English summary

2 Phenomenological Models

+ few equations, simple nonlinearities, feasible for bifurcation analysis
− only qualitative agreement of time series, low physiological correspondence

2.1 FitzHugh-Nagumo model

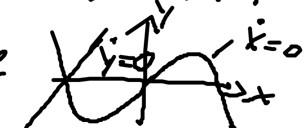
$$\varepsilon \dot{x} = x - \frac{x^3}{3} - y \qquad x: \text{activator} \qquad a: \text{bifurcation parameter}$$

$$\dot{y} = x + a - \gamma y \qquad y: \text{inhibitor} \qquad \varepsilon: \text{time scale separation } \varepsilon \ll 1 \; \begin{cases} x: \text{fast} \\ y: \text{slow} \end{cases}$$

extended FHN

$$\left.\begin{array}{l} |a|<1: \text{oscillatory (limit cycle)} \\ |a|>1: \text{excitable (fixed point)} \end{array}\right\} \quad (x^*, y^*) = \left(-a, -a + \frac{a^3}{3}\right) \quad \begin{array}{l} \text{unstable for } |a|<1 \\ \text{stable for } |a|>1 \end{array}$$

- also known / initially introduced as Bonhoeffer – van der Pol model



- Canard trajectory separates subthreshold oscillations from large excursions
- in phase space
- excitability type II: at bifurcation point, limit cycle starts with amplitude 0 and finite frequency $\operatorname{Im} \lambda \big|_{|a|=1} = \frac{1}{\sqrt{\varepsilon}}$

2.2 SNIPER model

Saddle-node infinite period bifurcation

$$\left.\begin{array}{l} \dot{x} = x(1-x^2-y^2) + y(x-b) \\ \dot{y} = y(1-x^2-y^2) - x(x-b) \end{array}\right\} \overset{x = r\cos\varphi}{\underset{y = r\sin\varphi}{\Longleftrightarrow}} \left\{\begin{array}{l} \dot{r} = r(1-r^2) \\ \dot{\varphi} = b - r\cos\varphi \end{array}\right.$$

fixed points: trivial $(x_A^*, y_A^*) = (0,0)$ with eigenvalues $\lambda_{1,2} = 1 \pm ib$ (focus)

exist only for $|b|<1$
$$\begin{cases} (x_B^*, y_B^*) = (+b, \sqrt{1-b^2}) & \text{with } \underset{\text{stable}}{\lambda_1 = -2}, \; \underset{\text{unstable direction}}{\lambda_2 = \sqrt{1-b^2}} \text{ (saddle)} \\ (x_C^*, y_C^*) = (+b, -\sqrt{1-b^2}) & \end{cases}$$

2.2 SNIPER-Modell (Fortsetzung)

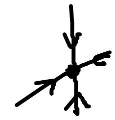
Jacobi-Matrix:
$$\underline{\underline{DF}} = \begin{pmatrix} 1 - 3x^2 - y^2 + y & -2xy + x - b \\ -2xy - 2x - b & 1 - x^2 - 3y^2 \end{pmatrix}$$

3. Fall: $(x_C^*, y_C^*) = (b, -\sqrt{1-b^2})$ → charakteristische Gleichung

$$\det\left(\underline{\underline{DF}}\big|_{x_C^*, y_C^*} - \Lambda \mathbb{1}\right) = \ldots = \underbrace{(\Lambda + 2)}\underbrace{(\Lambda + \sqrt{1-b^2})}$$

$\Lambda_1 = -2 \quad \Lambda_2 = -\sqrt{1-b^2}$

$\Rightarrow$ beide Eigenwerte sind negativ $\Rightarrow$ Knoten (zwei stabile Richtungen) (node)



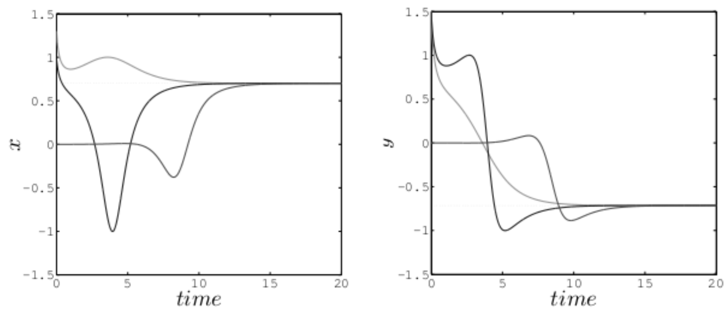
An der Bifurkation $|b|=1$: $(x_B^*, y_B^*) = (1,0) = (x_C^*, y_C^*)$

