Consider $\begin{cases} \dot{x} = -y \\ \dot{y} = x \end{cases}$ and $\begin{cases} \dot{x} = -2y \\ \dot{y} = 2x \end{cases}$ with the same phase portraits are not topologically conjugate. Because the topologically conjugate preserves the minimum positive orbits.

Definition 2.2.14. $\phi_t, \psi_t : \mathbb{R}^n \to \mathbb{R}^n$ flows, h is a homeomorphism $\mathbb{R}^n \to \mathbb{R}^n$ maps the orbit of ϕ to the orbit of ψ preserves the orientation. Then ϕ and ψ is called **topologically equivalent** or **flow equivalent**.

Theorem 2.2.15 (Grobman-Hartman)
If x_0 is a hyperbolic singularity of $f(x)$, then the flows generated by $\dot{x} = f(x)$ and $\dot{y} = Ay$ where $y = Df(x_0)$ are topologically conjugate near 0.

§2.3 Non-autonomous linear systems

$A : \mathbb{R} \to M(n, \mathbb{R})$ continuous, consider the equation

$$\dot{x} = A(t)x, \quad x \in \mathbb{R}^n$$

a non-autonomous linear system.

Theorem 2.3.1
The followings hold:

1. The initial problem of the equation exist the unique solution.
2. The maximal interval of any solution is $(-\infty, \infty)$.
3. All solutions of the equation form an n-dimensional linear space S.

Theorem 2.3.2 (Liouville's Formular)
Assume $X(t)$ is a solution of $\dot{x} = A(t)x$, then

$$\frac{\mathrm{d}}{\mathrm{d}t} \det X(t) = \operatorname{tr} A(t) \det X(t),$$

hence $\det X(t) = \det X(t_0) \exp \int_{t_0}^{t} \operatorname{tr} A(s) \mathrm{d}s$.

Let $X_1(t), X_2(t), \cdots, X_n(t)$ be a basis of S, let

$$X(t) \coloneqq [X_1(t), X_2(t), \cdots, X_n(t)] \in \mathrm{GL}(n, \mathbb{R}),$$

it called a **fundamental solution** of the equation. The fundamental solution of

$$\begin{cases} \dfrac{\mathrm{d}X}{\mathrm{d}t} = A(t)X \\ X(t_0) = I_n \in \mathrm{GL}(n, \mathbb{R}) \end{cases}$$

is called the **standard fundamental solution**.

If $X(t), Y(t)$ are two fundamental solutions, suppose $Y(0) = X(0)C$, then

$$\frac{\mathrm{d}X(t)C}{\mathrm{d}t} = \frac{\mathrm{d}X(t)}{\mathrm{d}t}C = A(t)X(t)C,$$

is a non-degenerate solution of $\frac{\mathrm{d}X}{\mathrm{d}t} = AX$. By the uniqueness, we get $Y(t) = X(t)C$.

Example 2.3.3

$A(t) \equiv A$, the fundamental solution of $\dot{x} = Ax$ is

$$e^{tA} = \mathrm{Id} + tA + \frac{1}{2!}t^2A^2 + \cdots + \frac{1}{k!}t^kA^k + \cdots.$$

Example 2.3.4

$\dot{x} = f(x), x \in \mathbb{R}^n$, where $f \in C^1$, generates the flow $\varphi_t(x)$. Consider $\Phi_t(x) = \frac{\partial}{\partial t}\varphi_t(x)$ and the variation equation

$$\frac{\mathrm{d}}{\mathrm{d}t}\Phi_t(x) = Df_{\varphi_t(x)}\Phi_t(x).$$

Given $x \in \mathbb{R}^n$, let $A(t) := Df_{\varphi_t(x)}$, then $\Phi_t(x)$ is the standard fundamental solution $(t_0 = 0)$ of $\dot{x} = A(t)x$. Consider two special types of orbits:

- x is a singularity, denoted by σ. Then $\varphi_t(\sigma) = \sigma$, $\dot{x} = Ax$ where $A = Df(\sigma)$.
- x is a periodic point, denoted by p, the minimum period $T > 0$. Then A is T-periodic.

§2.4 Periodic linear systems

Definition 2.4.1. The equation $\dot{x} = A(t)x$ satisfies $A(t+T) = A(t)$ for some $T > 0$ is called a **periodic linear systems**.

Theorem 2.4.2 (Floquet)

Assume $\dot{x} = A(t)x$ is a T-periodic linear system, if X is a fundamental solution, then $X(t+T)$ is a fundamental solution, i.e. $\exists C \in \mathrm{GL}(n, \mathbb{R})$ such that $X(t+T) = X(t)C$. Moreover, there exists a T-periodic map $P : \mathbb{R} \to \mathrm{GL}(n, \mathbb{C})$ and a constant matrix $B \in M(n, \mathbb{C})$ such that $X(t) = P(t)e^{tB}$.

Lemma 2.4.3

$\forall C \in \mathrm{GL}(n, \mathbb{R})$, $\exists B \in M(n, \mathbb{C})$ such that $C = e^B$.

Proof. It suffices to show for Jordan block. This follows by the matrix series

$$\ln(I + N) = \sum_{k=1}^{\infty} \frac{(-1)^{k-1}}{k!} N^k$$

is convergence for nilpotent matrix N. □

Lemma 2.4.4

$\forall C \in \mathrm{GL}(n, \mathbb{R})$, $\exists B \in M(n, \mathbb{R})$ such that $C^2 = e^B$.

Proof. Note that the Jordan block of C^2 is either:

(i) $\begin{bmatrix} \lambda & 1 & \cdots & 0 \\ & \ddots & \ddots & \\ 0 & \cdots & \lambda & 1 \\ 0 & \cdots & & \lambda \end{bmatrix}$, where $\lambda > 0$, or

(ii) $\begin{bmatrix} J & I_2 & \cdots & 0 \\ & \ddots & \ddots & \\ 0 & \cdots & J & I_2 \\ 0 & \cdots & & J \end{bmatrix}$, where $J = \begin{bmatrix} a & -b \\ b & a \end{bmatrix}, a, b \in \mathbb{R}, b > 0.$

And $J = \begin{bmatrix} a & -b \\ b & a \end{bmatrix}$ have a real matrix logarithm because $\left\{ \begin{bmatrix} a & -b \\ b & a \end{bmatrix} \right\} \cong \mathbb{C} = \{a + bi\}$. $\square$

Theorem 2.4.5 (Real Form of Floquet Theorem)

Assume $\dot{x} = A(t)x$ is a T-periodic linear system, if X is a fundamental solution. Then there exists a **$2T$-periodic** map $P : \mathbb{R} \to \mathrm{GL}(n, \mathbb{R})$ and a constant matrix $B \in M(n, \mathbb{R})$ such that $X(t) = P(t)e^{tB}$.

