

ENGSCI 711

QUALITATIVE ANALYSIS OF DIFFERENTIAL EQUATIONS

(...and other dynamical systems) Oliver Maclaren
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LECTURE 5

Geometry

- Geometry of linear systems
- Geometry of nonlinear systems
- Connecting the geometry of linear and nonlinear systems

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MODULE OVERVIEW

Qualitative analysis of differential equations (Oliver Maclaren) [[~16-17 lectures/tutorials](#)]

2. Phase plane analysis, stability, linearisation and classification [[5-6 lectures/tutorials](#)]

General linear systems. Linearisation of nonlinear systems. Analysis of two-dimensional systems - stability and classification of fixed points, periodic orbits. Geometry (invariant manifolds).

MOTIVATING EXAMPLE (4.2 IN GLENDINNING)

$$\dot{x} = x$$

$$\dot{y} = -y + x^2$$

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GEOMETRY OF LINEAR SYSTEMS

Let's return to general linear systems in \mathbb{R}^n for a moment to give the following geometric definitions of three key *invariant manifolds/subspaces* for linear systems.

The *flow in the full phase space* is then given by a *linear superposition of motion on these three subspaces*.

These subspaces *also have nonlinear counterparts* (but we will need to consider some aspects more carefully, e.g. superposition fails)

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GEOMETRY OF LINEAR SYSTEMS - STABLE MANIFOLD

Suppose $x \in \mathbb{R}^n$ is a stationary solution to the linear system
$$\dot{x} = Ax.$$

The *stable manifold* (or subspace/generalised eigenspace) of the origin is then denoted by $E^s(0)$ and is the *span* of the eigenvectors/generalised eigenvectors corresponding to the eigenvalues of A with *real, negative part*.

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TERMINOLOGY: LINEAR SUBSPACES AND SPANS

A linear subspace of \mathbb{R}^n is a subset E of \mathbb{R}^n which contains the *zero vector* $0 \in \mathbb{R}^n$ and which is *closed* under *vector addition* $u + v$, where $u, v \in \mathbb{R}^n$, and *scalar multiplication* cu , where $c \in \mathbb{R}, u \in \mathbb{R}^n$.

The *span* of a set of vectors is the set generated by *all linear combinations* of those vectors i.e.

$$\text{span}\{u, v, \dots\} = \{x \in \mathbb{R}^n \mid x = au + bv + \dots, a, b \in \mathbb{R}, u, v, \dots \in \mathbb{R}^n\}$$

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GEOMETRY OF LINEAR SYSTEMS - UNSTABLE MANIFOLD

Similarly:

The *unstable manifold* (or subspace/generalised eigenspace) of the origin is then denoted by $E^u(0)$ and is the *span* of the eigenvectors/generalised eigenvectors corresponding to the eigenvalues of A with *real, positive part*.

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GEOMETRY OF LINEAR SYSTEMS

Finally:

The *centre manifold* (or subspace/generalised eigenspace) of the origin is then denoted by $E^c(0)$ and is the *span* of the eigenvectors/generalised eigenvectors corresponding to the eigenvalues of A with *zero real part*.

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TERMINOLOGY: WHAT'S A MANIFOLD?

A key property is that locally an $(n - m)$ -dimensional manifold embedded in n -dimensional space '*looks like*' a small 'open ball' of dimension $\mathbb{R}^{(n-m)}$.

E.g. a curve embedded in \mathbb{R}^2 can be considered as 'pieced together' from small segments of \mathbb{R} , a sphere in \mathbb{R}^3 can be considered as 'pieced together' from small 'patches' of \mathbb{R}^2

The more general definition throws away the 'background' space and works with the 'intrinsic' $(n - m)$ -dimensional object itself.

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TERMINOLOGY: WHAT'S A MANIFOLD?

For our purposes it suffices to think of a *manifold* embedded in \mathbb{R}^n as a subset of \mathbb{R}^n , each point of which satisfies $m \leq n$ *constraints*.

This means that, given regularity conditions, a manifold is an $(n - m)$ -dimensional object embedded in n dimensional space.

Example: a circle is a 1-dimensional manifold which is embedded in \mathbb{R}^2 and satisfies one constraint. So, the unit circle can be thought of as e.g. $\{x \in \mathbb{R}^2 \mid x_1^2 + x_2^2 = 1\}$.

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RECALL: HARTMAN-GROBMAN

We have previously considered how the *existence and stability of hyperbolic fixed points* are preserved during linearisation.

We now want consider the *differences in local dynamics between a nonlinear system and its linearisation in more detail*.

We'll look at how to do this using the *stable manifold theorem* and then using series expansions to approximate local stable/unstable manifolds.

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GEOMETRY: STABLE AND UNSTABLE MANIFOLDS

Above we defined the *stable and unstable manifolds for linear systems*. (For non-hyperbolic there is also a centre manifold)

Now we want to give the definitions for *nonlinear hyperbolic fixed points*.