$\Rightarrow$ Fixpunkte B und C entstehen gleichzeitig bei $|b|=1$

$\Rightarrow$ intrinsische Zeitskala $T \sim \frac{1}{\mathrm{Im}\,\Lambda} \to \infty$ (infinite period)

Dynamische Szenarien:

(i) unterhalb der Bifurkation $|b|<1$ z.B.: $b = 0.7$

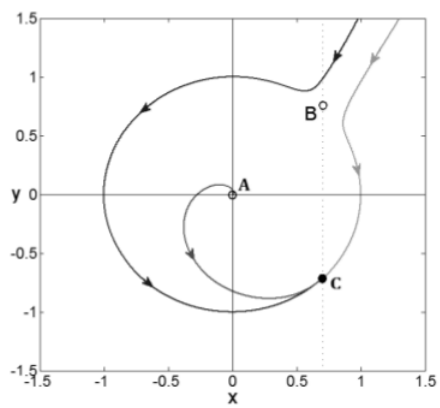


3 Fixpunkte:

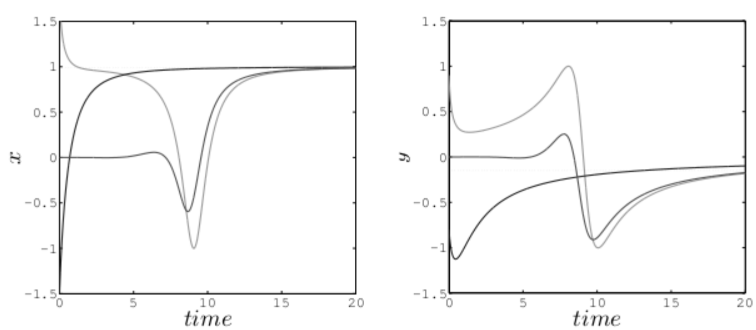
Fokus A

Sattel B

Stabiler Knoten C

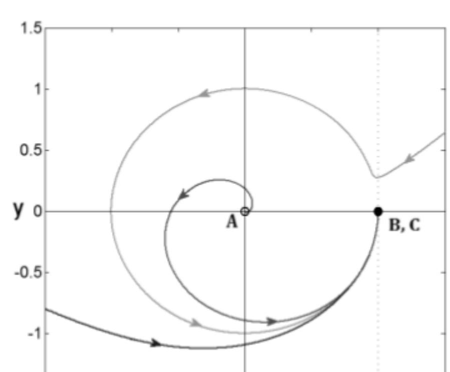


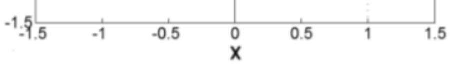
(ii) an der Bifurkation $|b|=1$



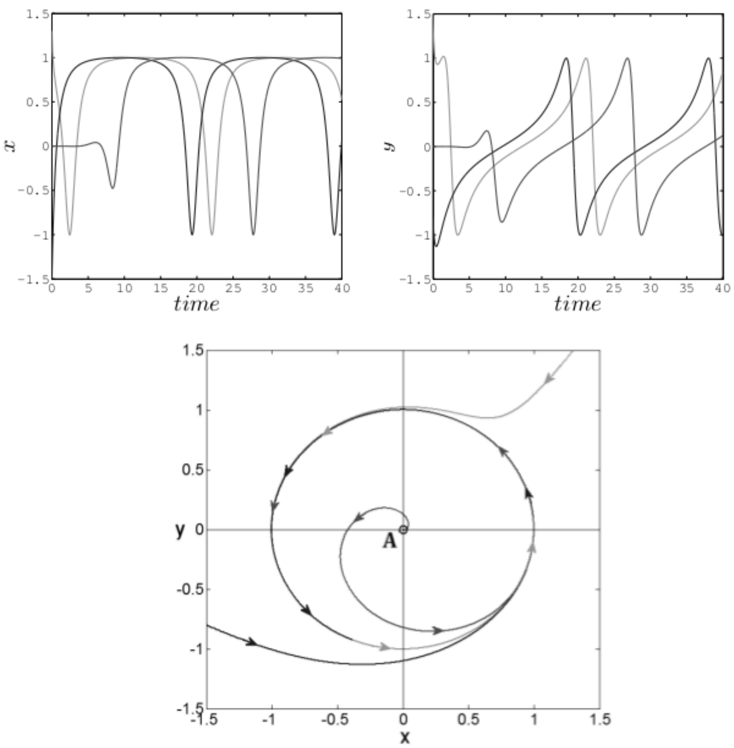
Fokus A

Fixpunkte (Sattel & Knoten) kollidieren





