Synergetic Computer and Physical Intelligence

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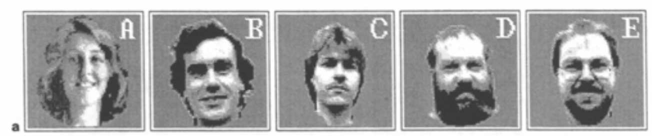
Topics Today

- Synergetic computer
- What is physical intelligence?
- Links between human, artificial, physical intelligence
- Smart physical systems

Synergetic Computer

Haken (1991) Synergetic computers and cognition, Springer
Michael Bestehorn
Lisa Borland
Andreas Daffertshofer
Thomas Ditzinger
Rudolf Friedrich
Armin Fuchs
Michael Schanz
Jens Starke
…

Prototype patterns

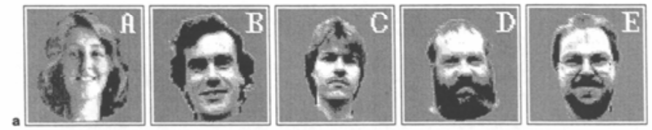


Incomplete initial pattern recognized as prototype

Algorithm for pattern recognition based on self-organization principles

Fuchs, Haken (1988)

Coding: patterns/pictures → vectors



$$\vec{v}_A, \vec{v}_B, \vec{v}_C, \vec{v}_D, \vec{v}_E$$

Time-dependent state vector $\vec{q}(t)$

Evolution equation

$$\frac{d}{dt}\vec{q}(t) = \vec{N}(\vec{q}(t), \vec{v}_A, \vec{v}_B, \vec{v}_C, \vec{v}_D, \vec{v}_E)$$

$\xi_j(t) = \vec{v}_j \bullet \vec{q}(t)$ Pattern amplitudes → order parameters ξ_j

Amplitude equations

$$\frac{d}{dt}\xi_j(t) = \lambda \cdot \xi_j - A \cdot \xi_j^3 - C \cdot \xi_j \sum_{m \neq j} \xi_m^2$$

$$\lambda > 0, A > 0, C > 0$$

Winner-takes-all dynamics

Stable fixed points: one amplitude finite, all others zero

Topics Today

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- **What is physical intelligence?**
- Links between human, artificial, physical intelligence
- Smart physical systems

Physical Intelligence

- Human intelligence
  - General ability including various aspects
  - E.g., ability to store knowledge, evaluate & judge
- Artificial intelligence
  - Algorithms mimicking human intelligence
  - E.g., pattern recognition
- Physical intelligence
  - No consensus on general definition
  - Frequently, physical intelligence refers to intelligence
    - produced in non-algorithmic way
    - by systems of in-animate world
    - or by biological systems without brains

Why Physical Intelligence?

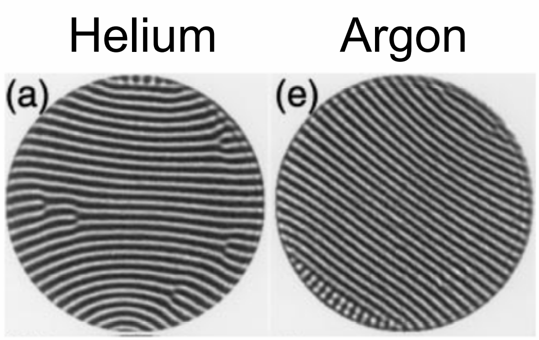
- DARPA (US defense agency)
  - New type of computers → dramatic performance increase
  - E.g., DNA computer
- J. Starke
  - Robust against default
  - Intelligence based on self-organization → self-organization process less likely to break down even if parts go default

Haken (1988)
Bestehorn, Haken (1991)
Haken (1991) Synergetic computers and Cognition, Springer

Are there Intelligent Physical Systems at all?

Lessons from the Synergetic Computer

From the Benard Instability to Artificial Intelligence

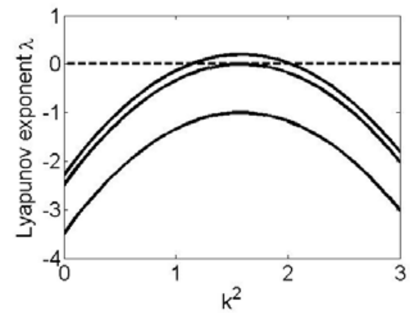


Liu/Ahlers 1996

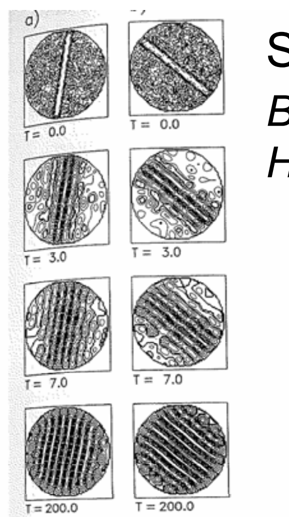
Swift-Hohenberg (SH) model

$$\frac{\partial}{\partial t} c(r,t) = \left(\varepsilon - \left[B + \Delta\right]^2\right) c(r,t) - [c(r,t)]^3$$

-- B>0
-- Control parameter ε
-- Critical value ε=0



- SH-model: Emergence of convection patterns due to Benard instability
- Temperature variation field c(r,t) of a fluid layer with r=(x,y)



Simulations
Bestehorn, Haken 1991

2D → there are several critical modes with $L=L_c$

Evolution equation for amplitudes of critical modes

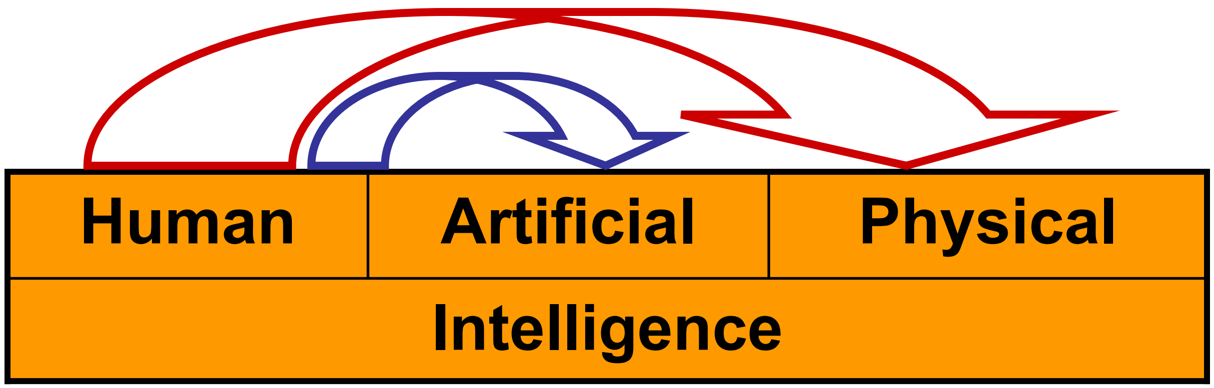
$$\boxed{\frac{d}{dt}\xi_j(t) = \lambda \cdot \xi_j - A \cdot \xi_j^3 - C \cdot \xi_j \sum_{m \neq j} \xi_m^2}$$

Amplitude equations of synergetic computer
Haken (1991)

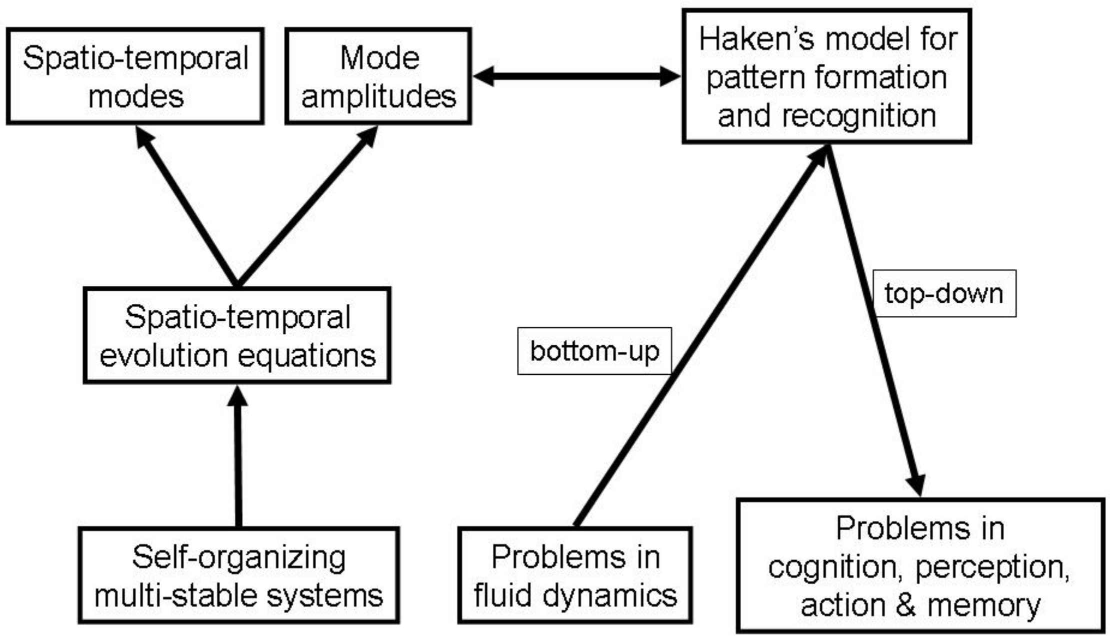
Topics Today

- Synergetic computer
- What is physical intelligence?
- **Links between human, artificial, physical intelligence**
- Smart physical systems

