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Large-Scale Biologically Realistic Models of Cortical Mesocircuit Dynamics

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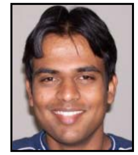


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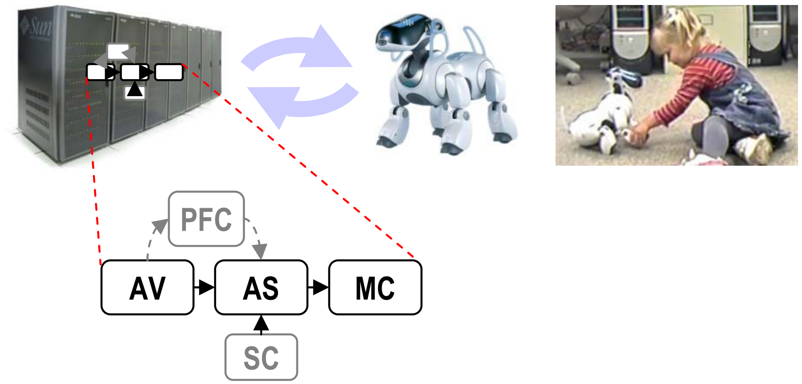
Large-Scale Cortical Mesocircuit Dynamics



1. **Scope of Work**
2. Neurodynamics & Mesocircuit Theory
3. RAIN Concepts & Progress to Date
4. Future Directions

1. Scope of Work

➢ Assumptions:

- The **brain** is an analog system (with some digital-like features)
- The **brain** obeys classical, non-quantum physics, operating in biological time
- The **brain** can be reverse-engineered

➢ Obstacles to understanding relevant brain processing:

- No consensus on algorithmic basis of cognition, memory, or consciousness
- Biological brain models have an extreme no. of unconstrained parameters
- Extracting biological parameters from behaving brains is very difficult
- Emulating genetic/developmental neural cell biology doesn't "explain" it

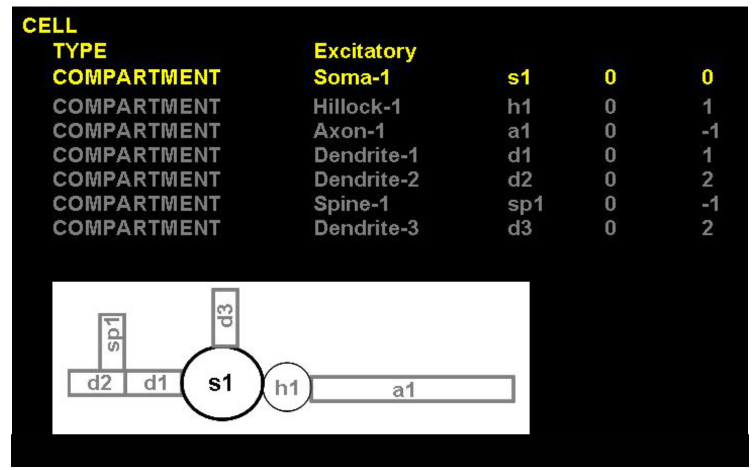
➢ Hypotheses:

- Phenomenologically-detailed brain mesocircuit models (to be described) could bridge this gap in our understanding (and give rise to novel hybrid analog-digital "AI")
- Robots based on mesocircuit theory and through social interaction can provide strong behavioral constraints on the cortical modeling (and result in immediate applications)

1. Scope of Work

➢ Simulation Software and Cluster Development

- ✓ 200-CPU cluster (Xeon/Opteron), Myrinet, 2 TB memory
- ✓ NCS software written in C/C++ with MPI architecture



- ✓ 100 columns x 10,000 cells = 1 million multicompartmental neurons, massively interconnected through 1 billion synapses

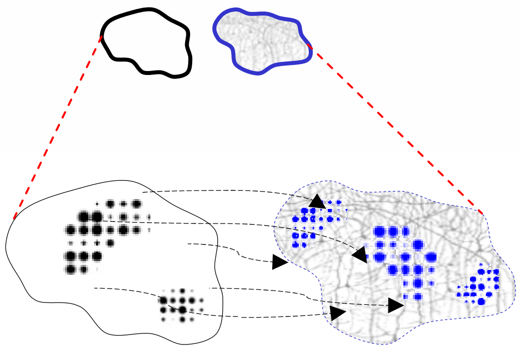
Large-Scale Cortical Mesocircuit Dynamics

1. Scope of Work

2. **Neurodynamics & Mesocircuit Theory**

3. RAIN Concepts & Progress to Date

4. Future Directions

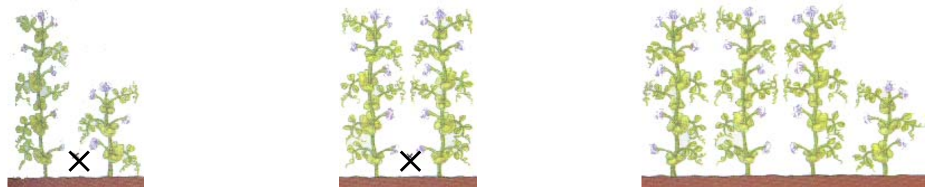


2. Neurodynamics

- **AI: symbols, syntax → production rules**
  - ✓ ***logical systems*** define high-level ***symbols*** that can be ***composed*** together in a generative way
  - → *they are lacking a "microstructure" needed to explain the fuzzy complexity of perception, categorization, motor control, learning*
- **Neural networks: neurons, links → activation rules**
  - ✓ in neurally inspired ***dynamical systems***, the ***nodes*** of a network ***activate*** each other by association
  - → *they are lacking a "macrostructure" needed to explain the systematic compositionality of language, reasoning, cognition*
- **Missing link: "mesoscopic" level of description**
  - ✓ cognitive phenomena emerge as ***complex systems*** from the underlying neurodynamics, via intermediary ***spatiotemporal patterns***

