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More non-linear circuits: integrated implementation, versatile motor pattern generation, criticality

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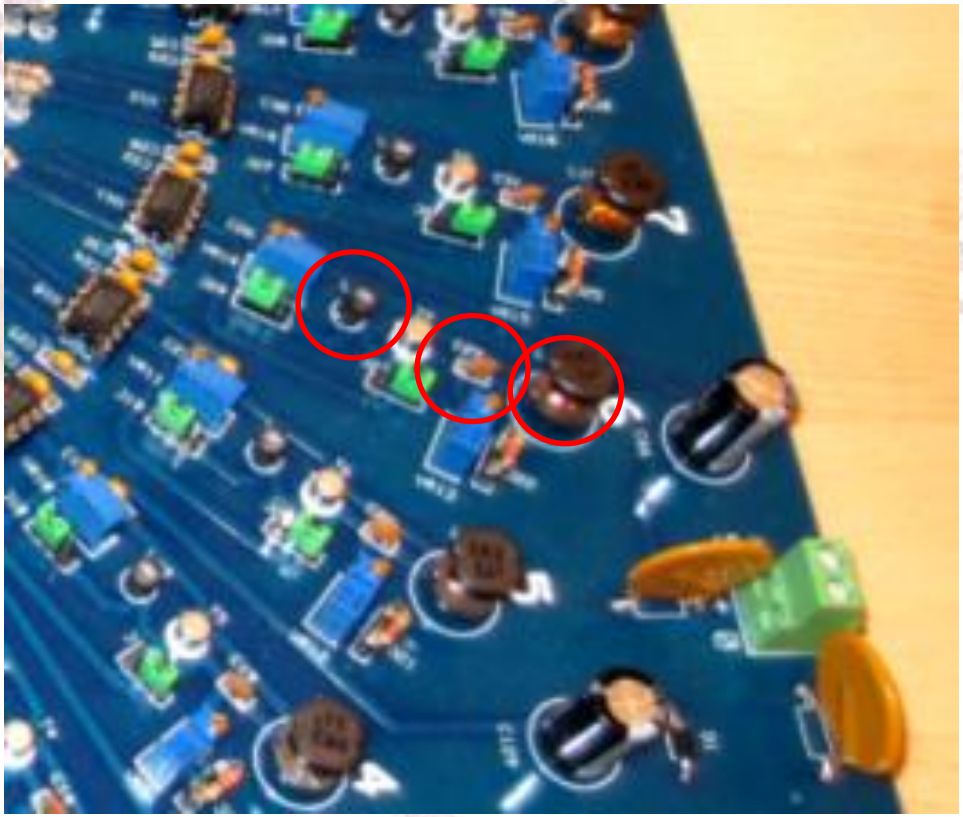
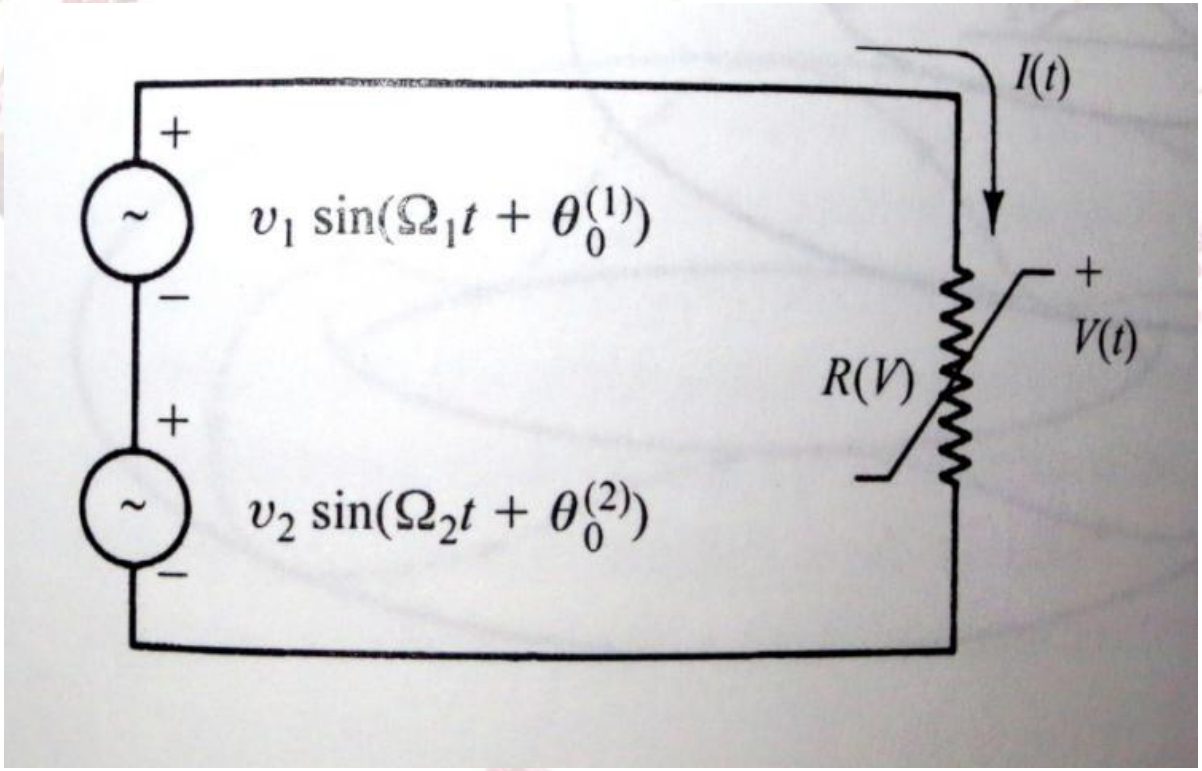
Integrated circuit implementation

Problem: inductors and capacitors not suitable for CMOS realization



Integrated circuit implementation

Quasi-periodicity route to chaos



Source: E. Ott, Chaos in Dynamical Systems (Cambridge University Press, Cambridge, 2002)

Integrated circuit implementation

Coupled inverter rings having length equal to smallest prime numbers

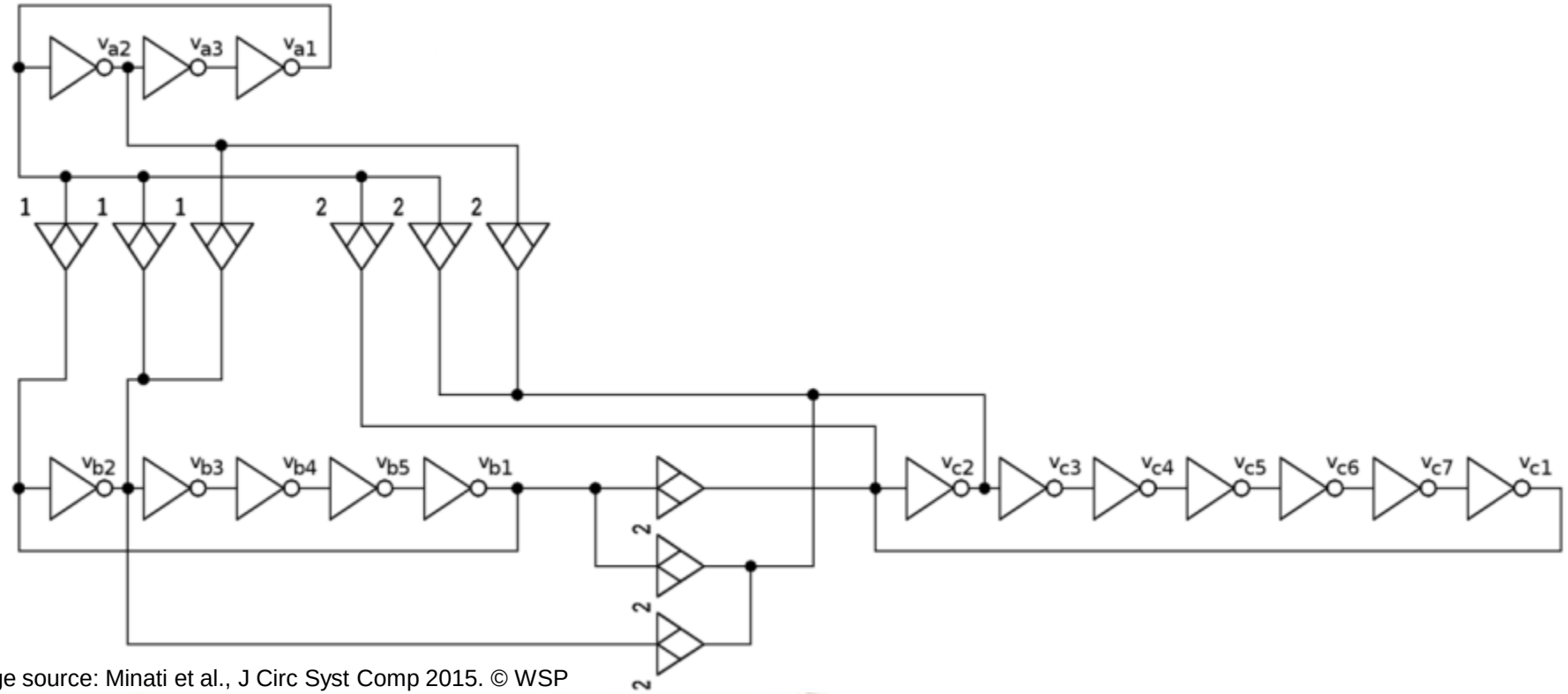


Image source: Minati et al., J Circ Syst Comp 2015. © WSP

Integrated circuit implementation

Coupled inverter rings

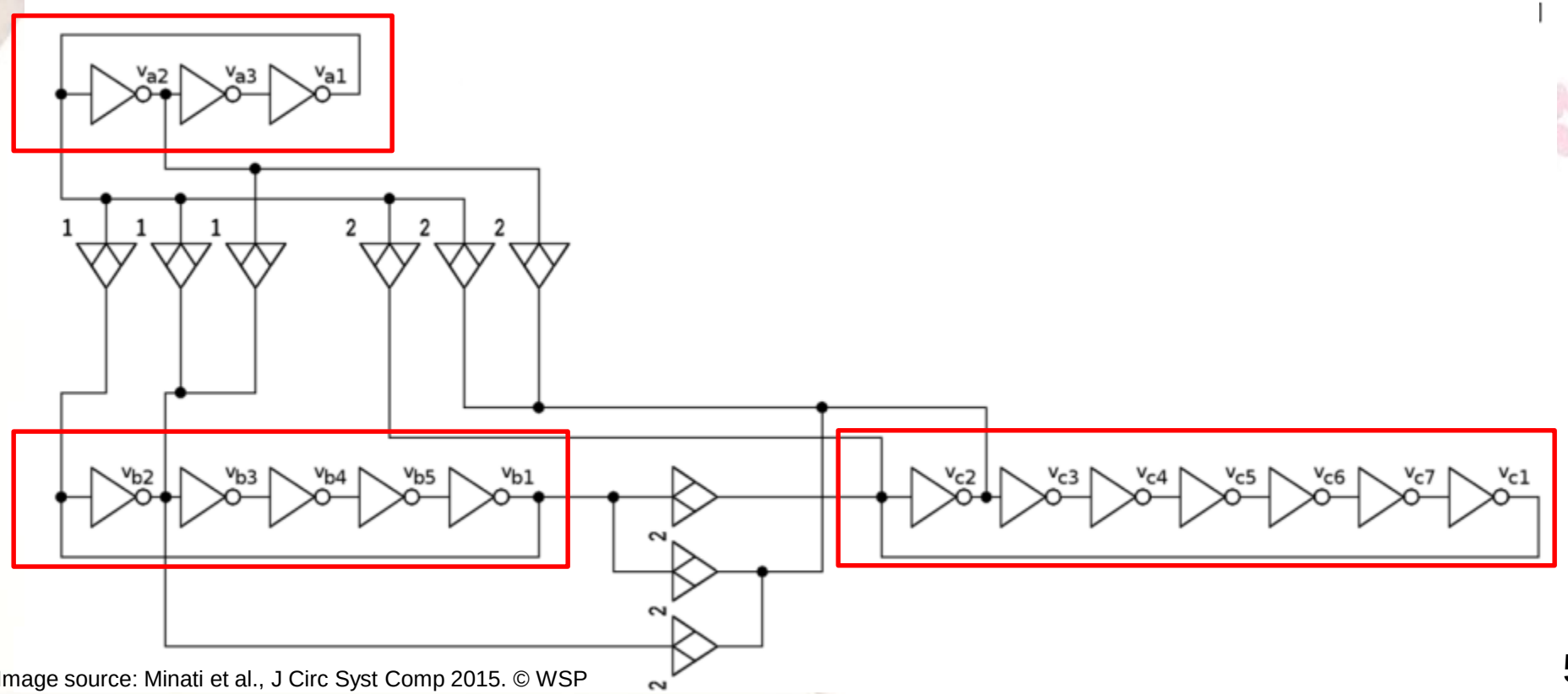
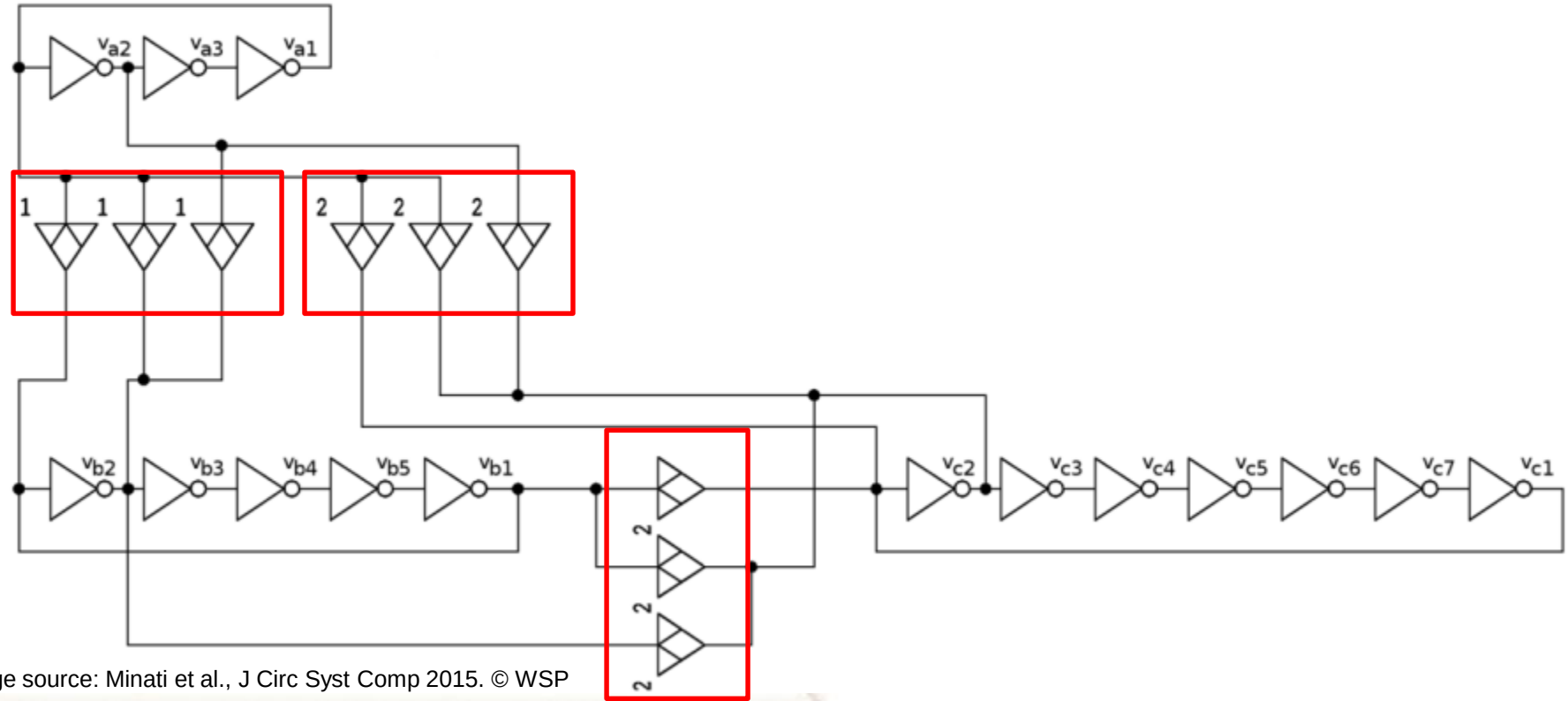


