King Abdullah University of Science and Technology
KAUST

CS 247 – Scientific Visualization
Lecture 29: Vector / Flow Visualization, Pt. 8

Markus Hadwiger, KAUST

Reading Assignment #15++ (1)

Reading suggestions:

- Data Visualization book, Chapter 6.7
- J. van Wijk: *Image-Based Flow Visualization*,
  ACM SIGGRAPH 2002

  `http://www.win.tue.nl/~vanwijk/ibfv/ibfv.pdf`

- T. Günther, A. Horvath, W. Bresky, J. Daniels, S. A. Buehler:
  Lagrangian Coherent Structures and Vortex Formation in High Spatiotemporal-Resolution Satellite Winds of an Atmospheric Karman Vortex Street, 2021

  `https://www.essoar.org/doi/10.1002/essoar.10506682.2`

- H. Bhatia, G. Norgard, V. Pascucci, P.-T. Bremer:
  The Helmholtz-Hodge Decomposition – A Survey, TVCG 19(8), 2013

  `https://doi.org/10.1109/TVCG.2012.316`

- Work through online tutorials of multi-variable partial derivatives, grad, div, curl, Laplacian:

  `https://www.khanacademy.org/math/multivariable-calculus/multivariable-derivatives`
  `https://www.youtube.com/watch?v=rB83DpBJQsE` (3Blue1Brown)

- Matrix exponentials:

  `https://www.youtube.com/watch?v=O85OWBJ2ayo` (3Blue1Brown)

Reading Assignment #15++ (2)

Reading suggestions:

- Tobias Günther, Irene Baeza Rojo:

  Introduction to Vector Field Topology

  `https://cgl.ethz.ch/Downloads/Publications/Papers/2020/Gun20b/Gun20b.pdf`

- Roxana Bujack, Lin Yan, Ingrid Hotz, Christoph Garth, Bei Wang:

  State of the Art in Time-Dependent Flow Topology: Interpreting Physical Meaningfulness Through Mathematical Properties

  `https://onlinelibrary.wiley.com/doi/epdf/10.1111/cgf.14037`

- B. Jobard, G. Erlebacher, M. Y. Hussaini:

  Lagrangian-Eulerian Advection of Noise and Dye Textures for Unsteady Flow Visualization

  `http://dx.doi.org/10.1109/TVCG.2002.1021575`

- Anna Vilanova, S. Zhang, Gordon Kindlmann, David Laidlaw:

  An Introduction to Visualization of Diffusion Tensor Imaging and Its Applications

  `http://vis.cs.brown.edu/docs/pdf/Vilanova-2005-IVD.pdf`

Vector Fields and Dynamical Systems (1)

Velocity gradient tensor, (vector field → tensor field)

- Gradient of vector field: how does the vector field change?
- In Cartesian coordinates: *spatial partial derivatives (Jacobian matrix)*

$$\nabla \mathbf{v}\,(x, y, z) = \begin{pmatrix} u_x & u_y & u_z \\ v_x & v_y & v_z \\ w_x & w_y & w_z \end{pmatrix}$$

these are partial derivatives!

- Can be decomposed into *symmetric* part + *anti-symmetric* part

$$\nabla \mathbf{v} = \mathbf{D} + \mathbf{S}$$ *velocity gradient tensor*

sym.: $\mathbf{D} = \frac{1}{2}\,(\,\nabla \mathbf{v} + (\nabla \mathbf{v})^{\mathrm{T}}\,)$ deform.: *rate-of-strain tensor*

skew-sym.: $\mathbf{S} = \frac{1}{2}\,(\,\nabla \mathbf{v} - (\nabla \mathbf{v})^{\mathrm{T}}\,)$ rotation: *vorticity/spin tensor*

Vector Fields and Dynamical Systems (2)

Vorticity/spin/angular velocity tensor

- Antisymmetric part of velocity gradient tensor
- Corresponds to vorticity/curl/angular velocity (beware of factor ½)

$$\mathbf{S} = ½ \, (\nabla \mathbf{v} - (\nabla \mathbf{v})^{\mathrm{T}})$$

these are partial derivatives!

$$\mathbf{S} = ½ \begin{pmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{pmatrix} \quad \omega = \begin{pmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{pmatrix} = \nabla \times \mathbf{v} = \begin{pmatrix} w_y - v_z \\ u_z - w_x \\ v_x - u_y \end{pmatrix}$$

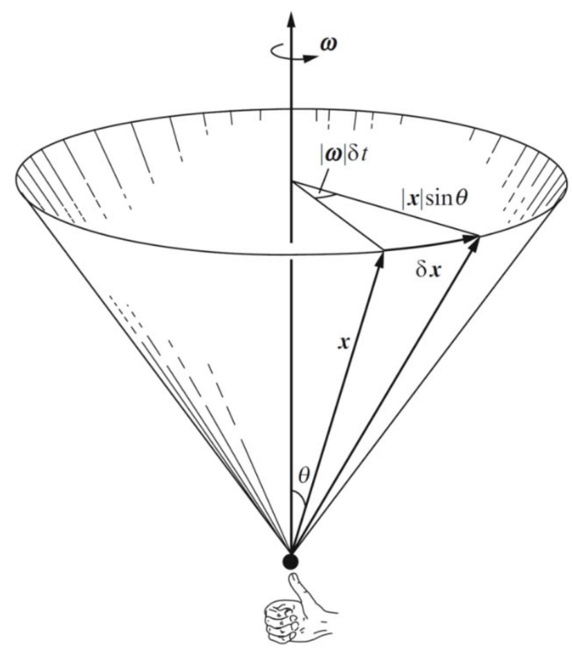
$\mathbf{S}$ acts on vector like cross product with ω : $\mathbf{S} \bullet = ½ \, \omega \times$

$$\mathbf{v}^{(r)} = \mathbf{S} \cdot d\mathbf{r} = \frac{1}{2} [\nabla \mathbf{v} - (\nabla \mathbf{v})^T] \cdot d\mathbf{r} = \frac{1}{2} \boldsymbol{\omega} \times d\mathbf{r}$$

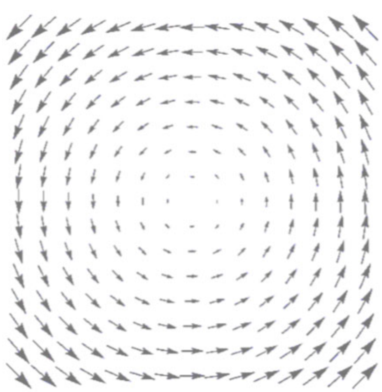
Angular Velocity of Rigid Body Rotation

Rate of rotation

- Scalar ω: angular displacement per unit time (rad s^{-1})
  - Angle Θ at time t is $\Theta(t) = \omega t$; $\omega = 2\pi f$ where f is the frequency ($f = 1/T$; s^{-1})
- Vector $\boldsymbol{\omega}$: axis of rotation; magnitude is angular speed (if $\boldsymbol{\omega}$ is curl: speed x2)
  - Beware of different conventions that differ by a factor of ½ !



Cross product of ½$\boldsymbol{\omega}$ with vector to center of rotation ($\mathbf{r}$) gives linear velocity vector $\mathbf{v}$ (tangent)



$$\mathbf{v}^{(r)} = \frac{1}{2}\boldsymbol{\omega} \times d\mathbf{r}$$

Velocity Gradient Tensor and Components (1)

Velocity gradient tensor

(here: in Cartesian coordinates)

$$\nabla \mathbf{v} = \begin{bmatrix} \frac{\partial}{\partial x} v^x & \frac{\partial}{\partial y} v^x & \frac{\partial}{\partial z} v^x \\ \frac{\partial}{\partial x} v^y & \frac{\partial}{\partial y} v^y & \frac{\partial}{\partial z} v^y \\ \frac{\partial}{\partial x} v^z & \frac{\partial}{\partial y} v^z & \frac{\partial}{\partial z} v^z \end{bmatrix}$$

these are the same partial derivatives as before!

$$\nabla \mathbf{v} = \frac{1}{2}\left(\nabla \mathbf{v} + (\nabla \mathbf{v})^T\right) + \frac{1}{2}\left(\nabla \mathbf{v} - (\nabla \mathbf{v})^T\right)$$

Velocity Gradient Tensor and Components (2)

Rate-of-strain (rate-of-deformation) tensor

(symmetric part; here: in Cartesian coordinates)

$$\mathbf{D} = \frac{1}{2}\begin{bmatrix} 2\frac{\partial}{\partial x}v^x & \frac{\partial}{\partial y}v^x + \frac{\partial}{\partial x}v^y & \frac{\partial}{\partial z}v^x + \frac{\partial}{\partial x}v^z \\ \frac{\partial}{\partial x}v^y + \frac{\partial}{\partial y}v^x & 2\frac{\partial}{\partial y}v^y & \frac{\partial}{\partial z}v^y + \frac{\partial}{\partial y}v^z \\ \frac{\partial}{\partial x}v^z + \frac{\partial}{\partial z}v^x & \frac{\partial}{\partial y}v^z + \frac{\partial}{\partial z}v^y & 2\frac{\partial}{\partial z}v^z \end{bmatrix}$$

$$tr(\mathbf{D}) = \nabla \cdot \mathbf{v}$$

Velocity Gradient Tensor and Components (3)