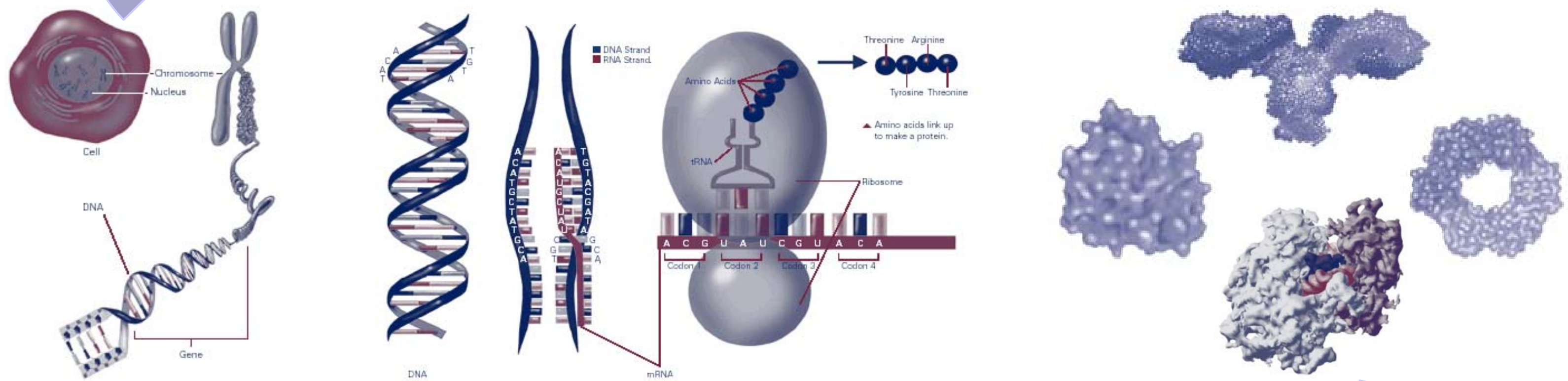
2. Neurodynamics

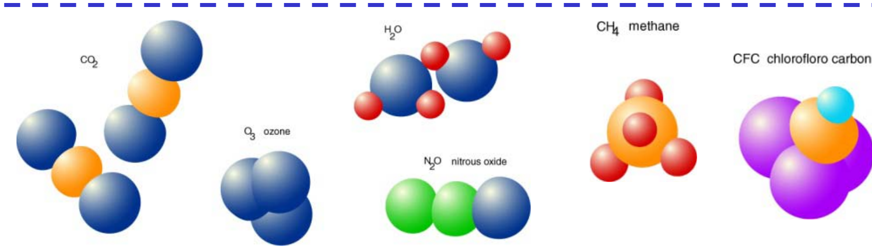
macrolevel:
genetics



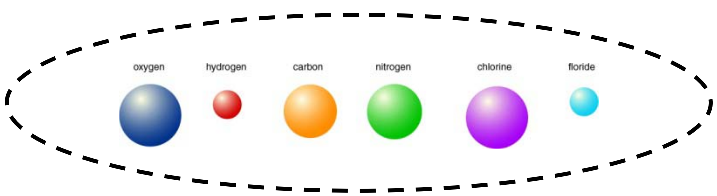
TT × Tt → Tt × Tt → TT, Tt, tT, tt

mesolevel:
molec. biology





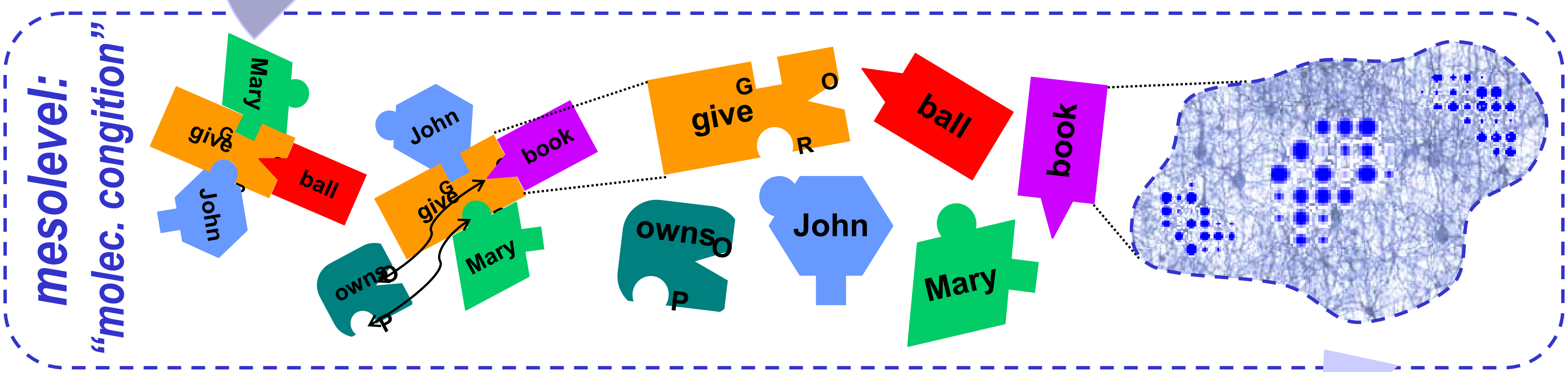
microlevel:
atoms



2. Neurodynamics

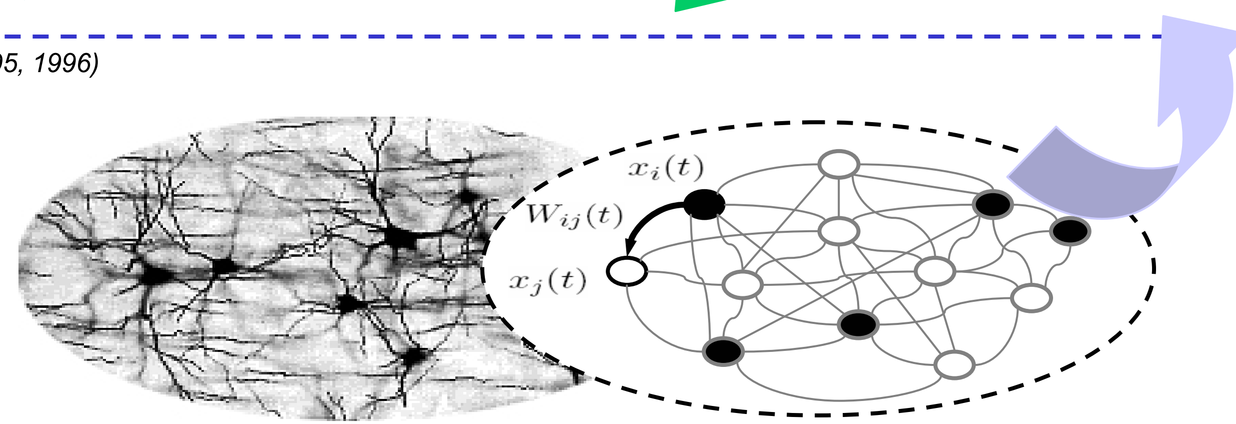
macrolevel:
symbols

"John gives a book to Mary" → **"Mary is the owner of the book"**



after Elie Bienenstock (1995, 1996)

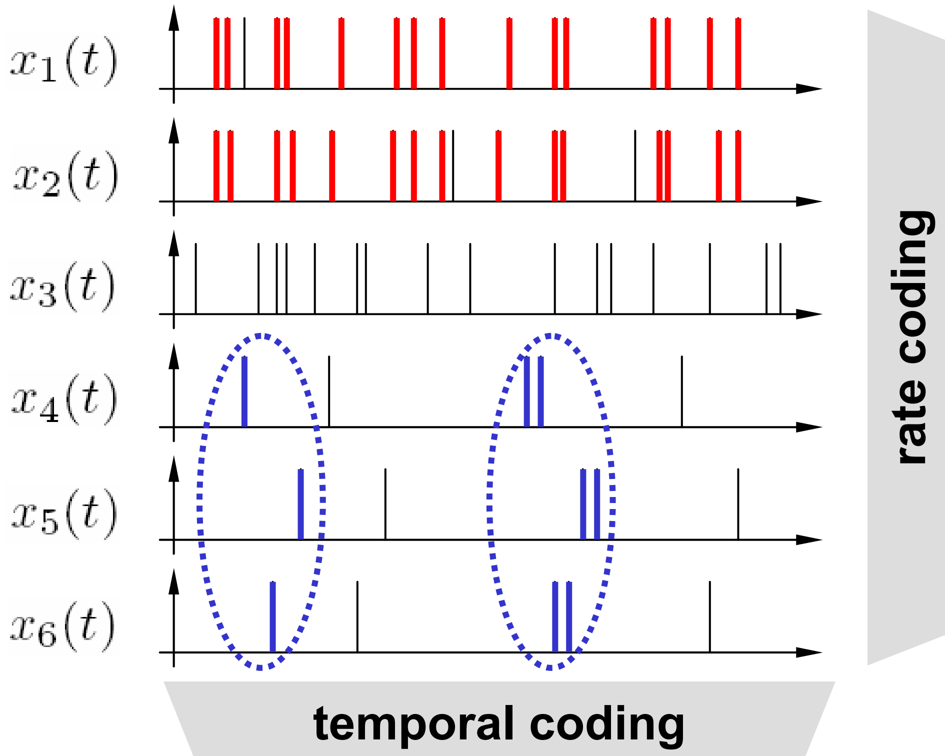
microlevel:
neurons



2. Neurodynamics

➢ Laws of neurodynamics: from rate to temporal coding

✓ more than mean rates → ***temporal correlations*** among spikes



$\langle x_1(t) \rangle =$ ● high activity rate

$\langle x_2(t) \rangle =$ ● high activity rate

$\langle x_3(t) \rangle =$ ● high activity rate

$\langle x_4(t) \rangle =$ ○ low activity rate

$\langle x_5(t) \rangle =$ ○ low activity rate

$\langle x_6(t) \rangle =$ ○ low activity rate

$$\boxed{\langle x_1(t)\, x_2(t) \rangle \gg \langle x_1(t)\, x_3(t) \rangle}$$

➢ zero-delays: synchrony
(1 and 2 more in sync than 1 and 3)