Example 2.4.6 ($2T$ is necessary)

Let $\Phi(t) = \begin{bmatrix} \cos t & -\sin t \\ \sin t & \cos t \end{bmatrix} \begin{bmatrix} 1 & t \\ 0 & 1 \end{bmatrix} = \exp\left(\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} t \right) \exp\left(\begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} t \right)$. Let

$$A(t) = \dot{\Phi}(t)\Phi(t)^{-1} = \begin{bmatrix} -\cos t \sin t & -\sin^2 t \\ \cos^2 t & \cos t \sin t \end{bmatrix},$$

then $A(t)$ is π-periodic. Then $\Phi(t)$ is a standard fundamental solution of $\dot{x} = A(t)x$, hence $\exists\pi$-periodic $P(t)$ and B such that $\Phi(t) = P(t)e^{tB}$. Then $e^{\pi B} = \begin{bmatrix} -1 & -\pi \\ 0 & -1 \end{bmatrix}$, there is no real matrix B satisfying this equation.

Definition 2.4.7. In Floquet theorem, $X(t+T) = X(t)C$. We call C is a **monodromy matrix**. The eigenvalues of C are called **Floquet multipliers**. If ρ is a Floquet multiplier with $\rho = e^{\lambda T}$, then λ is called a **Floquet exponent**.

Corollary 2.4.8

Consider a T-periodic linear system $\dot{x} = A(t)x$. Then there exists a linear transformation (non-autonomous) $x = P(t)y$ such that $\dot{y} = By$.

Proof. Let $X(t) = P(t)e^{tB}$ be a fundamental solution, then

$$AX = \dot{X} \implies \dot{P}e^{tB} + PBe^{tB} = APe^{tB},$$

hence $\dot{P} + PB = AP$. Then $APy = \frac{\mathrm{d}}{\mathrm{d}t}(Py) = \dot{P}y + P\dot{y}$, hence $\dot{y} = By$. $\square$

Remark 2.4.9 — This type of equation is called reducible, which means after some reduction, the equation can become independent with time t.

Corollary 2.4.10

Let λ be a Floquet multiplier of $\dot{x} = A(t)x$. Then there exists a T-periodic function $p(t)$ such that $e^{\lambda t}p(t)$ is a solution of the equation $\dot{x} = A(t)x$.

Proof. $e^{\lambda T}$ is an eigenvalue of C, then $\exists x_0$ such that $Cx_0 = e^{\lambda T}x_0$. Then $X(t)x_0$ is a solution. Let $p(t) = e^{-\lambda t}X(t)x_0$ is T-periodic and $e^{\lambda t}p(t)$ is a solution. $\square$

Corollary 2.4.11

The equation admits a nonzero T-periodic solution if and only if 1 is a Floquet multiplier.

Corollary 2.4.12

Assume $\rho_1, \rho_2, \cdots, \rho_n$ are all Floquet multipliers of $\dot{x} = A(t)x$, then

$$\rho_1\rho_2\cdots\rho_n = \det\Phi(T) = \exp\int_0^T \operatorname{tr} A(t)\ \mathrm{d}t.$$

Example 2.4.13

The equation $\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} \cos^2 t & \frac{1}{2}\sin 2t - 1 \\ \frac{1}{2}\sin 2t + 1 & \sin^2 t \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix}$ has an unbounded solution. Because the product of two multipliers is $\exp\int_0^\pi 1\ \mathrm{d}t = e^\pi > 1$.

Consider **Hill equation**

$$\ddot{x} + p(t)x = 0,$$

where $p(t)$ is π-periodic. This is equivalent to

$$\begin{cases} \dot{x} = y \\ \dot{y} = -p(t)x \end{cases},$$

then $\rho_1\rho_2 = \exp\int_0^\pi \operatorname{tr} A(t)\ \mathrm{d}t = 0$, where $A(t) = \begin{bmatrix} 0 & 1 \\ -p(t) & 0 \end{bmatrix}$.

Lemma 2.4.14

If ρ_1, ρ_2 both are imaginary numbers, then every solution of Hill equation is bounded.

Proof. Because ρ_1, ρ_2 are conjugate imaginary numbers, hence $\Phi(\pi)$ is similar to a rotation. Then $\Phi(\pi)^n$ is bounded independent of n and $\Phi(s)$ is bounded for $s \in [0, \pi]$. $\square$

Definition 2.4.15. A particular Hill equation with $p(t) = a + \varepsilon\cos 2t$ is called **Mathieu equation**.

Exercise 2.4.16. Consider Mathieu equation

$$\ddot{x} + (a + \varepsilon \cos 2t)x = 0.$$

(1) $U = \{(a, \varepsilon) \in [0, 10] \times [-1, 1] :$ every solution is bounded$\}$. Draw the figure of U by some calculation.

(2) Guess some conclusions by the figure of U.

Example 2.4.17

Let $p(t)$ be a π-periodic continuous function satisfying

(i) $p(t) \not\equiv 0$.

(ii) $\int_0^\pi p(t)\mathrm{d}t \geqslant 0$.

(iii) $\pi \int_0^\pi |p(t)|\mathrm{d}t \leqslant 4$.

Then every solution of $\ddot{x} + p(t)x = 0$ is bounded.