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GEOMETRY: STABLE MANIFOLD (LOCAL)

Given some neighbourhood U of a stationary point x , the *local stable manifold* on U for a nonlinear system $W_{loc}^s(x)$ is defined by

$$\{y \in U \mid \phi(y, t) \rightarrow x \text{ as } t \rightarrow \infty, \phi(y, t) \in U \text{ for all } t \geq 0\}$$

What does this mean?

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GEOMETRY: UNSTABLE MANIFOLD (LOCAL)

Similarly, given some neighbourhood U of a stationary point x , the *local unstable manifold* on U for a nonlinear system

$W_{loc}^u(x)$ is defined by

$$\{y \in U \mid \phi(y, t) \rightarrow x \text{ as } t \rightarrow -\infty, \phi(y, t) \in U \text{ for all } t \leq 0\}$$

What does this mean?

GLOBAL MANIFOLDS

Note that if we want *global* versions then we can '*glue*' *together* all the flows starting at points in the local stable/unstable manifolds. That is,

$$W^s(0) = \bigcup_{t \geq 0} \phi(W_{loc}^s(0), t)$$

$$W^u(0) = \bigcup_{t \leq 0} \phi(W_{loc}^u(0), t)$$

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STABLE MANIFOLD THEOREM

What's the *connection between these linear and nonlinear stable/unstable manifolds?* We have the following theorem (for local manifolds).

Suppose the origin is a *hyperbolic fixed point* for $\dot{x} = f(x)$ in \mathbb{R}^n and that $E^s(0)$ and $E^u(0)$ are the stable and unstable manifolds of the linearised system $\dot{x} = Df(0)x$.

Then...

STABLE MANIFOLD THEOREM

...there exist local stable and unstable manifolds $W_{loc}^s(0)$ and $W_{loc}^u(0)$ of the same dimension as $E^s(0)$ and $E^u(0)$, respectively, and which are (respectively) tangent to E^s and E^u at the origin.

These manifolds are equally smooth/unsMOOTH as the original function f .

CALCULATING THE MANIFOLDS - THE 'MANIFOLD EQUATION'

The basic idea is to substitute the defining equation $y = U(x)$ or $x = V(y)$ into the governing equations and use the *chain rule* applied *along the manifold*:

$$\frac{dy}{dt}(x, U(x)) = \frac{dy}{dx}(x) \frac{dx}{dt}(x, U(x))$$

from which to find $U(x)$.

Let's call this the '*manifold equation*'. We usually solve it locally by assuming a *power series solution* - justified by the SMT!

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POWER SERIES EXPANSIONS IN TWO-DIMENSIONAL SYSTEMS

Even on small neighbourhoods of our fixed points, *our manifolds are no-longer straight lines* (or hyperplanes etc in higher dims) as in the linear case - they are *curves* (or surfaces in higher-dimensions).

We can, however, use the information from the previous theorem to (try to) *compute local expressions for these curves*.

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POWER SERIES EXPANSIONS FOR ONE-DIMENSIONAL MANIFOLDS

Assume a stable/unstable manifold of interest can be described by a curve $y = U(x)$ (or $x = V(y)$).

We can try to approximate this by a *local series expansion* of the form

$$y = U(x) = \sum_{n=0}^{\infty} a_n x^n$$

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POWER SERIES: STEPS

- Use the above relationships along with an assumed *power series* expansion such as $U(x) = \sum_{n=0}^{\infty} a_n x^n$ to obtain *two expressions* in x for \dot{y}
- *Equate* powers of x to determine the unknown coefficients.
- Make sure to use the fact that the stable/unstable manifold *passes through* the fixed point and *is tangent* to the linearised stable/unstable manifold to determine the *first two terms* of the series.

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POWER SERIES: STEPS

- *Assume* the manifold can be described by $y = U(x)$ (or the other way around).
- *Substitute* $y = U(x)$ into our x and y equations to give $\dot{x} = f_1(x, U(x))$ and $\dot{y} = f_2(x, U(x))$.
- Use $y = U(x)$ *again*, along with the *chain rule* for our y (say) equation $\dot{y} = f_2(x, y)$, to relate \dot{x} and \dot{y} giving (e.g.)
$$\dot{y} = \frac{dU}{dx} \dot{x}.$$

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Eng Sci 711 LOS

o Geometry of Hyperbolic Systems

- Linear } connecting
- Nonlinear

Goals

- Given an ODE system,
- Find stable/unstable linear subspaces E^s, E^u
- Find stable/unstable nonlinear subspaces
ie stable/unstable manifolds, W^s, W^u
- Sketch local trajectories

Examples

(+ Assignment 1 (Tutorial 2))

Exam 2016

Question 5 (20 marks)

Consider the system

$$\begin{aligned}\dot{x} &= y(2x - y) \\ \dot{y} &= x^2 - y\end{aligned}$$

(a) Find the two fixed points of this system. Show your working. You do not need to classify these.

(b) Find the Jacobian derivative - first as a function of x and y and then evaluated at the origin $(0,0)$.

(c) Find the eigenvalues of the linearisation about the origin and - if they exist - the associated stable, unstable and centre eigenspaces, E^s, E^u and E^c respectively. Sketch the eigenspaces in the (x,y) plane. You do not need to show any nearby trajectories.