Vorticity tensor (spin tensor)

(skew-symmetric part; here: in Cartesian coordinates)

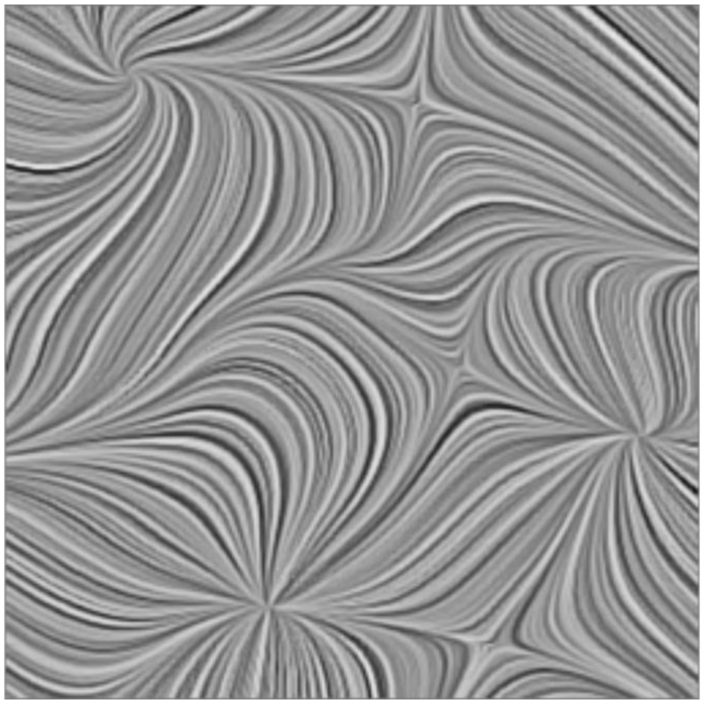
$$\mathbf{S} = \frac{1}{2}\begin{bmatrix} 0 & \frac{\partial}{\partial y}v^x - \frac{\partial}{\partial x}v^y & \frac{\partial}{\partial z}v^x - \frac{\partial}{\partial x}v^z \\ \frac{\partial}{\partial x}v^y - \frac{\partial}{\partial y}v^x & 0 & \frac{\partial}{\partial z}v^y - \frac{\partial}{\partial y}v^z \\ \frac{\partial}{\partial x}v^z - \frac{\partial}{\partial z}v^x & \frac{\partial}{\partial y}v^z - \frac{\partial}{\partial z}v^y & 0 \end{bmatrix}$$

$$\mathbf{S} = \frac{1}{2}\begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix} \qquad \boldsymbol{\omega} \equiv \nabla \times \mathbf{v}$$

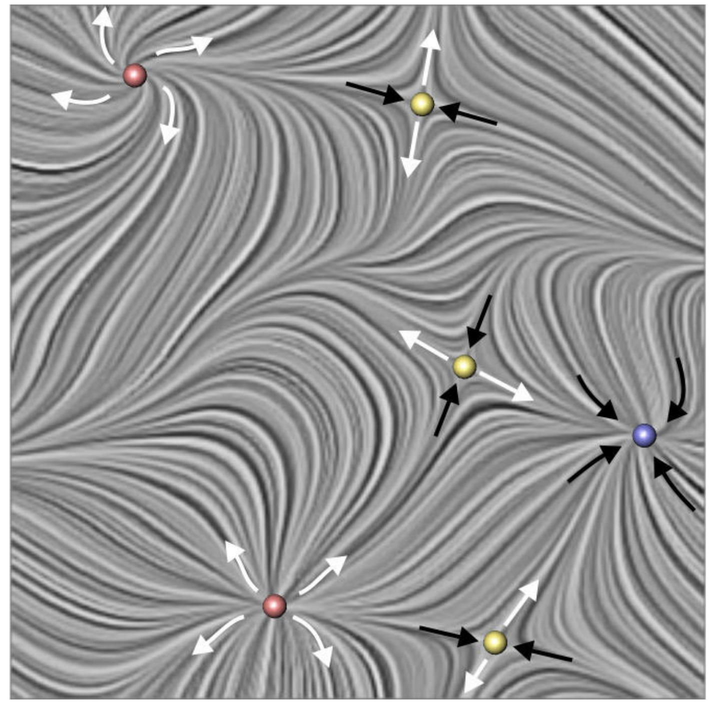
Critical Point Analysis

Critical Points (Steady Flow!)

Classify critical points according to the *eigenvalues* of the velocity gradient tensor at the critical point



stream lines (LIC)



critical points (**v** = 0)

(Non-Linear) Dynamical Systems

Start with system of linear ODEs (with constant coefficients)

- Non-linear systems can be linearized around critical points
- Use linearization for characterization

$\dot{\mathbf{x}} = A\mathbf{x}$ $\quad$ A is an $n \times n$ matrix $\quad \rightarrow \quad$ $\boxed{\begin{aligned} \mathbf{v} &= A\mathbf{x}, \\ \nabla \mathbf{v} &= A. \end{aligned}}$

$$\dot{\mathbf{x}} = \frac{d\mathbf{x}}{dt} = \begin{bmatrix} \frac{dx_1}{dt} \\ \vdots \\ \frac{dx_n}{dt} \end{bmatrix}$$

$$\mathbf{x}(0) = \mathbf{x}_0$$

solution: $\mathbf{x}(t) = e^{At}\mathbf{x}_0$

characterize behavior
through eigenvalues of A

A Few Facts about Eigenvalues and –vectors

The matrix $\begin{bmatrix} c & -s \\ s & c \end{bmatrix}$ has eigenvalues $\lambda_1 = c + s\mathbf{i}$ $\lambda_2 = c - s\mathbf{i}$

with eigenvectors $u_1 = \begin{bmatrix} 1 \\ -\mathbf{i} \end{bmatrix}$ $u_2 = \begin{bmatrix} 1 \\ +\mathbf{i} \end{bmatrix}$

If c = 0, this is a skew-symmetric matrix

Skew-symmetric matrices: “infinitesimal rotations” (infinitesimal generators of rot.)

For $c = \cos\theta$ and $s = \sin\theta$: 2x2 rotation matrix with

$$\begin{aligned} \lambda_1 = e^{\mathbf{i}\theta} &= \cos\theta + \mathbf{i}\sin\theta \\ \lambda_2 = e^{-\mathbf{i}\theta} &= \cos\theta - \mathbf{i}\sin\theta \end{aligned}$$

Eigenvalues

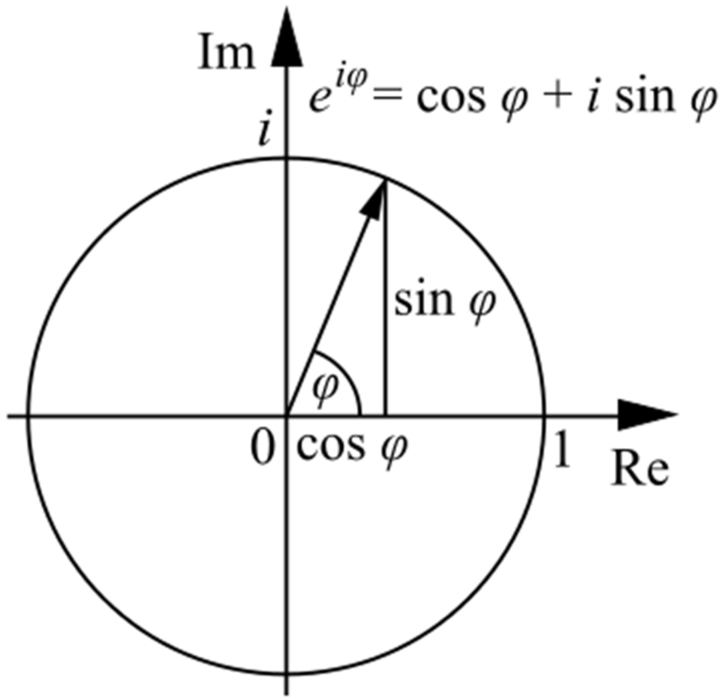
- Symmetric matrix: all eigenvalues are *real*
- Skew-symmetric matrix: all eigenvalues are *pure imaginary*

Euler's Formula

Can be derived from the infinite power series for exp(), cos(), sin()