Proof. If Floquet multipliers are conjugate imaginary numbers, the statement follows. Otherwise there is a real Floquet multiplier $\rho \neq 0$. There is a solution $x(t) \not\equiv 0$ such that $x(t + T) = \rho x(t)$. If $x(t)$ has no zeros, assume $x(t) > 0$, we have $\frac{\dot{x}}{x}(\pi) = \frac{\dot{x}}{x}(0)$. Note that

$$0 = \frac{\ddot{x}}{x} + p(t) = \left(\frac{\dot{x}}{x}\right)' + \left(\frac{\dot{x}}{x}\right)^2 + p(t) = 0,$$

take the integral and we get a contradiction. Then there must be some zeros, let a, b be two successive zeros, WLOG, $0 < a < b < \pi$. Assume $x(t) > 0$ in (a, b) and $x(c)$ takes the maximum. Then $\exists \alpha \in (a, c), \beta \in (c, b)$ such that $\dot{x}(\alpha) = \frac{x(c)}{c-a}, \dot{x}(\beta) = \frac{-x(c)}{b-c}$. We have

$$\frac{4}{\pi} \geqslant \int_0^\pi |p(t)|\mathrm{d}t > \int_a^b \left|\frac{\ddot{x}}{x}(t)\right| \mathrm{d}t \geqslant \frac{\int_\alpha^\beta |\ddot{x}(t)|\mathrm{d}t}{x(c)} \geqslant \frac{1}{c-a} + \frac{1}{b-c} \geqslant \frac{4}{a-b},$$

the identity holds if and only if $x \equiv 0$, contradiction. □

Back to Mathieu equation, consider

$$\ddot{x} + (\omega^2 + \varepsilon \cos 2t)x = 0, \quad \omega > 0, \varepsilon < \omega^2.$$

We apply the conclusion of the example, for $\omega < \frac{2}{\pi}$,

$$\int_0^\pi (\omega^2 + \varepsilon \cos 2t)\mathrm{d}t = \omega^2 \pi \leqslant \frac{4}{\pi}.$$

Consider $\varepsilon = 0$, then

$$\Phi(t) = \begin{bmatrix} \cos \omega t & \frac{1}{\omega} \sin \omega t \\ -\omega \sin \omega t & \cos \omega t \end{bmatrix}$$

is a standard fundamental solution. The monodromy matrix for (ω, ε) where $\omega > 0$ is a perturbation of

$$C = \Phi(\pi) = \begin{bmatrix} \cos \omega\pi & \frac{1}{\omega} \sin \omega\pi \\ -\omega \sin \omega\pi & \cos \omega\pi \end{bmatrix}.$$

Note that $|\mathrm{tr}\, \Phi(\pi)| = |2 \cos \omega\pi| < 2$ for $\omega \notin \mathbb{Z}$. Then there is a small neighborhood U of $(\omega, 0)$ such that every solution is bounded.

Definition 2.4.18. Let $A : \mathbb{R} \to M(n, \mathbb{R})$ continuous, bounded, assume that

$$\sup \{|A(t)| : t \in \mathbb{R}\} < \infty.$$

Let $\Phi(t)$ be a standard fundamental solution of the equation $\dot{x} = A(t)x$. For every $v \neq 0 \in \mathbb{R}^n$, define **Lyapunov exponent** of v

$$\chi(v) := \limsup_{t\to\infty} \frac{\ln \|\Phi(t)v\|}{t}.$$

> **Exercise 2.4.19.** For every $v \neq 0$, show that $\chi(v) \neq \pm\infty$.

Then $\chi : \mathbb{R}^n \to \mathbb{R}$ satisfying the following properties

1. $\chi(\alpha v) = \chi(v)$ for every $\alpha \neq 0$.
2. $\chi(v + w) \leqslant \max \{\chi(v), \chi(w)\}$.
3. If $\chi(v) < \chi(w)$, then $\chi(v + w) = \chi(w)$.

Fact 2.4.20. The number of different Lyapunov exponents $\leqslant n$.

Example 2.4.21

$\dot{X} = AX$, where $X = \begin{bmatrix} x \\ y \end{bmatrix}$ and A is a constant matrix. Regard as a T-periodic system, then the eigenvalues λ_1, λ_2 of A are Floquet exponents. Lyapunov exponents are

(1) λ_1, λ_2, if $\lambda_1 \neq \lambda_2$ real.

(2) $\lambda = \lambda_1 = \lambda_2$, if $\lambda_1 = \lambda_2$.

(3) α, if $\lambda_1 = \alpha + i\beta, \lambda_2 = \alpha - i\beta$.

For the T-periodic system, assume that λ is a Floquet exponent, then $\chi = \mathrm{Re}(\lambda)$ is a Lyapunov exponent. For $n = 2$, T-periodic system, we always have

$$\chi_1 + \chi_2 = \mathrm{Re}(\lambda_1 + \lambda_2) = \frac{1}{T} \int_0^T \mathrm{tr}\, A(t) \mathrm{d}t.$$

Example 2.4.22

Consider

$$\begin{cases} \dot{x} = (-\mu - (\sin \ln t + \cos \ln t))x \\ \dot{y} = (-\mu + (\sin \ln t + \cos \ln t))y \end{cases},$$

then the solution

$$\begin{cases} x = C_1 e^{-\mu t - t \sin \ln t} \\ y = C_2 e^{-\mu t + t \sin \ln t} \end{cases}.$$

Then $\chi(v) = -\mu + 1$ for every $v \neq 0$. But $\chi_1 + \chi_2 = -2\mu + 2 \neq \lim_{T\to\infty} \frac{1}{T} \int_0^T \mathrm{tr}\, A(t) \mathrm{d}t = -2\mu$. This example is called non-regular.

3 Stability

§3.1 Lyapunov stability

Let $f : \mathbb{R}^n \to \mathbb{R}^n, 0 \in \mathbb{R}^n, f(0) = 0$, generates a (local) flow $\varphi_t(x)$.

Definition 3.1.1. 1. σ is called **(forward Lyapunov) stable**, if $\forall \varepsilon > 0$, $\exists \delta > 0$, such that if $|x - \sigma| < \delta$, then $|\varphi_t(x) - \sigma| < \varepsilon$ for $t \geqslant 0$. Otherwise, we call σ is **unstable**.

2. σ is called **asymptotically stable**, if
   (i) σ is stable,
   (ii) there exists $\delta_0 > 0$, such that if $|x - \sigma| < \delta$, then $\lim_{t\to\infty} \varphi_t(x) = \sigma$.

3. σ is called **exponentially stable**, if exists $\delta_0 > 0$, $C \geqslant 1, \lambda > 0$, such that if $|x - \sigma| < \delta$, then $|\varphi_t(x) - \sigma| \leqslant Ce^{-\lambda t}|x - \sigma|$ for $t \geqslant 0$.

Similarly, we can define backward stable, backward asymptotically stable, backward exponentially stable.

Remark 3.1.2 — If we replace the condition of stability by **given** $t \geqslant 0$, then it always holds by the continuous independence of solutions with respect to initial value.