Image source: Minati et al., J Circ Syst Comp 2015. © WSP

Integrated circuit implementation

Coupling elements



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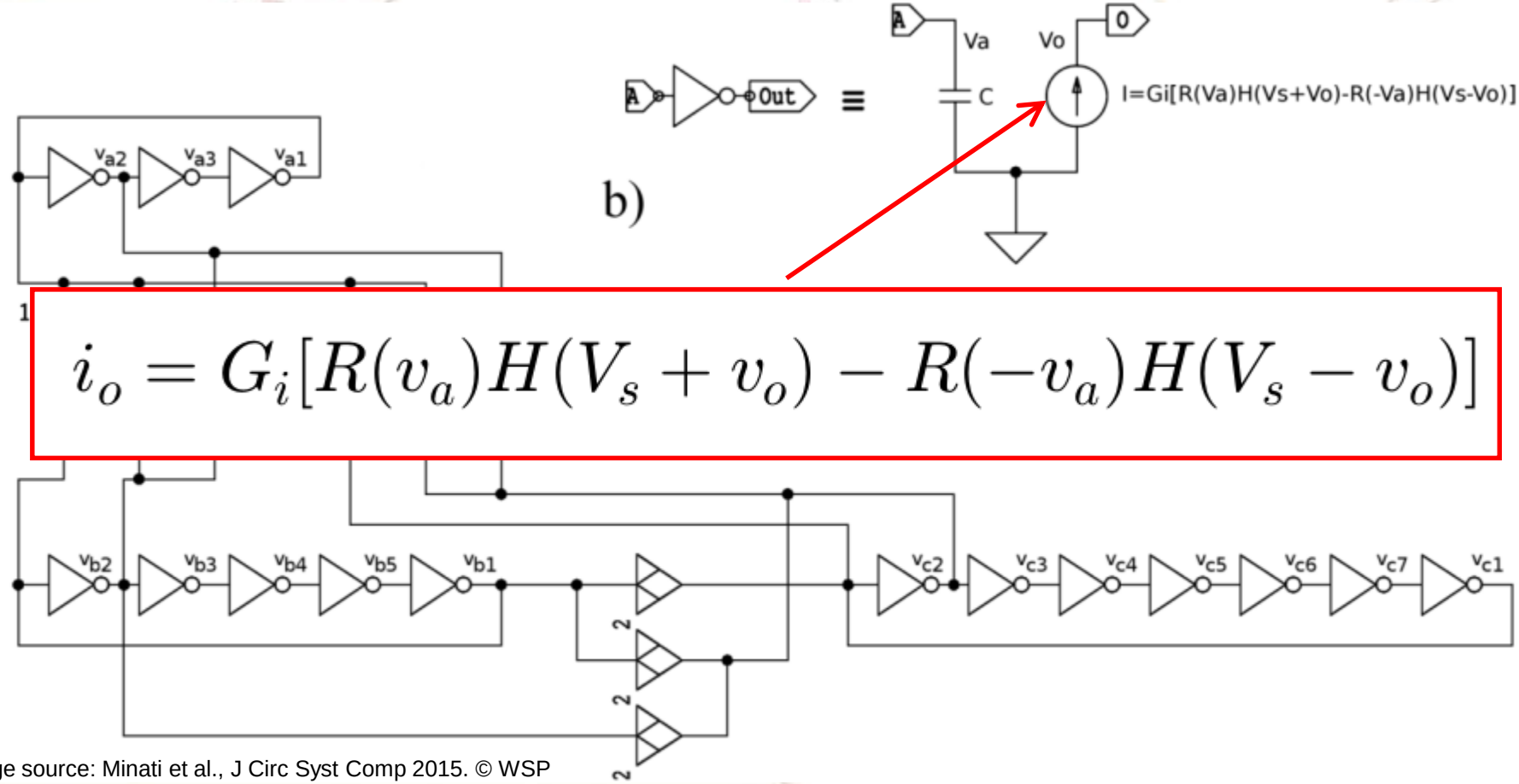
Integrated circuit implementation

Simplified numerical model



$$i_o = G_i[R(v_a)H(V_s + v_o) - R(-v_a)H(V_s - v_o)]$$

Image source: Minati et al., J Circ Syst Comp 2015. © WSP

Integrated circuit implementation

Simplified numerical model

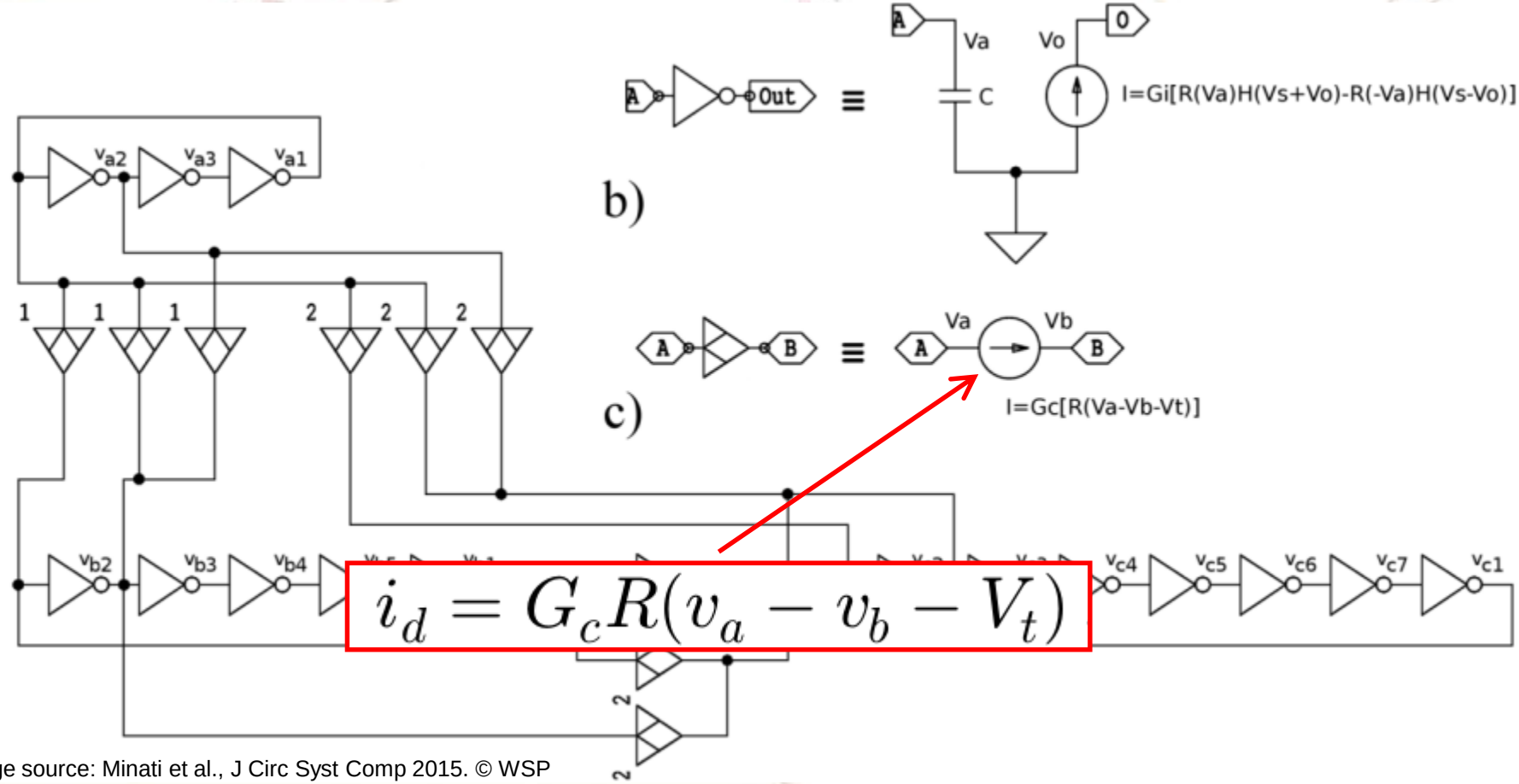


Image source: Minati et al., J Circ Syst Comp 2015. © WSP

Integrated circuit implementation

CMOS realization – single cell and ring

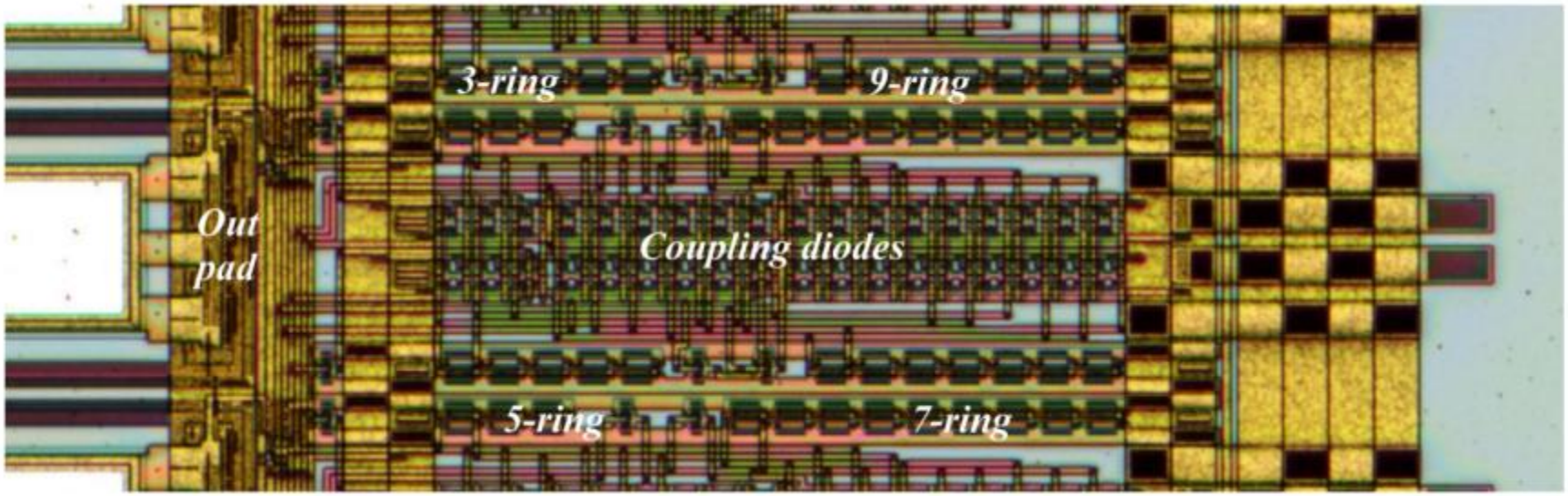
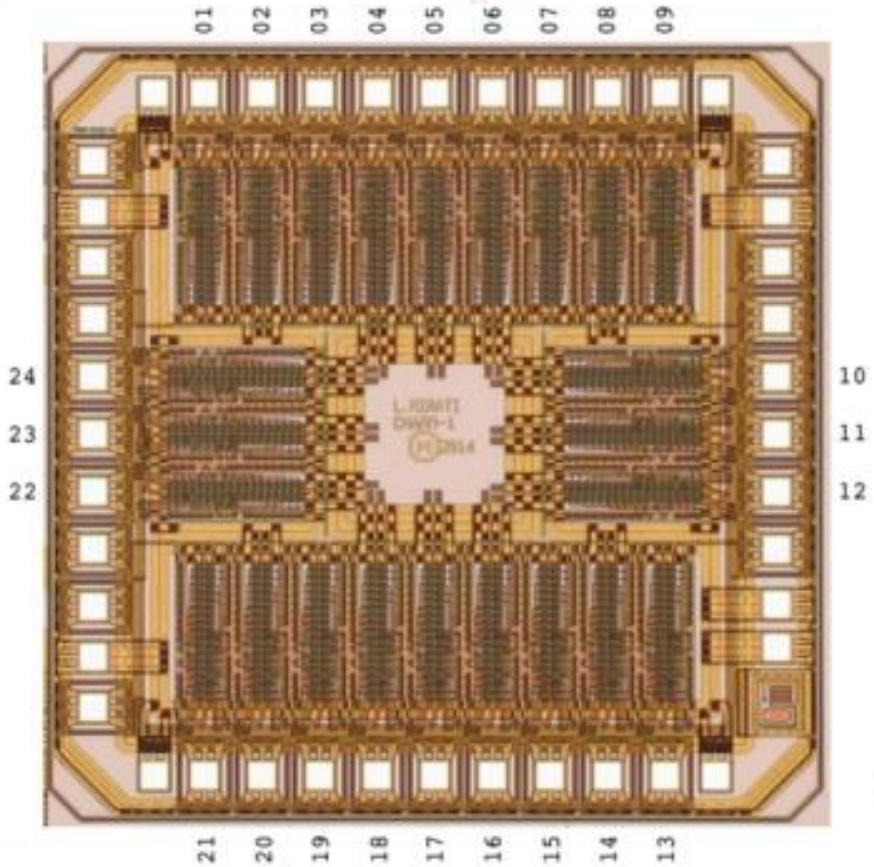