(d) Use a power series expansion to calculate an expression for the centre manifold $W^c_{loc}(0,0)$ that is correct up to and including cubic order.

(e) Use the previous expression to determine the dynamics on the centre manifold, again correct up to and including cubic order, and thus determine whether these dynamics are (asymptotically) stable or unstable.

Question 4 (16 marks)

Consider the system

$$\begin{aligned}\dot{x} &= 2xy + x^3 \\ \dot{y} &= -y - x^2\end{aligned}$$

where $x, y \in \mathbb{R}$.

(a) Verify that the origin is a fixed point of this system. (1 mark)

(b) Find the Jacobian derivative - first as a function of x and y and then evaluated at the origin $(0,0)$. (2 marks)

(c) Find the eigenvalues of the linearisation about the origin and - if they exist - the associated stable, unstable and centre eigenspaces, E^s, E^u and E^c respectively. Sketch the eigenspaces in the (x,y) plane. You do not need to show any nearby trajectories. (3 marks)

(d) Use a power series expansion to calculate an expression for the centre manifold $W^c_{loc}(0,0)$ that is correct up to and including cubic order. (8 marks)

(e) Use the previous expression to determine the dynamics on the centre manifold, again correct up to and including cubic order, and thus determine whether these dynamics are (asymptotically) stable or unstable. (2 marks)

Note: these focus on centre (non-hyperbolic) manifold
→ today we do same for stable & unstable manifolds.

We return to centre manifold case
later → same basic ideas tho'.

Example (4.2 in Atendimming)

Consider analysing

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

Key steps

- Find fixed points
- Linearise near fixed points
- Classify fixed points

- Sketch a 'local picture' of flow near fixed points

- Build up a more 'global' picture
 - ↳ extend/join flows
 - ↳ look for other 'global' objects (like periodic orbits etc)

so far

need to understand the local 'geometry'
- linearised
- nonlinear ↴ link

Local flow / trajectories?

Linear systems: superposition of flows
on eigen spaces
linear subspaces

Nonlinear systems: similar idea
→ decompose into flows
on 'nonlinear subspaces'
└ 'manifolds'
→ these are 'curved' versions
of linear subspaces!

Key idea: decompose into motions on/in
invariant sets / spaces:

$$x \in M \Rightarrow \varphi(x, t) \in M \text{ for all } t$$

'once in/on, stay in/on'

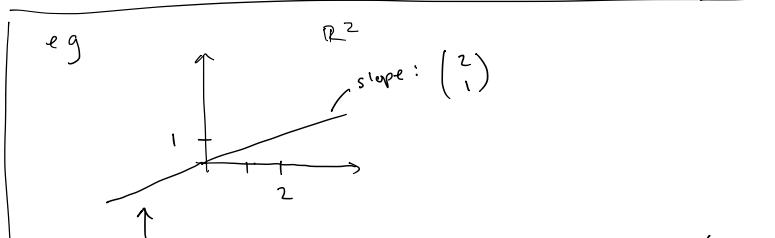
Linear subspace of \mathbb{R}^n : some 'mathy intuition'

a subset E of \mathbb{R}^n

where $\cdot 0 \in E$ } goes through zero
↳ note: 0 is a vector eg $\begin{pmatrix} 0 \\ \vdots \\ 0 \end{pmatrix} \in \mathbb{R}^n$

• if $u, v \in E$ then
 $u+v \in E$
• if $u \in E$ & $c \in \mathbb{R}$ then
 $cu \in E$

i.e.: lines & (hyper) planes



can define as: $\{x \in \mathbb{R}^2 \mid x = c \cdot u, c \in \mathbb{R}, u = \begin{pmatrix} 1 \\ 2 \end{pmatrix}\}$

so either:
• span of u (see next page)
or • a subset of \mathbb{R}^2 satisfying one
 (linear) constraint

both ideas can be generalised to nonlinear setting
- second easier for us
- but first useful in linear case

} explicit

} implicit

Span? of a set of vectors $\{u, v, \dots\}$

→ just the set of all linear combinations of the given vectors



e.g.

$$\begin{aligned} & \text{span } \{u, v, w\} \\ &= \left\{ x \mid x = au + bv + cw; a, b, c \in \mathbb{R} \right\} \end{aligned}$$

→ explicit construction

Q: what is the span of $\{(1, 0), (0, 1)\}$?

A: all of \mathbb{R}^2

Challenge: prove!

Linear subspaces - via linear constraints

- can also think of defining a linear subspace via linear constraints on vectors in a larger space
- 'Implicit' definition: 'what's left over' ('nullspace')
(independent)
- e.g. $x \in \mathbb{R}^n$, impose m linear constraints

→ get $\underbrace{\text{m}}_{\text{remaining}} \text{ degrees of freedom}$ } left over
or 'free'

Underdetermined linear system: implicitly define a 'free subspace'

A diagram illustrating an underdetermined linear system. A matrix with m rows and n columns is shown. The first $n-m$ columns are labeled 'Fixed' and the last m columns are labeled 'Free'. An arrow points from the 'Free' columns to the text 'use to satisfy m equations'.