Exploit Links Between HI, AI, PI



Top-down Modeling of Human Intelligent Behavior



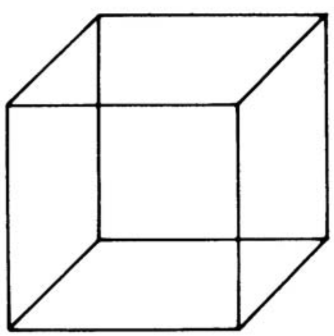
Perception, Action, Cognition (PAC) & Attention Parameter Spectrum

$$\frac{d}{dt}\xi_j(t) = \lambda \cdot \xi_j - A \cdot \xi_j^3 - C \cdot \xi_j \sum_{m \neq j} \xi_m^2$$

$$\frac{d}{dt}\xi_j(t) = \lambda_j \cdot \xi_j - \xi_j^3 - g \cdot \xi_j \sum_{m \neq j} \xi_m^2$$

- Lyaponov exponents of critical modes λ

- PAC
- → Attention parameters
- → Inhomogeneous



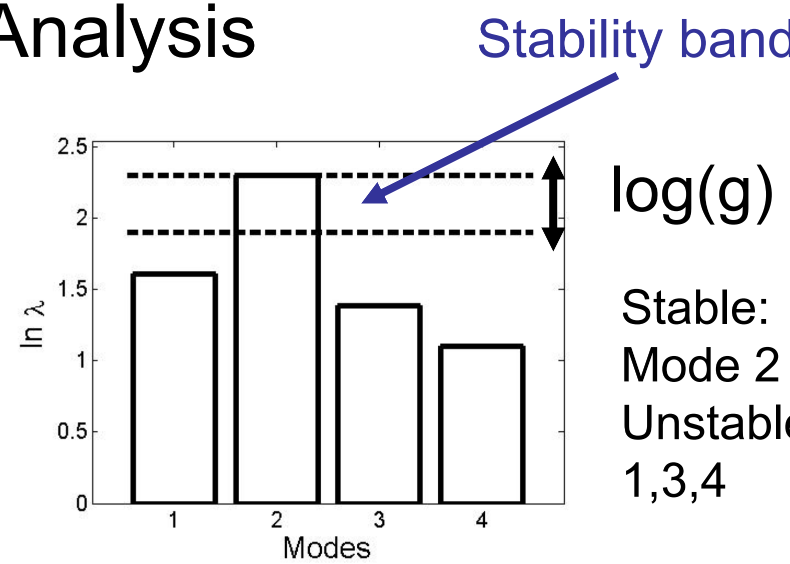
- Oscillatory perception of ambivalent figures *Ditzinger, Haken (1989)*

- Selective perception *Fuchs, Haken (1988)*

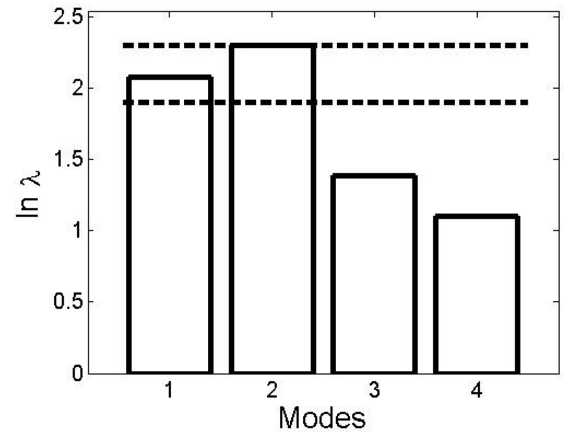
Attention Parameter Spectrum

Stability Analysis

$$\frac{d}{dt}\xi_k(t) = \lambda_k \cdot \xi_k - \xi_k^3 - g \cdot \xi_k \sum_{m \neq k} \xi_m^2$$



Stable:
Mode 2
Unstable:
1,3,4



Stable:
1,2
Unstable:
3,4

- Attention parameter *k* in stability band → mode *k* stable
- Otherwise: unstable

- Mode *k* becomes unstable at $\lambda_k = \lambda(\max)/g$

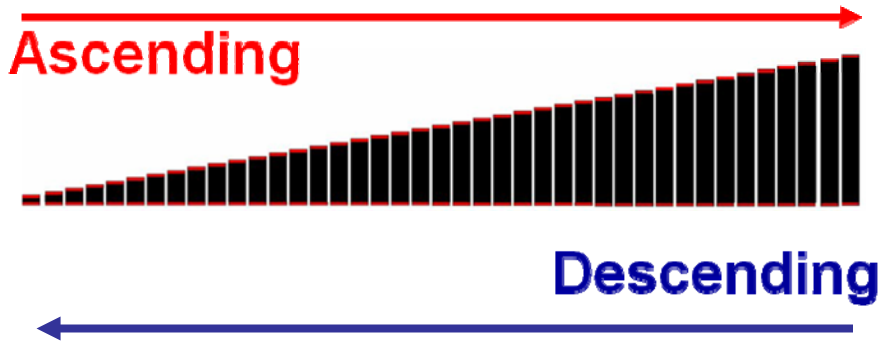
- Attention parameters are bifurcation parameters

Attention Parameters in Perception and Grasping

Holding candy bars on Halloween can easily be done with 1 hand …

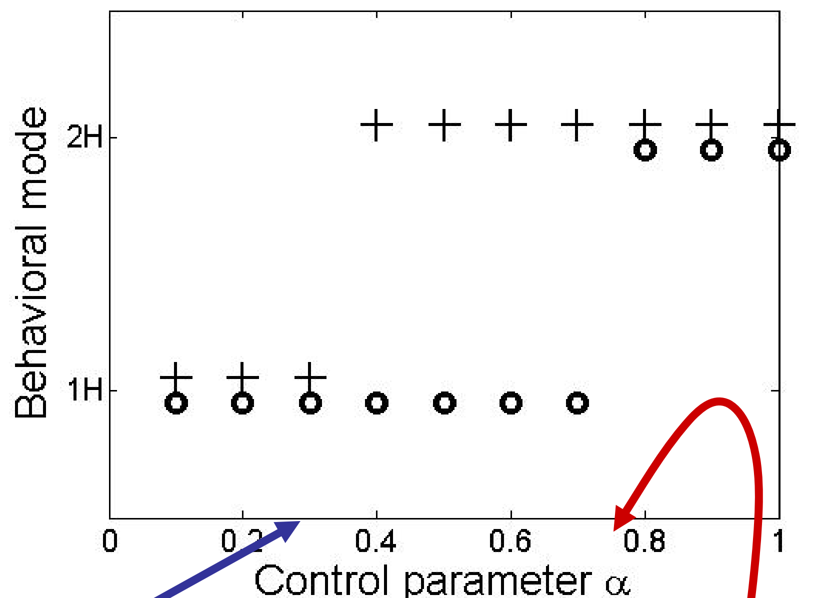
… others thing like first-school-day paper-cones (Germany custom) may better be taken with 2 hands

Perception & Grasping



o **Ascending**

+ **Descending**



Hysteresis

Object size

α(crit,desc)

α(crit,asc)

Perception & Grasping

Frank et al. (2009)

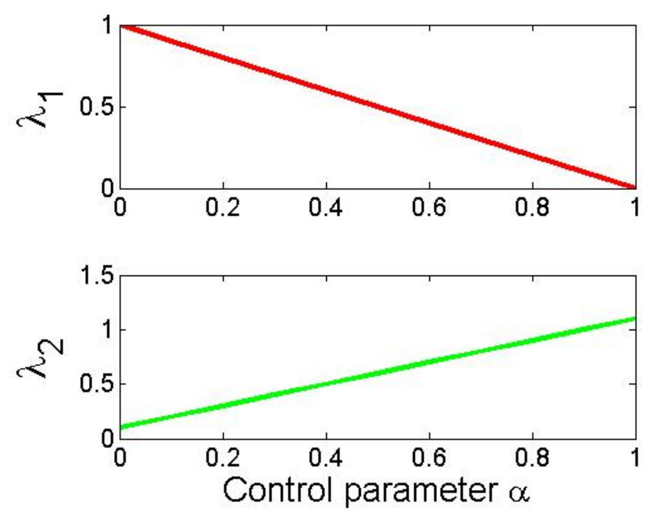
Two modes
j=1: One handed grasp
j=2: Two handed grasp

- Object size (bias)