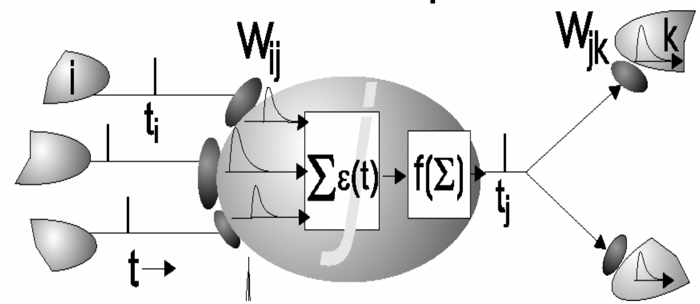
$$\boxed{\langle x_4(t)\, x_5(t-\tau_{4,5})\, x_6(t-\tau_{4,6}) \rangle}$$

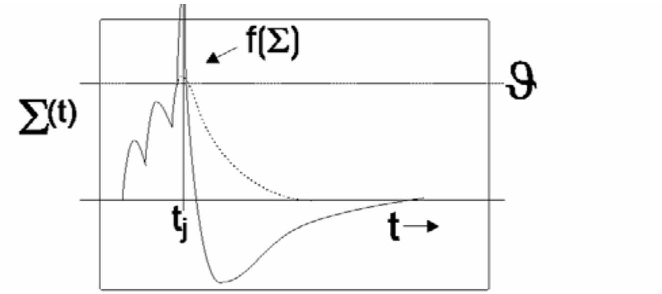
➢ nonzero delays: rhythms
(4, 5 and 6 correlated through delays)

2. Neurodynamics

➢ From digital to analog temporal coding

✓ more than discrete spikes → continuous ***membrane potential***

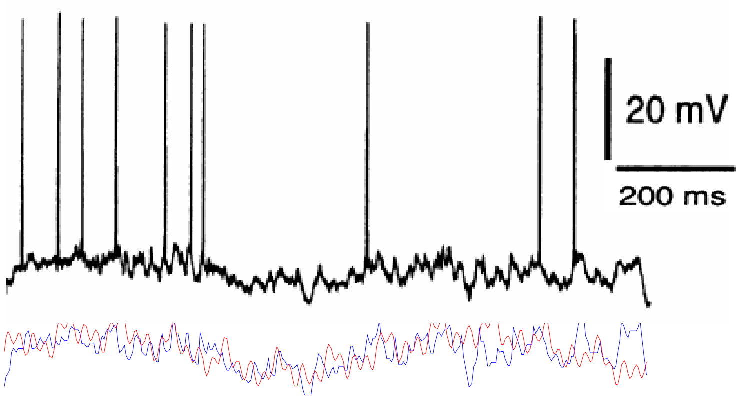




S. M. Bohte, 2003

✓ neurons receive a great amount of ***background activity*** from close or remote cortical areas

✓ this activity is ***irregular but somewhat rhythmic*** and has a critical influence on the neurons' ***responsiveness***



Destexhe & Pare, *Neurocomputing*, 2000

→ this suggests a new form of ***analog binding***, instead of spike synchrony

2. Neurodynamics

➢ Cognitive Neurodynamics

- ✓ Springer journal: “CN is a trend to study cognition from a dynamic view that has emerged as a result of the rapid developments taking place in nonlinear dynamics and cognitive science.”
  - focus on the spatiotemporal dynamics of neural activity in describing brain function
  - contemporary theoretical neurobiology that integrates recent and rapid advances in nonlinear dynamics, complex systems and statistical physics
  - often contrasted with computational and modular approaches of cognitive neuroscience

2. Neurodynamics

➢ Cognitive Neurodynamics. . . and beyond

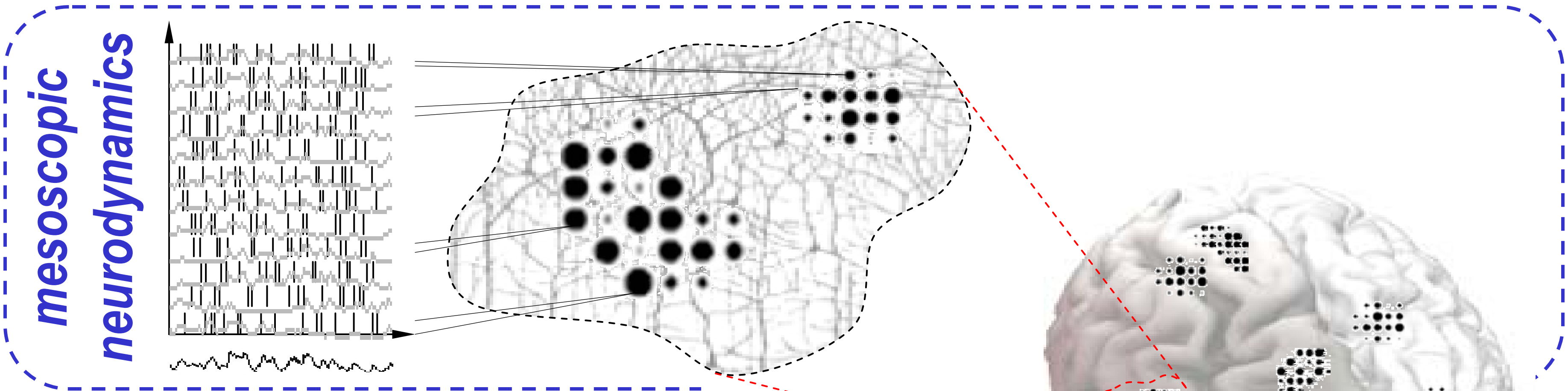
- ✓ CN also distinguishes three levels of organization (W. Freeman):
  - microscopic – multiple spike activity (MSA)
  - "mesoscopic" – local field potentials (LFP), electrocorticograms (ECoG)
  - macroscopic – electroencephalograms (EEG)
- ✓ however, in the CN view, upper levels are generally based on ***neural fields***:
  - continuum approximation of discrete neural activity by spatial and temporal integration of lower levels → loss of spatial and temporal resolution

→ *in our view, the mesoscopic level of description should retain the fine details of spiking (and subthreshold) patterns: what truly matters are the spatiotemporal **"shapes"** of mesoscopic objects*

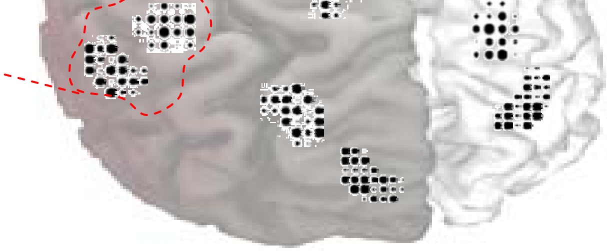
2. Neurodynamics

➢ Mesoscopic entities are spatiotemporal patterns (STPs)

- ✓ large-scale, localized dynamic cell assemblies that display complex, ***reproducible*** digital-analog regimes of neuronal activity
- ✓ these regimes of activity are supported by specific, ***ordered*** patterns of recurrent synaptic connectivity



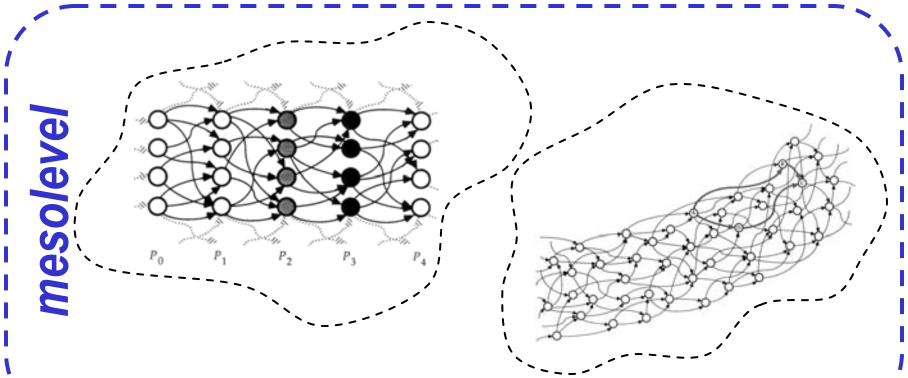
- ✓ paradigm shift: construing the brain as a ***pattern formation machine***