→ if $m=n$ then just define a unique point

→ if $m < n$ get 'infinitely' many sol's, lying on a (hyper) plane of dim $n-m$

→ nontrivial null space (implicit: null complement to range space)

So ... back to ODEs.

Linear subspaces (assume FP is at 0.)

- stable $E^s(0)$: span of eigenvectors/generalised eigenvectors associated with $\text{Re}(\lambda) < 0$
- unstable $E^u(0)$: span $\text{Re}(\lambda) > 0$
- centre $E^c(0)$: span $\text{Re}(\lambda) = 0$
 \hookrightarrow if $\text{Re}(\lambda) \neq \text{Im}(\lambda) = 0$
 ie $\lambda = 0$, also called 'slow'

Side note: in general we need to allow complex eigenvectors &/or generalised eigenvectors

\rightarrow I'll avoid as much as possible but give you a linear algebra handout later for fun!

Example cont'd.

$$\begin{aligned}\dot{x} &= x \\ \dot{y} &= -y + x^2\end{aligned}\left\{\right. \quad Df(x,y) = \begin{pmatrix} 1 & 0 \\ 2x & -1 \end{pmatrix}$$

$$\Rightarrow Df(0,0) = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = 'A'$$

Cont'd.

$$A = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\begin{aligned} \text{or} \\ \text{tr} &= \lambda_1 + \lambda_2 = 0 \\ \det &= \lambda_1 \lambda_2 = -1 \\ \Rightarrow \lambda_1 &= -\lambda_2 \\ &= 1 \end{aligned}$$

$$\Rightarrow \text{diagonal} \Rightarrow \lambda_1 = 1, \lambda_2 = -1$$

(see Linear Algebra supplement coming soon)

$\lambda = 1 \quad \text{unstable dir}$

$\lambda = -1 \quad \text{stable dir.}$

Find E^u . \rightarrow find eigenvector

$$[A - \lambda I]u = 0$$

$$\text{if } \lambda = 1, A - \lambda I$$

$$= \begin{pmatrix} 1-1 & 0 \\ 0 & -1-1 \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & -2 \end{pmatrix}$$

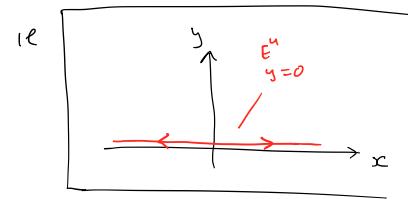
$$\text{ie } \begin{pmatrix} 0 & 0 \\ 0 & -2 \end{pmatrix} \begin{pmatrix} u_1 \\ u_2 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$$\Rightarrow u_2 = 0, u_1 = \text{free} \quad \left\{ e^u = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \right.$$

choose arb. value

$$\text{ie } E^u = \{(x,y) \mid y=0\} \quad \text{implicit}$$

$$= \text{span} \left\{ \begin{pmatrix} 1 \\ 0 \end{pmatrix} \right\} \quad \text{explicit.}$$

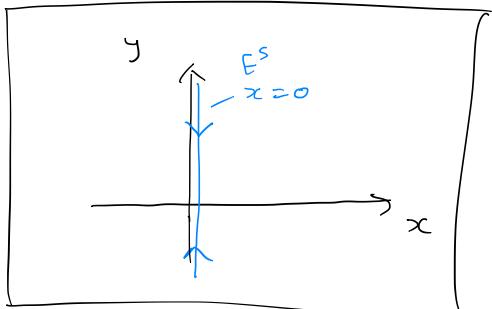


Find E^s (stable, $\lambda = -1$)

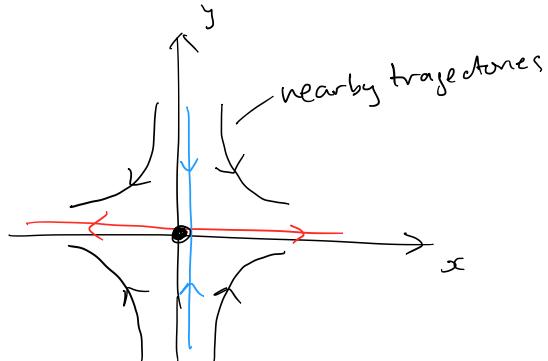
Similarly \rightarrow exercise!

should get $E^s = \{(x, y) \mid x = 0\}$

or $E^s = \text{span} \{ \begin{pmatrix} 0 \\ 1 \end{pmatrix} \}$



Put together: Local picture

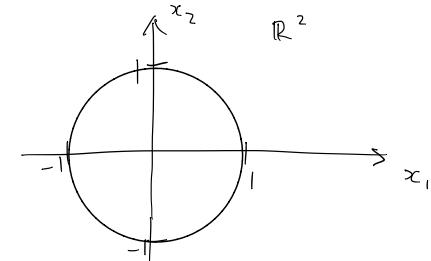


Manifolds - 'nonlinear subspaces'

- Basic idea: instead of 'E' for linear
↪ subset W of \mathbb{R}^n (here),
defined by m (possibly)

nonlinear constraints

- Example: nonlinear constraint
 $\{x \in \mathbb{R}^2 \mid x_1^2 + x_2^2 = 1\}$
 \rightarrow defines a circle!