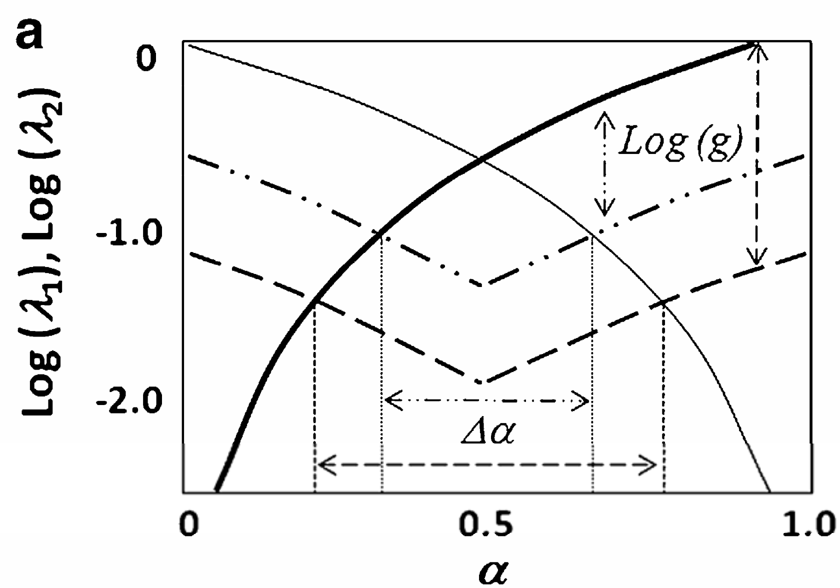
λ_1=1 - α

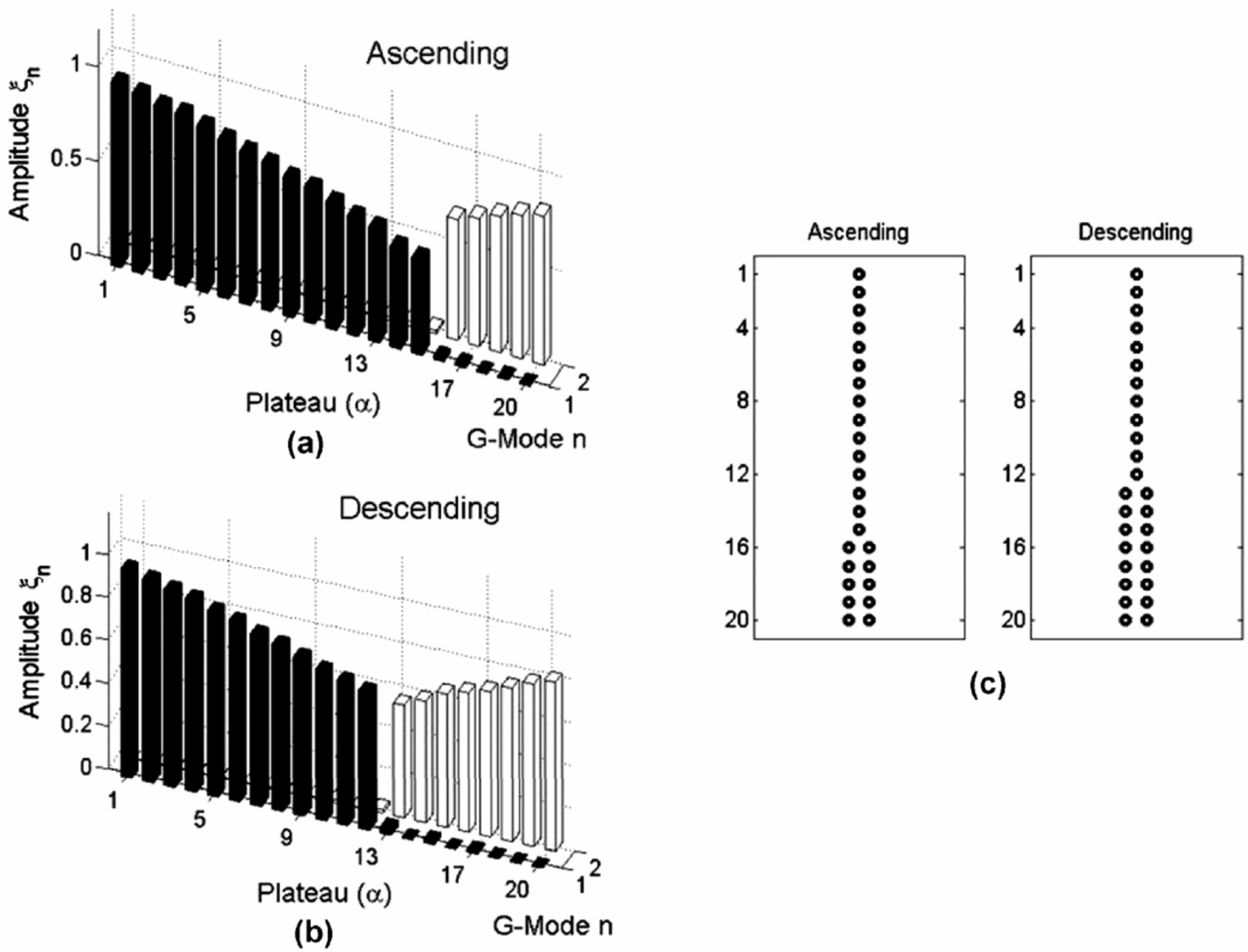
λ_2= +α

$$\frac{d}{dt}\xi_j(t) = \lambda_j \cdot \xi_j - \xi_j^3 - g \cdot \xi_j \sum_{m \neq i} \xi_m^2$$



Bifurcations & Hysteresis




Ascending
Amplitude ξ_n
1
0.5
0
1
5
9
13
17
20
Plateau (α)
2
1
(a)
G-Mode n
Descending
Amplitude ξ_n
1
0.8
0.6
0.4
0.2
0
1
5
9
13
17
20
Plateau (α)
2
1
(b)
G-Mode n
Ascending
Descending
1
4
8
12
16
20
(c)

Lopresti-Goodman et al. (2011)

Model-based Experimentation
Impact on the Coupling Parameter g?

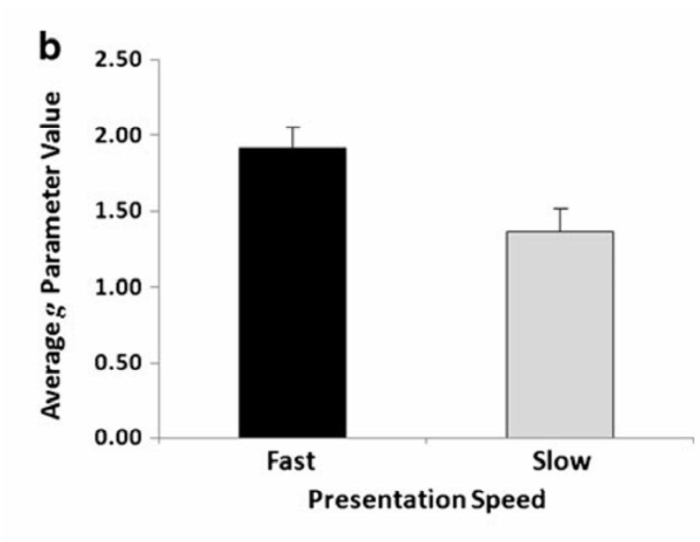
$$\frac{d}{dt}\xi_j(t) = \lambda_j \cdot \xi_j - \xi_j^3 - g \cdot \xi_j \sum_{m \neq j} \xi_m^2$$