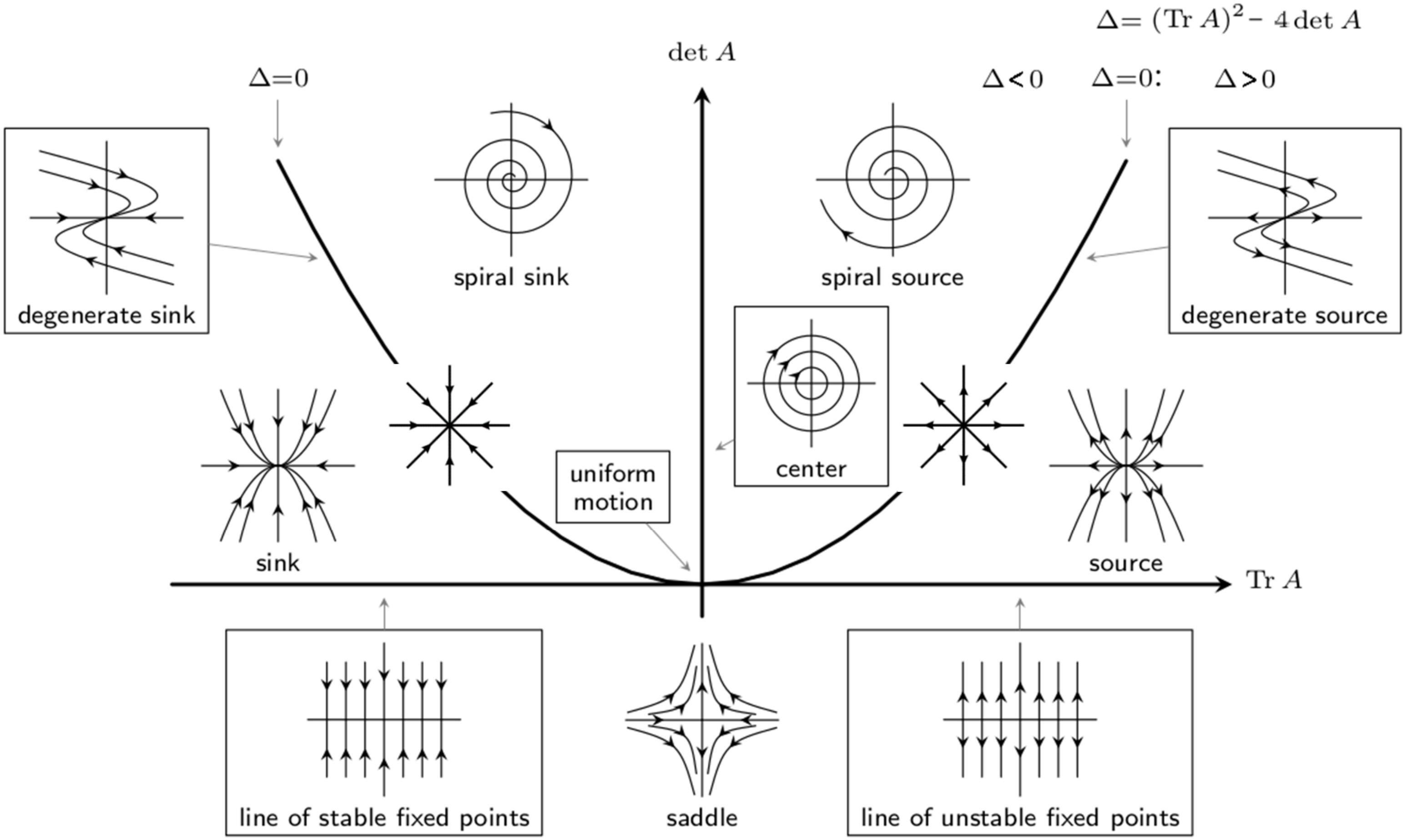
$$e^{ix} = \cos x + i \sin x$$

$$e^{i\pi} + 1 = 0$$



Critical Points (Steady Flow!)

Poincaré Diagram: Classification of Phase Portaits in the $(\det A, \operatorname{Tr} A)$-plane



Matrix Exponentials

Defined via same power series as usual exponential

$$\exp(X) = e^X := \sum_{k=0}^{\infty} \frac{X^k}{k!} = I + X + \frac{X^2}{2!} + \frac{X^3}{3!} + \ldots$$

Easy if *X* is diagonalizable

$$X = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix} \qquad \exp\left(tX\right) = \begin{pmatrix} e^{\lambda_1 t} & 0 \\ 0 & e^{\lambda_2 t} \end{pmatrix}$$

Exponentials of anti-symmetric matrices are rotation matrices

$$X = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \qquad \exp\left(tX\right) = \begin{pmatrix} \cos t & -\sin t \\ \sin t & \cos t \end{pmatrix}$$

Matrix Exponentials

Defined via same power series as usual exponential

$$\exp(X) = e^X := \sum_{k=0}^{\infty} \frac{X^k}{k!} = I + X + \frac{X^2}{2!} + \frac{X^3}{3!} + \ldots$$

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Complex eigenvalues lead to rotation

$$X = \begin{pmatrix} a & -\omega \\ \omega & a \end{pmatrix} \qquad \exp\left(tX\right) = e^{at} \begin{pmatrix} \cos\omega t & -\sin\omega t \\ \sin\omega t & \cos\omega t \end{pmatrix}$$

$$\lambda_{1,2} = a \pm \mathbf{i}\omega$$

Classification of Critical Points

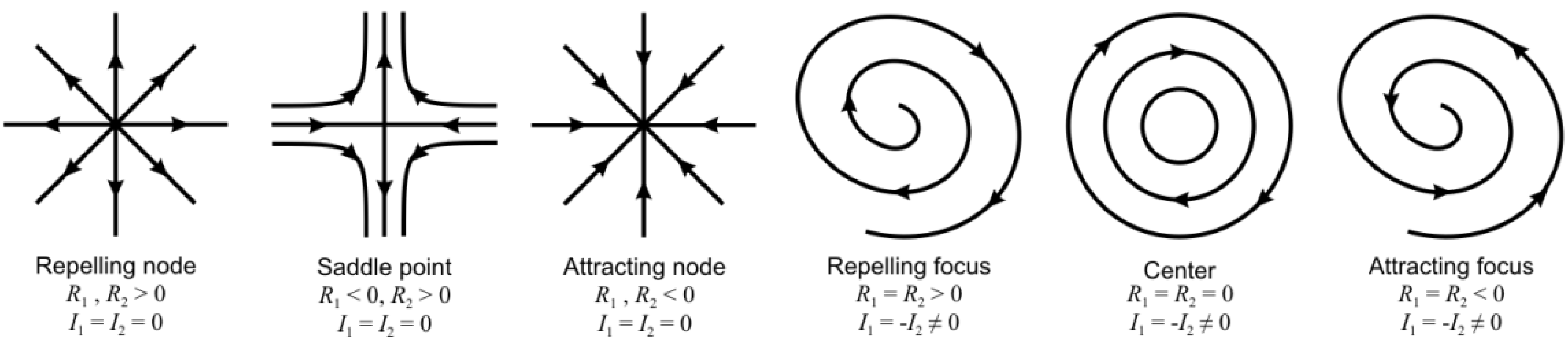
(Isolated) critical point (equilibrium point)

- Velocity vanishes (all components zero)

$$\mathbf{v}(\mathbf{x}_c) = \mathbf{0} \quad \text{with} \quad \mathbf{v}(\mathbf{x}_c \pm \boldsymbol{\epsilon}) \neq \mathbf{0} \qquad\qquad \det(\nabla\mathbf{v}(\mathbf{x}_c)) \neq 0$$

Characterize using velocity gradient $\nabla\mathbf{v}$ at critical point $\mathbf{x}_c$

- Look at eigenvalues (and eigenvectors) of $\nabla\mathbf{v}$

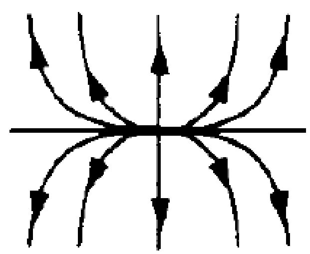


the first three phase portraits are special cases, see later slides!