Image source: Minati et al., J Circ Syst Comp 2015. © WSP

Integrated circuit implementation

CMOS realization – single cell and ring



Realized through

EUROPRACTICE

Image source: Minati et al., J Circ Syst Comp 2015. © WSP

Integrated circuit implementation

CMOS realization – test board

Image source: Minati et al., J Circ Syst Comp 2015. © WSP

Integrated circuit implementation

Effect of connecting rings: 3-ring alone

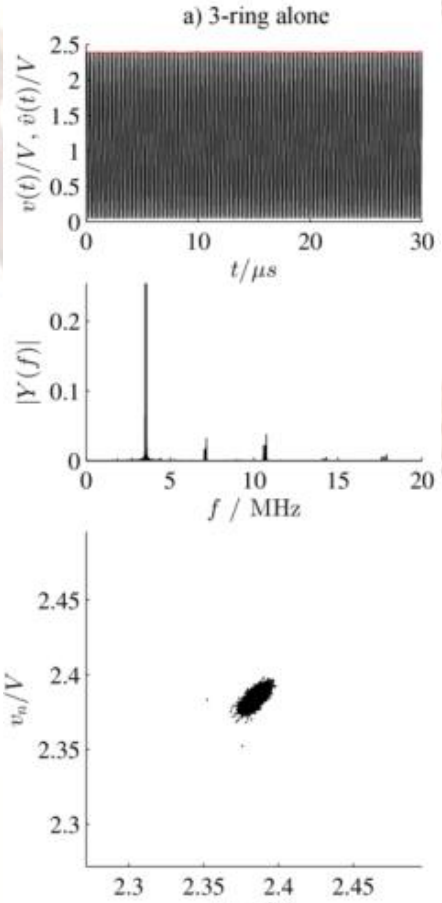


Image source: Minati et al., J Circ Syst Comp 2015. © WSP

Integrated circuit implementation

Effect of connecting rings: 3-ring + 5-ring

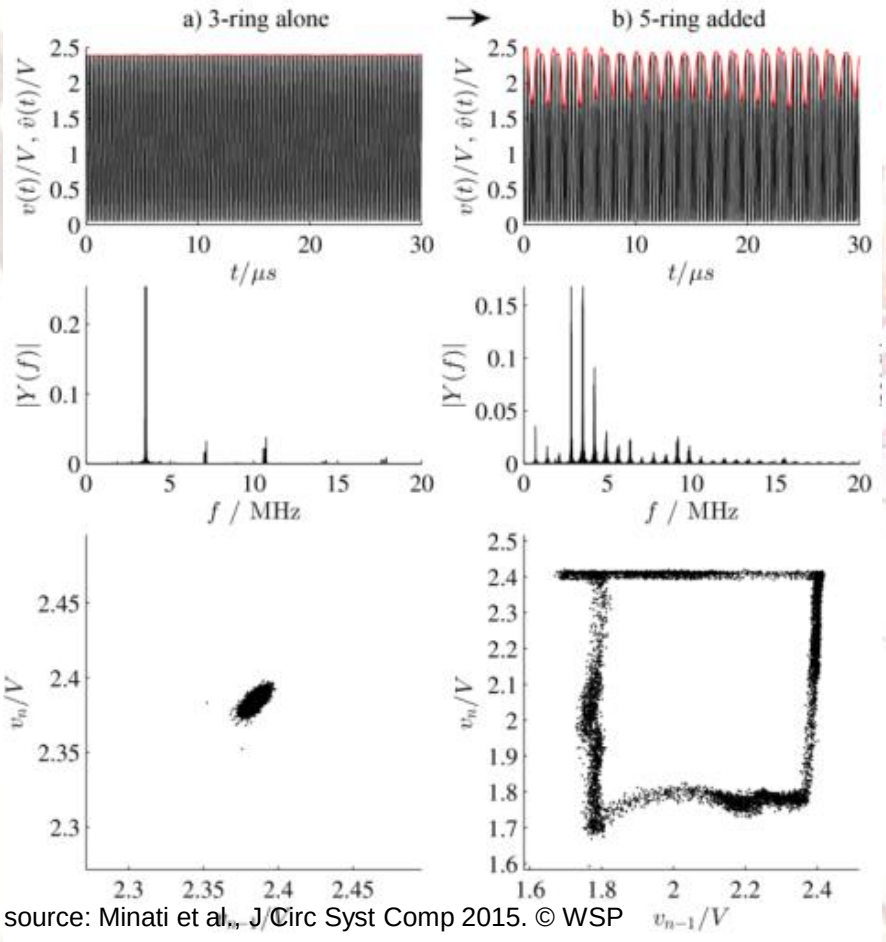


Image source: Minati et al., J Circ Syst Comp 2015. © WSP

Integrated circuit implementation

Effect of connecting rings: 3-ring + 5,7-rings

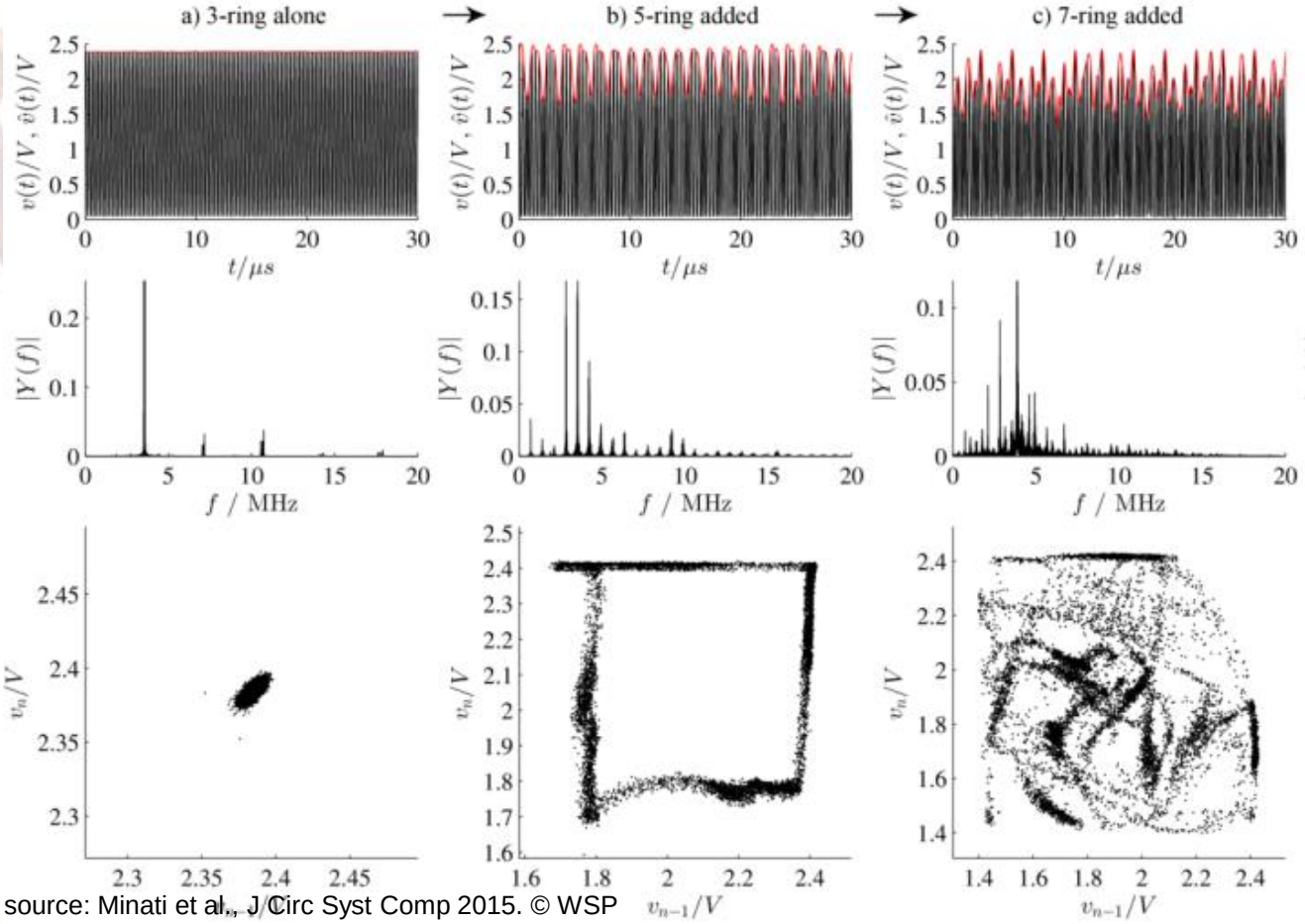


Image source: Minati et al., J Circ Syst Comp 2015. © WSP

Integrated circuit implementation

Effect of connecting rings: 3-ring + 5,7,9-rings

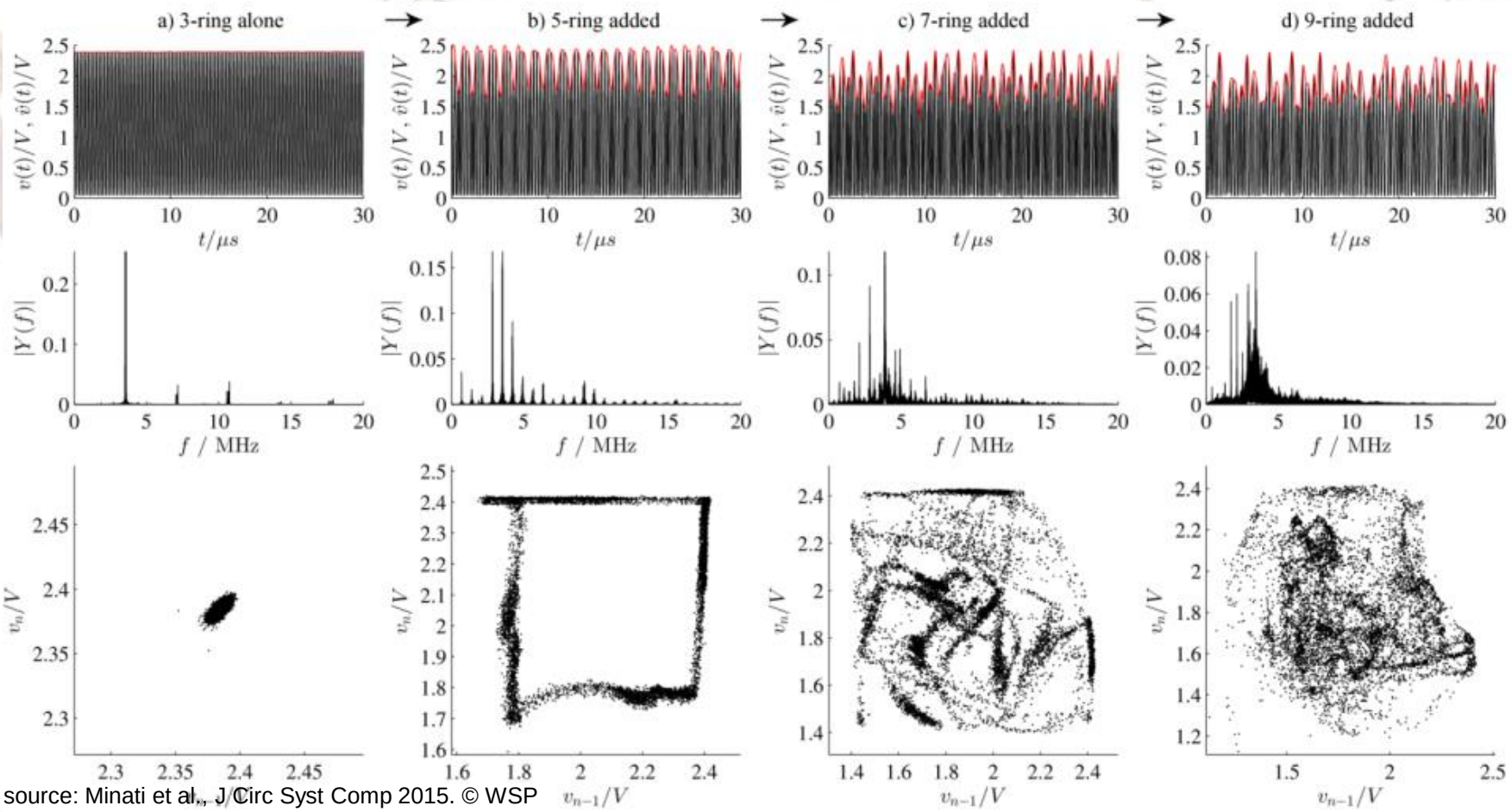


Image source: Minati et al., J Circ Syst Comp 2015. © WSP

Integrated circuit implementation

Effect of increasing coupling strength

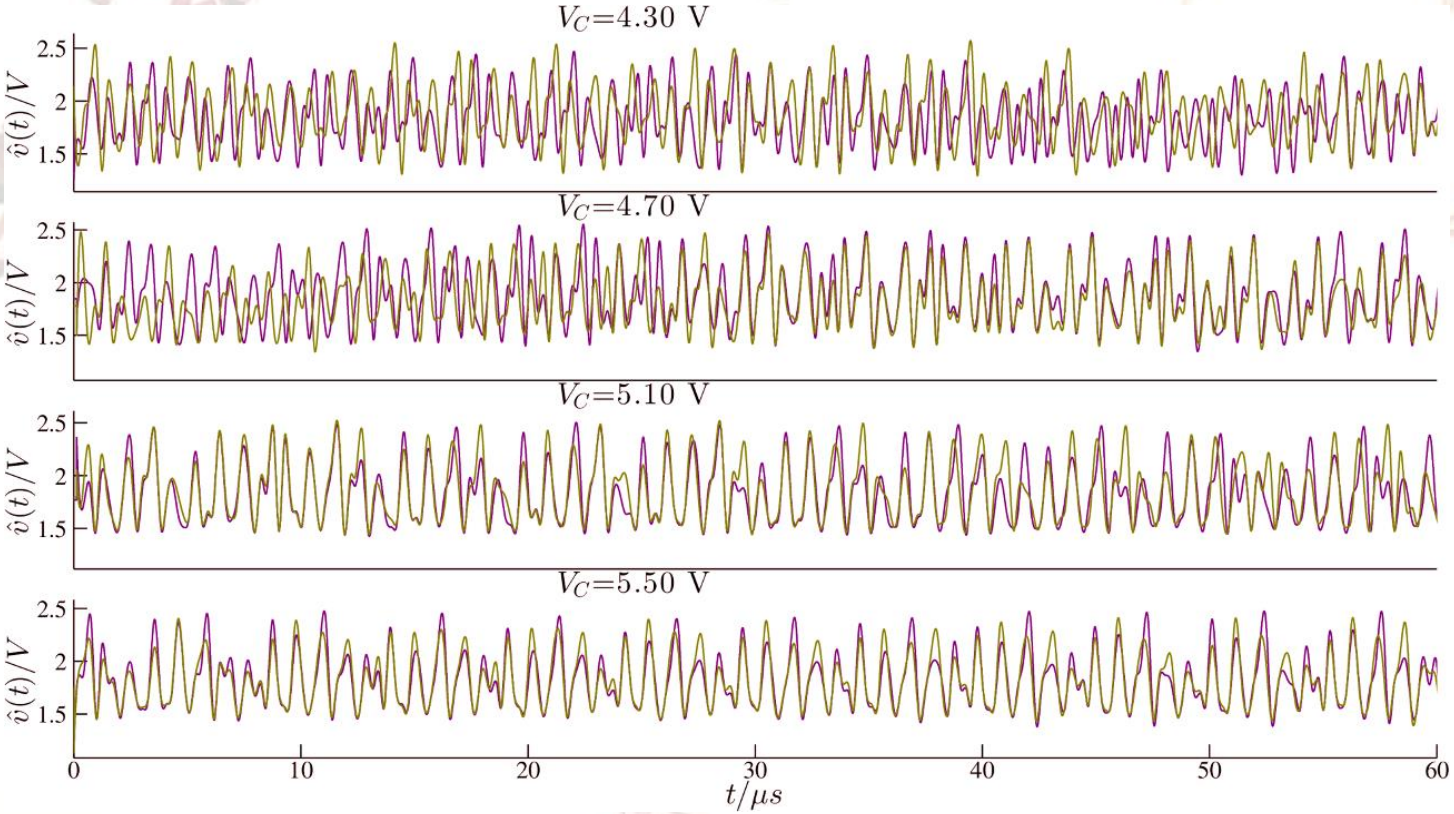


Image source: Minati et al., J Circ Syst Comp 2015. © WSP

Integrated circuit implementation

Cluster synchronization: formation of communities

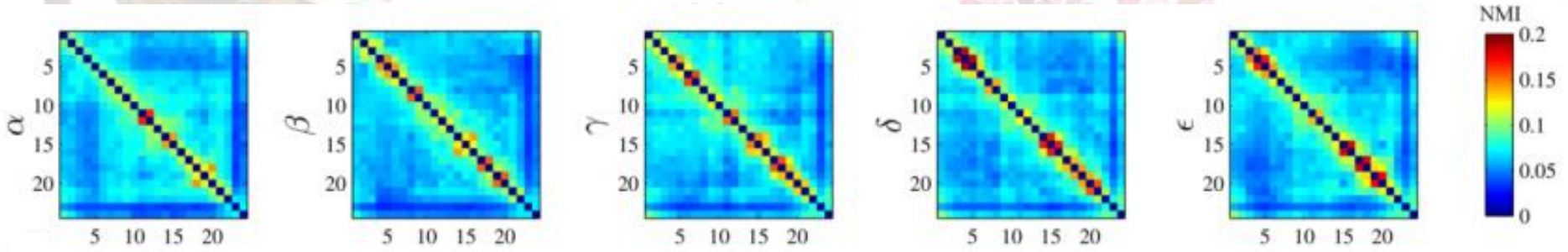
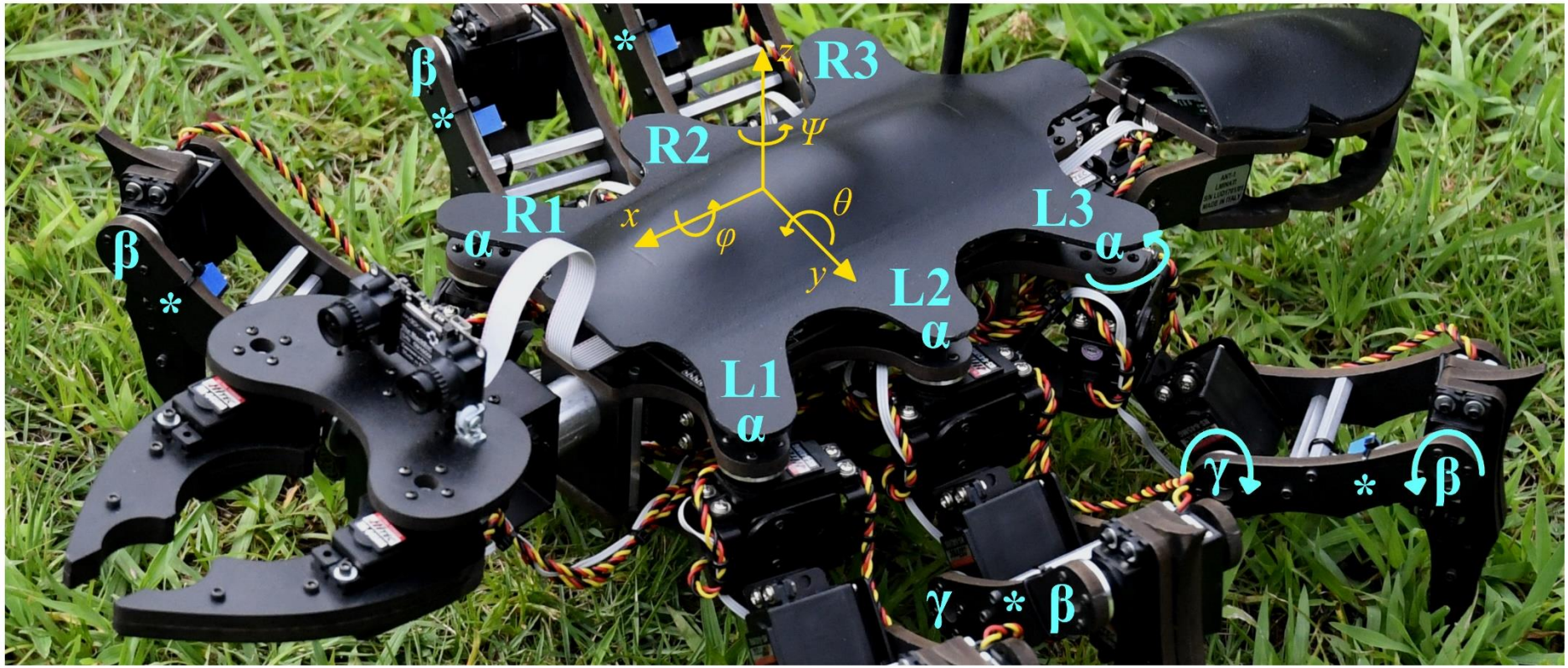


Image source: Minati et al., J Circ Syst Comp 2015. © WSP

Versatile motor pattern generation

Generation of viable walking gaits for the 非線形蟻-1 robot