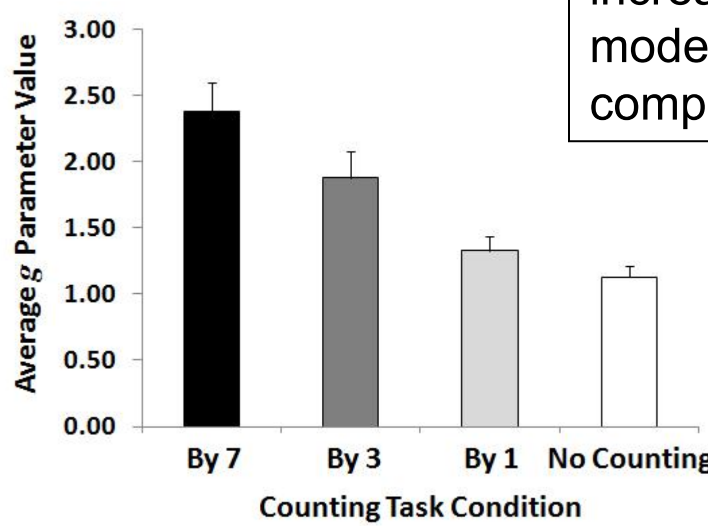
$$\lambda_1 = 1 - \alpha$$

$$\lambda_2 = +\alpha$$

Task difficulty: speed & cognitive load

Task difficulty increases mode-mode competition



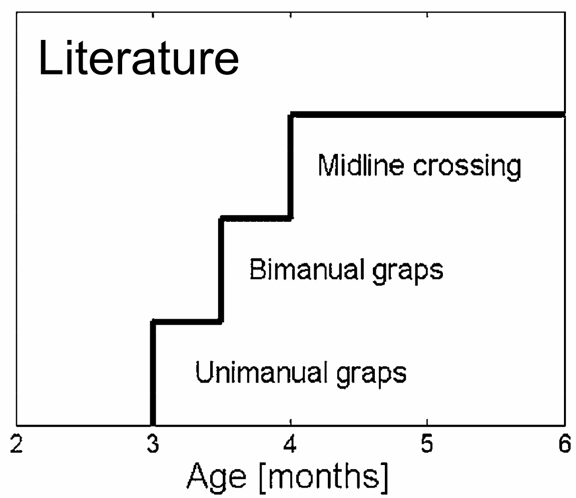


Attention Parameter Dependency on Maturation

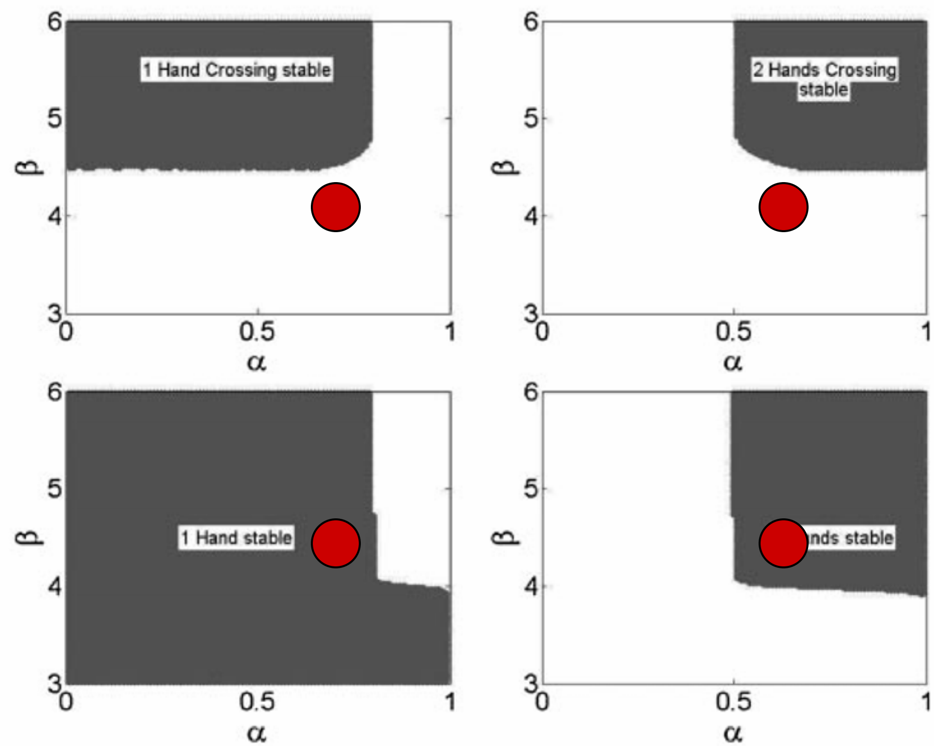
- General idea
- Motor abilities emerge via bifurcations
- Stability band becomes more and more populated during development
- Conditional population dependent on agent-environment relation

Frank/Kamp/Savelsbergh, 2010

Child Development



Age
β



Relative object size α

$$\frac{d}{dt}\xi_j(t) = \lambda_j \cdot \xi_j - \xi_j^3 - g \cdot \xi_j \sum_{m \neq j} \xi_m^2$$

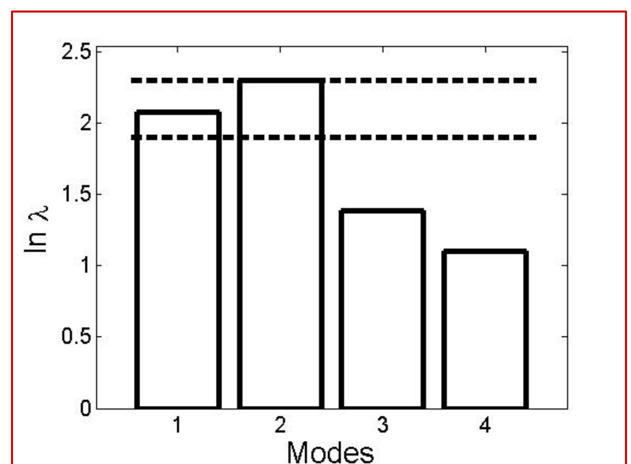
Four modes
j=1: One hand grasp
j=2: Two hand grasp
j=3: One hand + crossing
j=4: Two hand + crossing

$$\lambda_1 = 1 - \alpha$$

$$\lambda_2 = \alpha \cdot h(\beta; \gamma_2)$$

$$\lambda_3 = (1 - \alpha) \cdot h(\beta; \gamma_3)$$

$$\lambda_4 = \alpha \cdot h(\beta; \gamma_4)$$

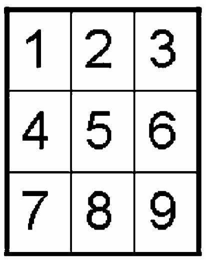


Attention Parameters in HI → AI

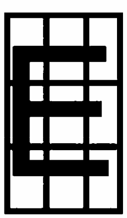
Three modes
j=1: Letter E
j=2: Letter F
j=3: Letter H

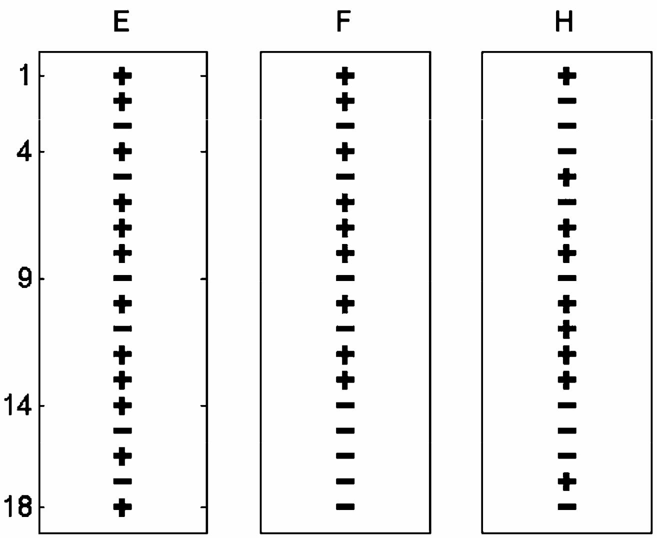
$$\frac{d}{dt}\vec{q}(t) = \vec{N}(\vec{q}(t), \vec{v}_E, \vec{v}_F, \vec{v}_H)$$

$$\frac{d}{dt}\xi_j(t) = \lambda_j \cdot \xi_j - \xi_j^3 - g \cdot \xi_j \sum_{m \neq j} \xi_m^2$$



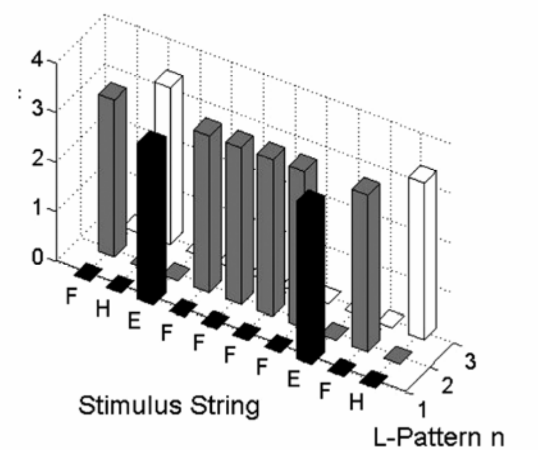
(a)


(b)



(c)

Input: incomplete letter pattern
Output: classification



Pattern Recognition with Adaptive Lyapunov Spectrum

- Goal
  - Improve recognition speed using adaptive Lyapunov spectrum
- Letter recognition
  - Artificial language based on 3 letter alphabet E,F,H
- Update Lyapunov spectrum utilizing a-priori-knowledge about language structure
- Artificial language
  - 'E' is followed most frequently by 'F'
  - Use rule: if 'E' is recognized increase Lyapunov exponent of mode 'F'

Fixed		Adaptive	
String* #	Recognition time [a.u.]	String #	Recogn. time [a.u]
1	212.9	6	**190.3**
2	211.8	7	**193.5**
3	212.8	8	**191.7**
4	213.8	9	**195.0**
5	212.7	10	**190.4**

$$\lambda_E = \lambda_F = \lambda_H = 1$$
$$\to \lambda_E + \lambda_F + \lambda_H = 3$$

$$\lambda_E + \lambda_F + \lambda_H = 3$$
$$\lambda_E , \lambda_F , \lambda_H \quad \text{adaptive}$$

*300 letters

Topics Today

- Synergetic computer
- What is physical intelligence?
- Links between human, artificial, physical intelligence
- **Smart physical systems**

TDF (2011) in: Perspectives of Pattern Recognition

Smart Physical Systems

Definition of ‘smart physical systems’

<table>
<tr><th>Human intelligence</th><th>Artificial intelligence</th><th>Physical
Smart physical systems</th></tr>
<tr><td colspan="2">Behavior*</td><td></td></tr>
<tr><td></td><td colspan="2">Evolution equations (Amplitude eq.)</td></tr>
</table>