A Few Details (1)

Repelling/attracting nodes

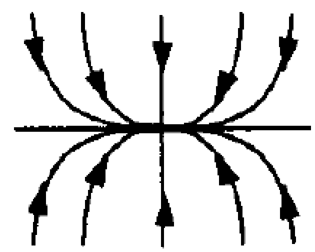
- Do not necessarily imply that streamlines are straight lines (do not confuse with the linear system of ODEs!)
- They are only straight lines when both eigenvalues are real and have the same sign, *and are also equal* (as in the phase portraits before)
- If they are not equal:



Repelling Node

R1, R2 > 0

I1, I2 = 0



Attracting Node

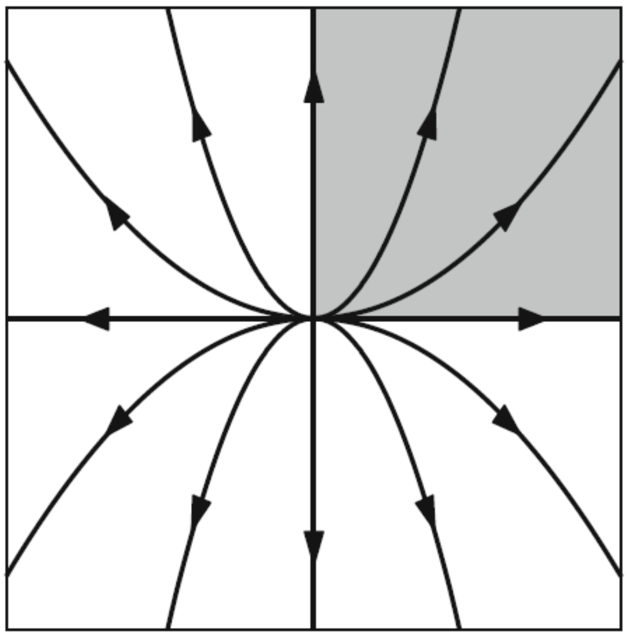
R1, R2 < 0

I1, I2 = 0

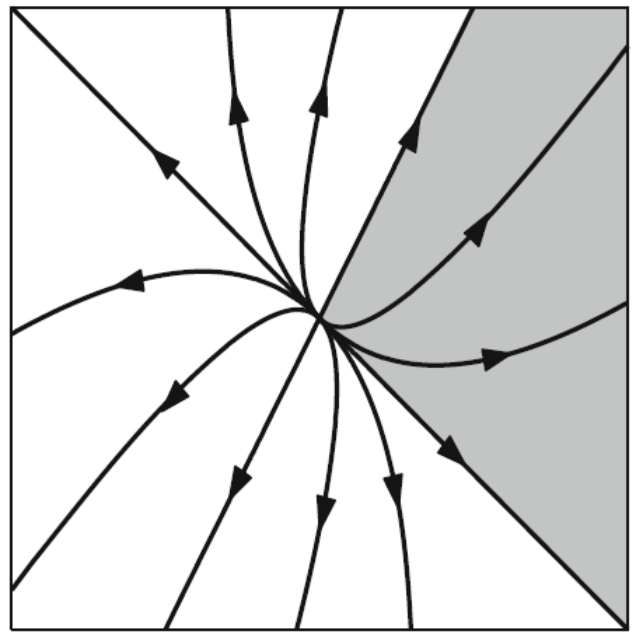
A Few Details (2)

What about skew axes?

- Both of the systems below have eigenvalues 3 and 6
- Jordan normal form (Jordan canonical form) gives details



$$\begin{bmatrix} 3 & 0 \\ 0 & 6 \end{bmatrix}$$



$$\begin{bmatrix} 4 & 1 \\ 2 & 5 \end{bmatrix}$$

Jordan Normal Form (2x2 Matrix)

For every real 2x2 matrix A there is an invertible P such that

$P^{-1}AP$ is one of the following Jordan matrices (all entries are real):

$$J_1 = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \qquad J_2 = \begin{bmatrix} \lambda & 0 \\ 1 & \lambda \end{bmatrix}$$ (defective matrix)

$$J_3 = \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix} \qquad J_4 = \begin{bmatrix} a & -b \\ b & a \end{bmatrix}$$

Each of these has its corresponding rule for constructing P

- Example on prev. slide (the two eigenvectors are not orthogonal):

$$P = \frac{1}{3}\begin{bmatrix} 1 & 1 \\ -1 & 2 \end{bmatrix} \qquad \frac{1}{3}\begin{bmatrix} 2 & -1 \\ 1 & 1 \end{bmatrix}\begin{bmatrix} 4 & 1 \\ 2 & 5 \end{bmatrix}\begin{bmatrix} 1 & 1 \\ -1 & 2 \end{bmatrix} = \begin{bmatrix} 3 & 0 \\ 0 & 6 \end{bmatrix}$$

See also *algebraic* and *geometric multiplicity* of eigenvalues

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(defective matrix)

same eigenvalues,
trace, determinant!

$$J_3 = \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix} \qquad J_4 = \begin{bmatrix} a & -b \\ b & a \end{bmatrix}$$

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See also *algebraic* and *geometric multiplicity* of eigenvalues

Another Example

$P^{-1}AP$ has form J_1

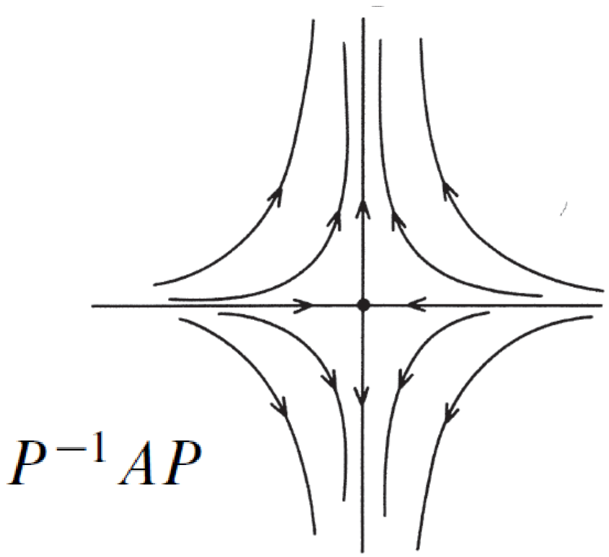
Eigenvalues:

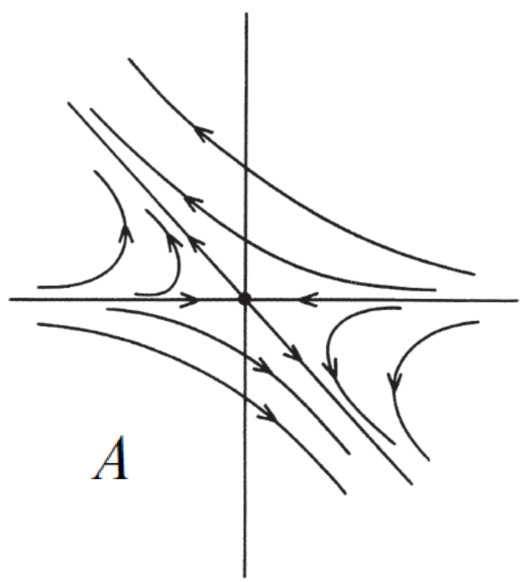
$\lambda_1 = -1$

$\lambda_2 = 2$

$$A = \begin{bmatrix} -1 & -3 \\ 0 & 2 \end{bmatrix}$$

$$P = \begin{bmatrix} 1 & -1 \\ 0 & 1 \end{bmatrix} \qquad P^{-1} = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$$

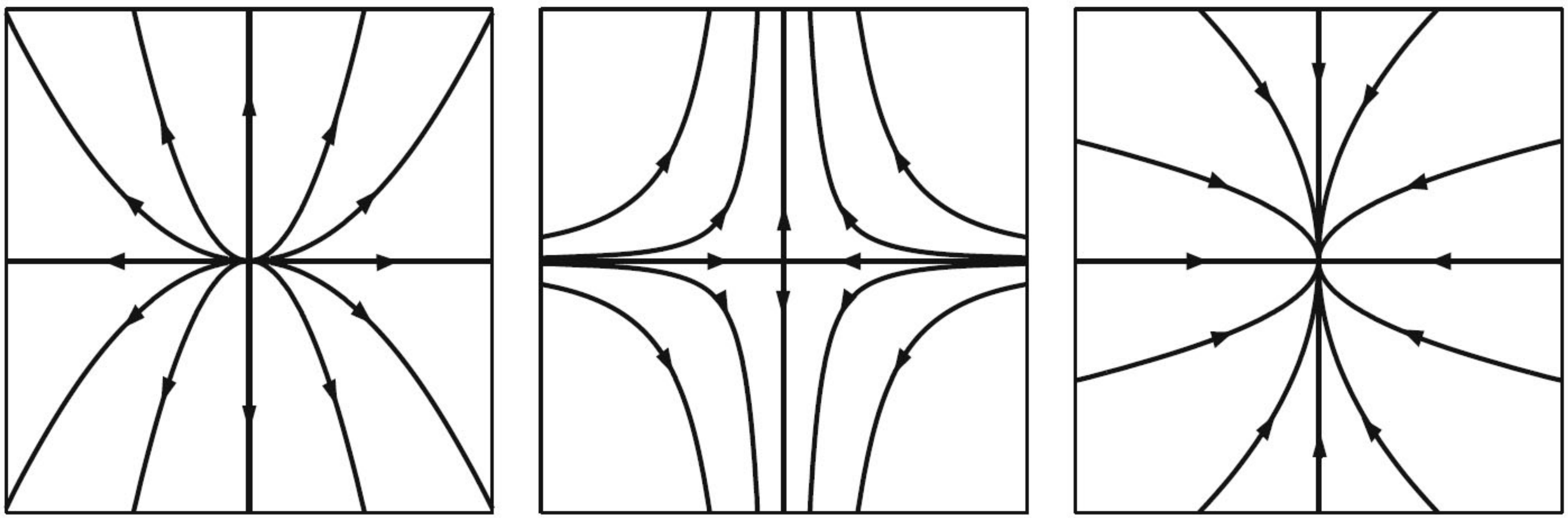




Jordan Form Characterization (1)