Original mechanics design: A-Pod by Kåre Halvorsen (a.k.a. "Zenta")

Versatile motor pattern generation

Central pattern generation (CPG)

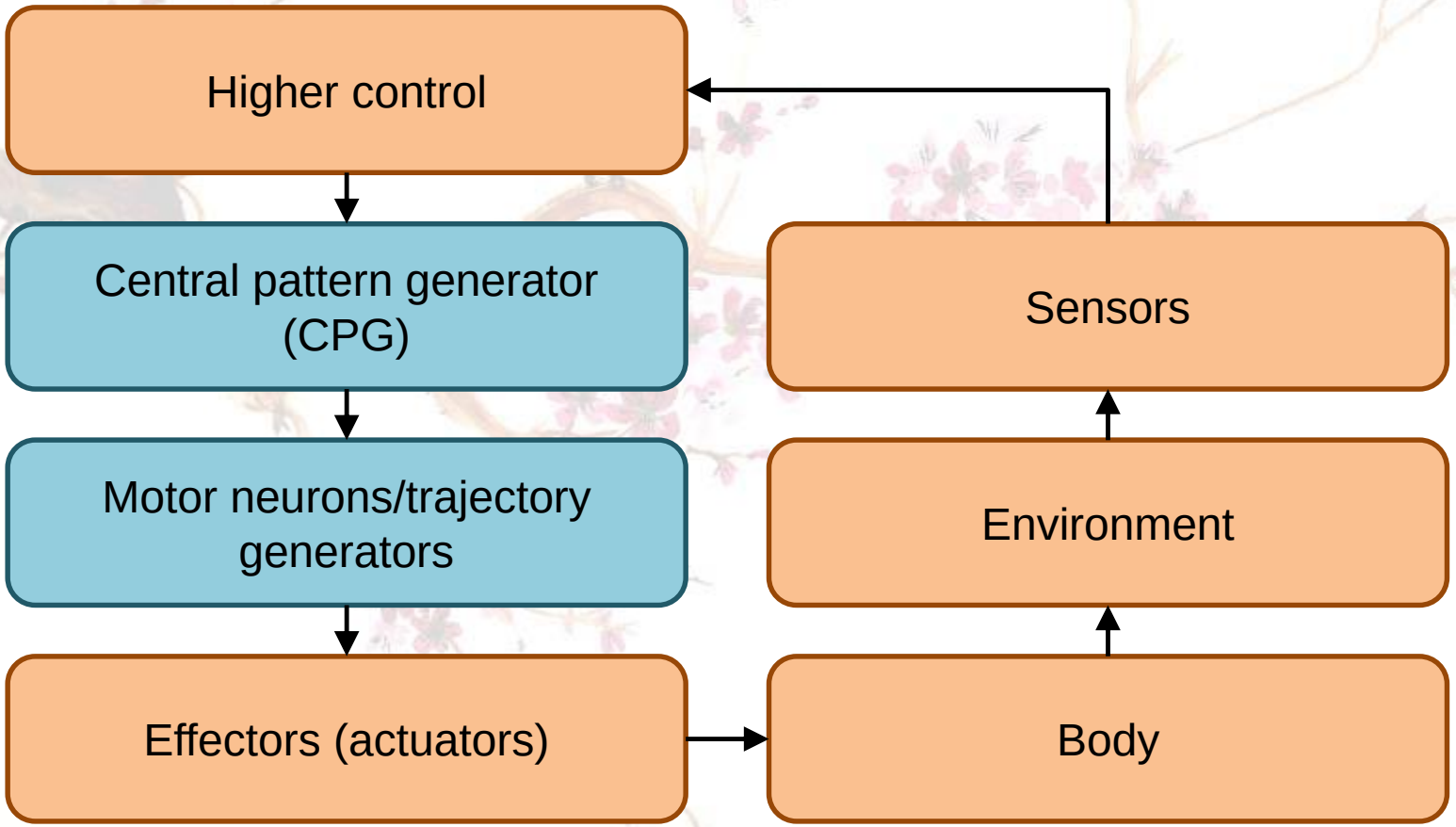


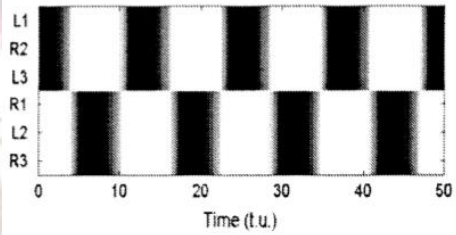
Image source: Minati et al., IEEE Access 2018 © IEEE

Versatile motor pattern generation

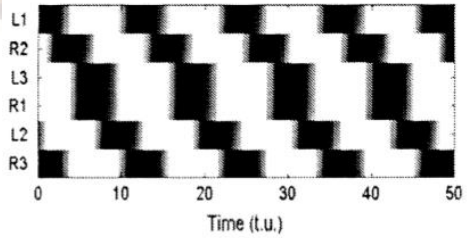
Canonical gaits and postures in insects

Gaits

Alternating tripod



Metachronal



Wave

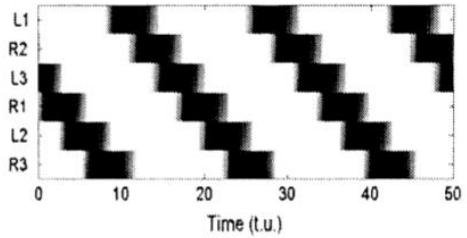


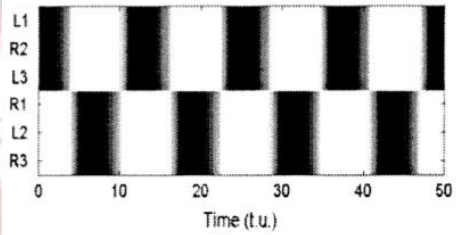
Image credit: M. Frasca, P. Arena

Versatile motor pattern generation

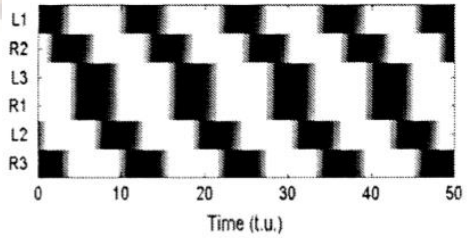
Canonical gaits and postures in insects

Gaits

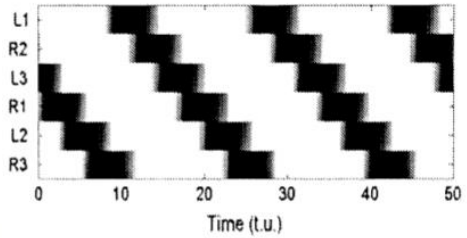
Alternating tripod



Metachronal



Wave



Postures

Ant

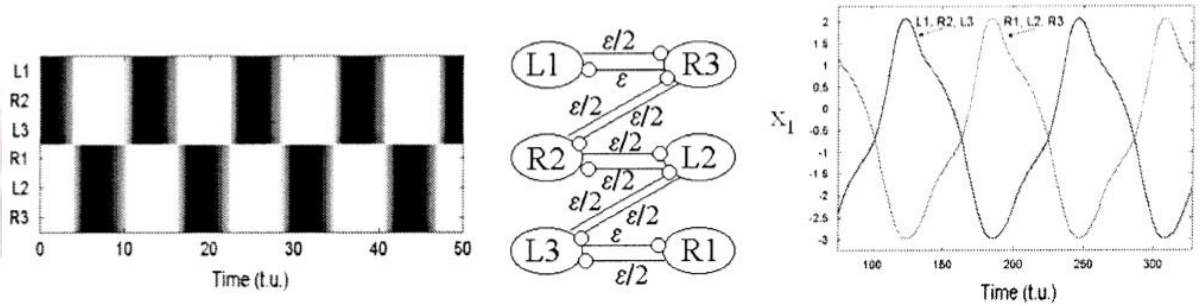
Cockroach

Image credit: M. Frasca, P. Arena, Wikipedia

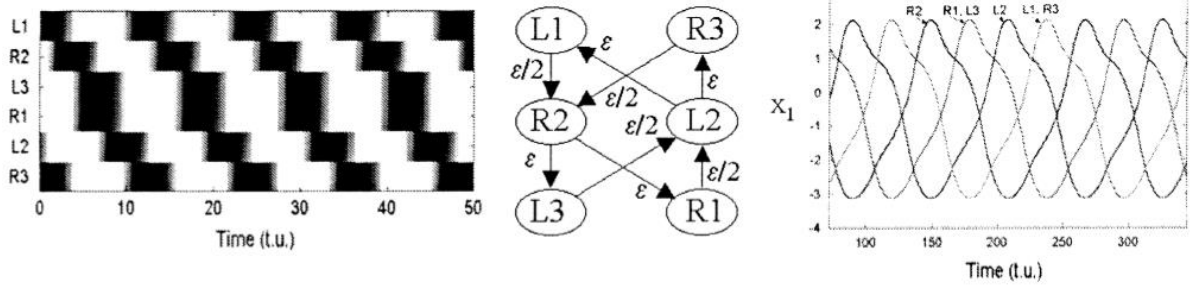
Versatile motor pattern generation

The connectionist approach

Alternating tripod



Metachronal



Wave

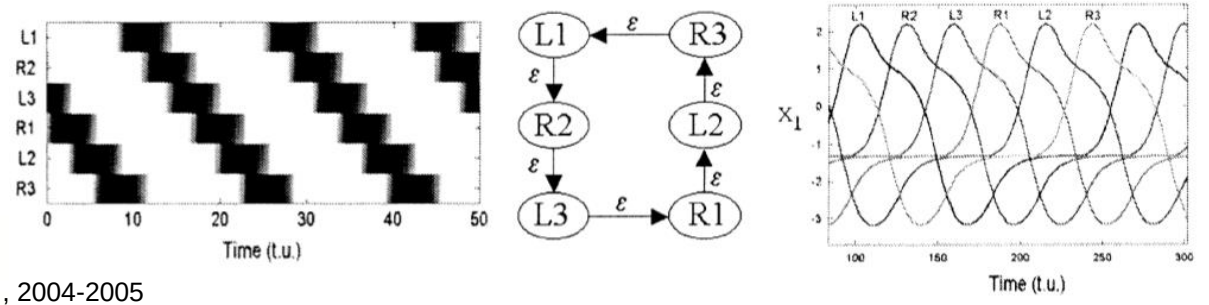
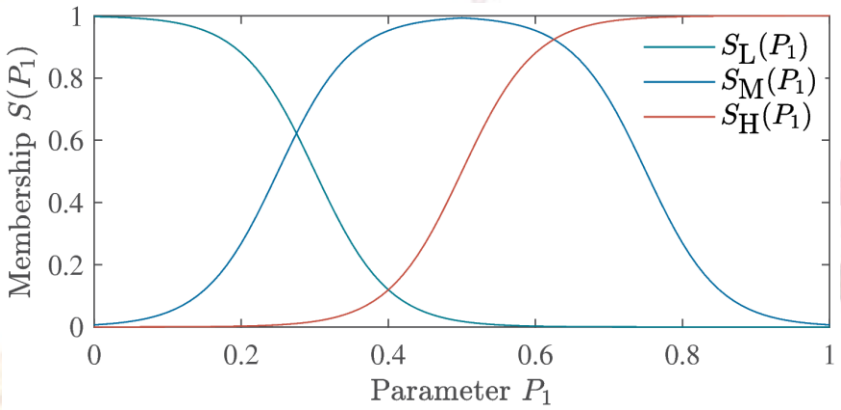


Image source: Arena et al., 2004-2005

Versatile motor pattern generation

Generalization via fuzzy membership functions



$$\begin{cases} S_{\mathrm{L}}(P_1) = 1 - \dfrac{1}{1 + e^{A_{\mathrm{L}}(P_1 + C_{\mathrm{L}})}} \\ S_{\mathrm{M}}(P_1) = 1 - \dfrac{1}{1 + e^{A_{\mathrm{M}}(|P_1 + C_{\mathrm{M}}| + C_{\mathrm{M}}/2)}} \\ S_{\mathrm{H}}(P_1) = \dfrac{1}{1 + e^{A_{\mathrm{H}}(P_1 + C_{\mathrm{H}})}} \end{cases}$$