* Turing

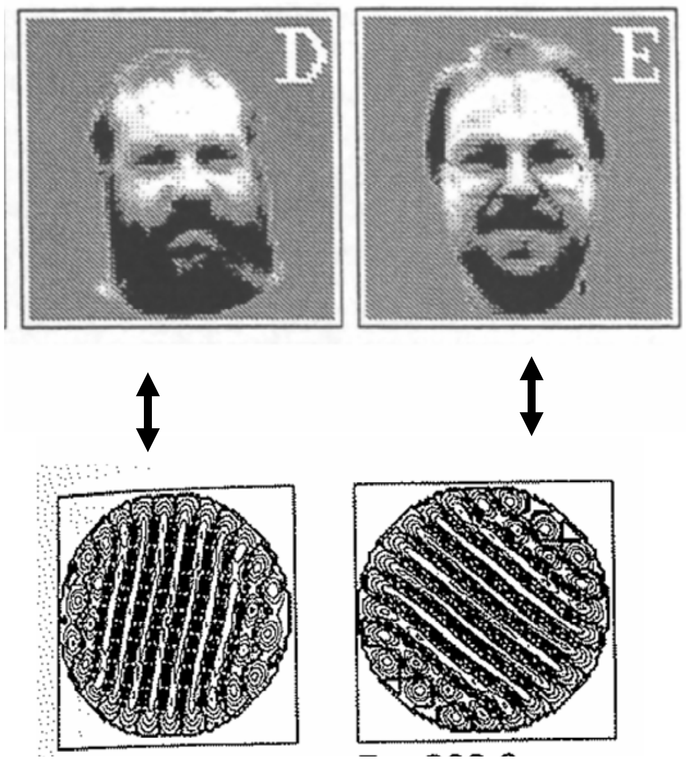
Intelligent Physical Systems

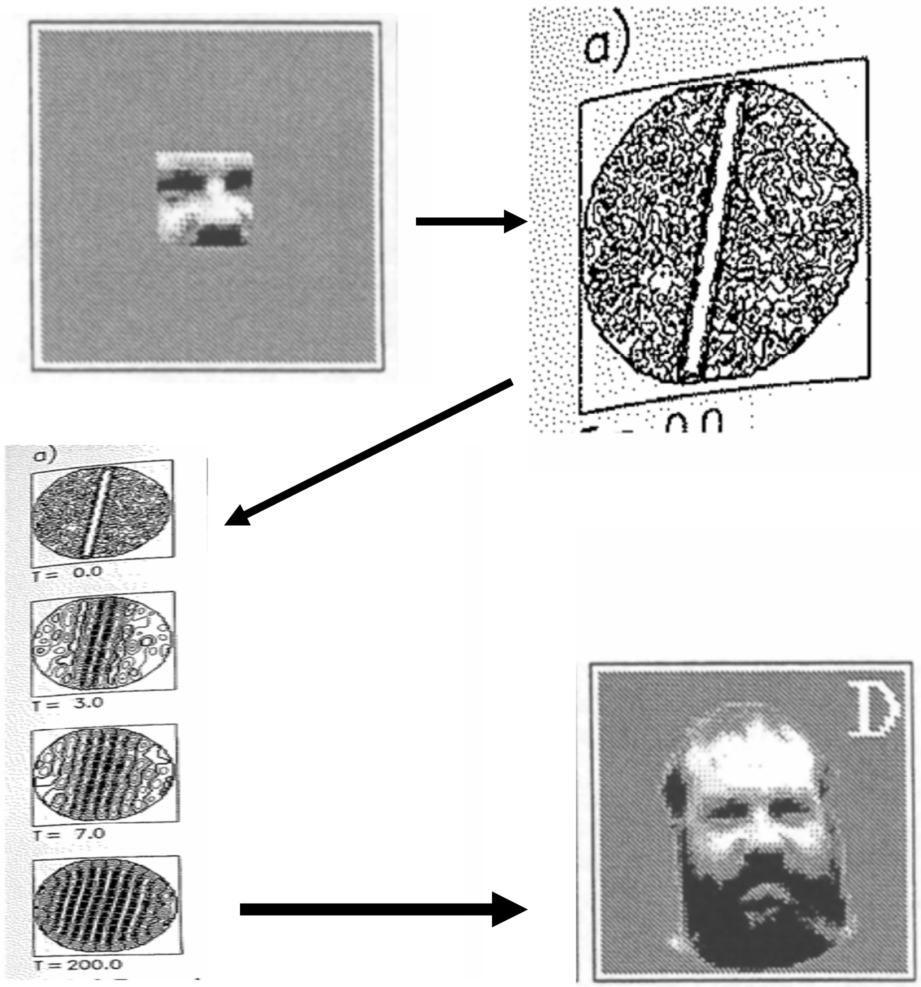
- Fluid dynamical systems?
- Gas discharge & electronic systems?

Fluid Dynamical PI Systems?

Coding
Pictures → Patterns

Input-output interface
Initial picture → initial fluid state
Final fluid state → recognized picture

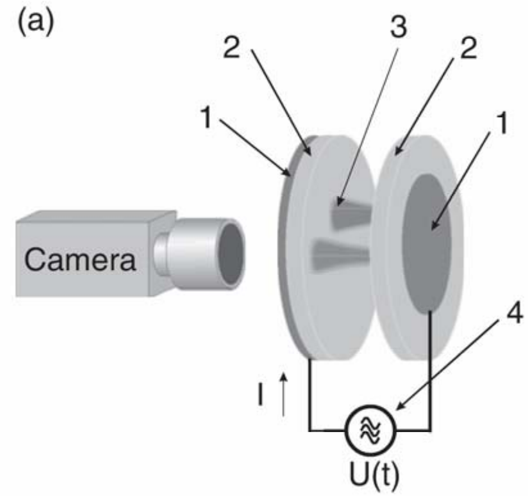


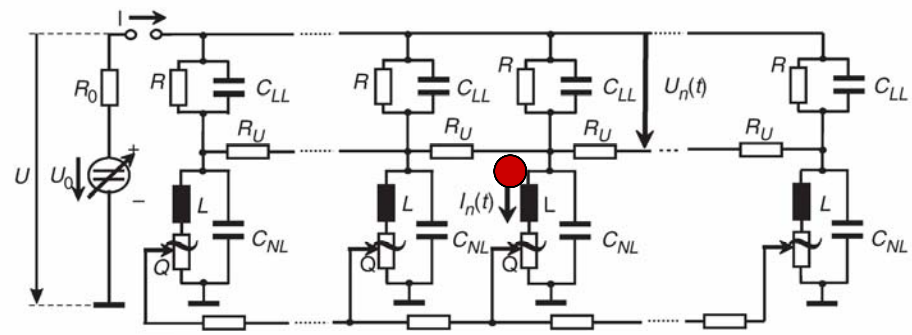


Nov 16, 2012

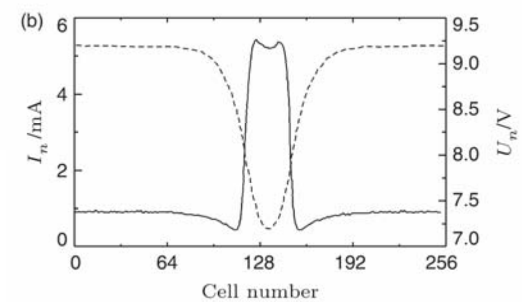
Purwins & co-workers
e.g., Purwins et al. (2010)

Gas discharge & electronic systems





Cell currents I_n



U= voltage between top and bottom of electronic layers

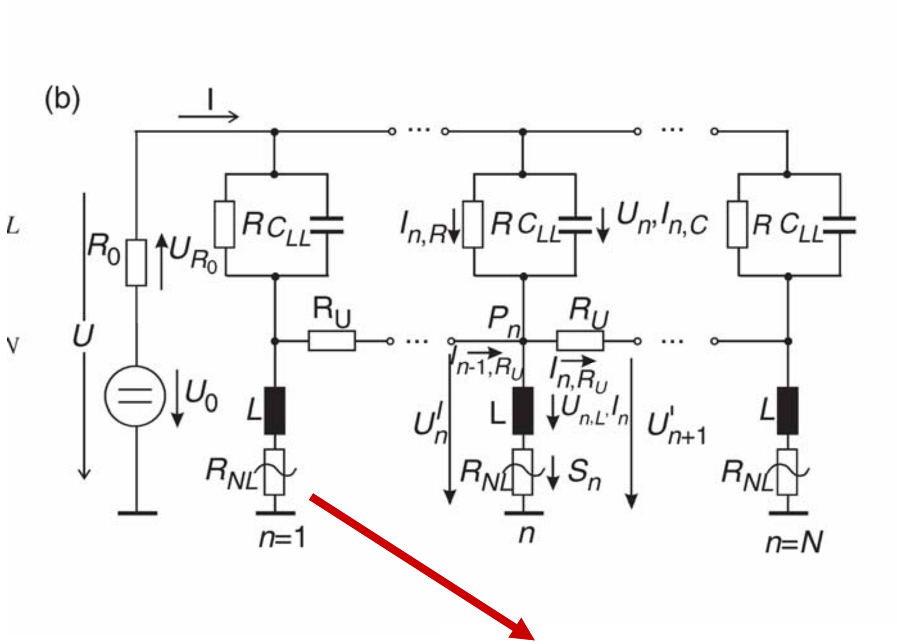
U= voltage between plates of gas layer

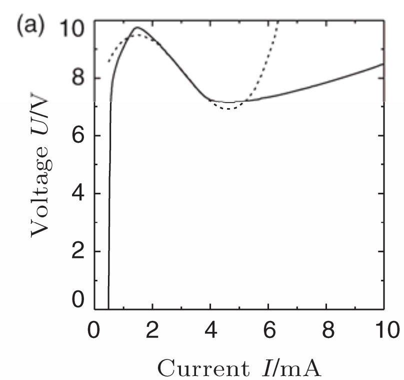
U< U_{crit}: gas = isolator
U> U_{crit} : gas = electrical conducting plasma (ionization)
'light object' (filaments) emerges