Example 3.1.3

For the equation in polar coordinates

$$\begin{cases} \dot{r} = r(1 - r) \\ \dot{\theta} = \sin^2(\theta/2) \end{cases}.$$

Then the fixed point $(1, 0)$ satisfy the second condition of asymptotically stable but it is **not** stable.

In general, we can prove that if $\varphi_t(x) \not\equiv \sigma$ and $\lim_{t\to\pm\infty} \varphi_t(x) = \sigma$, then σ is not stable.

Example 3.1.4

Consider the linear elementary singularities, recall the classification, then

1. Stable type: forward stable.
2. Unstable type: unstable, bet backward stable.
3. Saddle point: unstable.
4. Center: forward and backward stable.

Theorem 3.1.5

Let $A \in M(n, \mathbb{R})$, consider the equation $\dot{X} = AX$, 0 is a singularity, then

1. 0 is stable iff each eigenvalue of A is with non-positive real part and Jordan block are trivial for every eigenvalue with zero real part.
2. 0 is asymptotically stable iff 0 is exponentially stable iff every eigenvalue of A is with negative real part.

Lemma 3.1.6 (Gronwall's Inequality)

Let $u : [0, T] \to \mathbb{R}$ non-negative, continuous. If $C \geqslant 0, K > 0$ such that for every $t \in [0, T]$,

$$u(t) \leqslant C + K \int_0^t u(s) \mathrm{d}s,$$

then $u(t) \leqslant Ce^{Kt}$ for $t \in [0, T]$.

Theorem 3.1.7

$f : \mathbb{R}^n \to \mathbb{R}^n$, C^1, $f(\sigma) = 0$. Assume that every eigenvalue of $A = Df(0)$ is with negative real part, then σ is exponentially stable.

Proof. There $\exists C \geqslant 1, \mu > 0$, such that $|e^{At}| \leqslant Ce^{-\mu t}$ for $t \geqslant 0$. WOLG, $\sigma = 0$. Let $f(x) = Ax + g(x)$ where $g(x) = o(|x|)$, let $\varphi_t(x)$ be a maximal solution of the initial value problem. Then

$$e^{-tA}(\dot{\varphi}_t(x) - A\varphi_t(x)) = e^{-tA} g(\varphi_t(x)),$$

hence

$$\varphi_t(x) = e^{tA}x + \int_0^t e^{(t-s)A} g(\varphi_s(x)) \mathrm{d}s.$$

Fix $\varepsilon_0 > 0$ to be determined later, $\exists \delta_0 > 0$ such that $|g(x)| \leqslant \varepsilon_0 |x|$ if $|x| \leqslant \delta_0$. Assume the right maximal interval of φ_t is $[0, \beta), \beta > 0$. Let

$$T^* = T^*(x) = \sup \left\{ t < \beta : \varphi_{[0,t]}(x) \subseteq \overline{B(\delta_0, \sigma)} \right\}.$$

Then, for every $|x| \leqslant \delta_0, 0 \leqslant t \leqslant T^*$, we have

$$e^{\mu t} |\varphi_t(x)| \leqslant C|x| + C\varepsilon_0 \int_0^t e^{s\mu} |\varphi_s(x)| \mathrm{d}s.$$

By Gronwall's inequality, we have $|\varphi_t(x)| \leqslant C|x|e^{-(\mu - C\varepsilon_0)t}, \forall t < T^*$. Let $C\varepsilon_0 = \frac{\mu}{2}$ is enough. For all $|x| \leqslant \frac{\delta_0}{2C}$, then $|\varphi_t(x)| \leqslant \frac{\delta_0}{2} e^{-\mu t}$ for every $t < T^*$. Then we can show that $T^* = \beta = \infty$ and φ_t is exponentially stable. $\square$

Proposition 3.1.8

f, g, C^1 vector fields. Assume f, g are topologically conjugate, i.e. , $h \circ \varphi_t = \psi_t \circ h$ where φ_t, ψ_t are flows generated by f, g, respectively. Let $\sigma, h\sigma$ be singularities of f, g, respectively, then σ is stable if and only if $h\sigma$ is stable.

Now, we state a celebrated theorem, Hartman-Grobman Theorem. But we will not give a proof here.

Theorem 3.1.9 (Hartman-Grobman)

Let σ be a hyperbolic singularity of f. Then there exists a neighborhood $V \ni \sigma$ and a homeomorphism $h : V \to \mathbb{R}^n$ onto its image, $h(\sigma) = 0$, such that $h \circ \varphi_t(x) = Df(\sigma) \circ h(x)$ for every $x, \varphi_t(x) \in V$.

§3.2 Lyapunov functions

Definition 3.2.1. Let $f : \mathbb{R}^n \to \mathbb{R}^n$, be a C^1 vector field, $f(0) = 0$. A C^1 function $V : D \to \mathbb{R}$ where D is a neighborhood of σ is called a **Lyapunov function** of f (for σ) if

(i) $V(\sigma) = 0, V(x) > 0, \forall x \in D \setminus \{\sigma\}$.

(ii) $\forall x \in D \setminus \{\sigma\}, \dot{V}(x) \leqslant 0$, where

$$\dot{V}(x) = \left.\frac{\partial}{\partial t}\right|_{t=0} V(\varphi_t(x)) = DV(x)f(x).$$

V is called a **strict Lyapunov function** if $\dot{V}(x) \leqslant 0$ is replaced by $\dot{V}(x) < 0$.

Theorem 3.2.2

Assume σ is a singularity of f, if there is a Lyapunov function for σ, then σ is stable. If there is a strict Lyapunov function for σ, then σ is asymptotically stable.

Proof. Let V be a Lyapunov function, for every $\varepsilon > 0$, assume $B_\varepsilon(\sigma) = \{x : |x - \sigma| \leqslant \varepsilon\} \subseteq D$. Let $m = \min\{V(x) : x \in \partial B_\varepsilon(\sigma)\} > 0$, take $\delta > 0$ such that $V(x) < m, \forall x \in B_\delta(\sigma)$. By $\dot{V}(x) \leqslant 0$, we have that every solution curve start at $x \in B_\delta(\sigma)$ can not reach $\partial B_\varepsilon(\sigma)$.