Image source: Minati et al., IEEE Access 2018 © IEEE

Versatile motor pattern generation

Hierarchical approach (high level: gait, lower level: posture)

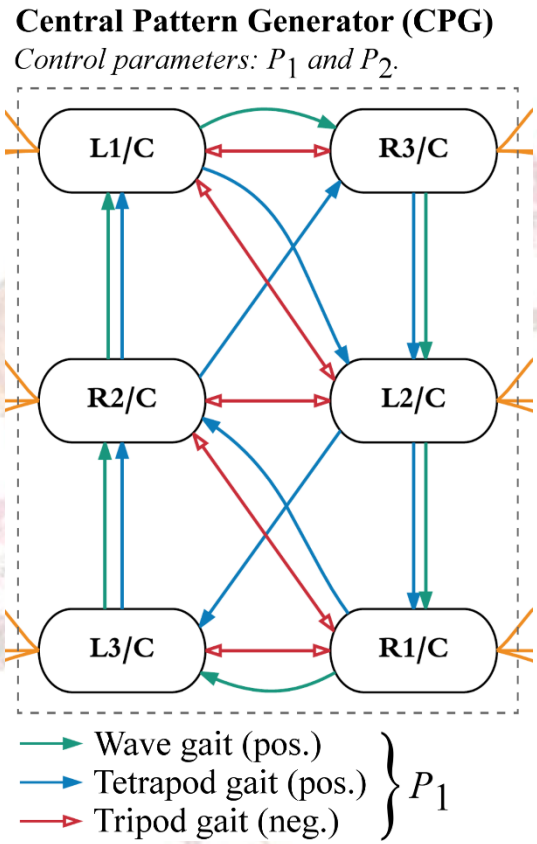


Image source: Minati et al., IEEE Access 2018 © IEEE

Versatile motor pattern generation

Hierarchical approach (high level: gait, lower level: posture)

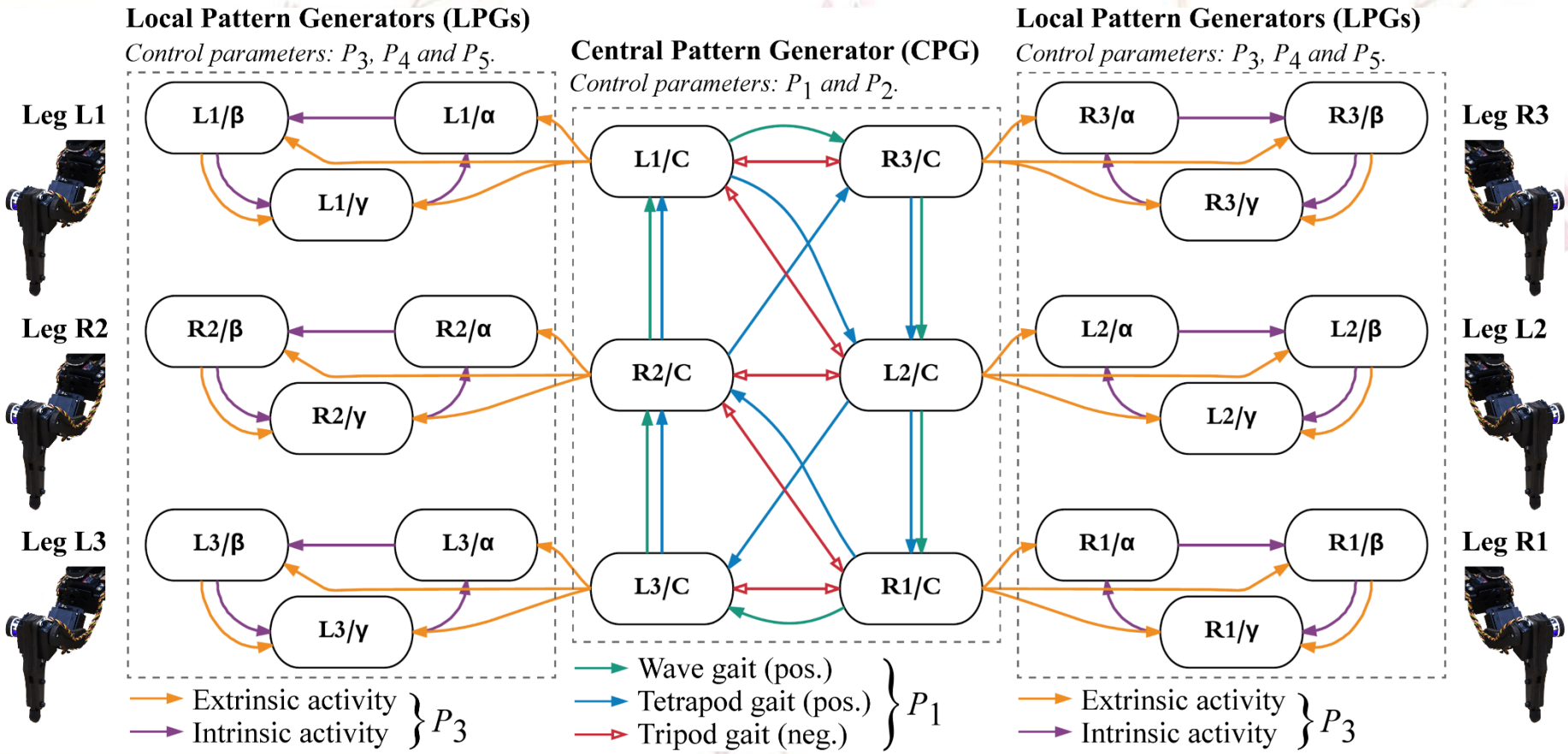


Image source: Minati et al., IEEE Access 2018 © IEEE

Versatile motor pattern generation

Problem: connectionist approach → huge number of parameters

$$\boldsymbol{A} = 2\begin{bmatrix} G_{1,\mathrm{L3}\to\mathrm{R3}} & G_{1,\mathrm{R3}\to\mathrm{L1}} & G_{1,\mathrm{L1}\to\mathrm{L2}} & G_{1,\mathrm{L2}\to\mathrm{R2}} & G_{1,\mathrm{L2}\to\mathrm{R1}} & G_{1,\mathrm{L2}\to\mathrm{L3}} \\ G_{2,\mathrm{R2}\to\mathrm{R3}} & G_{2,\mathrm{L2}\to\mathrm{L1}} & G_{2,\mathrm{R3}\to\mathrm{L2}} & G_{2,\mathrm{R1}\to\mathrm{R2}} & G_{2,\mathrm{R2}\to\mathrm{R1}} & G_{2,\mathrm{R1}\to\mathrm{L3}} \\ G_{3,\mathrm{L1}\to\mathrm{R3}} & G_{3,\mathrm{R2}\to\mathrm{L1}} & G_{3,\mathrm{R2}\to\mathrm{L2}} & G_{3,\mathrm{L3}\to\mathrm{R2}} & G_{3,\mathrm{L3}\to\mathrm{R1}} & G_{3,\mathrm{R3}\to\mathrm{L3}} \end{bmatrix}$$

$$= \begin{bmatrix} 0 & -S_\mathrm{H}/2 & (S_\mathrm{M}-S_\mathrm{H})/2 & -S_\mathrm{H}/2 & S_\mathrm{M}+S_\mathrm{L} & S_\mathrm{M} \\ S_\mathrm{M} & -S_\mathrm{H}/2 & S_\mathrm{M}/2+S_\mathrm{L} & (S_\mathrm{M}-S_\mathrm{H})/2 & -S_\mathrm{H}/2 & S_\mathrm{L}-S_\mathrm{H} \\ S_\mathrm{L}-S_\mathrm{H} & S_\mathrm{M}+S_\mathrm{L} & -S_\mathrm{H}/2 & S_\mathrm{M}/2+S_\mathrm{L} & -S_\mathrm{H}/2 & 0 \end{bmatrix}$$

$$\boldsymbol{B} = \begin{bmatrix} G_{1,\mathrm{L1},\gamma\to\alpha} & G_{2,\mathrm{L1},\mathrm{C}\to\alpha} & G_{3,\mathrm{L1},\circlearrowleft\alpha} & G_{1,\mathrm{L1},\alpha\to\beta} & G_{2,\mathrm{L1},\mathrm{C}\to\beta} & G_{3,\mathrm{L1},\circlearrowleft\beta} & G_{1,\mathrm{L1},\beta\to\gamma} & G_{2,\mathrm{L1},\mathrm{C}\to\gamma} & G_{3,\mathrm{L1},\circlearrowleft\gamma} \\ G_{1,\mathrm{R1},\gamma\to\alpha} & G_{2,\mathrm{R1},\mathrm{C}\to\alpha} & G_{3,\mathrm{R1},\circlearrowleft\alpha} & G_{1,\mathrm{R1},\alpha\to\beta} & G_{2,\mathrm{R1},\mathrm{C}\to\beta} & G_{3,\mathrm{R1},\circlearrowleft\beta} & G_{1,\mathrm{R1},\beta\to\gamma} & G_{2,\mathrm{R1},\mathrm{C}\to\gamma} & G_{3,\mathrm{R1},\circlearrowleft\gamma} \\ G_{1,\mathrm{L2},\gamma\to\alpha} & G_{2,\mathrm{L2},\mathrm{C}\to\alpha} & G_{3,\mathrm{L2},\circlearrowleft\alpha} & G_{1,\mathrm{L2},\alpha\to\beta} & G_{2,\mathrm{L2},\mathrm{C}\to\beta} & G_{3,\mathrm{L2},\circlearrowleft\beta} & G_{1,\mathrm{L2},\beta\to\gamma} & G_{2,\mathrm{L2},\mathrm{C}\to\gamma} & G_{3,\mathrm{L2},\circlearrowleft\gamma} \\ G_{1,\mathrm{R2},\gamma\to\alpha} & G_{2,\mathrm{R2},\mathrm{C}\to\alpha} & G_{3,\mathrm{R2},\circlearrowleft\alpha} & G_{1,\mathrm{R2},\alpha\to\beta} & G_{2,\mathrm{R2},\mathrm{C}\to\beta} & G_{3,\mathrm{R2},\circlearrowleft\beta} & G_{1,\mathrm{R2},\beta\to\gamma} & G_{2,\mathrm{R2},\mathrm{C}\to\gamma} & G_{3,\mathrm{R2},\circlearrowleft\gamma} \\ G_{1,\mathrm{L3},\gamma\to\alpha} & G_{2,\mathrm{L3},\mathrm{C}\to\alpha} & G_{3,\mathrm{L3},\circlearrowleft\alpha} & G_{1,\mathrm{L3},\alpha\to\beta} & G_{2,\mathrm{L3},\mathrm{C}\to\beta} & G_{3,\mathrm{L3},\circlearrowleft\beta} & G_{1,\mathrm{L3},\beta\to\gamma} & G_{2,\mathrm{L3},\mathrm{C}\to\gamma} & G_{3,\mathrm{L3},\circlearrowleft\gamma} \\ G_{1,\mathrm{R3},\gamma\to\alpha} & G_{2,\mathrm{R3},\mathrm{C}\to\alpha} & G_{3,\mathrm{R3},\circlearrowleft\alpha} & G_{1,\mathrm{R3},\alpha\to\beta} & G_{2,\mathrm{R3},\mathrm{C}\to\beta} & G_{3,\mathrm{R3},\circlearrowleft\beta} & G_{1,\mathrm{R3},\beta\to\gamma} & G_{2,\mathrm{R3},\mathrm{C}\to\gamma} & G_{3,\mathrm{R3},\circlearrowleft\gamma} \end{bmatrix}$$

$$= \begin{bmatrix} B_1P_3' & P_3 & B_2P_3'+B_3P_3P_4' & -P_3' & P_3(1+B_4P_4) & B_5P_3P_4 & B_6P_3'+B_7P_3P_4' & -B_8P_3P_4 & B_9P_3P_4' \\ B_1P_3' & P_3 & B_2P_3'+B_3P_3P_4' & -P_3' & P_3(1+B_4P_4) & B_5P_3P_4 & B_6P_3'+B_7P_3P_4' & -B_8P_3P_4 & B_9P_3P_4' \\ B_1P_3' & P_3 & B_2P_3'+B_3P_3 & -P_3' & P_3 & 0 & B_6P_3'+B_7P_3 & 0 & B_9P_3 \\ B_1P_3' & P_3 & B_2P_3'+B_3P_3 & -P_3' & P_3 & 0 & B_6P_3'+B_7P_3 & 0 & B_9P_3 \end{bmatrix}$$

B747-100

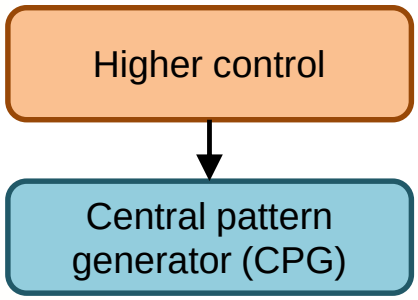
$$\boldsymbol{C} = 5\begin{bmatrix} G_{4,\mathrm{L1},\alpha} & G_{5,\mathrm{L1},\alpha} & G_{4,\mathrm{L1},\beta} & G_{5,\mathrm{L1},\beta} & G_{4,\mathrm{L1},\gamma} & G_{5,\mathrm{L1},\gamma} \\ G_{4,\mathrm{R1},\alpha} & G_{5,\mathrm{R1},\alpha} & G_{4,\mathrm{R1},\beta} & G_{5,\mathrm{R1},\beta} & G_{4,\mathrm{R1},\gamma} & G_{5,\mathrm{R1},\gamma} \\ G_{4,\mathrm{L2},\alpha} & G_{5,\mathrm{L2},\alpha} & G_{4,\mathrm{L2},\beta} & G_{5,\mathrm{L2},\beta} & G_{4,\mathrm{L2},\gamma} & G_{5,\mathrm{L2},\gamma} \\ G_{4,\mathrm{R2},\alpha} & G_{5,\mathrm{R2},\alpha} & G_{4,\mathrm{R2},\beta} & G_{5,\mathrm{R2},\beta} & G_{4,\mathrm{R2},\gamma} & G_{5,\mathrm{R2},\gamma} \\ G_{4,\mathrm{L3},\alpha} & G_{5,\mathrm{L3},\alpha} & G_{4,\mathrm{L3},\beta} & G_{5,\mathrm{L3},\beta} & G_{4,\mathrm{L3},\gamma} & G_{5,\mathrm{L3},\gamma} \\ G_{4,\mathrm{R3},\alpha} & G_{5,\mathrm{R3},\alpha} & G_{4,\mathrm{R3},\beta} & G_{5,\mathrm{R3},\beta} & G_{4,\mathrm{R3},\gamma} & G_{5,\mathrm{R3},\gamma} \end{bmatrix} =$$

$$\begin{bmatrix} C_1P_3P_4 & C_2P_3'+C_3P_3P_4'P_5' & C_4P_3'+C_5P_3P_4' & C_6P_3'+C_7P_3P_4P_5' & C_8P_3'+C_9P_3P_4'+C_{10}P_3P_4 & C_{11}P_3' \\ C_1P_3P_4 & C_2P_3'+C_3P_3P_4'P_5'' & C_4P_3'+C_5P_3P_4' & C_6P_3'+C_7P_3P_4P_5'' & C_8P_3'+C_9P_3P_4'+C_{10}P_3P_4 & C_{11}P_3' \\ 0 & C_{12}P_3'+C_{13}P_3P_5' & C_{14} & C_{15}P_3' & C_{16}P_3'+C_{17}P_3 & C_{18}P_3' \\ 0 & C_{12}P_3'+C_{13}P_3P_5'' & C_{14} & C_{15}P_3' & C_{16}P_3'+C_{17}P_3 & C_{18}P_3' \\ C_{19}P_3P_4 & C_{20}P_3'+C_{21}P_3P_4'P_5' & C_{22}P_3'+C_{23}P_3P_4' & C_{24}P_3'+C_{25}P_3P_4P_5' & C_{26}P_3'+C_{27}P_3P_4'+C_{28}P_3P_4 & C_{29}P_3' \\ C_{19}P_3P_4 & C_{20}P_3'+C_{21}P_3P_4'P_5'' & C_{22}P_3'+C_{23}P_3P_4' & C_{24}P_3'+C_{25}P_3P_4P_5'' & C_{26}P_3'+C_{27}P_3P_4'+C_{28}P_3P_4 & C_{29}P_3' \end{bmatrix} \quad (10)$$