\rightarrow a linear subspace is just a special kind of manifold:
generated by linear constraints

\rightarrow manifolds can 'curve' & 'close', but locally look linear

Connection between linear & nonlinear

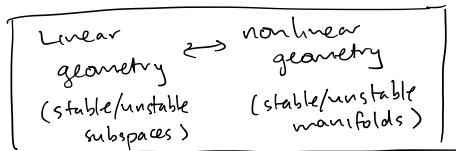
Hartman-Grobman

→ existence & stability of FP for hyperbolic:



stable manifold theorem } today

→ existence & tangency of manifolds for hyperbolic:

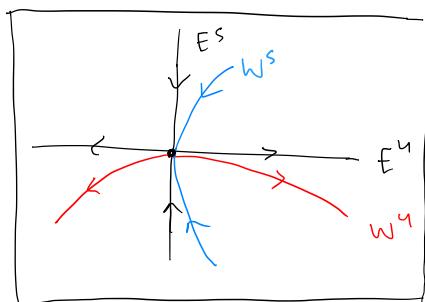


i.e.

$E^s \rightarrow W^s$	} for hyperbolic	} today
$E^u \rightarrow W^u$		

use above

$E^c \rightarrow ?$	} need 'centre manifold theorem'	} later
\circ		



Key: linear & nonlinear manifolds

- same dimension
- tangent at FP.
- each is invariant for respective (linear/nonlinear) system

Defining nonlinear stable/unstable manifolds

- same 'issue' as stability in nonlinear case

→ can't define in terms of eigenvalues/eigenvectors \nparallel linear ideas

→ want 'truly nonlinear' / general definitions

→ BUT: as before, want to then relate the general case back to linear case

} Stable manifold theorem

Intuition:

- stable as an invariant set near origin / FP such that:
points \rightarrow FP as $t \rightarrow \infty$



- unstable: invariant set near origin / FP such that:
points \rightarrow FP as $t \rightarrow -\infty$



L trick: unstable as $t \rightarrow \infty$
is stable as $t \rightarrow -\infty$!

Local vs global

- These are local definitions

- But, as invariant manifolds, can trace out / piece together / extend to global objects

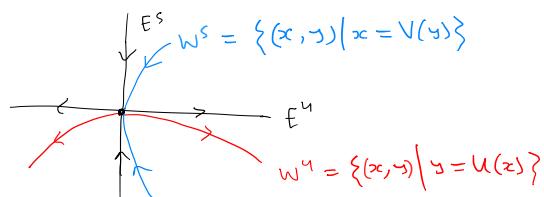
- see videos for Lorenz (MoA math dep.)

'Manifold Equation'

Let's calculate our manifolds & the flows on these!

- Idea: exists either $y = u(x)$ or $x = v(y)$ } local (or multivariable surface if higher dim)

expressions for manifolds:



- Substitute in & use chain rule

- subs: $\dot{x} = f_1(x, y) = f_1(x, u(x))$
 $y = f_2(x, y) = f_2(x, u(x))$

- chain: $\frac{dy}{dt} = \frac{dx}{dt} \frac{dy}{dx} \Leftrightarrow \left[\dot{y} = \dot{x} \cdot \frac{dy}{dx} \right]$
(along $y = u(x)$)

Gives the 'Manifold (or homological) eqn'

$$\boxed{\dot{y}(x) = \dot{x}(x) \cdot \frac{dy}{dx}(x)}$$

Solution is
 $\boxed{y = U(x)}$

Power Series Soln

We only really want 'local' soln to a given order

→ use a power series expansion

Example cont'd: unstable w^u for

$$\dot{x} = x$$

$$\dot{y} = -y + x^2$$

$$y = U(x) = a_0 + a_1 x + a_2 x^2 + \dots \quad (1)$$

$$\frac{dy}{dx} = a_1 + 2a_2 x + \dots \quad (2).$$

$$\dot{x}(x) = f_1(x, y(x)) = x \quad (3)$$

$$\begin{aligned} \dot{y}(x) &= f_2(x, y(x)) = -(a_0 + a_1 x + \dots) + x^2 \\ &= -a_0 - a_1 x + (1 - a_2)x^2 + \dots \quad (4) \end{aligned}$$

Gives:
 $\dot{y} = \frac{dy}{dx} \cdot \dot{x} = \left[a_1 + 2a_2 x + \dots \right] x \quad (\text{manifold eqn})$

$$= -a_0 - a_1 x + (1 - a_2)x^2$$

Cont'd.