If $\dot{V}(x) < 0$ for every $x \in D \setminus \{\sigma\}$, it suffices to show that each convergent subsequence of $\varphi_t(x)$ converges to σ. Otherwise, assume converges to $y \neq \sigma$, but $\dot{V}(y) < 0$, there is some $s > 0$ such that $V(\varphi_s(y)) < V(y)$. Contradiction. ∎

Example 3.2.3

Consider the equation

$$\begin{cases} \dot{x} = -y \\ \dot{y} = x \end{cases}.$$

Let $V(x, y) = x^2 + y^2$, then $\dot{V}(x, y) = 0$, hence 0 is stable.

Example 3.2.4

Consider the equation

$$\begin{cases} \dot{x} = -x + y \\ \dot{y} = -x - y^3 \end{cases}.$$

Let $V(x,y) = x^2 + y^2$, then $\dot{V}(x,y) = -2x^2 - 2y^4 < 0$, hence 0 is asymptotically stable.

Example 3.2.5

Consider the equation

$$\begin{cases} \dot{x} = -x - y + x^2 \\ \dot{y} = x \end{cases}.$$

Let $V(x,y) = x^2 + y^2$, then $\dot{V}(x,y) = -2x^2(1-x) \leqslant 0$, hence 0 is stable. In fact, 0 is asymptotically stable, but we need to consider another Lyapunov function $Q(x,y) = x^2 + y^2 + xy$.

Theorem 3.2.6

If V is a Lyapunov function of f, assume

$$K = \left\{ x \in D \setminus \{\sigma\}, \dot{V}(x) = 0 \right\}$$

does not contain any complete positive orbit $\varphi_{[0,\infty)}(x)$, then σ is asymptotically stable.

Example 3.2.7

Let $f : \mathbb{R} \to \mathbb{R}, C^1, f(0) = 0$, satisfying $xf(x) > 0, \forall x \neq 0$. Consider the stability of $\ddot{x} + f(x) = 0$, or

$$\begin{cases} \dot{x} = y \\ \dot{y} = -f(x) \end{cases}.$$

Let

$$E(x,y) = \frac{1}{2}y^2 + \int_0^x f(z)\mathrm{d}z$$

be an energy function, then $\dot{E}(x,y) \equiv 0$.

Example 3.2.8

Let $V : \mathbb{R}^n \to \mathbb{R}, C^2$, the gradient of V is

$$\nabla V(x) = \begin{bmatrix} \frac{\partial V}{\partial x_1} \\ \vdots \\ \frac{\partial V}{\partial x_n} \end{bmatrix}.$$

The system $\dot{x} = -V(x)$ is called the **gradient system** generated by V. Then,

1. $\dot{V}(x) \leqslant 0$.
2. σ is a singularity if and only if $\dot{V}(\sigma) = 0$.
3. If σ is a minimum point of $V(x)$, then σ is stable.

Theorem 3.2.9

Let σ be a singularity of C^1 vector field f, a C^1 function $V : D \to \mathbb{R}$ satisfies

(i) $V(\sigma) = 0$, and V can take positive value on any neighborhood of σ.

(ii) $\dot{V}(x) > 0, \forall x \in D \setminus \{0\}$.

Then σ is unstable.

Example 3.2.10

Consider the equation

$$\begin{cases} \dot{x} = x \\ \dot{y} = -y \end{cases}.$$

Let $V(x, y) = x^2 - y^2$, then $\dot{V}(x, y) = 2x^2 + 2y^2 > 0$, hence 0 is unstable.

Theorem 3.2.11

Let f be a C^1 vector field, $f(\sigma) = 0$. If σ is stable, then every eigenvalue of $Df(\sigma)$ is with non-negative real part.

Proof. Prove for $n = 2$. Assume $\sigma = 0$, the equation is

$$\begin{cases} \dot{x} = \lambda x + \alpha(x, y) \\ \dot{y} = \mu y + \beta(x, y) \end{cases},$$

where $\lambda < \mu, \mu > 0, |\alpha|, |\beta| = o(r)$. Let $V(x, y) = -x^2 + y^2$, then

$$\dot{V}(x, y) = -2\lambda x^2 + 2\mu y^2 - 2x\alpha + 2y\beta.$$

If $\lambda < 0$, then $\dot{V} > 0$ in a neighborhood of 0, then 0 is unstable. If $\lambda \geqslant 0$, consider

$$C = \{(x, y) : V(x, y) \geqslant 0\}.$$

We can show that for some $\varepsilon_0 \geqslant 0$, $\dot{V}(x,y) > 0$ on $C \cap B(0,\varepsilon_0) \setminus \{0\}$. Let $H(x,y) = x^2 + y^2$, then $\dot{H}(x,y) \geqslant \frac{\mu}{2} H(x,y)$ on some neighborhood of 0. Hence

$$H(\varphi_t(x,y)) \geqslant H(x,y) e^{\frac{\mu}{2} t}$$

will be out of $C \cap B_\varepsilon(x,y)$. □

Remark 3.2.12 — In fact, there exists $(x,y) \in B(0,\varepsilon_0) \setminus \{0\}$, such that

$$\lim_{t \to -\infty} \varphi_t(x,y) = 0, \quad \frac{f(\varphi_t(x,y))}{|f(\varphi_t(x,y))|} \to (0,1).$$

$\varphi_t(x,y)$ is called the unstable manifold.

Exercise 3.2.13. Prove the theorem for general dimension n.

Now, we consider a perturbation of a singularity of center type. Consider the system

$$\begin{cases} \dot{x} = -y + \alpha(x,y) \\ \dot{y} = x + \beta(x,y) \end{cases},$$

then

$$\dot{\theta} = 1 + \frac{x\beta - y\alpha}{x^2 + y^2},$$

$$\dot{r} = \frac{x\alpha + y\beta}{r} = \alpha \cos\theta + \beta \sin\theta = R_2(\theta) r^2 + R_3(\theta) r^3 + \cdots.$$

Example 3.2.14

Consider the equation

$$\begin{cases} \dot{x} = -y \\ \dot{y} = x + (x^2 y + x^3) \end{cases}.$$

Then

$$\dot{r} = \sin\theta(x^2 y + x^3) = r^3(\cos^2\theta \sin^2\theta + \cos^3\theta \sin\theta),$$

we calculate

$$\overline{R}_3 = \int_0^{2\pi} R_3(\theta) \mathrm{d}\theta = \frac{\pi}{4} > 0.$$

Let $g(\theta) = \int_0^\theta R_3(\theta) \mathrm{d}\theta$, then

$$\varphi_3(\theta) = g(\theta) - \frac{\theta}{2\pi} \int_0^{2\pi} R_3(\theta) \mathrm{d}\theta$$

is 2π-periodic. Let $r = \rho + \varphi_3(\theta)\rho^3$, then

$$\frac{\mathrm{d}\rho}{\mathrm{d}\theta} = \overline{R}_3 \rho^3 + \cdots,$$

hence ρ is increasing. Therefore, 0 is unstable.