2. Neurodynamics

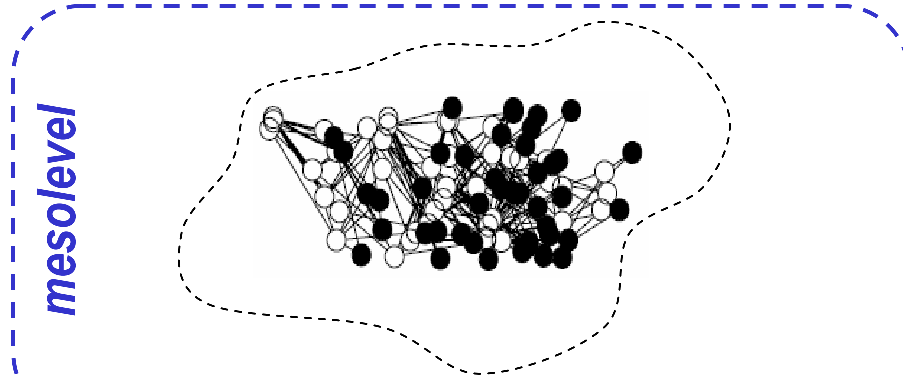
➢ Theories populating the mesolevel: a zoology of STPs

✓ synfire chains & braids



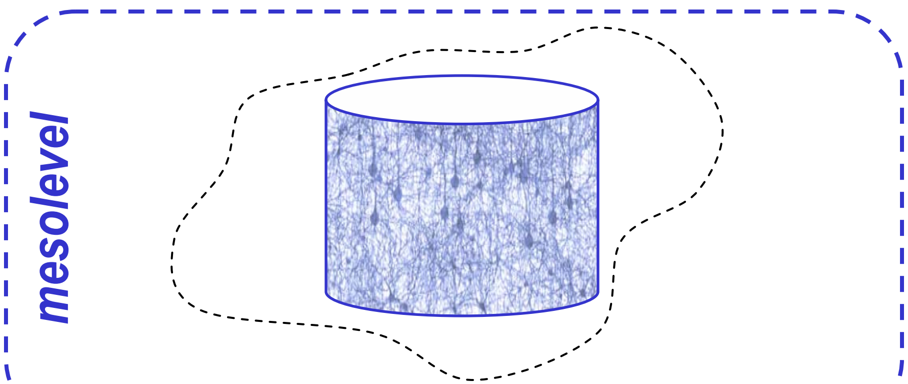
Abeles (1982), Bienenstock (1995), Doursat (1991)

✓ polychronous groups



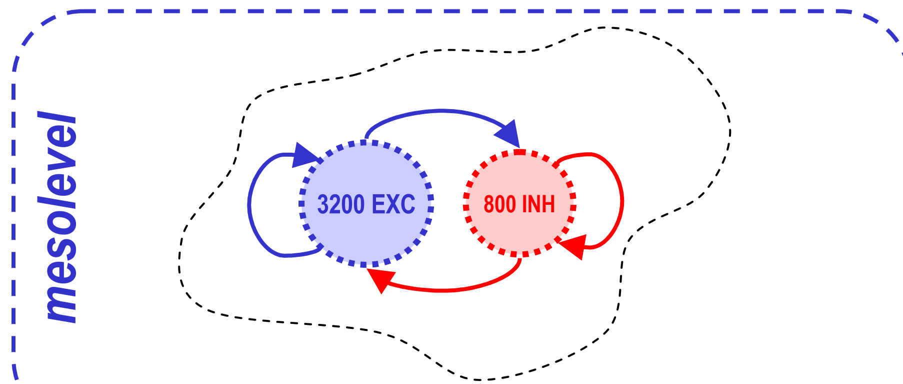
Izhikevich (2006)

✓ BlueColumn



Markram (2006)

✓ RAIN & mesocircuits

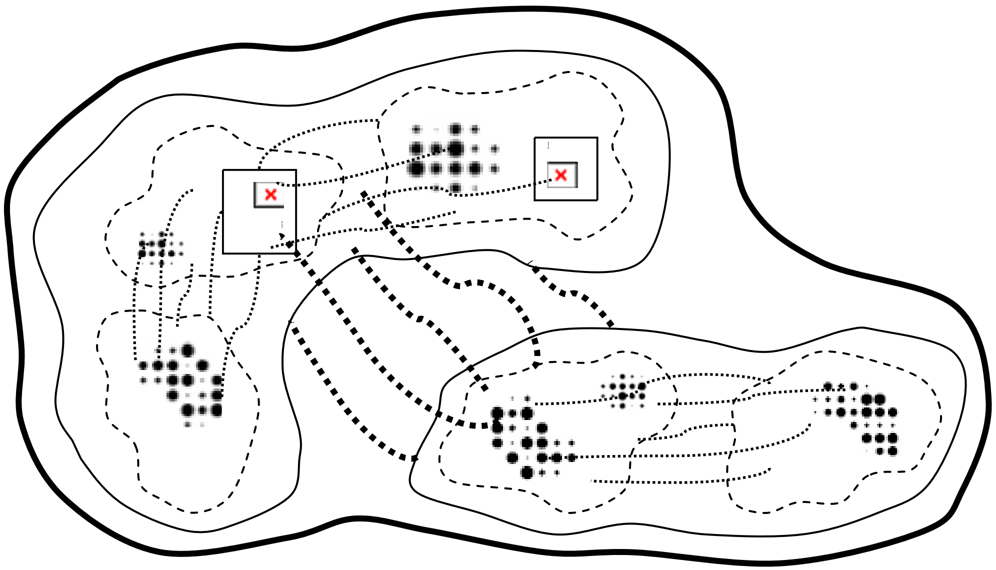


Brunel (2000), Vogels & Abbott (2006), Goodman & Doursat (2006)

2. Neurodynamics

➢ A building-block game of mental representations

- ✓ STPs can ***bind***, ***interact*** and/or ***assemble*** at several levels, forming complex structures from simpler ones in a hierarchy

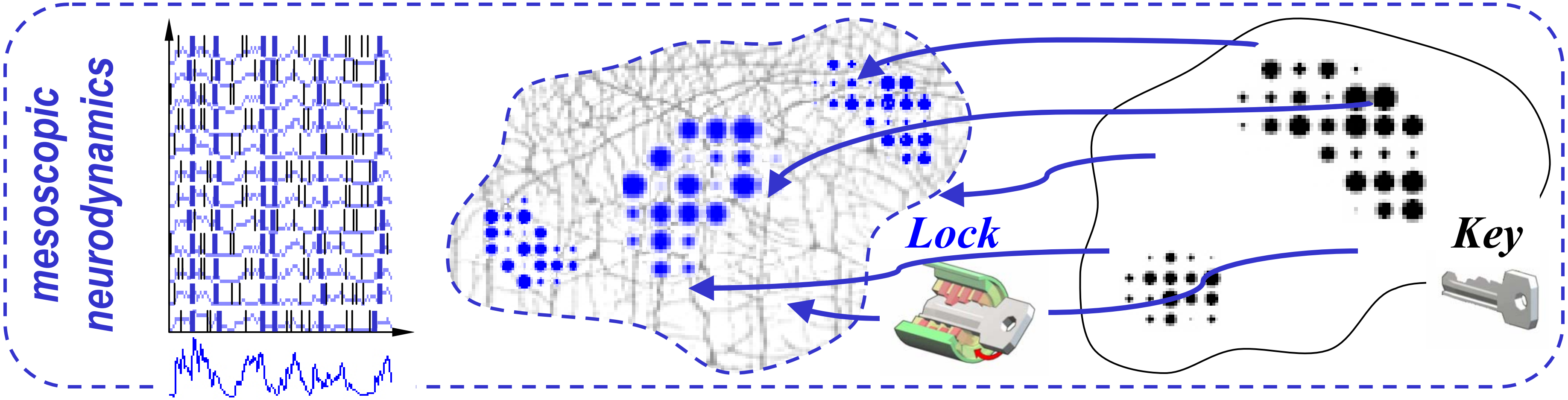


- ✓ binding by ***temporal correlations*** and ***fast synaptic plasticity***
  - synchronization
  - delayed correlations, waves
  - analog induction, resonance, etc.