So

$$a_0 + 2a_1 x + \dots = -a_0 - a_1 x + (1-a_2)x^2$$

Solving:

1. use
 a) pass through origin
 b) tangent to E^u at origin } distinguishes
 c) equate coefficients E^u & E^s
 for rest.
-

a & b) (From SM theorem)

$$\begin{aligned} y &= a_0 + a_1 x + \dots \\ y(0) &= 0 \Rightarrow \boxed{a_0 = 0} \\ \frac{dy}{dx} &= a_1 + 2a_2 x + \dots \\ \frac{dy}{dx}(0) &= 0 \Rightarrow \boxed{a_1 = 0} \end{aligned} \quad \left. \begin{array}{l} \text{tip:} \\ \text{do this} \\ \text{straight away!} \end{array} \right\}$$

c). $2a_2 x^2 + \dots = (1-a_2)x^2$

$$\begin{aligned} \Rightarrow 2a_2 &= 1-a_2 \\ \Rightarrow \boxed{a_2 = \frac{1}{3}} & \end{aligned}$$

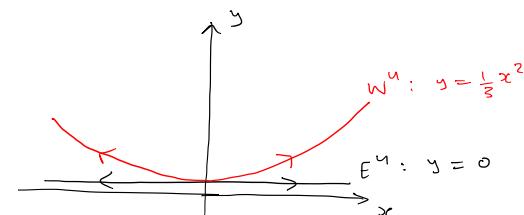
So we have:

$$y = \frac{1}{3}x^2$$

Unstable manifold:

$$W^u = \{(x, y) \mid y = \frac{1}{3}x^2\}$$

So:



Note:

$$\begin{aligned} \dot{x}(u(x)) &= x &< 0 & \text{if } x < 0 \\ &&> 0 & \text{if } x > 0 \\ \dot{y}(u(x)) &= -y(x) + x^2 \\ &= -\frac{1}{3}x^2 + x^2 \\ &= \frac{2}{3}x^2 > 0 \end{aligned} \quad \left. \begin{array}{l} \text{flow on} \\ \text{unstable} \end{array} \right\}$$

Exercise: Use $\dot{x} = V(y)$ & find stable manifold!

(I'll go over in tutorial ---)

There are two important theorems for hyperbolic stationary points, the stable manifold theorem and Hartman's theorem. The first shows that the local structure of hyperbolic stationary points of nonlinear flows, in terms of the existence and transversality of local stable and unstable manifolds, is the same as the linearized flow, and the second asserts that there is a continuous invertible map in some neighbourhood of the stationary point which takes the nonlinear flow to the linear flow preserving the sense of time.

Let U be some neighbourhood of a stationary point, x . Then, by analogy with the definition of the invariant manifolds for linear systems we can define the local stable manifold of x , $W_{loc}^s(x)$, and the local unstable manifold of x , $W_{loc}^u(x)$, by

$$W_{loc}^s(x) = \{y \in U | \varphi(y, t) \rightarrow x \text{ as } t \rightarrow \infty, \varphi(y, t) \in U \text{ for all } t \geq 0\}$$

and

$$W_{loc}^u(x) = \{y \in U | \varphi(y, t) \rightarrow x \text{ as } t \rightarrow -\infty, \varphi(y, t) \in U \text{ for all } t \leq 0\}.$$

The stable manifold theorem states that these manifolds exist and are of the same dimension as the stable and unstable manifolds of the linearized equation $\dot{y} = Df(x)y$ if x is hyperbolic, and that they are tangential to the linearized manifolds at x .

(4.7) THEOREM (STABLE MANIFOLD THEOREM)

Suppose that the origin is a hyperbolic stationary point for $\dot{x} = f(x)$ and E^s and E^u are the stable and unstable manifolds of the linear system $\dot{x} = Df(0)x$. Then there exist local stable and unstable manifolds $W_{loc}^s(0)$ and $W_{loc}^u(0)$ of the same dimension as E^s and E^u respectively. These manifolds are (respectively) tangential to E^s and E^u at the origin and as smooth as the original function f .

Note that in Chapter 3 the centre manifold of a stationary point was also defined, but that for a hyperbolic stationary point the centre manifold is empty. We shall return to the problems of finding nonlinear centre manifolds in Chapters 7 and 8, where the basic ideas of bifurcation theory are introduced. The content of this theorem is illustrated in Fig. 4.1. The proof is, unfortunately, long and technical and we leave this to the end of this chapter, since we will be much more concerned with the use of this theorem.

4.2 Hyperbolic stationary points and the stable manifold theorem

One further point can be made without difficulty: suppose that x_0 is a hyperbolic stationary point, then there are three possibilities. Either $W_{loc}^s(x_0) = \emptyset$, or $W_{loc}^u(x_0) = \emptyset$, or both manifolds are non-empty. These three possibilities are given names: x_0 is called a source, sink or saddle respectively. From the definition of the linear stable and unstable manifolds and the stable manifold theorem it should be obvious that these definitions can be made in terms of the eigenvalues of the Jacobian matrix at x_0 in the following way.