Example 3.2.15

Consider the equation

$$\begin{cases} \dot{x} = -y \\ \dot{y} = x + y^2 \end{cases}.$$

We want to construct a Lyapunov function of the form $V(x,y) = x^2 + y^2 + F(x,y)$, where $F(x,y)$ is a homogeneous polynomial of deg $= 3$. Then

$$\dot{V}(x,y) = -yF_x + xF_y + 2y^3 + y^2 F_y,$$

we want $-yF_x + xF_y + 2y^3 = 0$. Consider $L : H_k \to H_k$, where H_3 is the family of homogeneous polynomials of deg $= k$, $L(F) = -yF_x + xF_y$. After repetition, we can let

$$V(x,y) = \lambda(x^2 + y^2)^k + \cdots.$$

Then 0 is stable if $\lambda < 0$, 0 is unstable if $\lambda > 0$. Or we can find V such that $\dot{V}(x,y) = 0$, then 0 is still a center.

Example 3.2.16

Consider the equation

$$\begin{cases} \dot{x} = -y \\ \dot{y} = x + y^2 \end{cases}.$$

We can solve this equation,

$$y^2 = -x + \frac{1}{2}(1 - e^{-2x}) + Ce^{-2x},$$

hence $e^{2x}(x^2 + y^2) = C + \cdots$. 0 is still a center.

Example 3.2.17

Consider the equation

$$\begin{cases} \dot{x} = -y & = X(x,y) \\ \dot{y} = x + y^2 & = Y(x,y) \end{cases}.$$

Notice that $X(x,-y) = -X(x,y), Y(x,-y) = Y(x,y)$, hence the solution curve is symmetric with respect to x-axis. We can prove this fact by showing $(x(-t), -y(-t))$ is a solution if $(x(t), y(t))$ is a solution. Then we can show 0 is a center.

§3.3 Stability under perturbations

Definition 3.3.1. Consider an autonomous system $\dot{x} = f(x)$, generating a flow φ_t. For every $x_0 \in \mathbb{R}^n$, the orbit $\varphi_t(x_0)$ is said to be **stable** if for any $\varepsilon > 0$, there exists $\delta > 0$ such that

$$|\varphi_t(x) - \varphi_t(x_0)| < \varepsilon, \quad \forall t \geqslant 0, x \in B(x_0, \delta).$$

Example 3.3.2

Consider the equation

$$\begin{cases} \dot{r} = 0 \\ \dot{\theta} = r^2 \end{cases}.$$

Then the orbit of $(r_0, \theta_0) = (1, 0)$ is **not** stable.

Definition 3.3.3. Consider a non-autonomous system $\dot{x} = f(x,t)$, let $\varphi(t; t_0, x_0)$ be the solution of the initial value problem $x(t_0) = x_0$. The orbit $x(t; t_0, x_0)$ is said to be **stable**, if, for any $\varepsilon > 0$, there exists $\delta > 0$ such that

$$|\varphi(t; t_0, x) - \varphi_t(t; t_0, x_0)| < \varepsilon, \quad \forall t \geqslant t_0, x \in B(x_0, \delta).$$

Similarly, we can define the asymptotically stable and the exponentially stable for general orbits of autonomous or non-autonomous systems.

Theorem 3.3.4

$A : \mathbb{R} \to M(n, \mathbb{R})$, consider a non-autonomous system $\dot{x} = A(t)x$. Then

1. Every solution is stable iff 0 is stable.
2. 0 is stable iff $\sup_{t \geqslant 0} |X(t)| < \infty$, where $X(t)$ is a fundamental solution.
3. 0 is asymptotically stable iff $\lim_{t \to \infty} |X(t)| = 0$.

Theorem 3.3.5

Consider a T-periodic system $\dot{x} = A(t)x$. Then

2. 0 is stable iff the Floquet exponents are of non-positive real parts and Jordan block are trivial for every Floquet exponent with zero real part.

2. 0 is asymptotically stable iff Floquet exponents are of negative real parts iff 0 is exponentially stable.

For an autonomous system, let $f(0) = 0, f(x) = Ax + \varphi(x)$, where $\varphi(0) = 0, D\varphi(0) = 0$. Rewrite the system as $\dot{x} = Ax + \varphi(x)$, if every eigenvalue of A is with negative real parts, then 0 is stable.

For a non-autonomous system, assume

$$\dot{x} = Ax + \varphi(t, x), \quad , \varphi(t, 0) = 0, D\varphi(t, 0) = 0,$$

if every eigenvalue of A is with negative real parts, then 0 is stable. In general,

$$\dot{x} = A(t)x + \varphi(t, x),$$

but the negativeness of Lyapunov exponents do **not** imply the stableness. See the following example.

Example 3.3.6

Consider

$$\begin{cases}\dot{x} = (-\mu - (\sin\ln t + \cos\ln t))x \\ \dot{y} = (-\mu + (\sin\ln t + \cos\ln t))y + x^2\end{cases},$$

let $a(t) = t\sin\ln t$, the solutions are

$$\begin{cases}x = C_1 e^{-\mu t - a(t)} \\ y = C_2 e^{-\mu t + a(t)} + C_1^2 e^{-\mu t + a(t)} \displaystyle\int_1^t e^{-\mu s - 3a(s)}\mathrm{d}s\end{cases}.$$

For $\mu = 1 + \sigma, \sigma$ is sufficiently small, then 0 is not stable.

For this case, we need a stronger condition. Let $\Phi(t)$ be a fundamental solution of the linear part, if $\exists \mu > 0$,

$$|\Phi(t)\Phi(-s)| \leqslant Ce^{-\mu(t-s)}, \quad \forall t \geqslant s \geqslant 0,$$

then 0 is also stable under the perturbation .