(iii) oberhalb der Bifurkation $|b|>1$ z.B. $b=1.05$



Fokus A

Grenzzyklus mit Radius $\sqrt{x^2+y^2}=1$

langsame Dynamik in der Nähe der ehemaligen Fixpunkte B, C, d.h. in der Nähe von $(1,0)$

$\Rightarrow$ Geist der Sattelknoten-Bifurkation

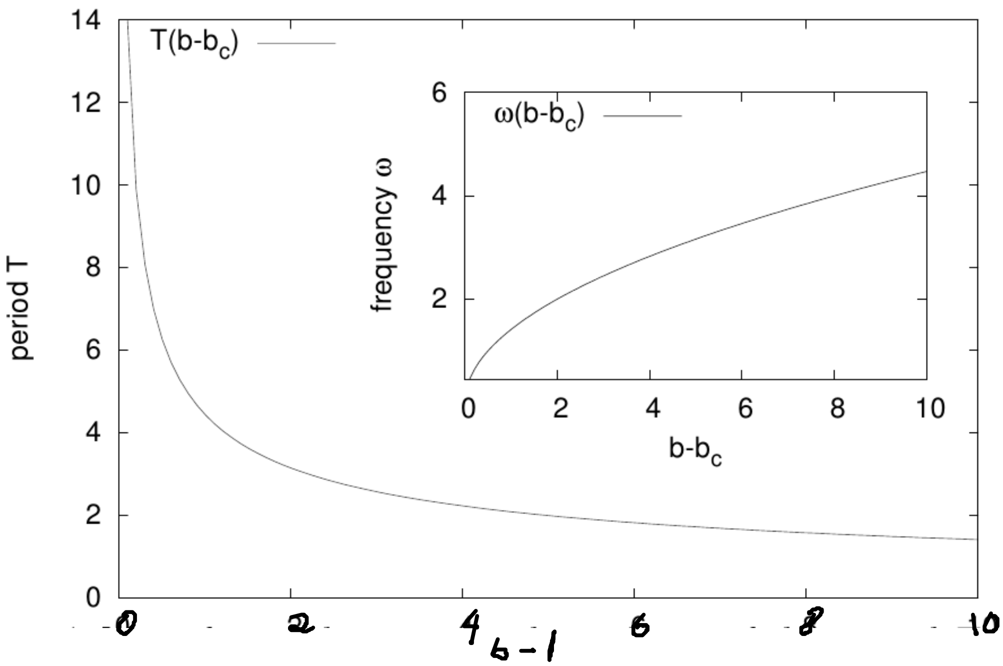
Berechnung der Periode des Grenzzyklus $(|b|>1)$:

$$\dot{\varphi} = b \underset{r=1}{-} \cos\varphi \Rightarrow d\varphi = (b-\cos\varphi)\,dt$$

$$\Rightarrow \frac{d\varphi}{b-\cos\varphi} = dt$$

$$\text{Periode } T = \int_0^{2\pi} \frac{d\varphi}{b-\cos\varphi} = \ldots = \frac{2\pi}{\sqrt{b^2-1}}$$