(4.8) DEFINITION

Suppose that x_0 is a hyperbolic stationary point of $\dot{x} = f(x)$ and let $Df(x_0)$ denote the Jacobian matrix of f evaluated at x_0 . Then x_0 is a sink if all the eigenvalues of $Df(x_0)$ have strictly negative real parts and a source if all the eigenvalues of $Df(x_0)$ have strictly positive real parts. Otherwise x_0 is a saddle.

We shall see in Sections 4.3 and 4.5 that for small perturbations of the defining equations, a source remains a source, a sink remains a sink and a saddle remains a saddle. Furthermore, as one would expect, if x_0 is a sink then it is asymptotically stable.

If we choose a coordinate system for which the linear part of the differential equation at the origin is in normal form we can always arrange

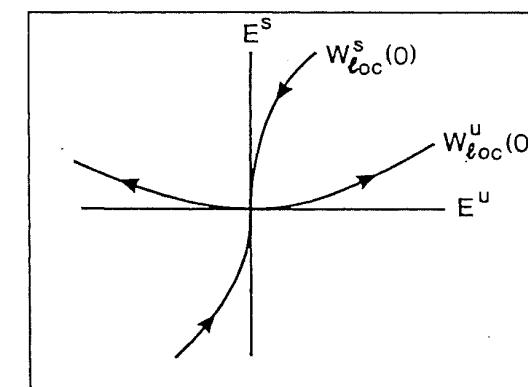


Fig. 4.1 Stable and unstable manifolds.

for the differential equation to be of the form

$$\dot{x} = Ax + g_1(x, y) \quad \dot{y} = -By + g_2(x, y) \quad (4.21)$$

where $x \in \mathbb{R}^{n_u}$, $y \in \mathbb{R}^{n_s}$ (where n_u is the dimension of the local unstable manifold and n_s is the dimension of the local stable manifold, $n_u + n_s = n$) and both the square matrices A and B have eigenvalues with positive real parts. The functions $g_i(x, y)$, $i = 1, 2$, contain the nonlinear parts of the equation, so they vanish, together with their first derivatives at the origin, $(x, y) = (0, 0)$. Hence

$E^s(0, 0) = \{(x, y) | x = 0\}$ and $E^u(0, 0) = \{(x, y) | y = 0\}$.

Since the stable and unstable manifolds are smooth and are tangential to these manifolds at the origin they can be described as the graphs of functions, so the stable manifold is given by

$$x_i = S_i(y), \quad i = 1, \dots, n_u \quad (4.22)$$

where

$$\frac{\partial S_i}{\partial y_j}(0) = 0, \quad 1 \leq i \leq n_u, 1 \leq j \leq n_s \quad (4.23)$$

since the manifold is tangential to E^s at 0. Similarly we can write the unstable manifold (again locally) as

$$y_j = U_j(x), \quad \frac{\partial U_j}{\partial x_i}(0) = 0, \quad 1 \leq i \leq n_u, 1 \leq j \leq n_s. \quad (4.24)$$

This observation allows us to approximate the stable and unstable manifolds by expanding the functions S_i and U_j as power series. Consider U_j (the argument is the same for S_i). We begin by expanding U_j as a power series in x , so

$$U_j(x) = \sum_{r \geq 2} \sum_{m \in M_r} u_{mj} x^m \quad (4.25)$$

where the notation is as in the previous section. If B is diagonal then with eigenvalues (λ_i) , $i = 1, 2, \dots, n_s$ then

$$\dot{y}_j = -\lambda_j y_j + g_{2j}(x, y) \quad (4.26)$$

and on the unstable manifold $y = U(x)$ so

$$\dot{y}_j = -\lambda_j U_j(x) + g_{2j}(x, U(x)). \quad (4.27)$$

On the other hand

$$\dot{y}_j = \frac{d}{dt} U_j(x) = \sum_{k=1}^{n_u} \dot{x}_k \frac{\partial}{\partial x_k} U_j(x). \quad (4.28)$$

Comparing the right hand sides of (4.27) and (4.28) we find that

$$-\lambda_j U_j(x) + g_{2j}(x, U(x)) = \sum_{k=1}^{n_u} \dot{x}_k \frac{\partial}{\partial x_k} U_j(x) \quad (4.29)$$

and we can now substitute the series expansion for the functions U_j into these equations and equate coefficients of powers of x in order to get a set of simultaneous equations for the coefficients u_{mi} which can be solved to arbitrary order. An example may make this clearer.

Example 4.2

Consider the equations

$$\dot{x} = x, \quad \dot{y} = -y + x^2.$$

This has a unique stationary point at $(x, y) = (0, 0)$ and the equation is already in normal form near the stationary point. The linearized equation is

$$\dot{x} = x, \quad \dot{y} = -y,$$

giving a saddle at the origin with invariant linear subspaces

* $E^s(0, 0) = \{(x, y) | x = 0\}$ and $E^u(0, 0) = \{(x, y) | y = 0\}$.