Versatile motor pattern generation

Answer: declutter by collapsing into few higher-level parameters

Parameter	Range	Target	Denomination	Function
P_1	$[0, 1]$	CPG	Gait selection parameter	Determines the phase relationships between legs, e.g. allows choosing between wave (slow), tetrapod (metachronal, medium speed) and tripod (fast) gaits
P_2	$[-1, 1]$	CPG	Activation parameter	Allows inhibiting and approximately reversing the CPG activity, i.e. walking
P_3	$[0, 1]$	LPG	CPG $\rightarrow$ LPG coupling strength parameter	Determines the level of synchronization between the CPG and the LPGs (i.e., movement coordination)
P_4	$[0, 1]$	LPG	Posture parameter	Allows choosing between the ant-like and cockroach-like postures
P_5	$[-1, 1]$	LPG	Steering parameter	Allows steering the robot trajectory sideways



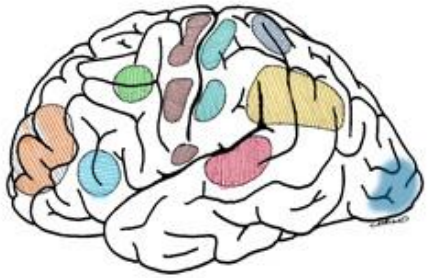
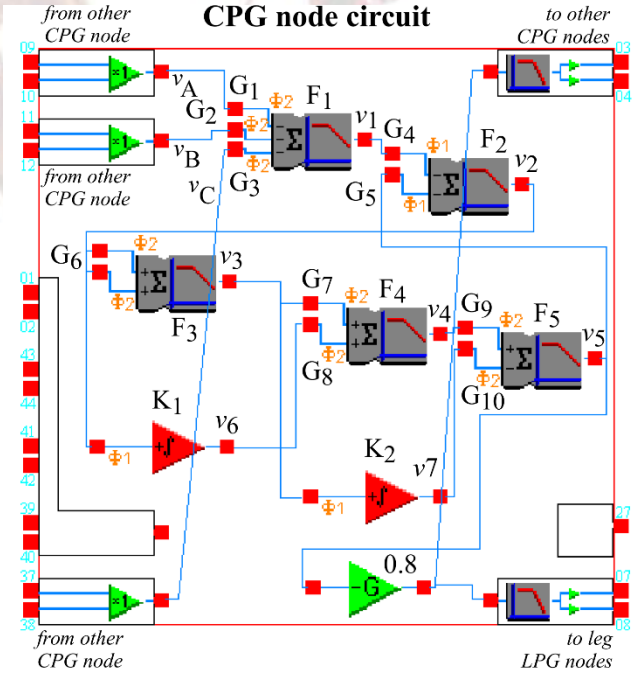


Image source: Wikipedia, public domain

Versatile motor pattern generation

Node oscillator – almost same as in experiments on remote sync.

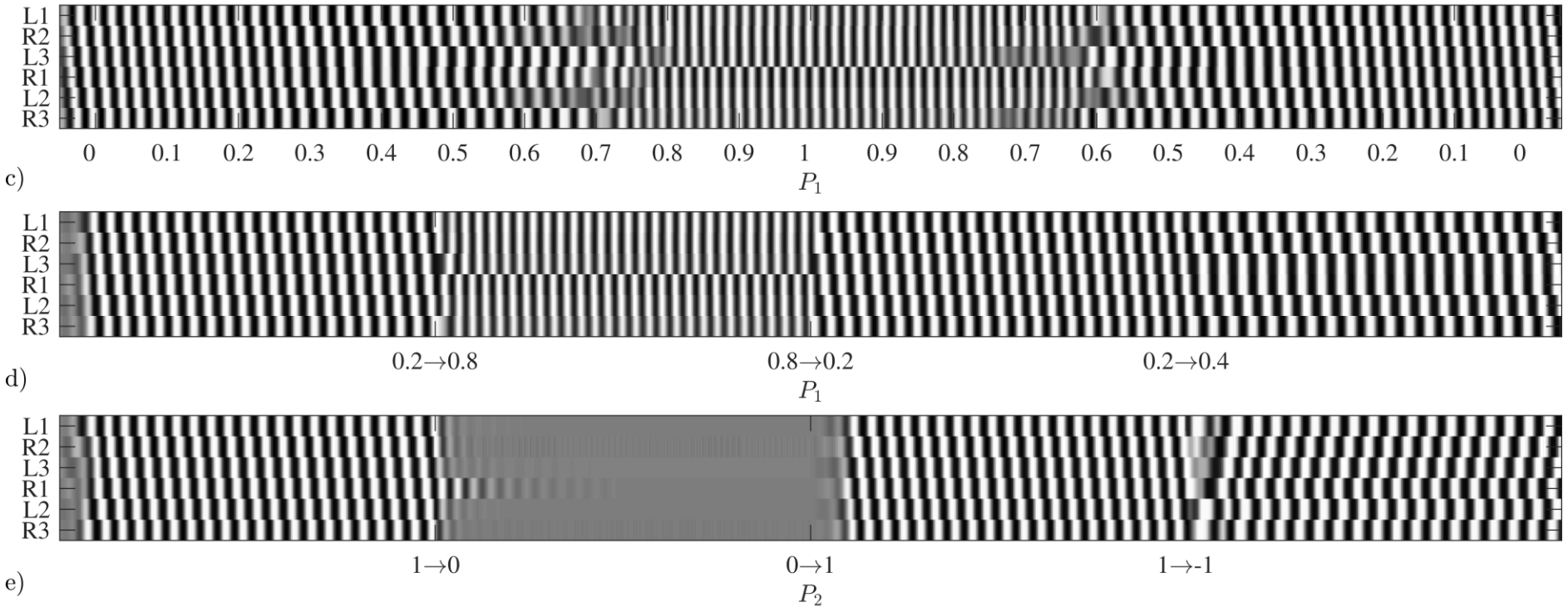


For node	G_1	G_2	G_3
L1/C	$-S_H/2$	$-S_H/2$	$S_M + S_L$
R2/C	$-S_H/2$	$(S_M - S_H)/2$	$S_M/2 + S_L$
L3/C	S_M	$S_L - S_H$	0
R1/C	$S_M + S_L$	$-S_H/2$	$-S_H/2$
L2/C	$(S_M - S_H)/2$	$S_M/2 + S_L$	$-S_H/2$
R3/C	0	S_M	$S_L - S_H$

Image source: Minati et al., IEEE Access 2018 © IEEE

Versatile motor pattern generation

CPG controllability – effect of parameters P1 and P2



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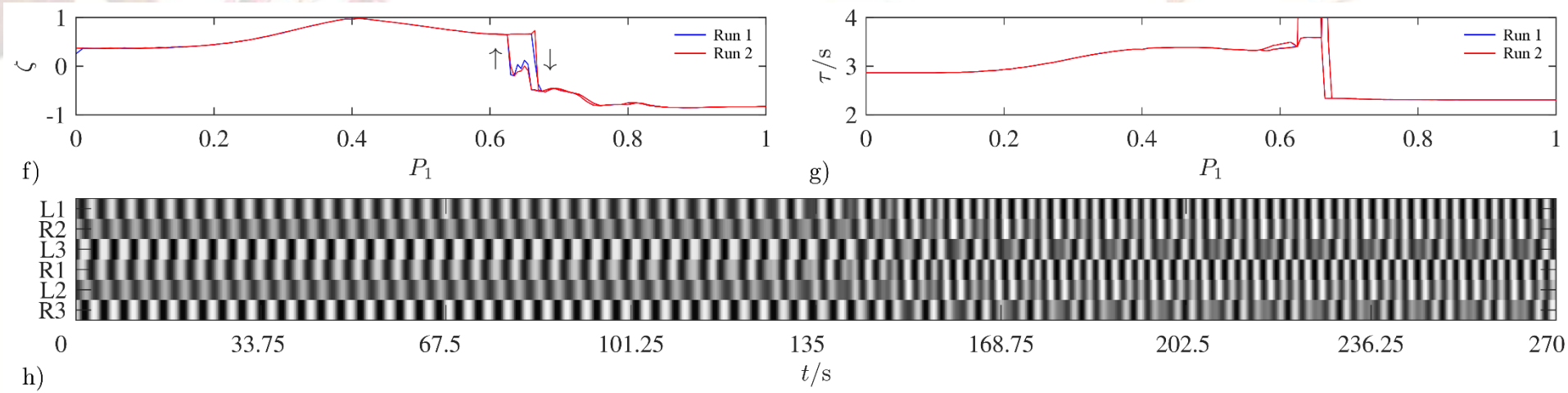
Versatile motor pattern generation

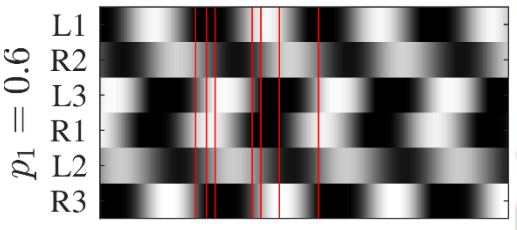
Emergent hysteresis and metastability, as in living insects!

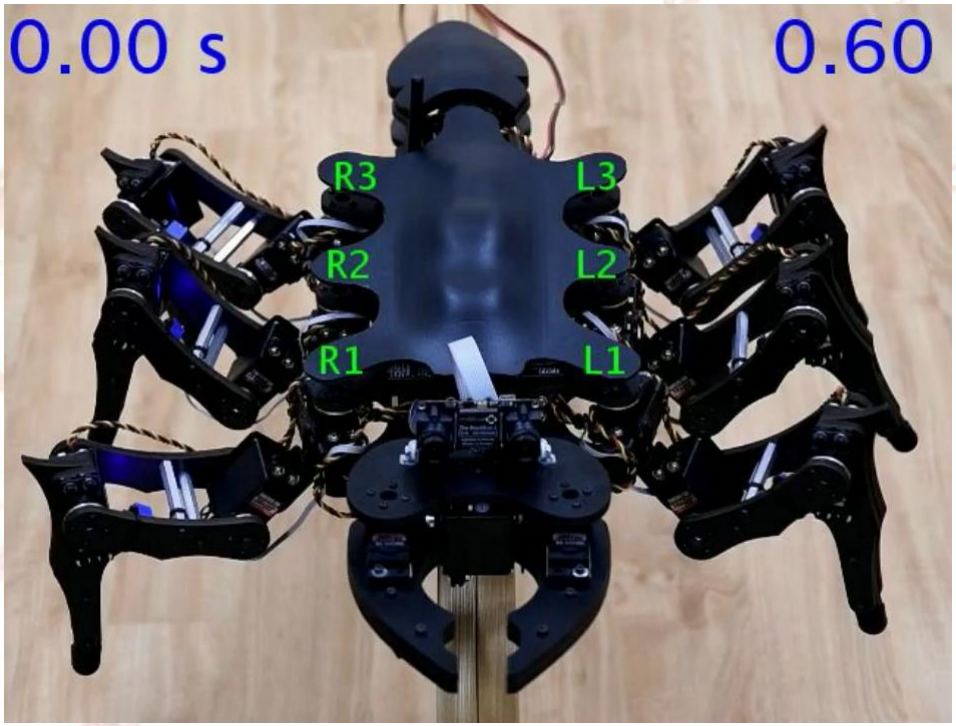


Versatile motor pattern generation

Emergent intermediate patterns, turn out to be viable

Paradoxical gait





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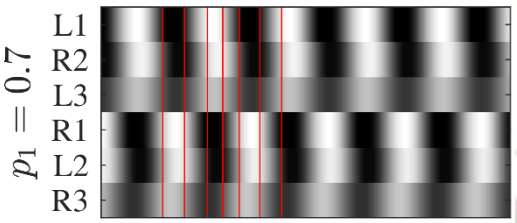
Versatile motor pattern generation