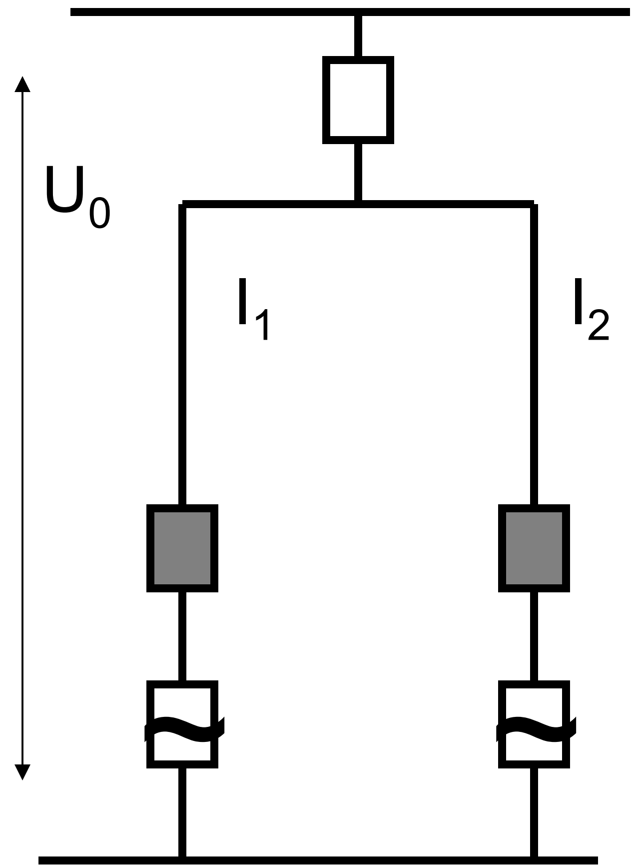
U< U_{crit} : homogeneous current distribution
U> U_{crit} : current distribution akin to localized particle

'Current particle' can emerge at any cell position → system is multistable

5 Piece Core Model







Nonlinear (cubic) resistor approximation

$$U_N(I) = U^* + b\left\{\left(I - s\right)^3 - \left(I - s\right)\right\}$$

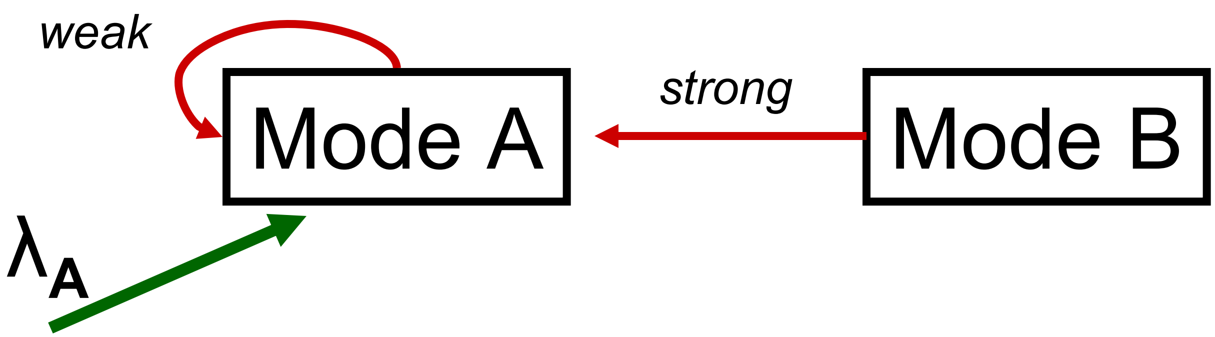
$$U^* = b\left(s^3 - s\right)$$

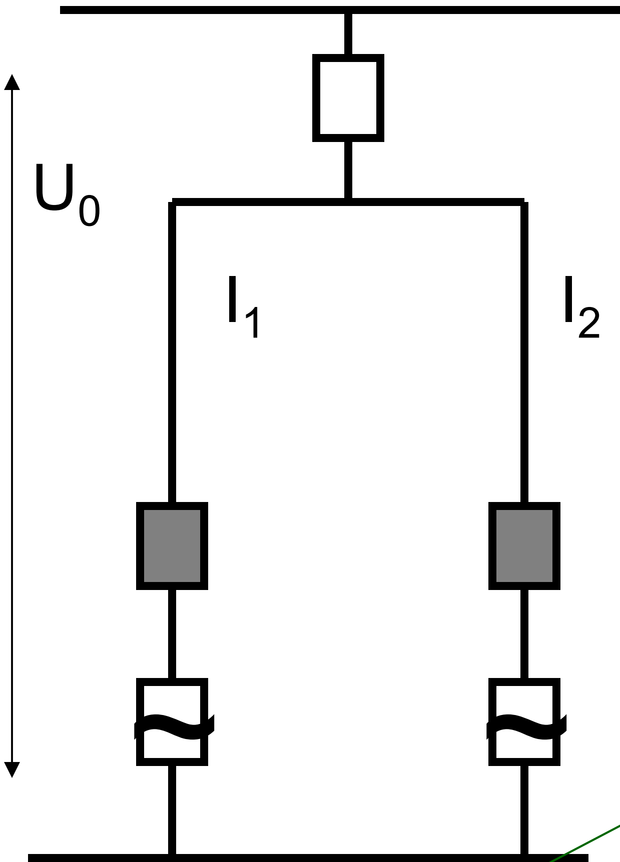
Synergetic Computer – Fundamental Property

$$\frac{d}{dt}\xi_j(t) = \lambda_j \cdot \xi_j - \xi_j^3 - g \cdot \xi_j \sum_{m \neq j} \xi_m^2$$

- Modes have
  - **Activation**
  - **Cross-inhibition**
  - **Self-inhibition**
- Multistability when

  Cross-inhibition > self-inhibition, i.e., **g>1**





Evolution equations for cell currents

$$\tilde{I}_1 = I_1 - s$$
$$\tilde{I}_2 = I_2 - s$$

$$\frac{d}{dt}\tilde{I}_1 = \tilde{\lambda} - (1-b)\cdot\tilde{I}_1 - \tilde{I}_2 - G(\tilde{I}_1)$$

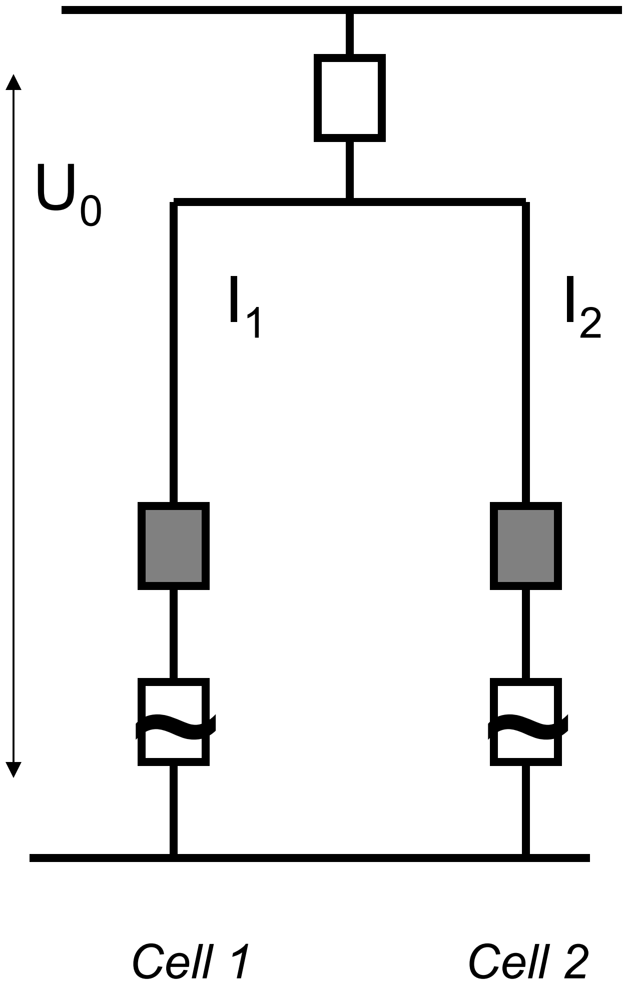
$$\frac{d}{dt}\tilde{I}_2 = \overset{\frown}{\lambda} - (1-b)\cdot\tilde{I}_2 - \tilde{I}_1 - G(\tilde{I}_2)$$

$$G(I) = b \cdot I^3$$

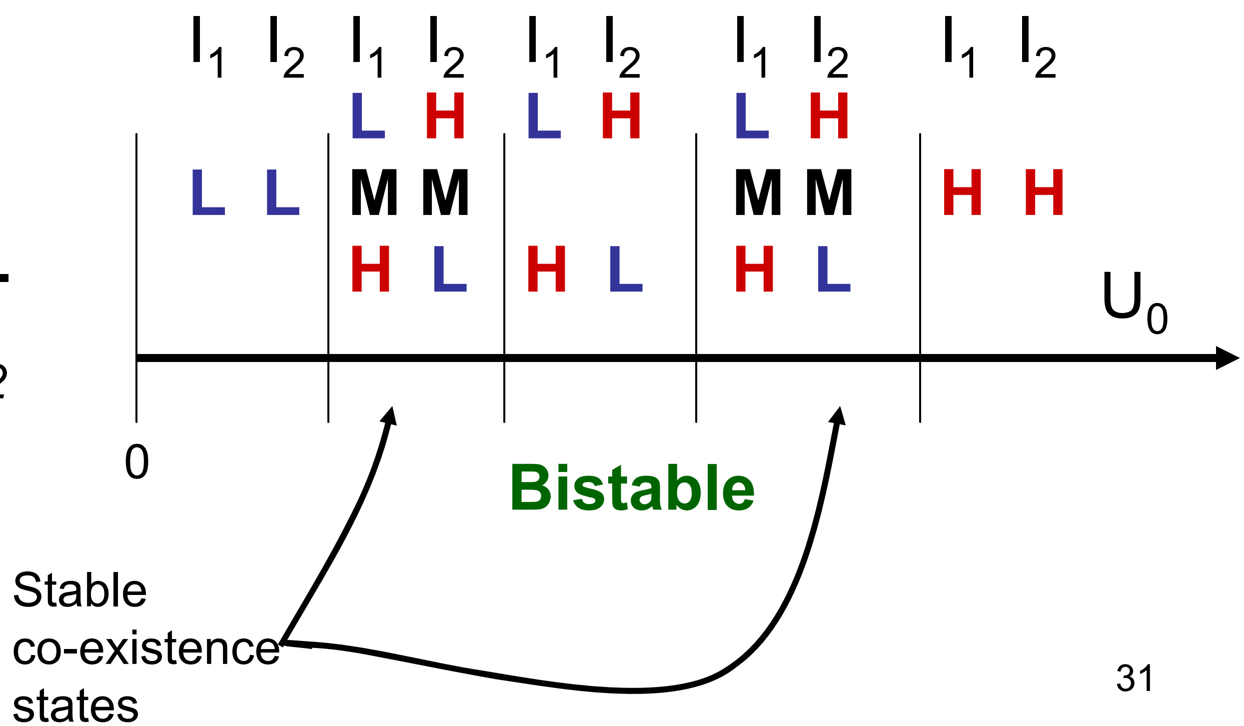
Exhibits fundamental structure of Haken's multistable networks
(i) **Activation**, (ii) **Weak (lin.) self-inhibition**, (iii) **Strong cross-inhibition**