$\Rightarrow$ Periode T divergiert für $|b| \rightarrow 1$



unendliche Periode T

bei endlicher Amplitude

$r=1$

$\Rightarrow$ Anregbarkeit Typ I

2.3 Hindmarsh-Rose-Modell

zweidimensionale Version

Parameter

$$\dot{x} = c\left(x - \frac{x^3}{3} - y + z\right)$$

kubische Nullkline für x

$$\dot{y} = \frac{1}{c}\left(x^2 + dx - by + a\right)$$

quadratische Nullkline für y

7. Egan, R. W., Galen, P. H., Beveridge, G. C., Phillips, G. B. & Marnett, L. J. *Prostaglandins* **16,** 861–869 (1978).
8. Mason, R. T. & Staszewska-Barczak, J. *J. clin. exp. Pharmac. Physiol.* **6,** 678–685 (1979).
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12. Kemper, F. & Ameln, G. *Z. ges. exp. Med.* **131,** 407–415 (1959).
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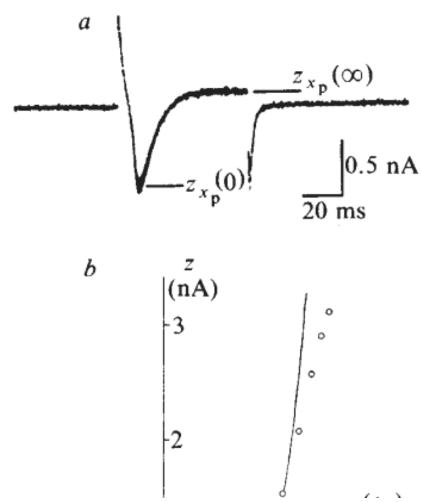
A model of the nerve impulse using two first-order differential equations

J. L. Hindmarsh & R. M. Rose

Department of Applied Mathematics and Astronomy and Department of Physiology, University College, Cardiff, Cardiff CF1 1XL, UK



Thus the assumed form for our equations is

$$\dot{x} = -a(f(x) - y - z) \tag{7}$$

$$\dot{y} = b(f(x) - q\,e^{rx} + s - y) \tag{8}$$

where $f(x) = cx^3 + dx^2 + ex + h$, and a–h, q, r and s are constants. After measuring a and b, and fitting cubic and exponential functions to the $z_{x_p}(0)$ and $z_{x_p}(\infty)$ data of Fig. 1b, the solutions of equations (7) and (8) were obtained by numerical integration.

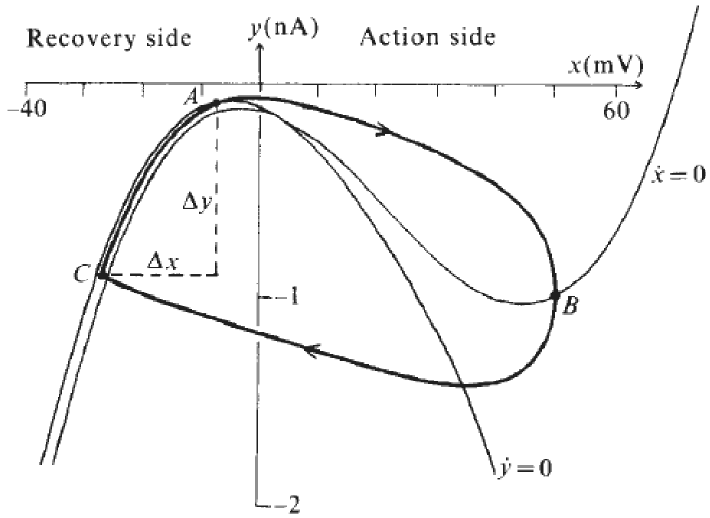


Fig. 3 Phase plane representation of the limit cycle solution to equations (7) and (8). The values of the constants are the same

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BIFURCATIONS IN TWO-DIMENSIONAL HINDMARSH–ROSE TYPE MODEL

SHIGEKI TSUJI*

†*Aihara Complexity Modelling Project, ERATO, JST, 3-23-5-201 Uehara, Shibuya-ku, Tokyo 151-0064, Japan*

TETSUSHI UETA

Center for Advanced Information Technology, The University of Tokushima, 2-1 Minami-Josanjima, Tokushima 770-8506, Japan

HIROSHI KAWAKAMI

The University of Tokushima, 2-24, Shinkura, Tokushima 770-8501, Japan

HIROSHI FUJII

Department of Information and Communication Sciences, Kyoto Sangyo University, Kamigamo-Motoyama, Kita-ku, Kyoto 603-8555, Japan

KAZUYUKI AIHARA†

**Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan*

Bestimmung der Fixpunkte: $\dot{x} = 0$, $\dot{y} = 0$

$\Rightarrow$ Lösung der Gleichung: $\alpha x^3 + \beta x^2 + \gamma x + \delta = 0$