4 Poincaré-Bendixson Theory

§4.1 Basic notions

Let $f:\mathbb{R}^n\to\mathbb{R}^n$ be a C^1 vector field, generating a flow $\varphi_t:\mathbb{R}^n\to\mathbb{R}^n$.

Definition 4.1.1. $A\subseteq\mathbb{R}^n$ is said to be $f(\varphi_t)$ **invariant** if for every $t\in\mathbb{R},\varphi_t(A)=A$.

For every $x\in\mathbb{R}^n$, the orbit $\mathrm{Orb}(x)=\{\varphi_t(x):t\in\mathbb{R}\}$ is an invariant set. In general, if A is invariant, then

$$A=\mathrm{Orb}_{x\in A}\mathrm{Orb}(x).$$

Definition 4.1.2. Let A be a compact invariant set, A is said to be **Lyapunov orbit stable** if for every neighborhood $U\supseteq A$, there exists a neighborhood $V\supseteq A$ such that

$$\varphi_t(x)\in U,\quad \forall x\in V,t\geqslant 0.$$

Let

$$\mathrm{Orb}^+ := \{\varphi_t(x):t\geqslant 0\},\quad \mathrm{Orb}^- := \{\varphi_t(x):t\leqslant 0\}$$

be the **positive semi-orbit** and the **negative semi-orbit**.

Definition 4.1.3. Given $p\in\mathbb{R}^n$, x is called a **positive limit point** if $\exists t_n\to+\infty$, $\varphi_{t_n}\to x$. The set of all positive limit points is called the **α-limit set** of p, denoted by $\alpha(p)$. Similarly, we can define the **negative limit points**, they form a set is called **ω-limit set**, denoted by $\omega(p)$.

Remark 4.1.4 — In the Greek alphabet, α is the first letter and ω is the last letter, it is very graphic that the orbit of p ran from α to ω.

Example 4.1.5

Consider the equation

$$\begin{cases}\dot r=r(1-r^2)\\ \dot\theta=1\end{cases}.$$

Then $\omega(0)=\alpha(0)=0$. For every $p\in\mathbb{S}^1$, we have $\omega(p)=\alpha(p)=\mathbb{S}^1$. Otherwise, let $p=(x,y)$, we have

(1) If $0<x^2+y^2<1$, then $\omega(p)=\mathbb{S}^1,\alpha(p)=\{0\}$.

(2) If $x^2+y^2>1$, then $\omega(p)=\mathbb{S}^1,\alpha(p)=\varnothing$.

Proposition 4.1.6

$\forall p\in\mathbb{R}^n$, we have

$$\omega(p)=\bigcap_{t\geqslant 0}\overline{\mathrm{Orb}^+(\varphi_t(p))}=\bigcap_{k\in\mathbb{Z}_+}\overline{\mathrm{Orb}^+(\varphi_k(p))}.$$

Proposition 4.1.7

Assume $\mathrm{Orb}^+(p)$ is bounded, then

1. $\omega(p)$ is non-empty, compact, invariant, connected.
2. $\lim_{t\to\infty} d(\varphi_t(p), \omega(p)) = 0$.

Proof. 1. Non-empty, compact, invariant are trivial. The connected follows by the fact that $A_k = \overline{\mathrm{Orb}^+(\varphi_k(p))}$ are connected and $A_k \supseteq A_{k+1} \supseteq \cdots$.

2. For every $\varepsilon > 0$, $A_k \subseteq B(\omega(p), \varepsilon)$ for every k sufficiently large.

□

Definition 4.1.8. p is said to be **positively recurrent** if $p \in \omega(p)$,

The singularities and periodic points are called trivial recurrent points, other recurrent points are said to be non-trivial.

Definition 4.1.9. Let Λ be a non-empty, compact, invariant set. Λ is called a **minimal set** of φ_t if it does not contain a proper, nonempty, compact invariant set.

Theorem 4.1.10 (Flow Box Theorem)

Let f be a C^1 vector field, $p \in \mathbb{R}^n$, $f(p) \neq 0$. Then there is a neighborhood $U \ni p$ and a C^1 diffeomorphism $h : U \to h(U)$ on to its image, such that $Dh(x)f(x) = (1, 0, \cdots, 0)^t$.

Proof. WLOG, $p = 0, f(p) = (1, 0, \cdots, 0)^t$. We construct $g : (-\varepsilon_0, \varepsilon_0) \times L \to U$ some neighborhood of p. Let

$$x = g(y) = g(y_1, y_2, \cdots, y_n) \coloneqq \varphi_{y_1}(0, y_2, y_3, \cdots, y_n).$$

Then

$$\frac{\partial}{\partial t}\varphi_t(x)\bigg|_{(t,x)=(y_1,0,y_2,\cdots,y_n)} = f(\varphi_{y_1}(0, y_2, \cdots, y_n)) = f(g(y)),$$

let $(y_1, y_2, \cdots, y_n) = (0, 0, \cdots, 0)$, then $\frac{\partial g}{\partial y_1}(y) = f(g(y))$. Moreover,

$$\mathrm{Id} = \frac{\partial \varphi_t(x_1, \cdots, x_n)}{\partial(x_1, \cdots, x_n)}\bigg|_{t=0} \implies \frac{\partial g}{\partial y}\bigg|_{y=0} = \mathrm{Id}.$$

Hence, g gives a local diffeomorphism. Let $h = g^{-1}$, the statement follows. □

Remark 4.1.11 — Let $L_{\varepsilon_0} = \left\{(y_2, \cdots, y_n) : y_2^2 + \cdots + y_n^2 \leqslant \varepsilon_0^2\right\}$, let

$$U = h^{-1}((-\varepsilon_0, \varepsilon_0) \times L_{\varepsilon_0}),$$

then U is called a **tubular neighborhood** near p, or a **flow box** near p.

§4.2 The Poincaré-Bendixson Theorem

Definition 4.2.1. $C \subseteq \mathbb{R}^2$ is called a **Jordan curve** if it is homeomorphism to $\mathbb{S}^1$.

Theorem 4.2.2 (Jordan Seperation Theorem)
Let $C \subseteq \mathbb{R}^2$ be a Jordan curve. Then $\mathbb{R}^2 \setminus C$ has exactly two connected components. One of them is bounded, which is called the interior of C. Another one is bounded, which is called the exterior of C. Both of them are with bound C.