2. Mesocircuit Theory

➢ Inter-pattern perturbation and coherence induction

- ✓ cell assemblies can interact through weak coupling contacts and ***influence*** each other's dynamical activity modes
- ✓ an input "key" stimulating a "lock" pattern induces a transient regime change and a ***greater or lesser response*** in the lock

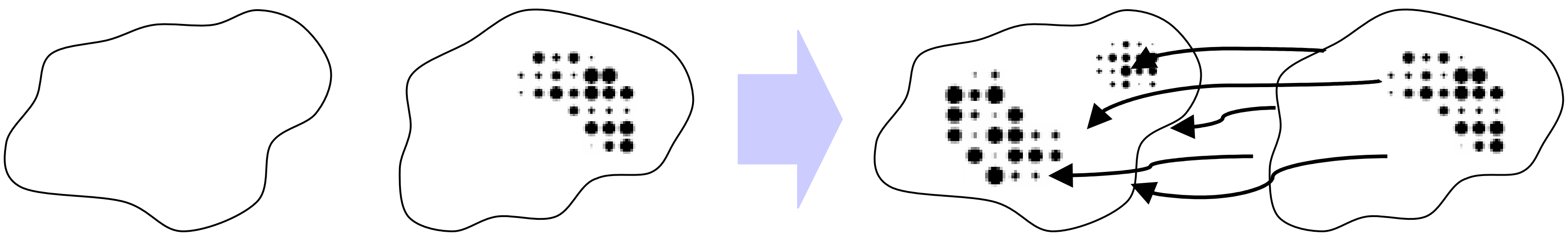


- ✓ the lock has ***key-specific*** recognition/representation abilities; it is
  - similar to a "template", except not a copy of, or analogous to the key
  - similar to an "attractor", except does not need the key to be active

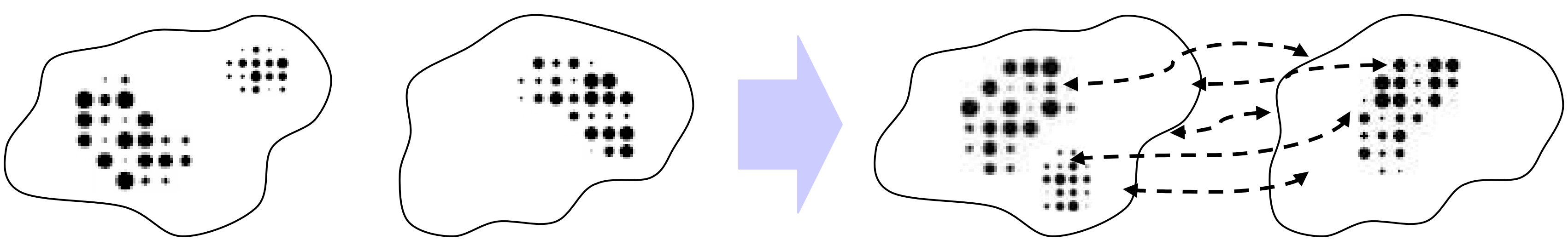
2. Mesocircuit Theory

➢ New neural dynamics: perturbation by coupling

- ✓ subtle but fundamental distinction between ***activating*** and ***perturbing/influencing***
- ✓ old paradigms (input/output processing chain): a lower area literally ***activates*** a higher area, initially silent



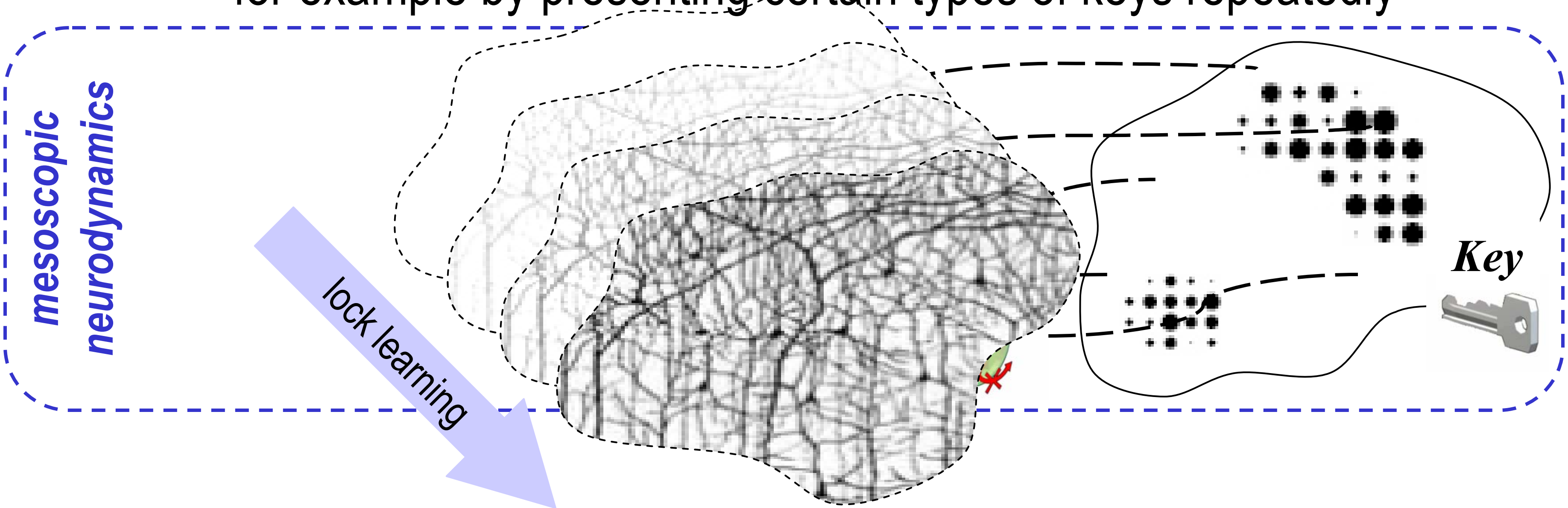
- ✓ new paradigm: subnetworks already possess endogenous modes of activity, ***perturbed*** by coupling interactions, possibly two-way



2. Mesocircuit Theory

➢ "Molding" locks by Hebbian learning

- ✓ a lock's ability to respond more to certain types of keys relies on its ***specific distribution*** of synaptic contacts
- ✓ these contacts could be ***learned*** through Hebbian modification, for example by presenting certain types of keys repeatedly

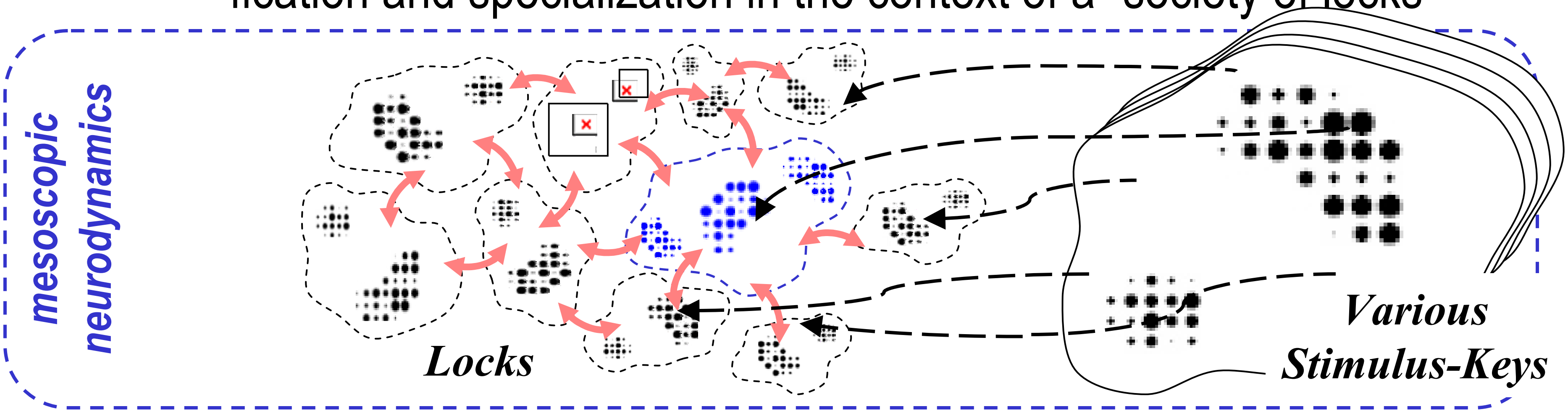


- ✓ during the training phase, ***undifferentiated*** locks are transformed into ***specialized*** locks