Emergent intermediate patterns, turn out to be viable

Unstable gait



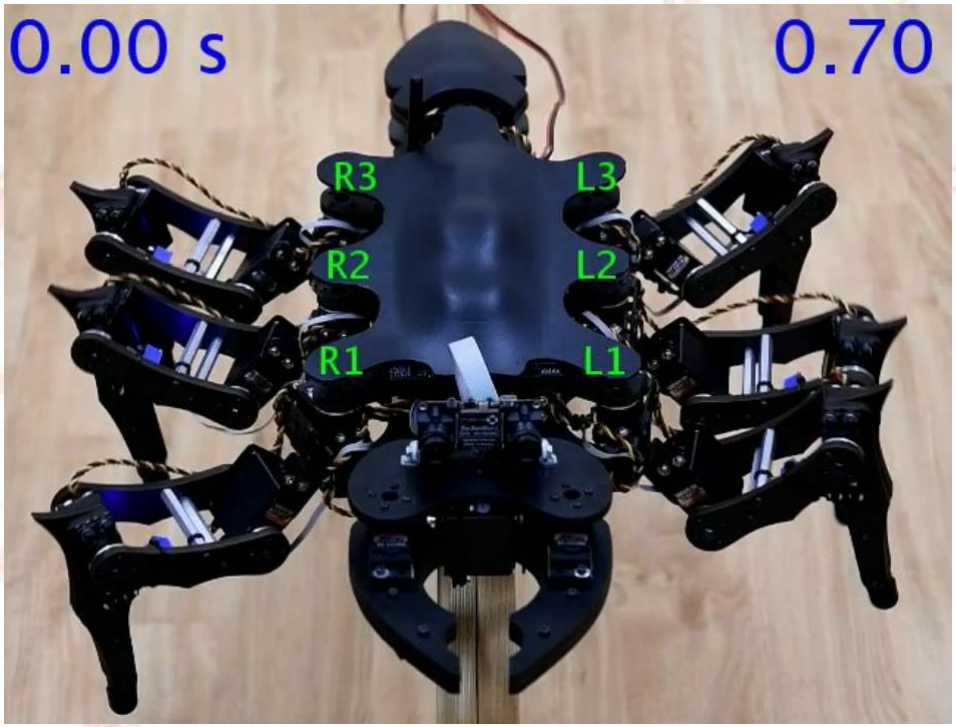


Image source: Minati et al., IEEE Access 2018 © IEEE

Versatile motor pattern generation

Posture and leg kinematics – Different power stroke delivery

Ant

All: coxa-body

Cockroach

Front, hind: femur-tibia
Middle: coxa-body

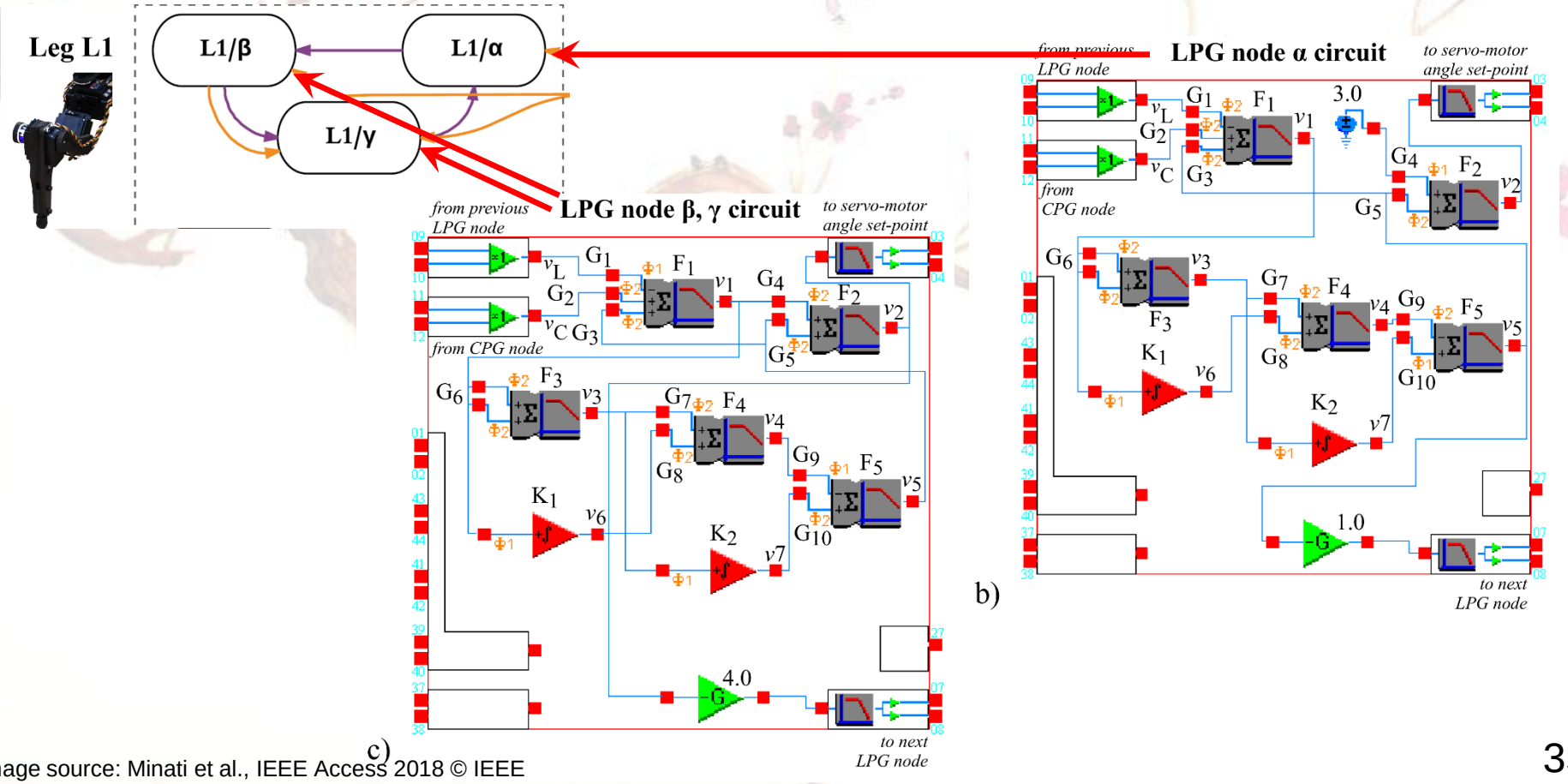
Image source: Wikipedia, public domain

Versatile motor pattern generation

Posture and leg kinematics – Different power stroke delivery

Versatile motor pattern generation

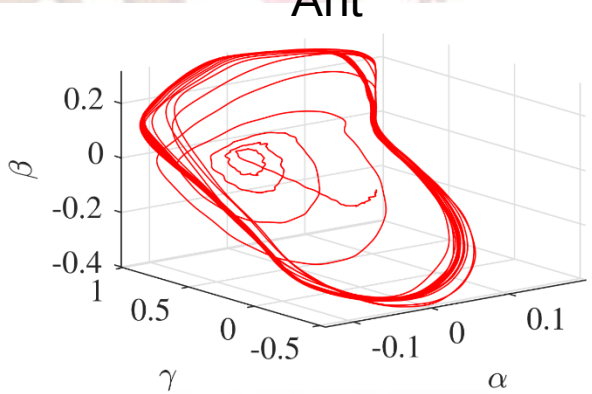
No explicit kinematic model, but dedicated oscillator variants



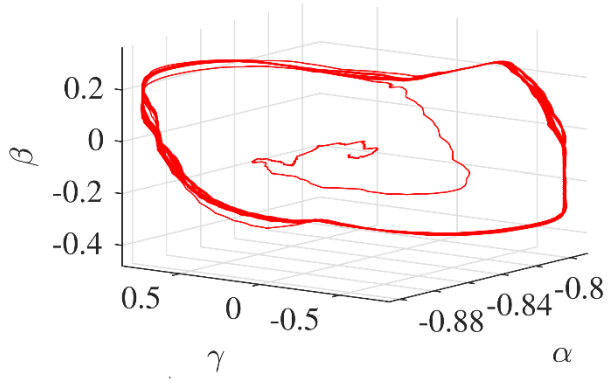
Versatile motor pattern generation

Emergence of limit cycle

Ant



Cockroach



Deafferentated

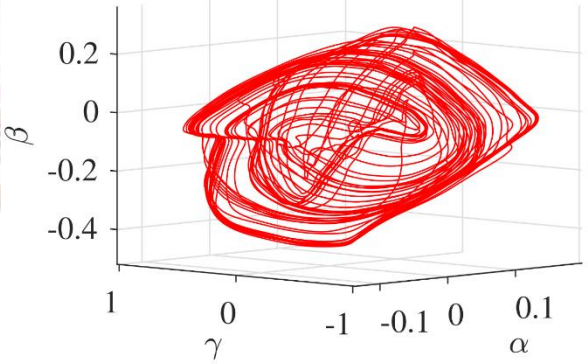


Image source: Minati et al., IEEE Access 2018 © IEEE, Wikipedia

Versatile motor pattern generation

Emergence of motor pattern – ant

Image source: Minati et al., IEEE Access 2018 © IEEE, Wikipedia

Versatile motor pattern generation

Generation of motor pattern - ant

Image source: Minati et al., IEEE Access 2018 © IEEE, Wikipedia

Versatile motor pattern generation

Generation of motor pattern - cockroach

Image source: Minati et al., IEEE Access 2018 © IEEE, Wikipedia

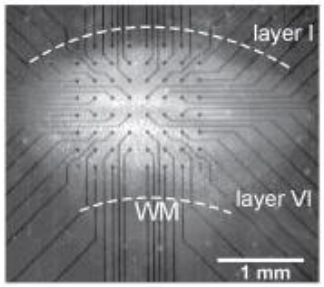
Versatile motor pattern generation

Generation of motor pattern - deafferentated

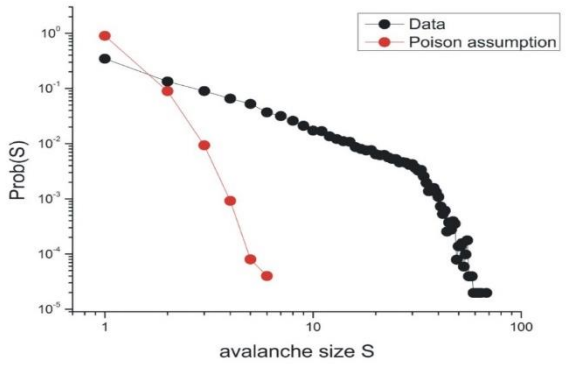
Image source: Minati et al., IEEE Access 2018 © IEEE, Wikipedia

Critical phenomena

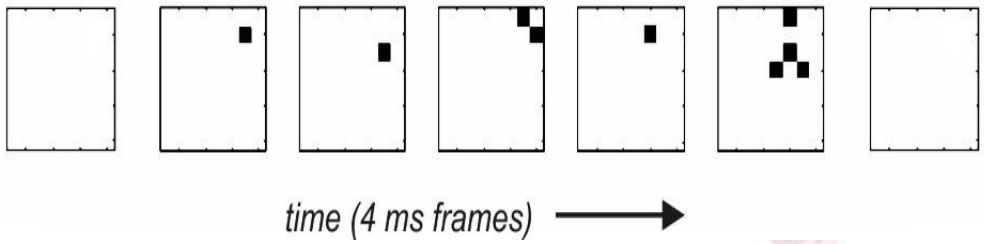
Neural avalanches recorded in-vitro and in-vivo

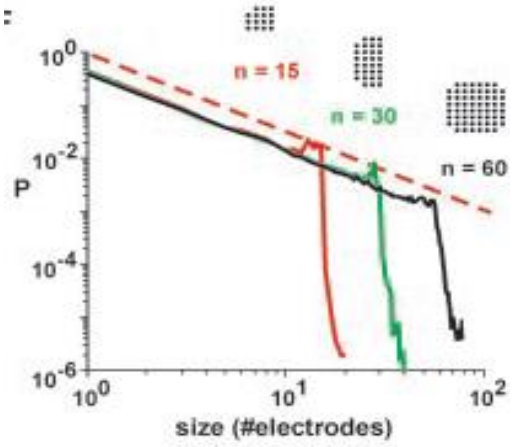


Cortical slice on array



Example of avalanche:

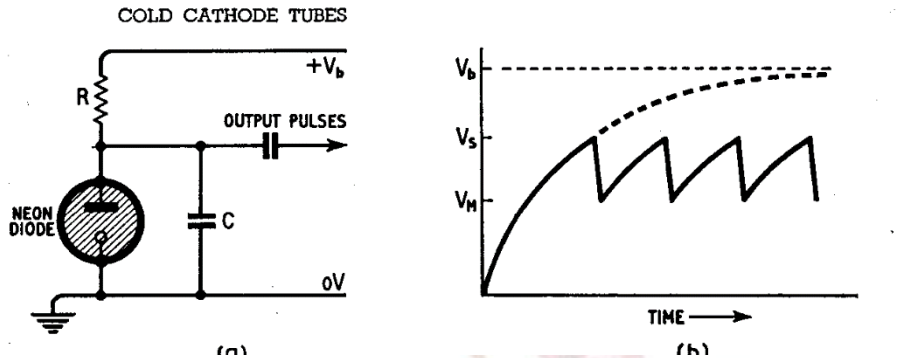


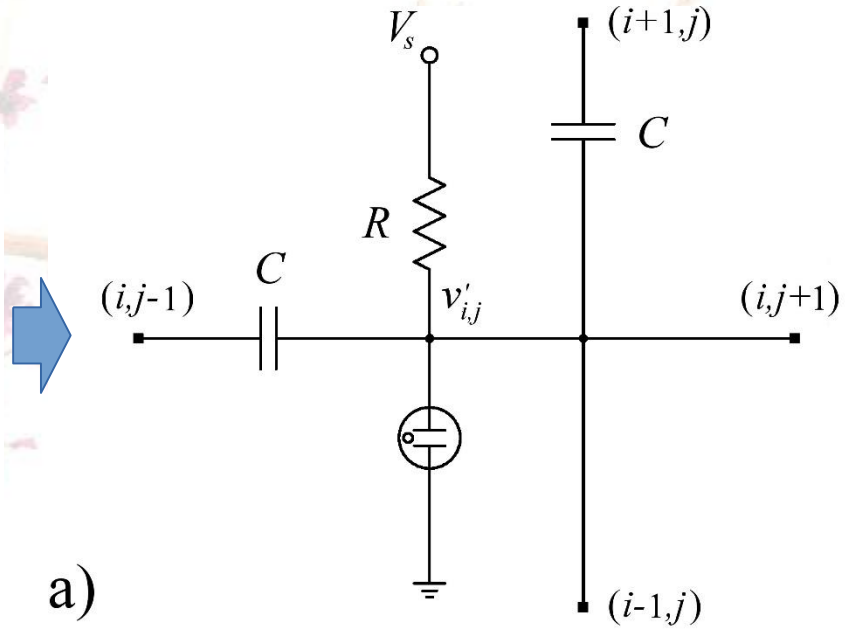


Source: J. Beggs, D. Plenz, J Neuroscience 2003; D. Chialvo, Nature Phys. 2010

Critical phenomena

In-silico "replica" of critical dynamics in a 2D lattice

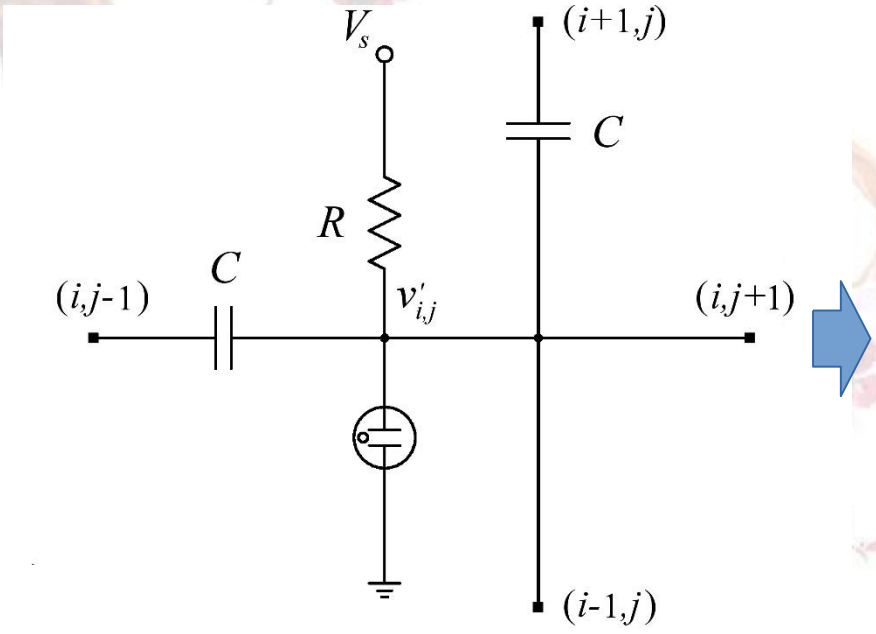


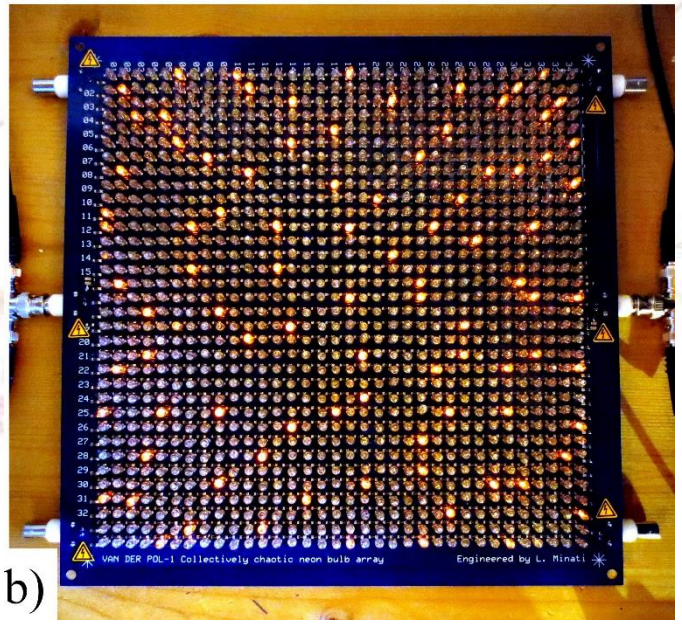


Source: F. Hoppensteadt, Math Biosci 2013

Critical phenomena

In-silico "replica" of critical dynamics in a 2D lattice





b)