Stability Analysis

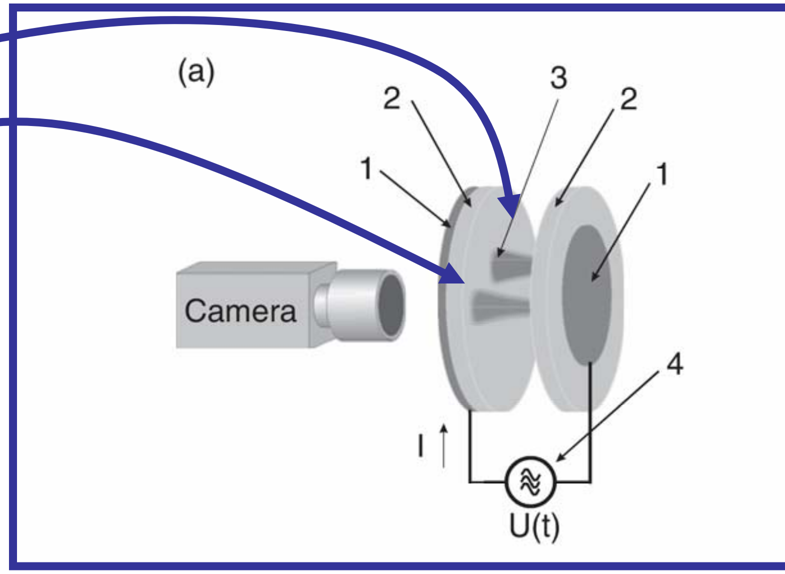
Currents I_1 and I_2 can be
Low
Medium
High

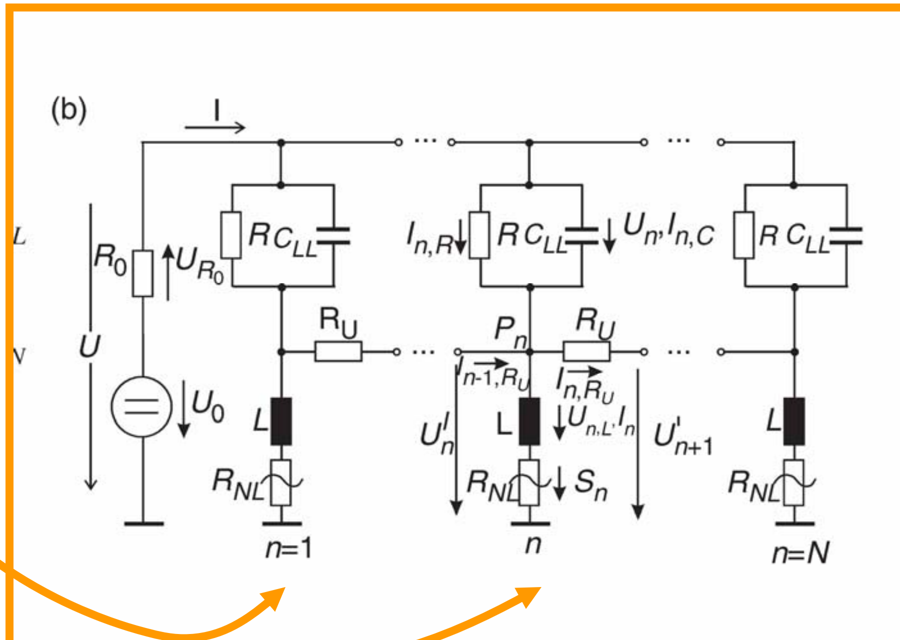


Stable fixed points of two-cells circuit



PI Systems?

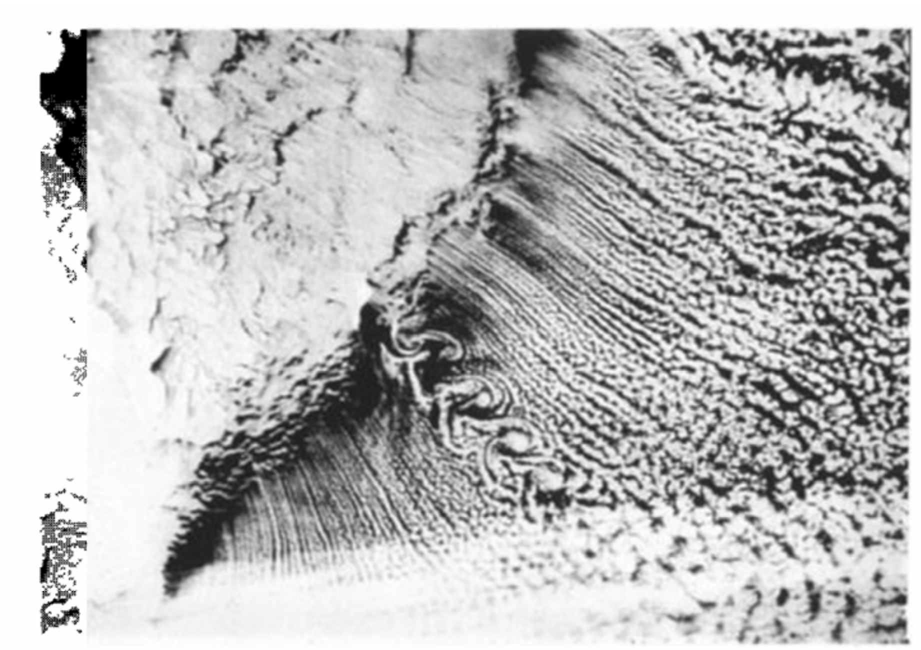




THANK YOU

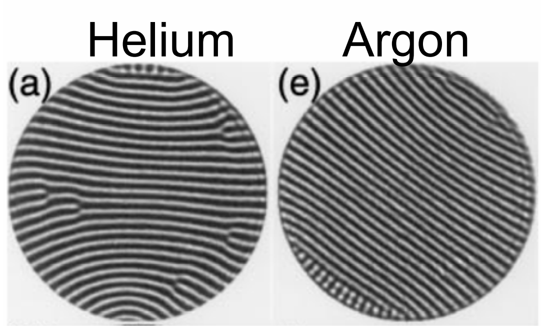
Appendix

Pattern Formation in the **Animate** and **Inanimate** World



Atkinson et al. 1996

Laboratory work: gases heated from below



Liu/Ahlers 1996

Self-Organization

Generalized Reaction-Diffusion Equations Approach

Reaction-diffusion equation

Reaction step

$$\frac{d}{d}c(t) = f(c)$$

Diffusion step

$$\frac{\partial}{\partial t}c(x,t) = D\frac{\partial^2}{\partial x^2}c(x,t)$$

$$\frac{\partial}{\partial t}c(x,t) = f(c) + D\frac{\partial^2}{\partial x^2}c(x,t)$$

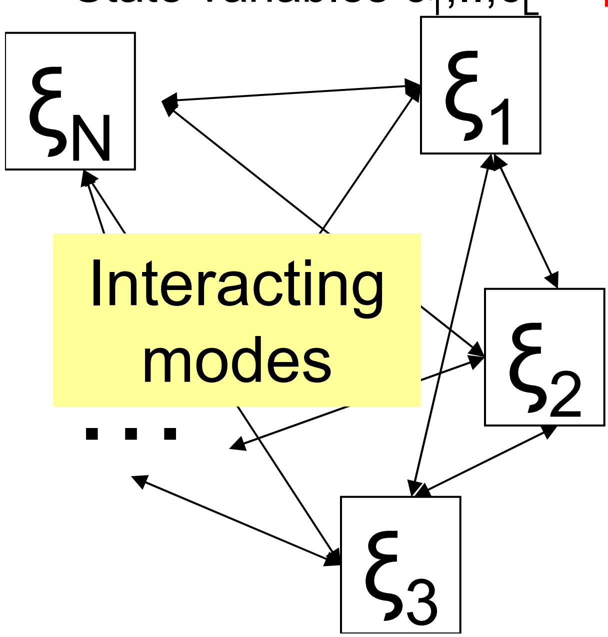
Generalized reaction-diffusion equations