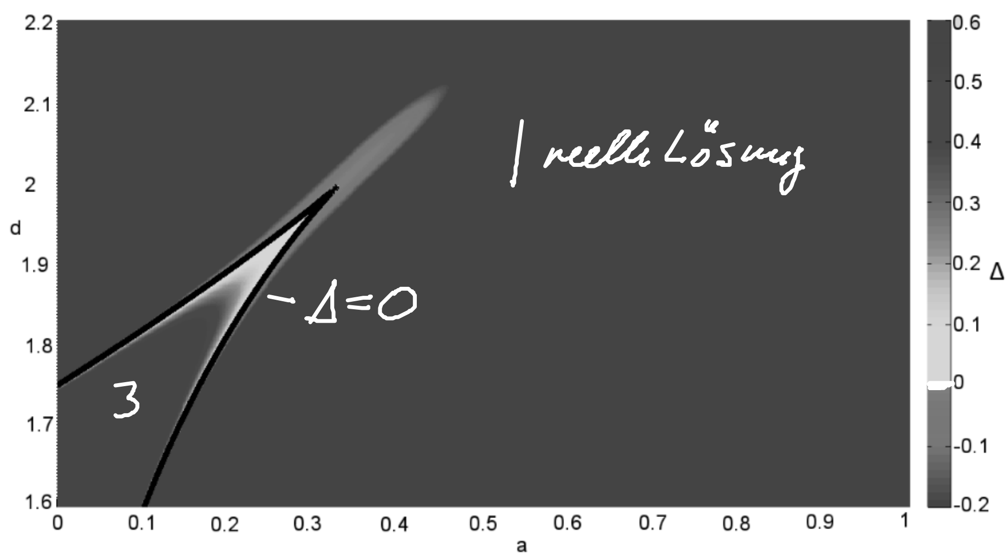
z.B: $b=1$, $c=3$, $z=0$: $\alpha = 1$, $\beta = 3$, $\gamma = 3(d-1) + 3a$

$\Rightarrow$ Berechne die sog. Diskriminante $\Delta = \beta^2\gamma^2 - 4\alpha\gamma^3 - 4\beta^3\delta - 27\alpha^2\delta^2 + 18\alpha\beta\gamma\delta$

(a) $\Delta > 0$: 3 reelle Lösungen

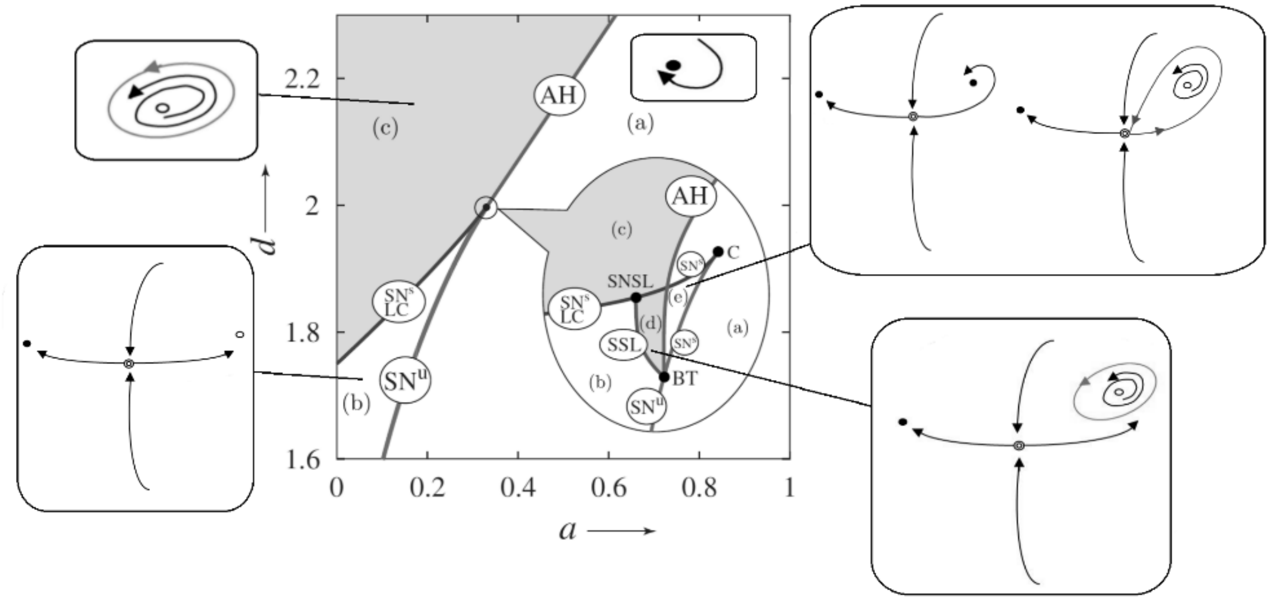
(b) $\Delta = 0$: 1 Lösung mit Vielfachheit 2, 1 weitere Lösung