By the stable manifold theorem we know that the nonlinear system has a local unstable manifold of the form

$$y = U(x), \quad \frac{\partial U}{\partial x}(0) = 0 \quad] \text{ in this case}$$

and so we try a series expansion for U ,

$$U(x) = \sum_{k \geq 2} u_k x^k.$$

Now,

$$\dot{y} = -y + x^2 = -\sum_{k \geq 2} u_k x^k + x^2$$

on the unstable manifold and also

$$\dot{y} = \dot{x} \frac{\partial U}{\partial x}(x) = \sum_{k \geq 2} k u_k x^k.$$

Equating terms of order x^2, x^3 and so on gives

$$-u_2 + 1 = 2u_2, \text{ and } -u_k = ku_k, \quad k \geq 3.$$

Hence $u_2 = \frac{1}{3}$, $u_k = 0$ for $k \geq 3$ and so

$$W_{loc}^u(0, 0) = \{(x, y) | y = \frac{1}{3}x^3\}.$$

A similar exercise shows that $W_{loc}^s(0, 0) = E^s(0, 0)$.

Later in this book (Chapter 12) we will see that a great deal of interesting dynamics is controlled by the behaviour of the stable and unstable manifolds of stationary points; for this we need to extend the local manifolds to obtain global stable and unstable manifolds defined by

$$W^u(0) = \bigcup_{t \leq 0} \varphi(W_{loc}^u(0), t) \text{ and } W^s(0) = \bigcup_{t \geq 0} \varphi(W_{loc}^s(0), t).$$

The second result of this section is associated with a weakening of the requirements of Poincaré's Linearization Theorem. In the previous section we looked for a change of variable such that the equation in the new variable is locally just the linear flow. This turned out to be quite a tough condition to meet, but in Example 4.1 we saw that even when the linearization has resonant eigenvalues the flow was remarkably similar to the linear flow (at least for the hyperbolic stationary point considered). This suggests that an alternative strategy might be to look for a map from the nonlinear flow to the linear flow in a neighbourhood of the stationary point, which takes trajectories of the nonlinear flow to trajectories of the linear flow.

* (4.9) THEOREM (HARTMAN'S THEOREM)

If $x = 0$ is a hyperbolic stationary point of $\dot{x} = f(x)$ then there is a continuous invertible map, h , defined on some neighbourhood of $x = 0$ which takes orbits of the nonlinear flow to those of the linear flow $\exp(tDf(0))$. This map can be chosen so that the parametrization of orbits by time is preserved.

Note that the map is only continuous (not necessarily differentiable) and so it does not distinguish between, for example, a logarithmic spiral (cf. (3.31)) and the phase portrait obtained when the Jacobian at the stationary point has real eigenvalues. If we want greater smoothness we find ourselves involved once again in problems of resonance.

4.3 Persistence of hyperbolic stationary points

Another important feature of hyperbolic stationary points is the fact that they persist under small perturbations of the defining differential equations. Hence if the origin is a hyperbolic stationary point of $\dot{x} = f(x)$ and v is any smooth vector field on \mathbb{R}^n then for sufficiently small ϵ the equation

$$\dot{x} = f(x) + \epsilon v(x) \quad (4.30)$$

has a hyperbolic stationary point near the origin of the same type as the hyperbolic point of the unperturbed equation. This robustness, together with the results of the previous section, shows that the dynamics in a neighbourhood of a hyperbolic stationary point is not radically altered by small perturbations. This will be of crucial importance when we come to consider bifurcation theory in Chapters 7 and 8. To see this, suppose that $f(0) = 0$ and look for stationary points of the perturbed system. They satisfy

$$f(x) + \epsilon v(x) = 0. \quad (4.31)$$

Expanding this equation about $x = 0$ (or using the implicit function theorem) gives

$$[Df(0) + \epsilon Dv(0)]x + \epsilon v(0) + O(|x|^2) = 0 \quad (4.32)$$

with solutions

$$x = -\epsilon[Df(0) + \epsilon Dv(0)]^{-1}v(0) + O(\epsilon^2) \quad (4.33)$$

provided $[Df(0) + \epsilon Dv(0)]$ is invertible. Now, if $x = 0$ is a hyperbolic stationary point, the eigenvalues of $Df(0)$ are bounded away from zero and hence the eigenvalues of $[Df(0) + \epsilon Dv(0)]$ are bounded away from zero for sufficiently small ϵ . So $\det[Df(0) + \epsilon Dv(0)] \neq 0$ for sufficiently small ϵ and hence this matrix is invertible. We now want to show that the stationary point of the perturbed equation is also hyperbolic. By continuity in ϵ , there is a neighbourhood of $\epsilon = 0$ for which the real parts of the eigenvalues of $[Df(x) + \epsilon Dv(x)]$ are all non-zero for sufficiently small x . In particular, no eigenvalue can cross the imaginary axis and so the number of eigenvalues on the right of the imaginary axis and on the left of the imaginary axis is the same for all x sufficiently small in this neighbourhood of $\epsilon = 0$. Now simply choose ϵ small enough so that it is in this neighbourhood of $\epsilon = 0$ and the stationary point of the perturbed equation has sufficiently small $|x|$. Then for all values of ϵ sufficiently small the stationary point of the perturbed equation is hyperbolic.