Phase portraits corresponding to Jordan matrix

$$J_1 = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix}$$



$0 < \lambda_1 < \lambda_2$
unstable node

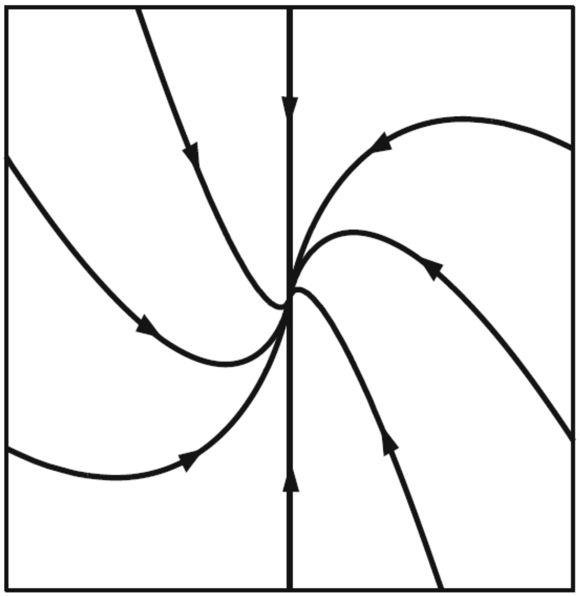
$\lambda_1 < 0 < \lambda_2$
saddle

$\lambda_1 < \lambda_2 < 0$
stable node

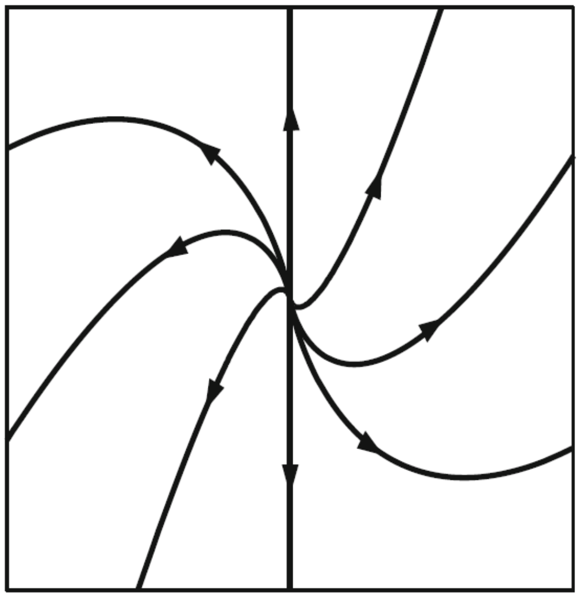
Jordan Form Characterization (2)

Phase portraits corresponding to Jordan matrix
(matrix is defective: eigenspaces collapse,
geometric multiplicity less than algebraic multiplicity)

$$J_2 = \begin{bmatrix} \lambda & 0 \\ 1 & \lambda \end{bmatrix}$$



$\lambda < 0$
stable improper node

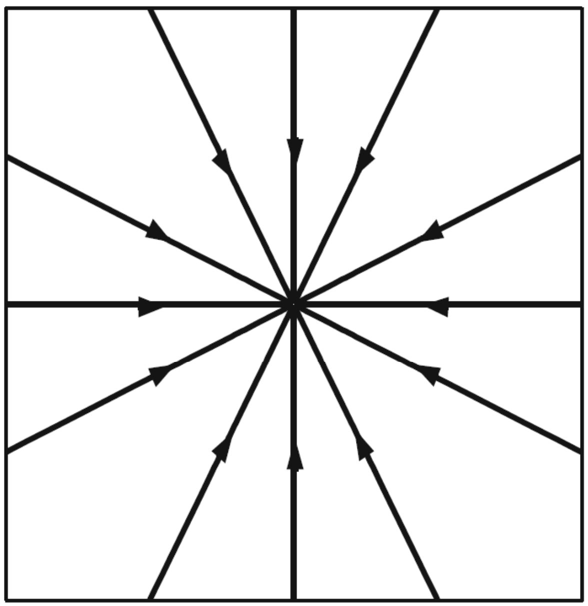


$\lambda > 0$
unstable improper node

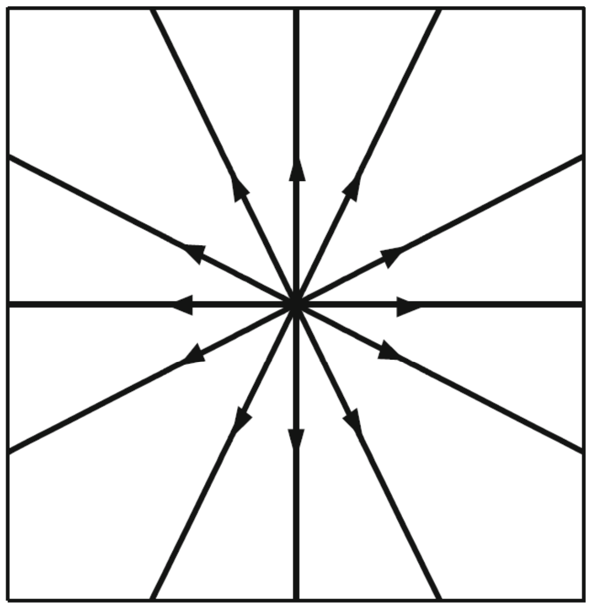
Jordan Form Characterization (3)

Phase portraits corresponding to Jordan matrix

$$J_3 = \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix}$$



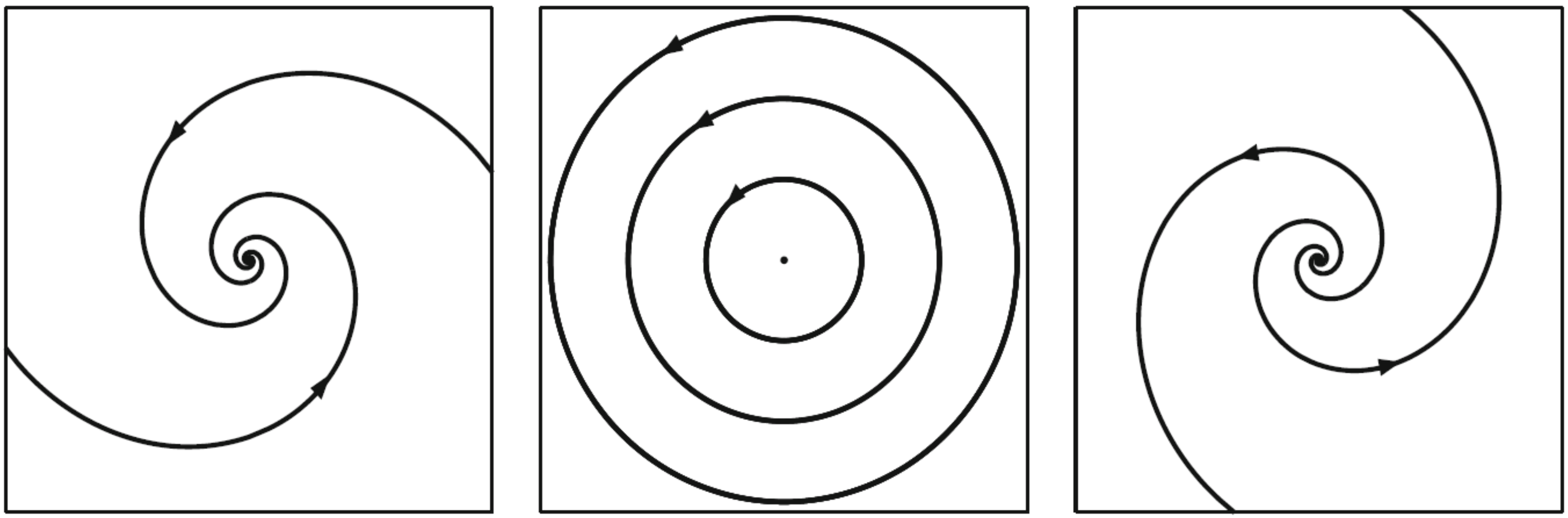
$\lambda < 0$
stable star node



$\lambda > 0$
unstable star node

Jordan Form Characterization (4)