Theorem 4.2.3 (Jordan-Schoenflies)
Let C be a Jordan curve, then there is a homeomorphism $h : \mathbb{R}^2 \to \mathbb{R}^2$, such that $h(C) = \mathbb{S}^1$.

Definition 4.2.4. Let $f : \mathbb{R}^2 \to \mathbb{R}^2$ be C^1, $L \subseteq \mathbb{R}^2$ is a line segment. L is called **transverse** to f if $\forall x \in L$, $f(x)$ and the direction of L generates $\mathbb{R}^2$. We then say L is a **transversal** to f.

Lemma 4.2.5
Let $f : \mathbb{R}^2 \to \mathbb{R}^2$ be C^1, L is a transversal to f. Assume there are three points $P_1, P_2, P_3 \in L$ and $x \in \mathbb{R}^2$ such that

$$\varphi_{t_i}(x) = P_i, \quad t_1 < t_2 < t_3,$$

$$\varphi_{(t_1,t_2)}(x) \cap L = \varnothing, \quad \varphi_{(t_2,t_3)}(x) \cap L = \varnothing,$$

then $P_2 \in (P_1, P_3)$.

Proof. Assume A, B are extreme points of L. Consider a Jordan curve

$$C = \varphi_{[t_1,t_2]}(x) \cup (P_1, P_2),$$

let D be the interior of C. Assume $B \in D$, we show that $P_3 \in D$. By the Flow Box Theorem, there exists $\varepsilon > 0$ such that $\varphi_{(t_2,t_2+\varepsilon]}(x) \subseteq D$. Let $\tau = \inf\{t > t_2 : \varphi_t(x) \notin D\} > t_2+\varepsilon$ if exists. Then $\varphi_\tau(x) \in C$, but it can not on $\varphi_{(t_1,t_2)}(x)$ or P_1, P_2. So $\varphi_\tau(x) \in (P_1, P_2)$, but this contradict with L is a transversal to f. □

Remark 4.2.6 — Assume $\varphi_t(x)$ intersect with a transversal L at $P_i = \varphi_{t_i}(x), i = 1, 2, \cdots$ in chronological order, i.e., $0 < t_1 < t_2 < \cdots$, then

$$P_1 < P_2 < \cdot \quad \text{or} \quad P_1 > P_2 > \cdots \quad \text{or} \quad P_1 = P_2 = \cdots.$$

Proposition 4.2.7
Assume L is a transversal of f, then for every $x \in \mathbb{R}^2$,

$$\sharp(\omega(x) \cap L) \leqslant 1.$$

Proof. Assume for a contradiction. Let $q \neq q' \in \omega(x) \cap L$, then $\exists t_n \to \infty, t_n' \to \infty$ such that $\varphi_{t_n}(x) \to q, \varphi_{t_n'}(x) \to q'$. WLOG, assume $t_1 < t_1' < t_2 < t_2' < \cdots$. By the Flow Box Theorem, for k sufficiently large, there exists τ_k, τ_k' such that

$$|\tau_k - t_k| \to 0, |\tau_k' - t_k'| \to 0, \quad \varphi_{\tau_k}(x), \varphi_{\tau_k'}(x) \in L, \quad \varphi_{\tau_k}(x) \to q, \varphi_{\tau_k'} \to q'.$$

We can also assume that $\tau_k < \tau_k' < \tau_{k+1} < \cdots$, then this contradicts with the monotonicity of $\varphi_t(x)$ intersecting the transversal. □

Theorem 4.2.8 (Poincaré-Bendixson Theorem)

Assume $\mathrm{Orb}^+(x)$ is bounded and $\omega(x)$ contains no singularities, then $\omega(x)$ is a periodic orbit.

Proof. Because $\mathrm{Orb}^+(x)$ is bounded, $\omega(x) \neq \varnothing$. For every $p \in \omega(x)$, take $q \in \omega(p) \subseteq \omega(x)$ arbitrarily. Take a transversal L_q of f through q, then $\exists t_n \to \infty, \varphi_{t_n}(p) \to q$. WLOG, $\varphi_{t_n}(x) \in L_q$. Because $\varphi_{t_n}(p) \in \omega(x)$ and $\sharp\omega(x) \cap L_q = 1$, then $\varphi_{t_n}(p) = \varphi_{t_{n+1}}(p)$, hence p is a periodic point.

Take $p \in \omega(x)$, it is a periodic point. If $\omega(x) \neq \mathrm{Orb}(x)$, take a transversal L_p of f through p. Because $\omega(x)$ is connected, hence $\mathrm{Orb}(p)$ is not isolated in $\omega(x)$. Take $q_n \in \omega(x) \setminus \mathrm{Orb}(p), q_n \to \mathrm{Orb}(p)$. WLOG, $q_n \to p$ and $q_n \in L_p$, this contradicts with $\sharp\omega(x) \cap L_p \leqslant 1$. □

Theorem 4.2.9 (P-B Annular Region Theorem)

Assume A is an annular region and ∂A is two C^1 curves. If for every $x \in \partial A$, $f(x)$ is pointing inside of A, and A contains no singularities. Then there is a periodic orbit in A.

Example 4.2.10

The system

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

contains a non-trivial periodic orbit.

Proof. 0 is the only singularity. Let

$$A = \left\{(x, y) \in \mathbb{R}^2, r^2 \leqslant x^2 + y^2 \leqslant R^2\right\}, \quad r < R,$$

let $V(x, y) = x^2 + y^2$. Then for r small enough $\dot{V} < 0$, for R large enough $\dot{V} > 0$. Hence $f(x)$ is pointing outside of A on ∂A, consider the α-limit set. □

The **Liénard equation**

$$\ddot{x} + f(x)\dot{x} + g(x) = 0.$$

Let $F(x) = \int_0^x f(t)\mathrm{d}t$, then the equation is equivalent to

$$\begin{cases} \dot{x} = y - F(x) \\ \dot{y} = -g(x) \end{cases}.$$

Consider a particular Liénard equation, which is called **van der Pol equation**: $f(x) = x^2 - 1, g(x) = x$. Then this equation is equivalent to

$$\begin{cases} \dot{x} = y - (\dfrac{1}{3}x^3 - x) \\ \dot{y} = -x \end{cases}.$$

We introduce the **Liénard graphing method.** Consider $V = x^2 + y^2$, then $\dot{V} = 2x^2(1 - \frac{1}{3}x^2) \geqslant 0$ when $|x| < 1$.