(c) $\Delta < 0$: 1 reelle Lösung, 2 komplex konjugierte Lösungen



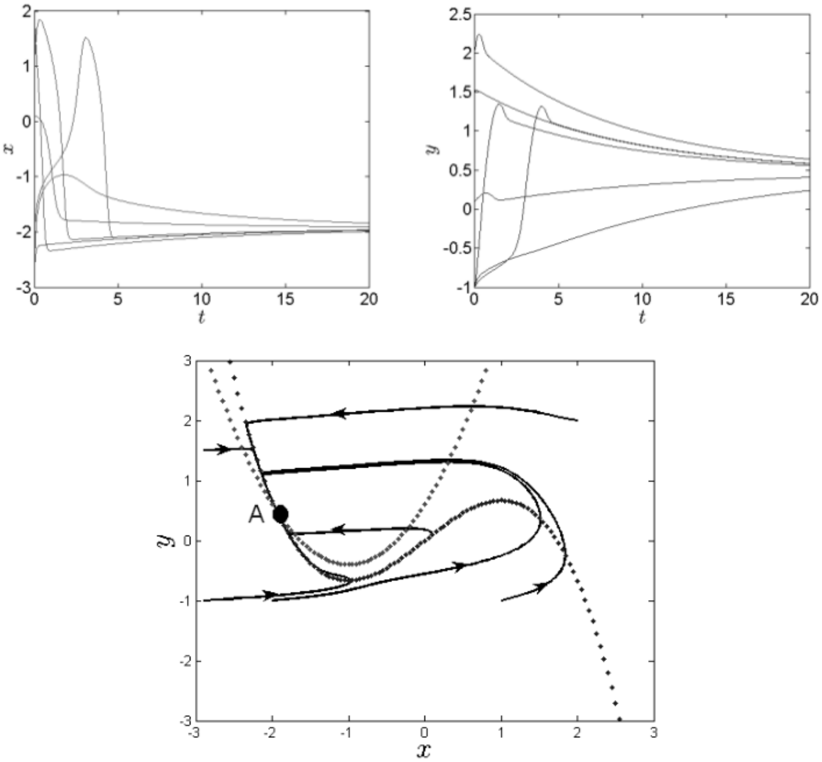
Eigenwerte der linearen Stabilitätsanalyse:

$$\underline{\underline{DF}} = \begin{pmatrix} c - cx^2 & -c \\ \frac{1}{c}(2x+d) & -\frac{b}{c} \end{pmatrix}$$