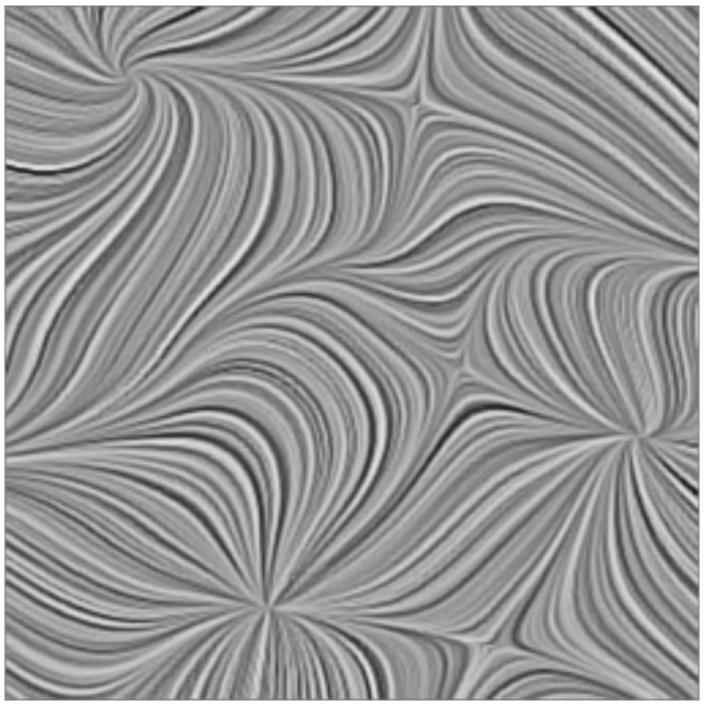
Phase portraits corresponding to Jordan matrix $J_4 = \begin{bmatrix} a & -b \\ b & a \end{bmatrix}$



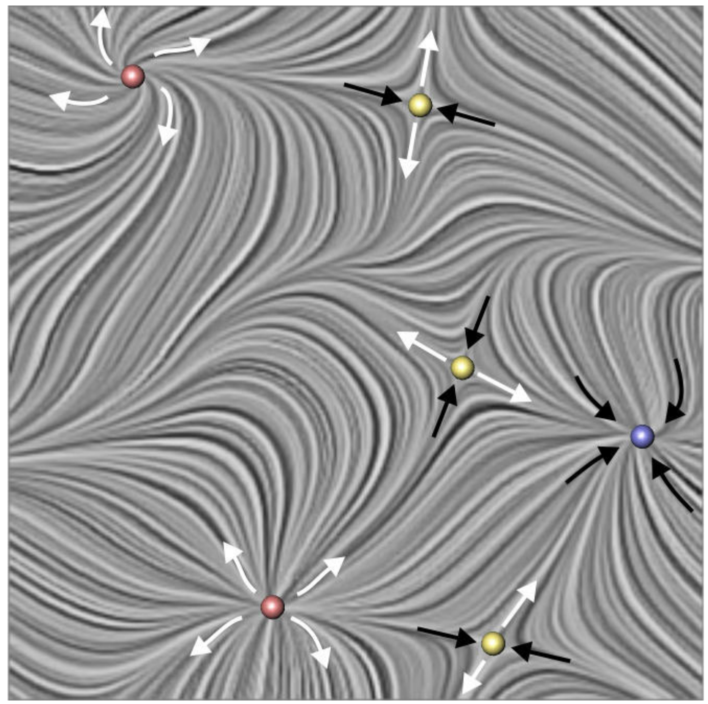
$a < 0$	$a = 0$	$a > 0$
stable spiral node	center	unstable spiral node

Critical Points (Steady Flow!)

Classify critical points according to the *eigenvalues* of the velocity gradient tensor at the critical point



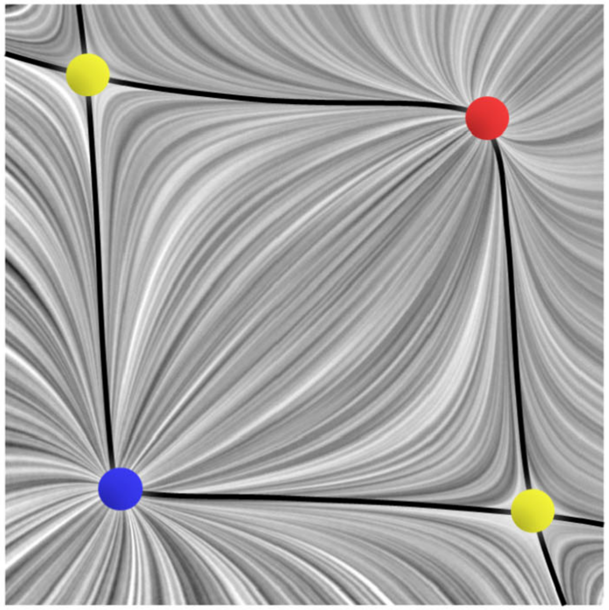
stream lines (LIC)

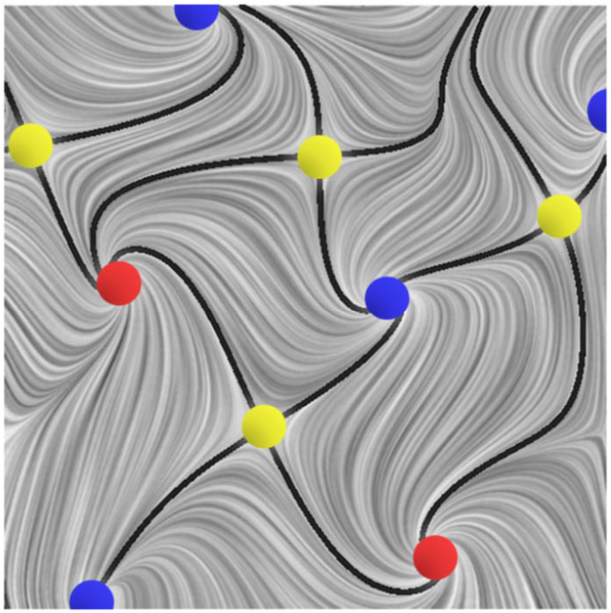


critical points (**v** = 0)

Vector Field Topology: Topological Skeleton

Connect critical points by *separatrices*

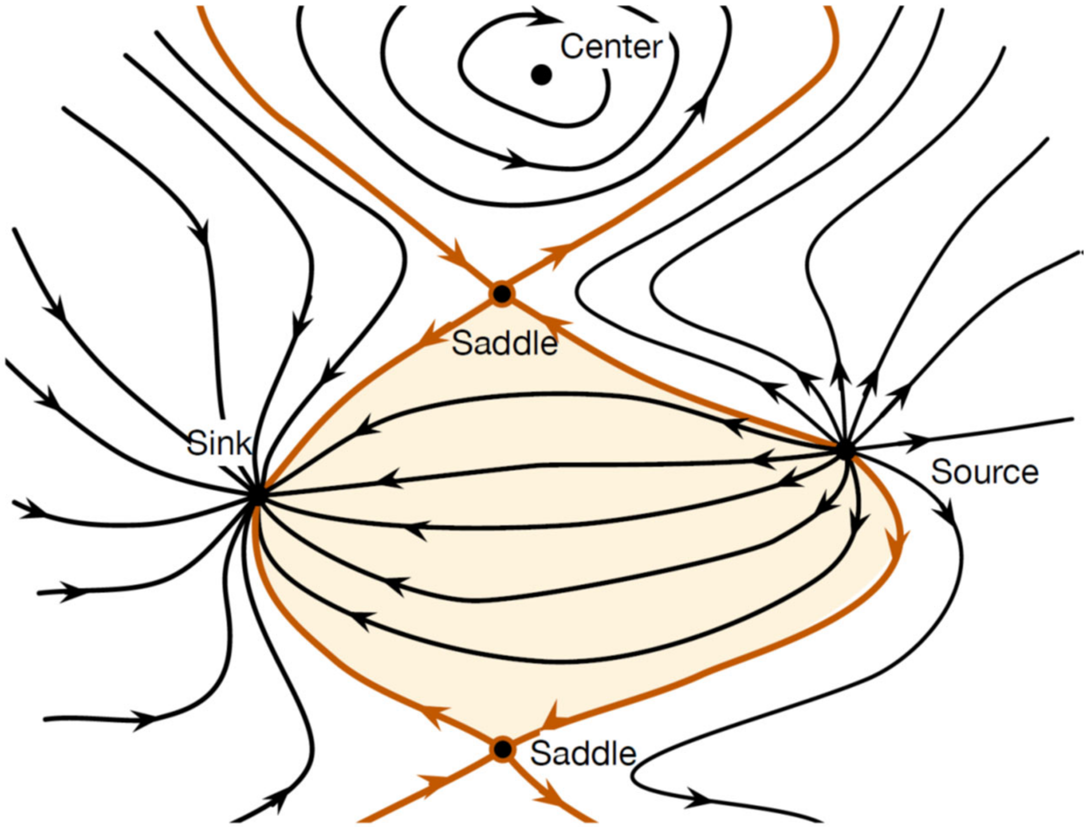




Sources (red), sinks (blue), saddles (yellow)