$$\frac{\partial}{\partial t}\vec{c}(\vec{x},t) = N(\vec{c},\nabla)$$

State variables $c_1,..,c_L$

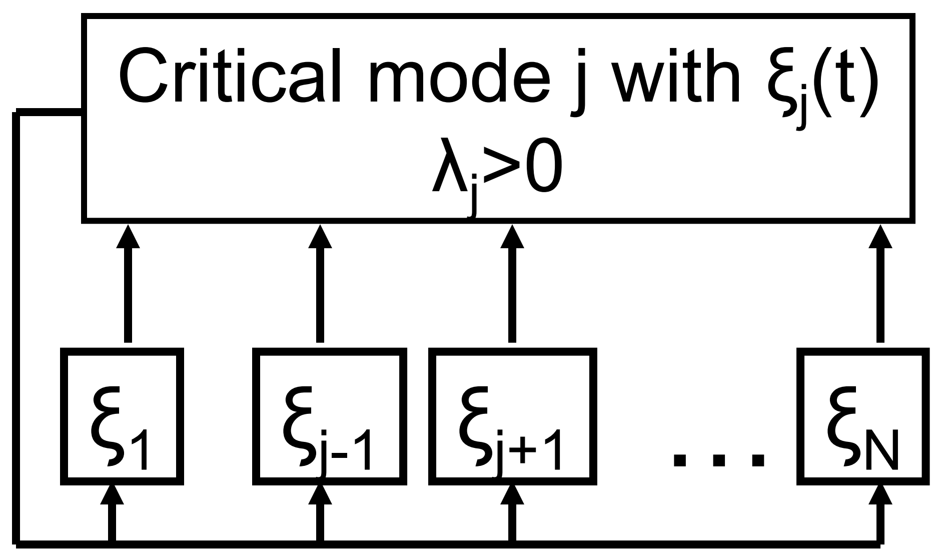
Solution method via mode skeleton

$$\vec{c}(\vec{x},t) = \sum \xi_j(t)\cdot\vec{w}_j(\vec{x})$$

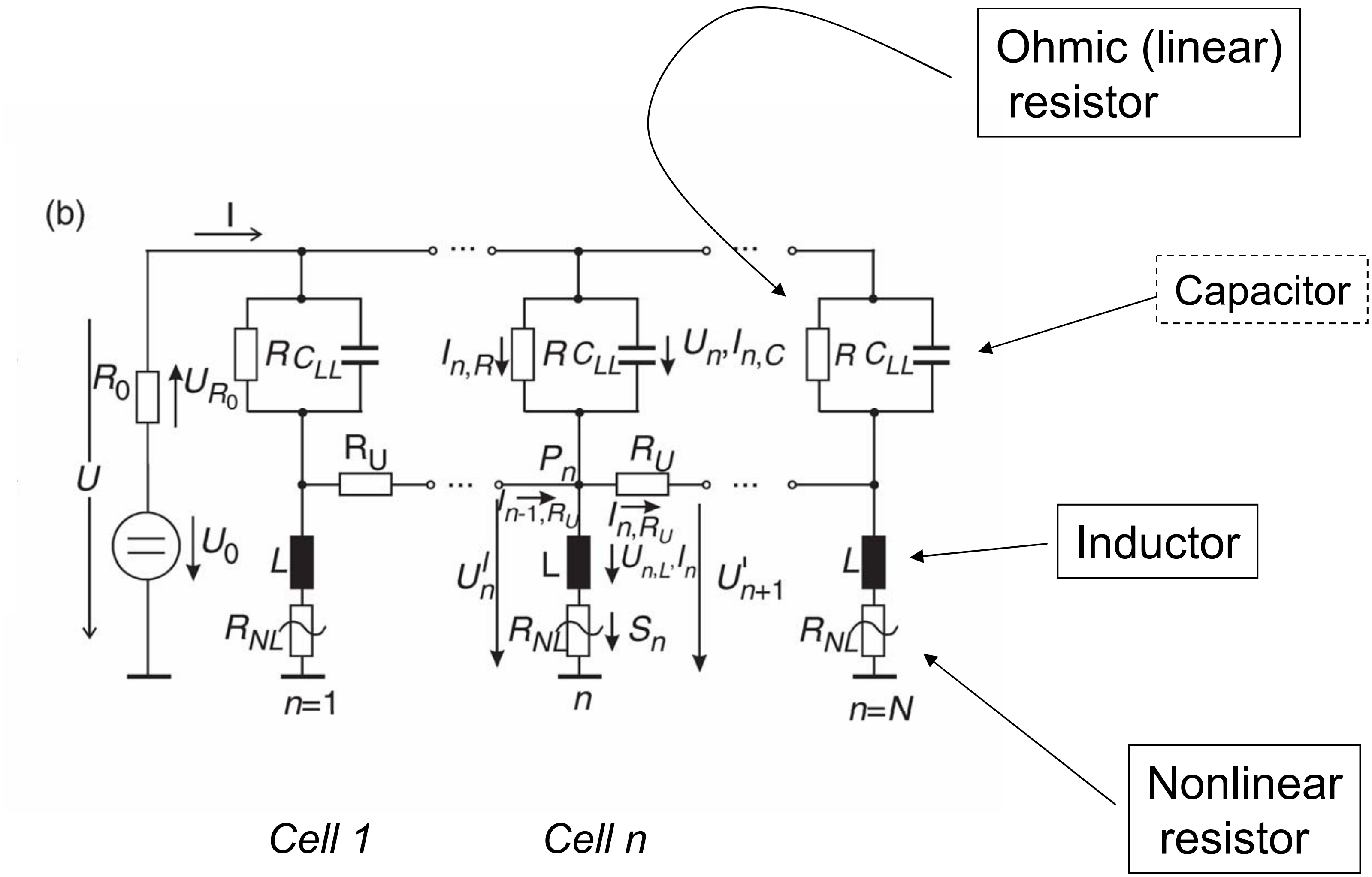


Lyapunov spectrum at bifurcation point

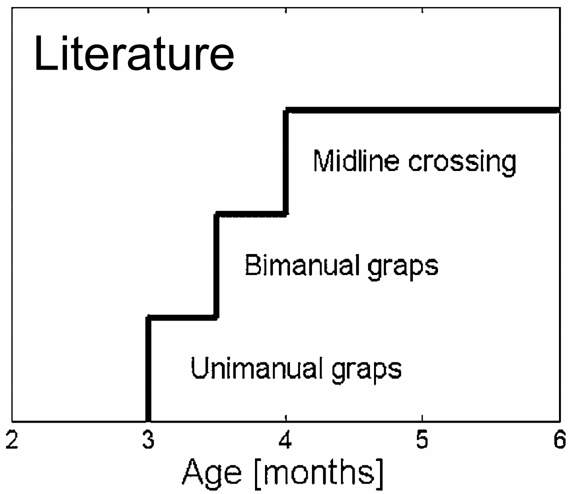
critical mode j λ_j>0



Electronic GDS circuit

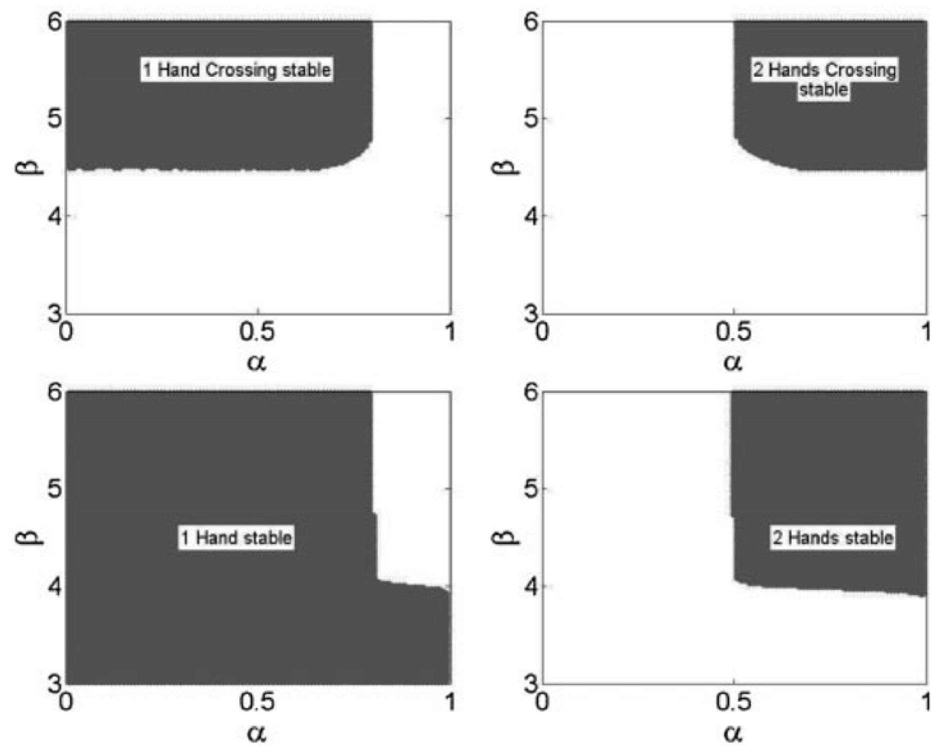


Child Development



Age
β

Model



Relative object size α

Frank/Kamp/Savelsbergh 2010

Clinical
Term & Preterm infants

Term infants Chronological age	Preterm infants Chronological age	Motor skill
4.5 m	6 m	Rolling over
7.5 m	11 m	Manages to sit up
14 m	16 m	Walk (including walking backwards)

Literature

Model

Individual life trajectories

TERM *PRE-TERM*

Frank 2011