2. Mesocircuit Theory

➢ Lock diversification and inter-lock competition

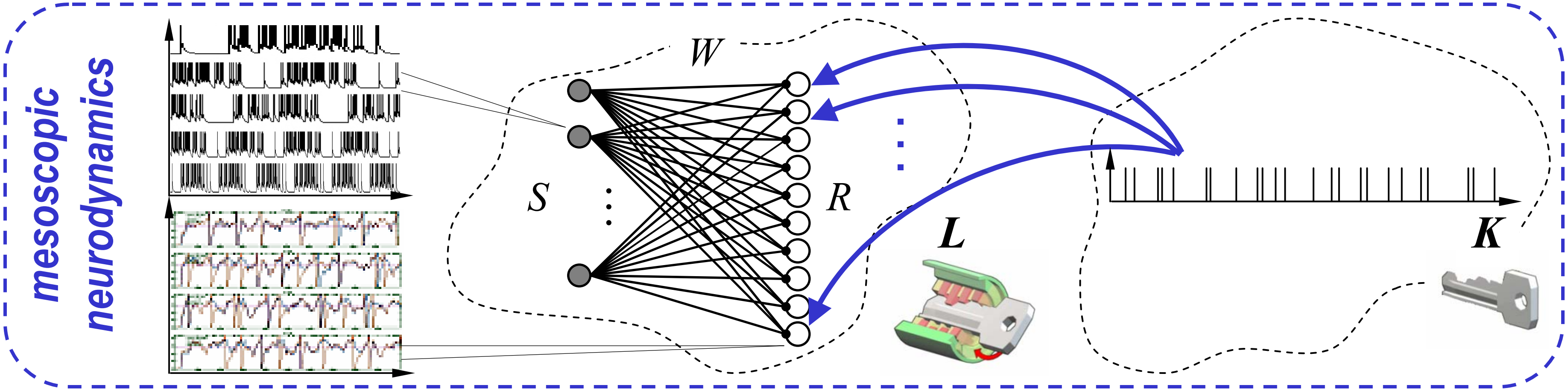
- ✓ both training and functional phases could be carried out on multiple locks in parallel
- ✓ inter-lock competition by inhibitory feedback could create diversification and specialization in the context of a "society of locks"



2. Mesocircuit Theory

➢ Preliminary lock & key experiments

- ✓ lock L: 100 neurons (R) driven by 20 source cells (S) via different combinations of synaptic weights (W), which make L's specificity
- ✓ S cells are bursting at various frequencies and phases, creating complex potential landscapes in R cells with low spike frequency

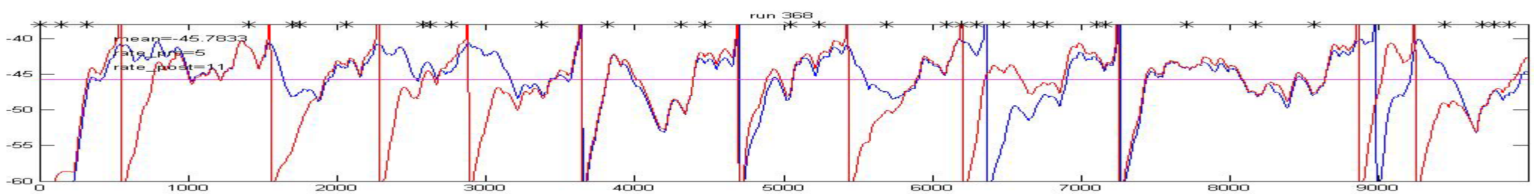


- ✓ key K is a random train of spikes: when L is stimulated by K, the R cells' firing rates increase more or less, depending on the match between their endogenous temporal structure and K's structure

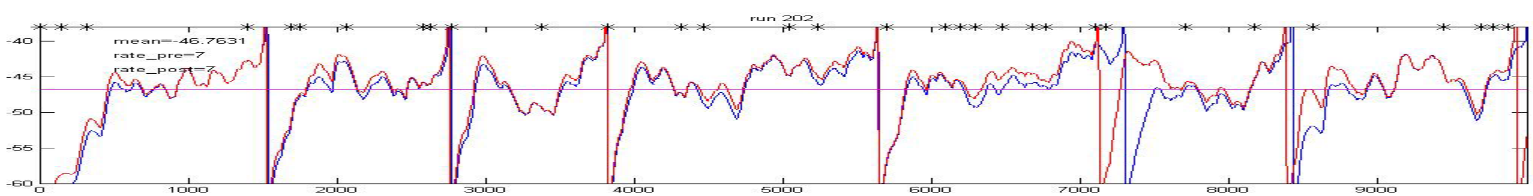
2. Mesocircuit Theory

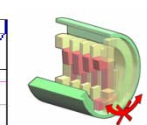
➢ Lock excited by key

- ✓ example of strongly resonant L-cell $\rightarrow$ 6 extra spikes when stimulated by K:
  - blue signal = intrinsic L potential
  - red signal = potential when excited by K



- ✓ example of nonresonant L-cell $\rightarrow$ 0 extra spikes when stimulated by K:

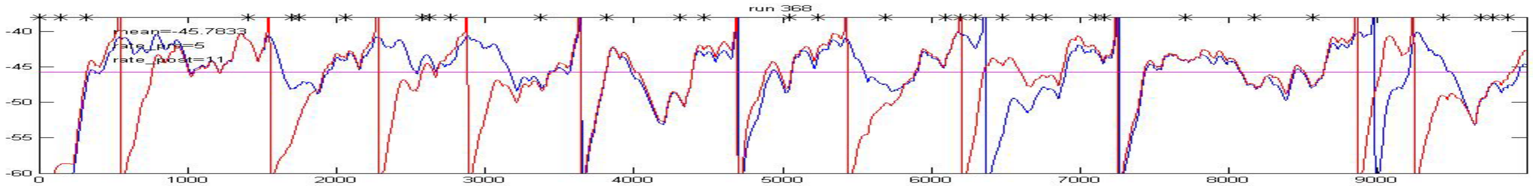


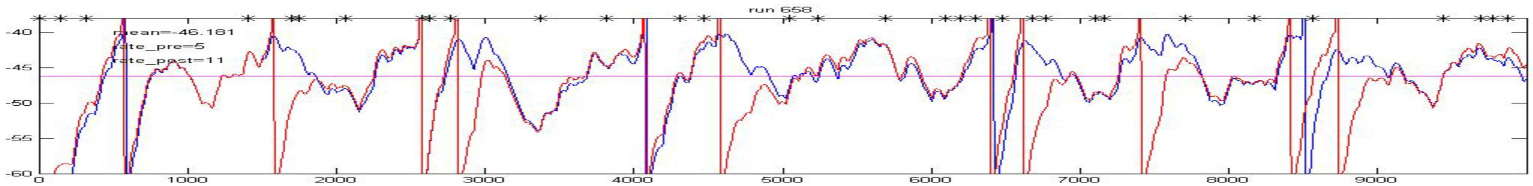


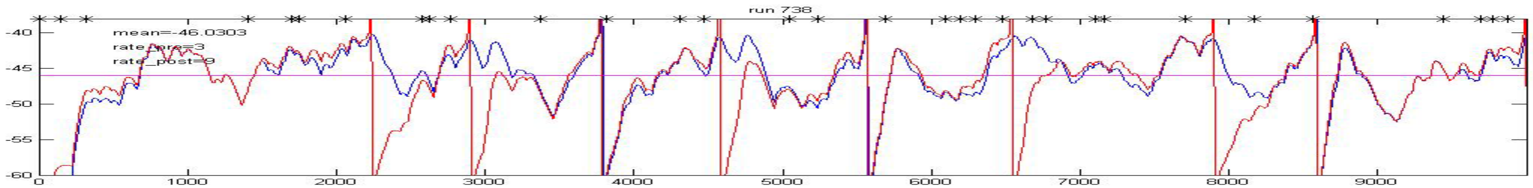
2. Mesocircuit Theory

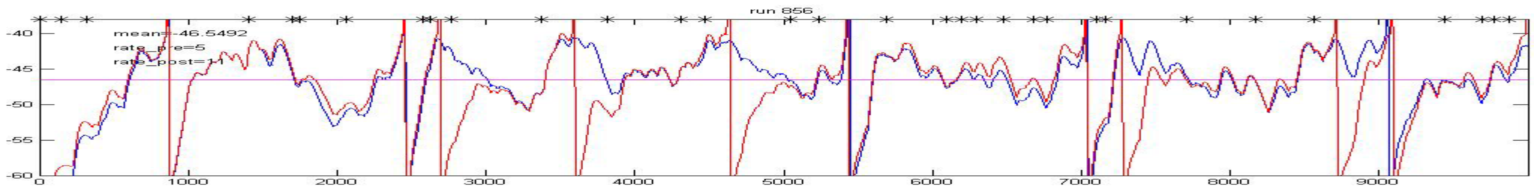
➢ Lock excited by key

- ✓ other examples of L-cells strongly excited by the K spikes









2. Mesocircuit Theory

➢ Next stages in the model

- ✓ **driven mode** – L modeled as a subthreshold SNN driven by source cells, and K as spike trains
- – **endogenous mode** – add to L recurrent connections (possibly delayed) and inhibitory neurons $\rightarrow$ ***RAIN Concepts***
- – **Hebbian learning** – add STDP synaptic plasticity and devise training procedure, so that lock L “molds” around specific keys K
- – **brain module** – integrate a society of L networks into the association module (AS) of the brain architecture