Vector Field Topology: Topological Skeleton

Connect critical points by *separatrices*



Index of Critical Points / Vector Fields

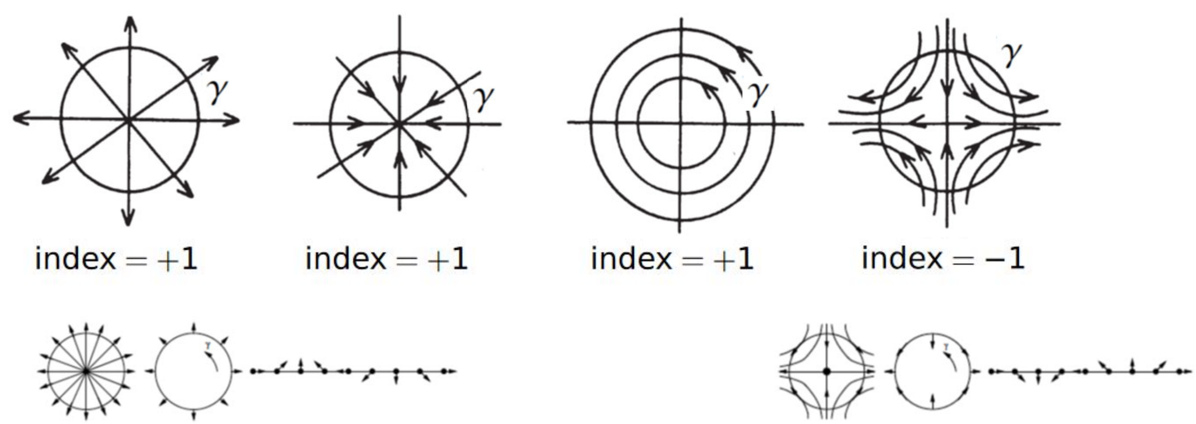
Poincaré index (in scalar field topology we had the *Morse index*)

- Can compute index (winding number) for each critical point
- Index of a region is the sum of the critical point indexes inside
- Sum of all indexes over a manifold is its Euler characteristic

Do a loop (Jordan curve) around each critical point: the index is its (Brouwer) degree: integer how often the vector field along the loop turns around (determined by angle 1-form integrated over oriented 1-manifold)

$$\text{index}_\gamma = \frac{1}{2\pi} \oint_\gamma \mathrm{d}\alpha$$

$$\alpha = \arctan \frac{v}{u}$$

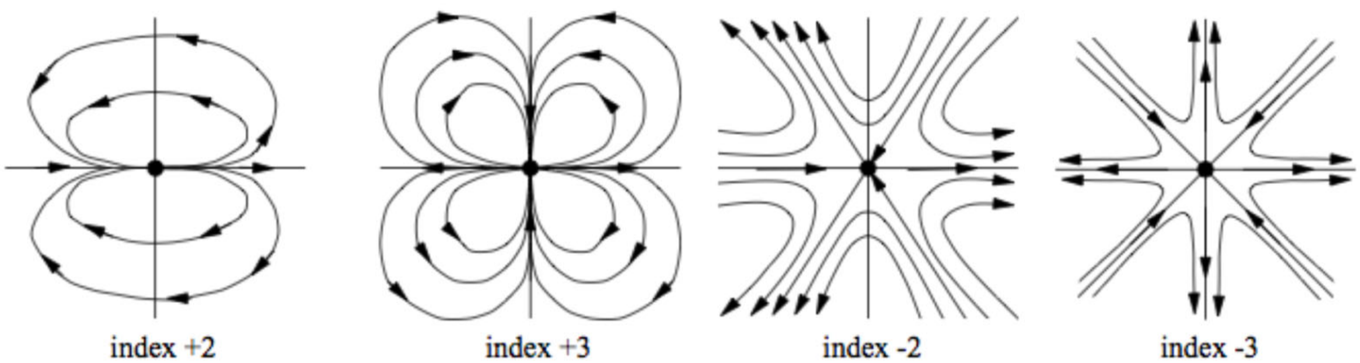


Higher-Order Critical Points

Higher than first-order

- Sectors can by elliptic, parabolic, hyperbolic
- For index sum over number of elliptic and hyperbolic sectors

$$\text{index}_{cp} = 1 + \frac{n_e - n_h}{2}$$



(dipole)

(see monkey saddle)

Example: Differential Topology

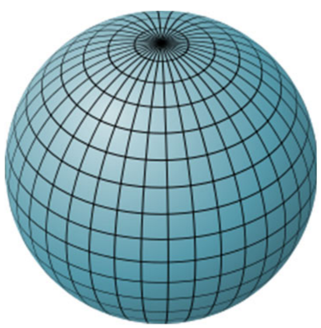
Topological information from vector fields on manifold

- Independent of actual vector field! Poincaré-Hopf theorem
- Useful constraints: vector field editing, simplification, sphere always has critical point, …

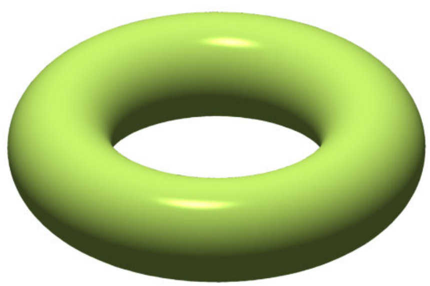
Topological invariant: Euler characteristic $\chi(M)$ of manifold M

(for 2-manifold mesh: $\chi(M) = V - E + F$)

$\chi = 2 - 2g$ (orientable)