Lattice size: 34 x 34

V_{strike}=76.3±0.8 V, $V_{extiction}$=61.4±0.6 V

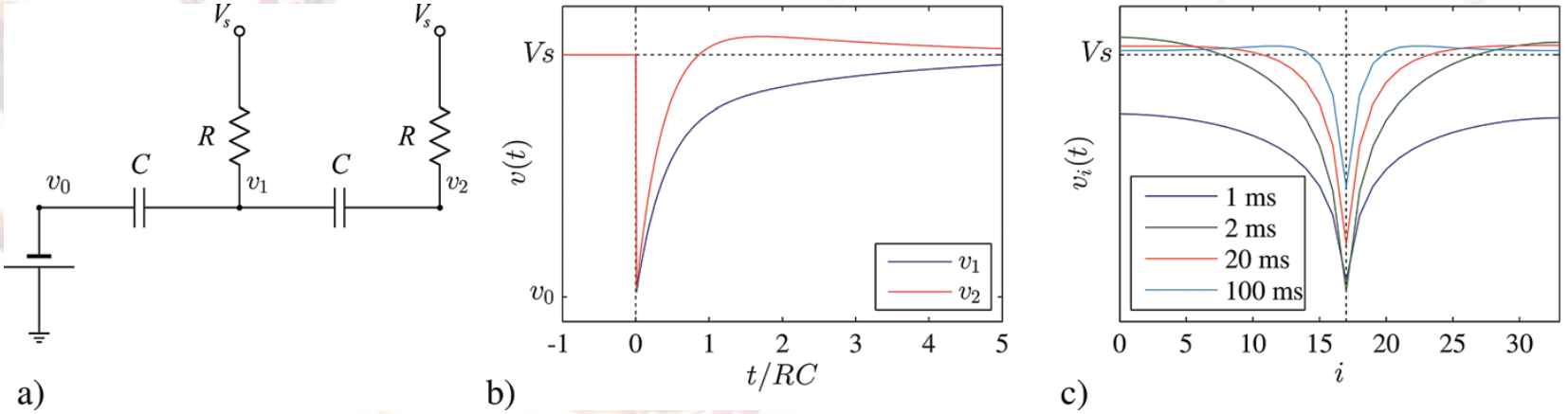
R = 2.2 MΩ, C = 220 nF

2 CCD cameras, 1 photodiode

Image source: Minati et al., CHAOS 2016 © AIP

Critical phenomena

Activity propagation

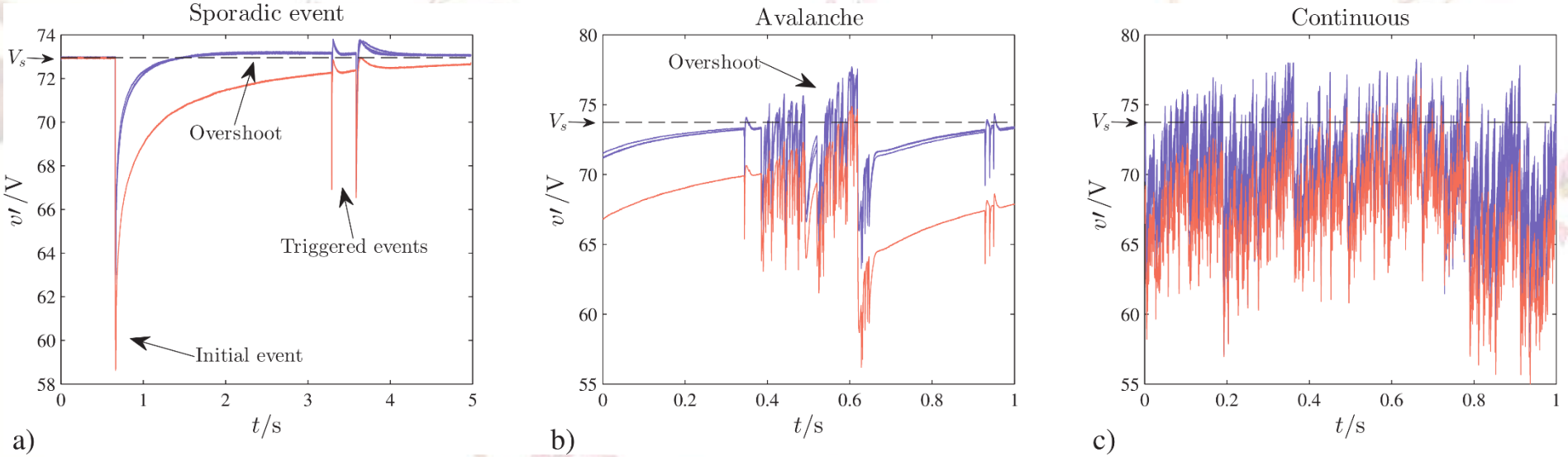


Despite short-range structural coupling, interactions are effectively long-range!

Image source: Minati et al., CHAOS 2016 © AIP

Critical phenomena

Activity propagation



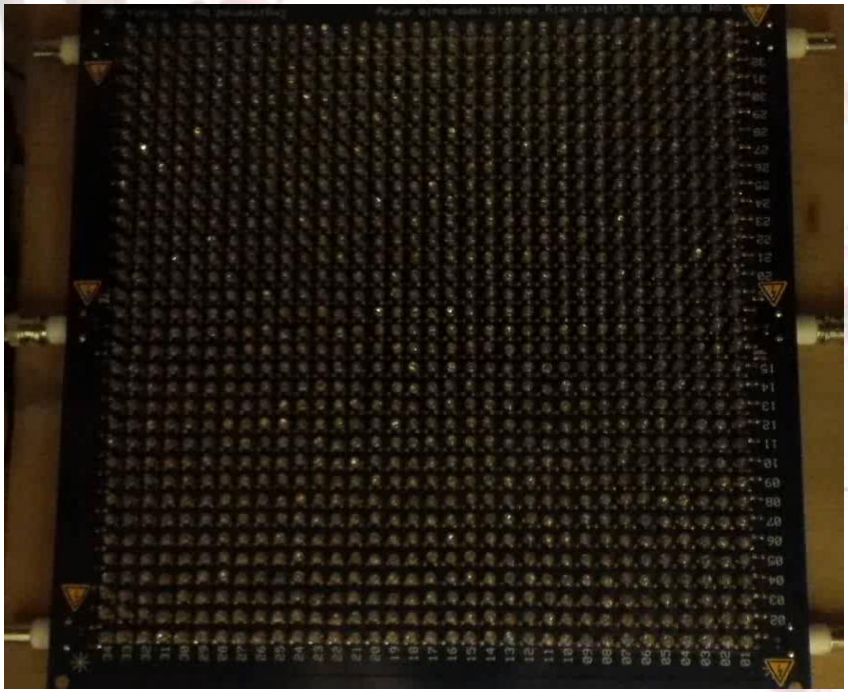
Increasing the supply voltage, activity eventually can propagate and self-sustain.

Image source: Minati et al., CHAOS 2016 © AIP

Critical phenomena

Phases I and II

Phase I (low rate, disordered, glass-like)



Phase II (high rate, ordered, crystal-like)

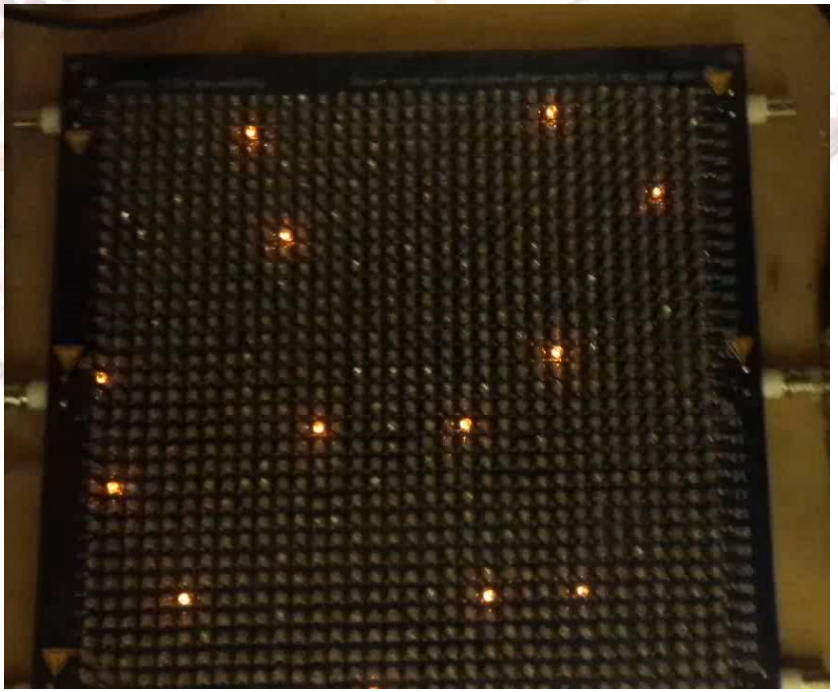
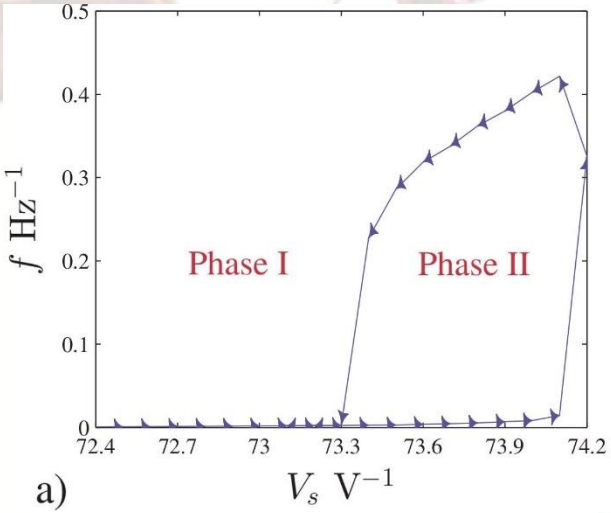
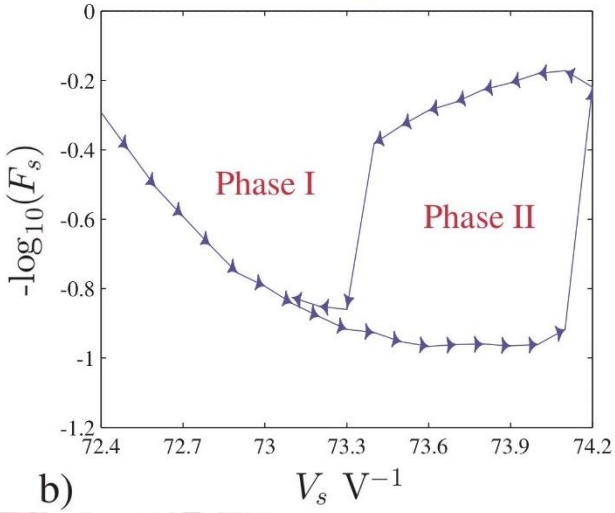


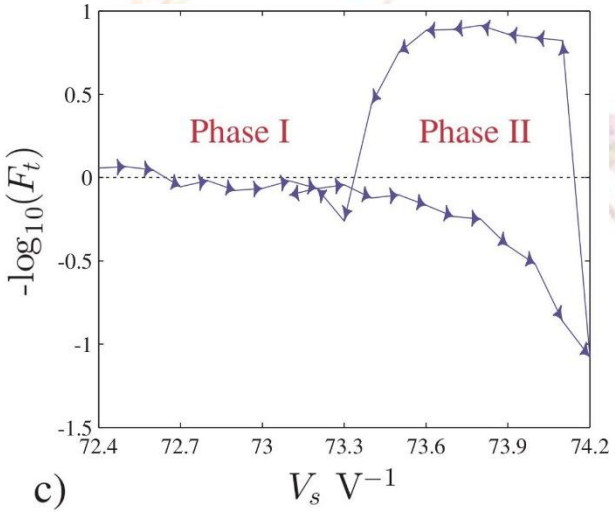
Image source: Minati et al., CHAOS 2016 © AIP

Critical phenomena

Transition between phases I and II







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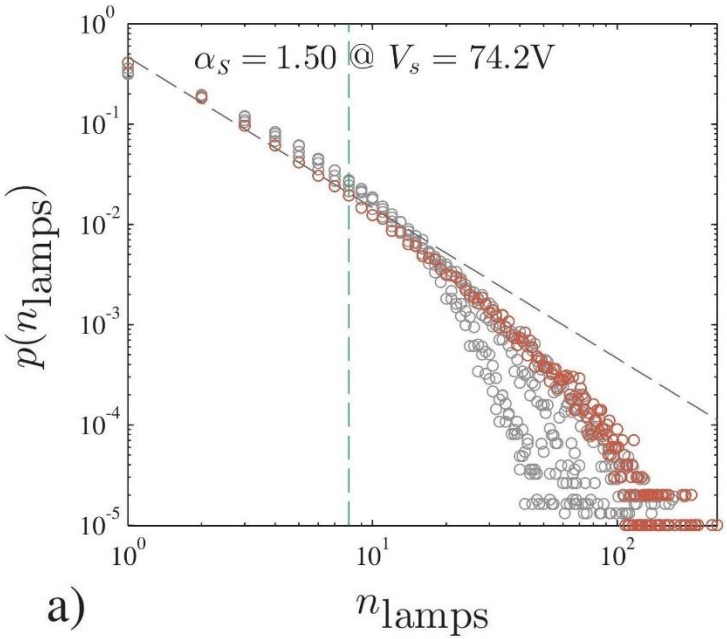
Critical phenomena

Avalanching



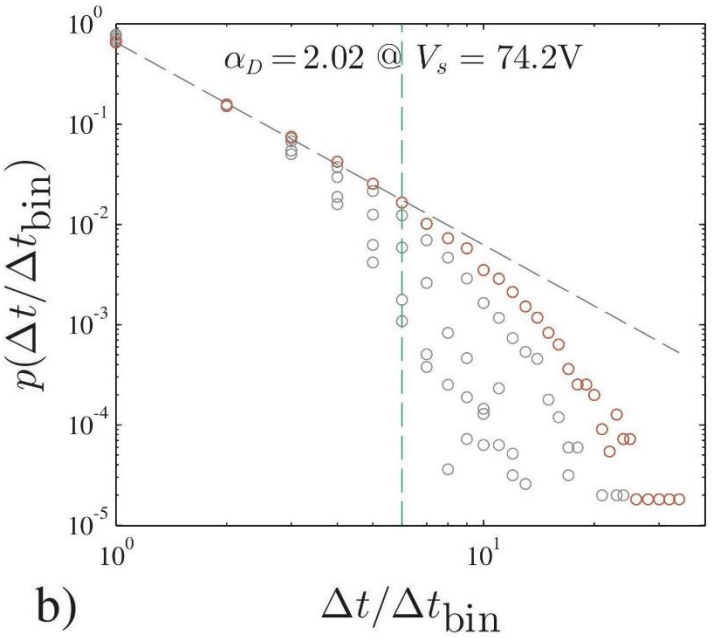


Image source: Minati et al., CHAOS 2016 © AIP

Conclusions

1) Integrated circuit-friendly (area efficient) realization of these circuits is feasible

2) Demonstration of application to gait and motor pattern generation. What about sensory processing, or other control functions in homeostasis?

3) Possibility to replicate critical phenomena even in elementary configuration (but not self-organized)

Thank you for your attention

References:

1. Minati L. Experimental Implementation of Networked Chaotic Oscillators Based on Cross-Coupled Inverter Rings in a CMOS Integrated Circuit. J Circuit Syst Comp 2015; 24:1550144
2. Minati L, de Candia A, Scarpetta S. Critical phenomena at a first-order phase transition in a lattice of glow lamps: Experimental findings and analogy to neural activity. Chaos. 2016; 26(7):073103
3. Minati L, Frasca M, Yoshimura N, Koike Y. Versatile locomotion control of a hexapod robot using a hierarchical network of non-linear oscillator circuits. IEEE Access 2018; 99:2799145

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