Large-Scale Cortical Mesocircuit Dynamics

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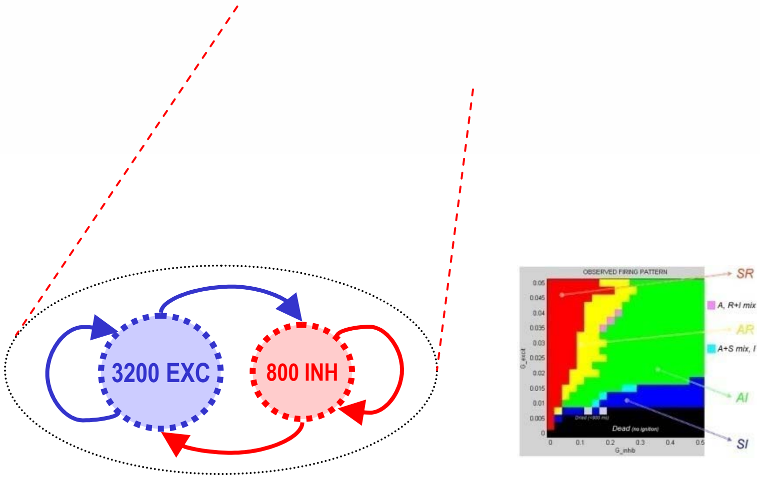
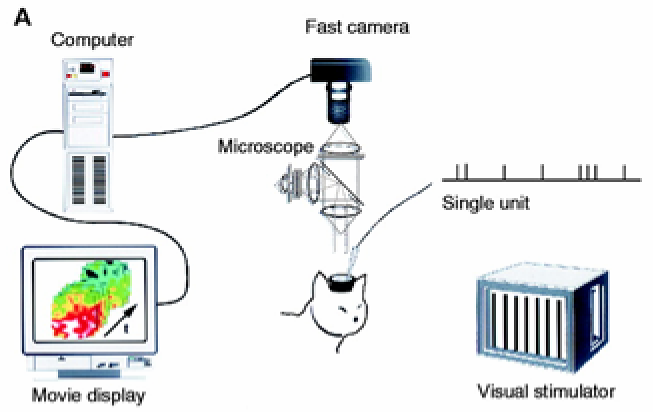
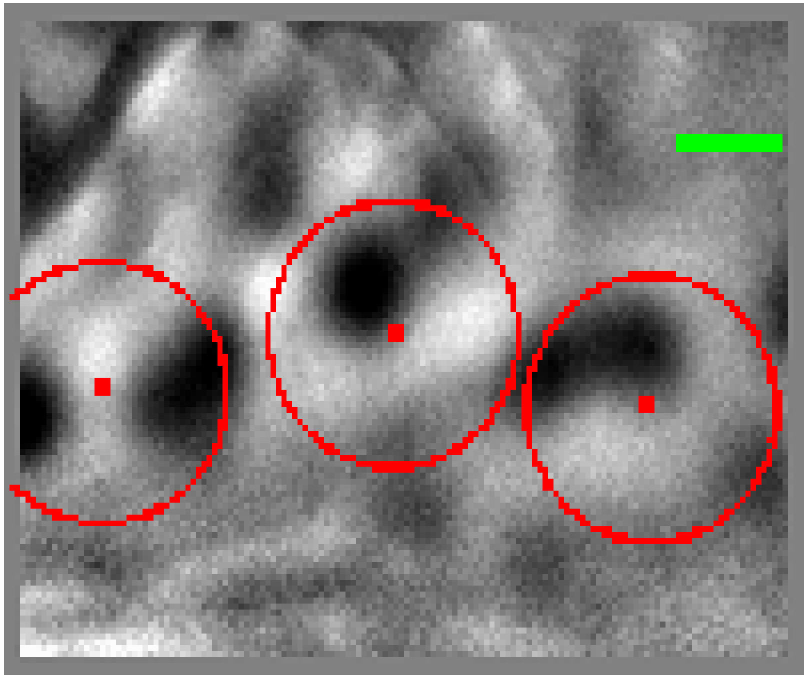


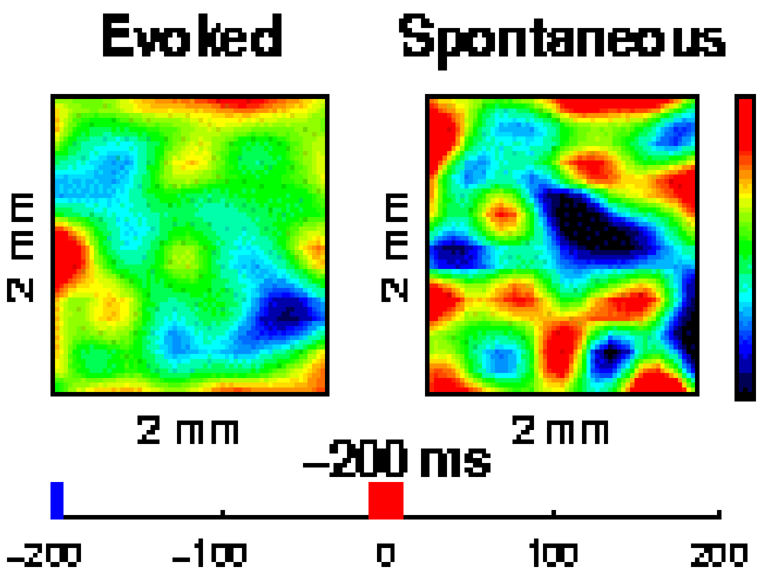
3. RAIN Concepts

- Evoked vs. ongoing activity





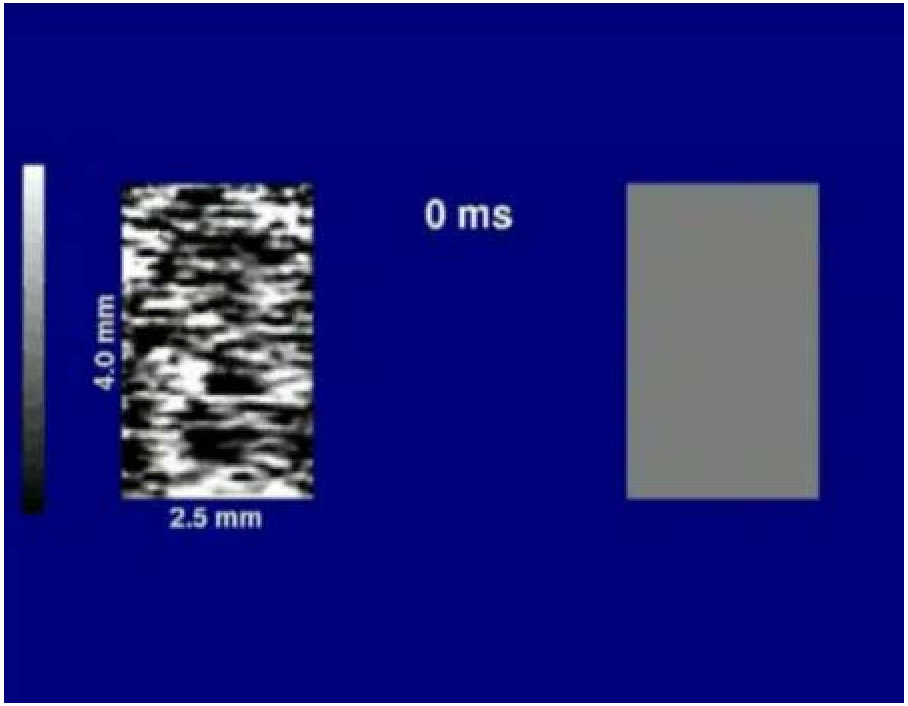
(Weliky M, Bosking WH, Fitzpatrick D. Nature 1996;379:725-728)