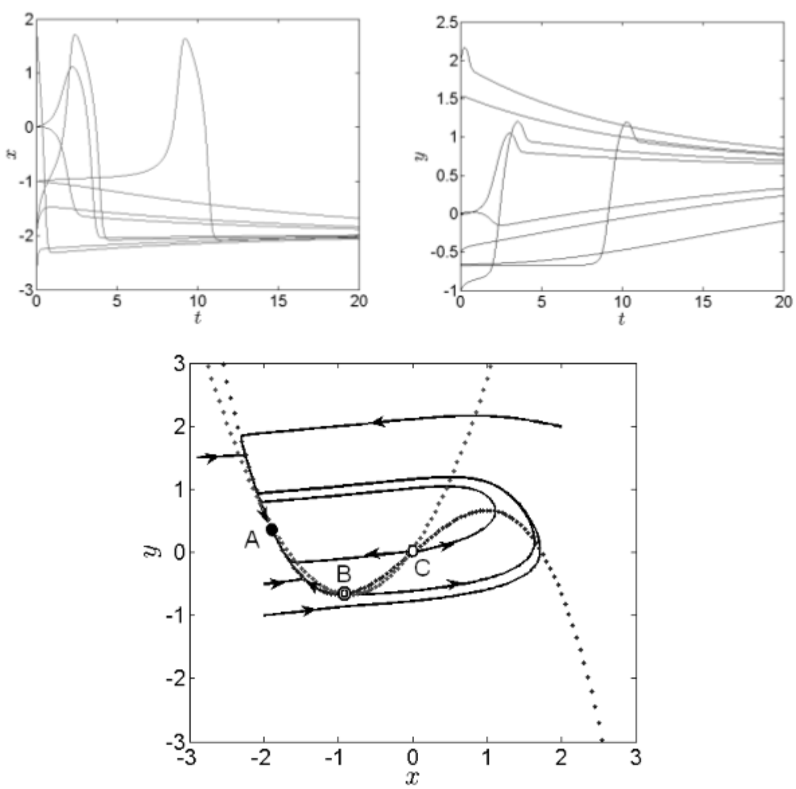
Label	Description
(a)	1 stable fixed point
(b)	1 saddle, 1 stable, 1 unstable fixed point
(c)	1 unstable fixed point, 1 stable limit cycle
(d)	1 saddle, 1 stable fixed points, 1 unstable fixed point, 1 stable limit cycle
(e)	1 saddle, 2 stable fixed points
AH	(Andronov-)Hopf bifurcation
SNLC	Saddle-node bifurcation on a limit cycle
SN	Saddle-node bifurcation (of equilibria)
BT	Bogdanov-Takens bifurcation
C	Cusp bifurcation
SSN	Saddle-separatrix loop bifurcation
SNSL	Saddle-node on separatrix loop bifurcation

(a) $a = 0.6$, $d = 1.7$



stabiler Knoten $\lambda_{1,2} < 0$

(b) $a = 0.05$, $d = 1.7$



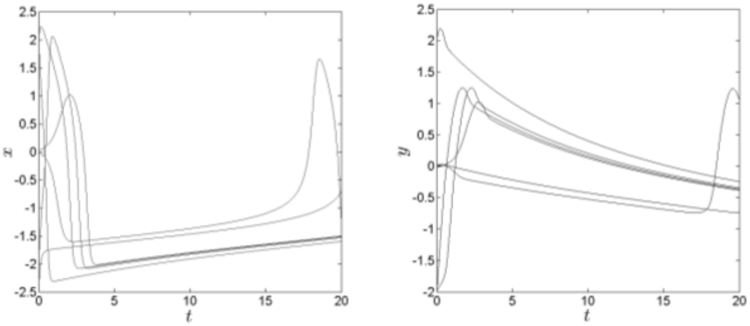
3 Fixpunkte:

stabiler Knoten A: $\lambda_{1,2} < 0$

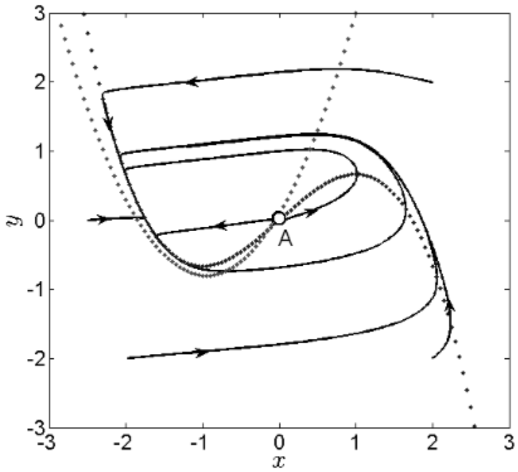
instabiler Knoten B: $\lambda_{1,2} > 0$

Sattelpunkt C: $\lambda_1 < 0$, $\lambda_2 > 0$

(c) $a = 0.1$, $d = 1.9$



instabiler Knoten $\lambda_{1,2} > 0$



Hindmarsh-Rose-Modell mit 3 Variablen:

$\dot{x} = y - ax^3 + bx^2 - z$ kubisch

$\dot{y} = c - dx^2 - y$ quadratisch

$\dot{z} = \varepsilon(s(x - x_0) - z)$ linear

$\Rightarrow$ Bursting-Verhalten