genus $g = 0$
Euler characteristic $\chi = 2$

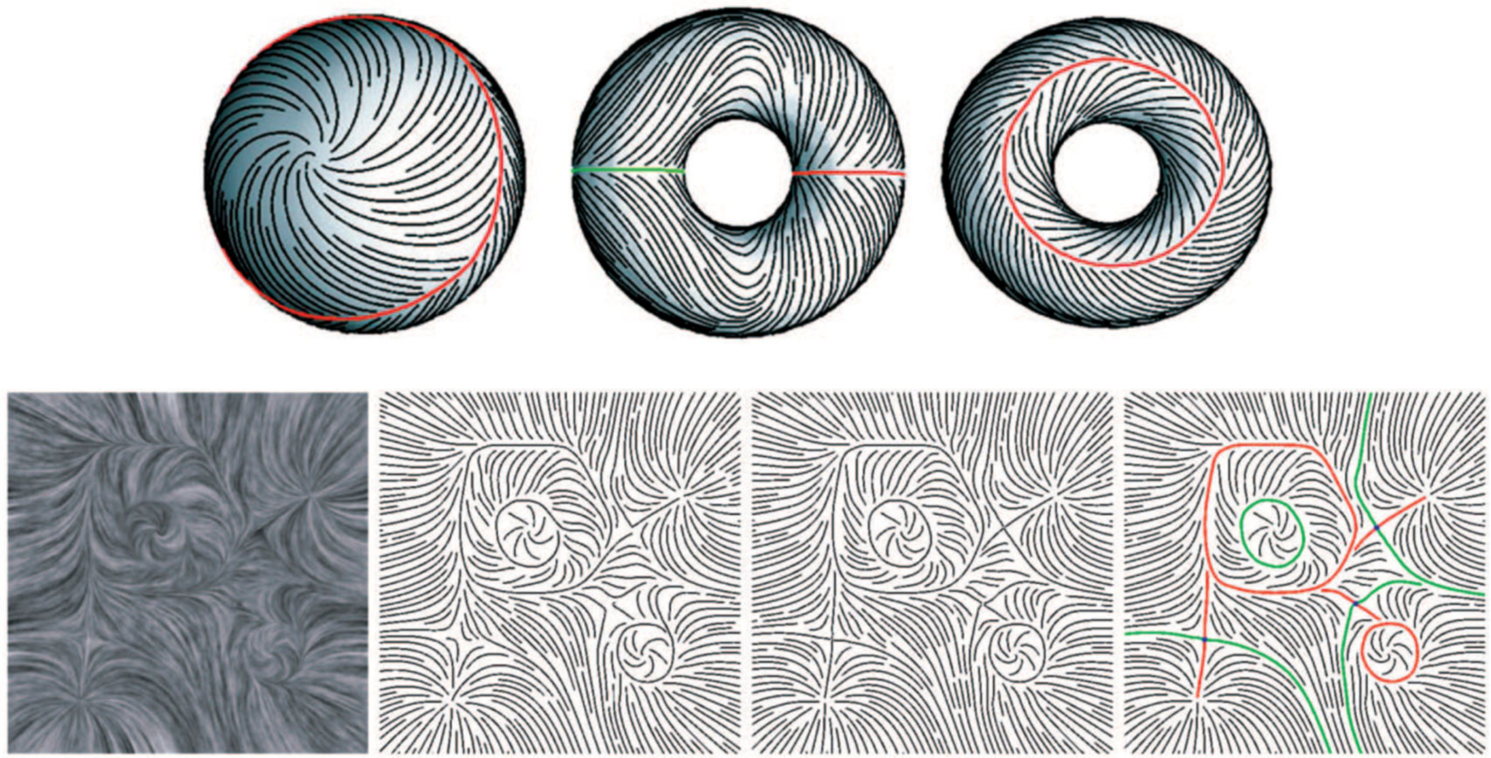


genus $g = 1$
Euler characteristic $\chi = 0$

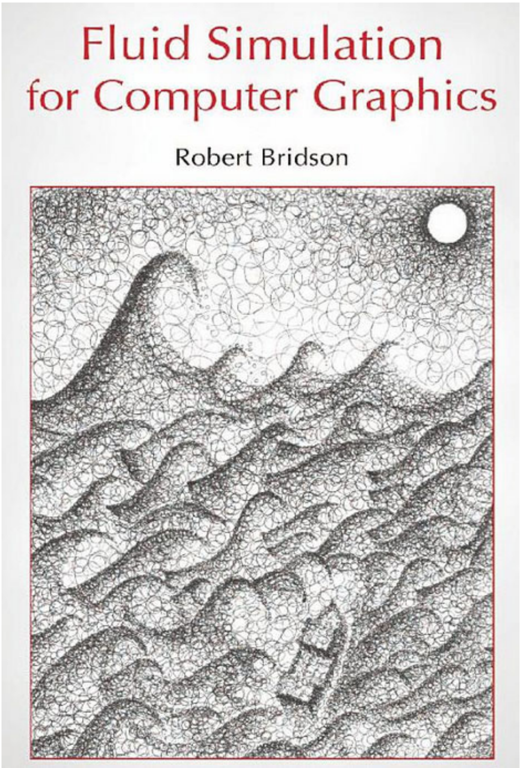
genus $g = 2$
Euler characteristic $\chi = -2$

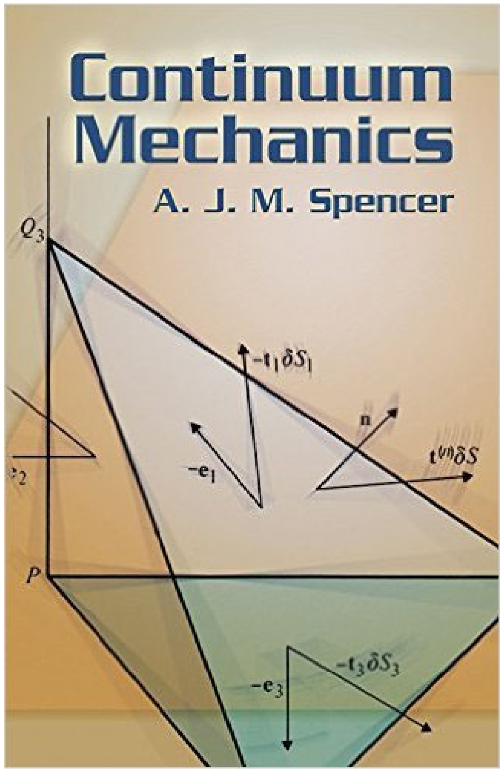
Example: Vector Field Editing

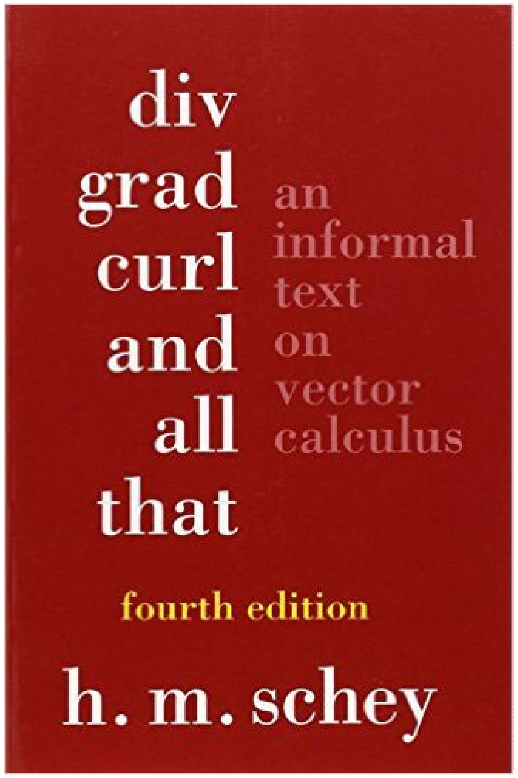
Guoning Chen et al., Vector Field Editing and Periodic Orbit Extraction Using Morse Decomposition, IEEE TVCG, 2007



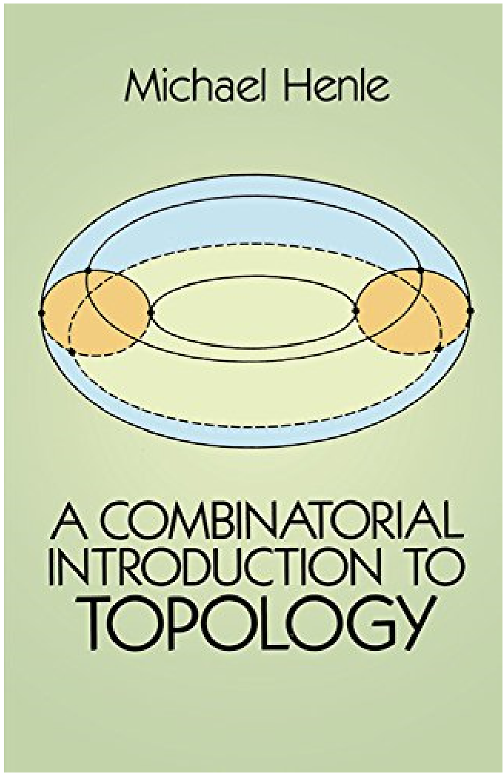
Recommended Books (1)

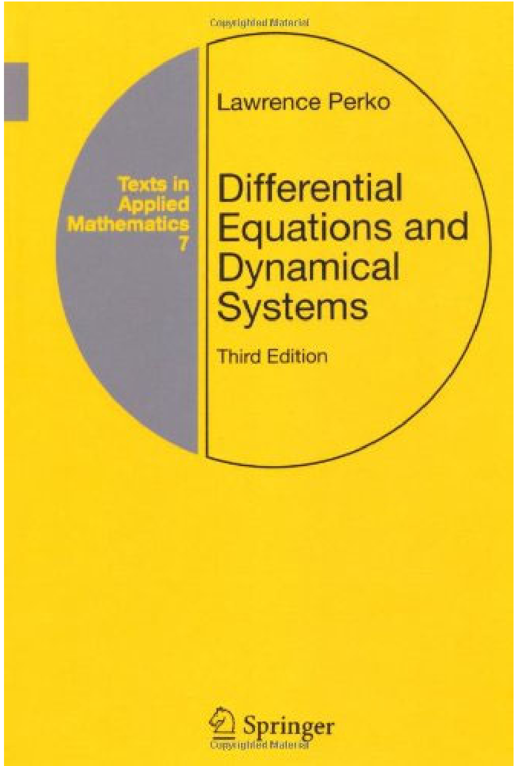


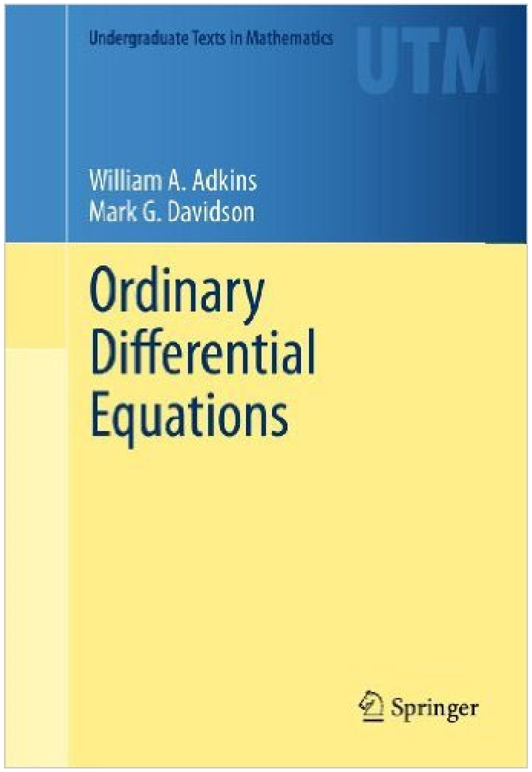




Recommended Books (2)







Thank you.

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