(Tsodyks et al. Science 1999; 286, 1943 -1946)

3. RAIN Concepts

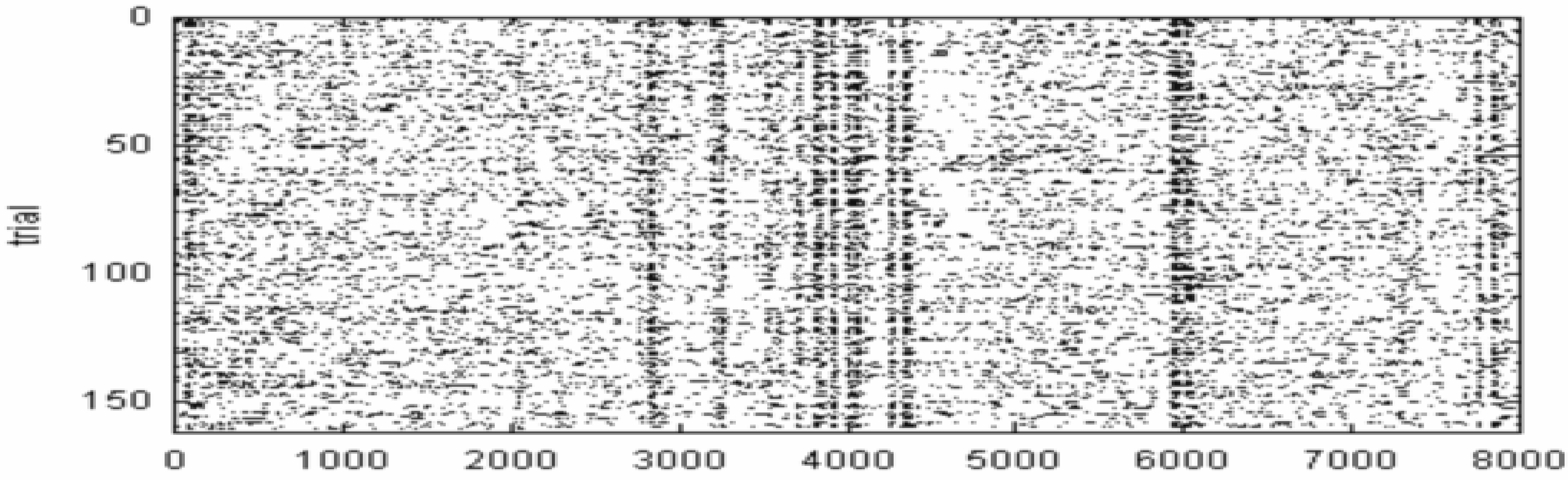
- **Ongoing activity** **-transient coherence**



(Kenet et al. Spontaneously emerging cortical
representations of visual attributes. Nature 2003;425:954-956)

3. RAIN Concepts

- ***in vivo* awake spiking** (identical cell, repeated trials)

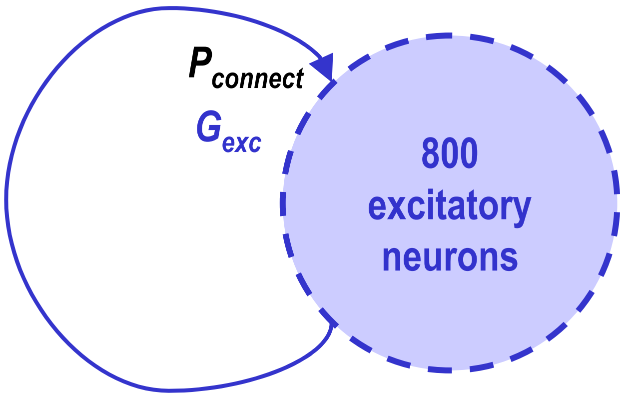


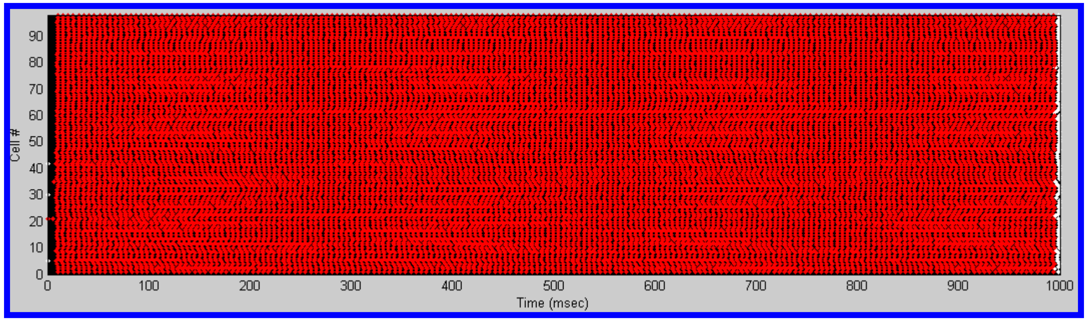
Rat Thalamus LGN (Erik Flister, Pam Reinagel): 2006, UCSD online course

Monkey Lateral Prefrontal Cortex (Shima et al. Nature 2007; 445:315-318)

3. RAIN Concepts

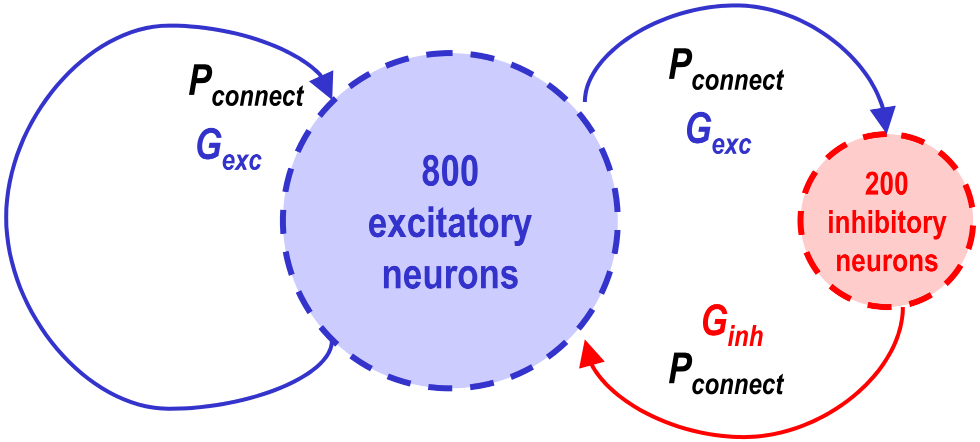
- First, we stimulate a recurrently connected **excitatory** network...

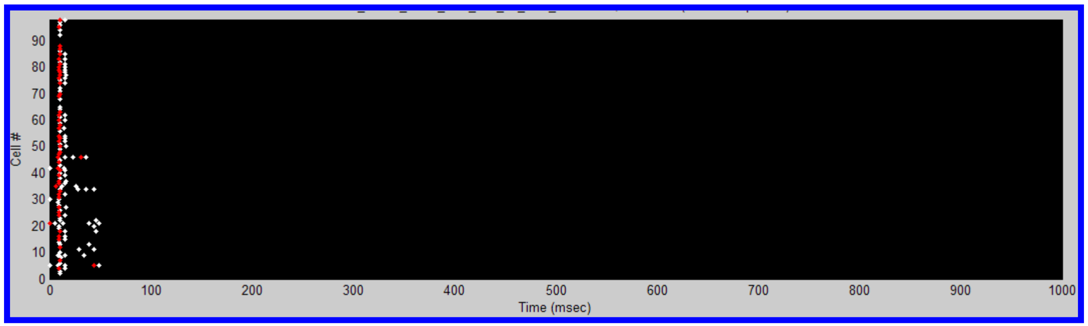


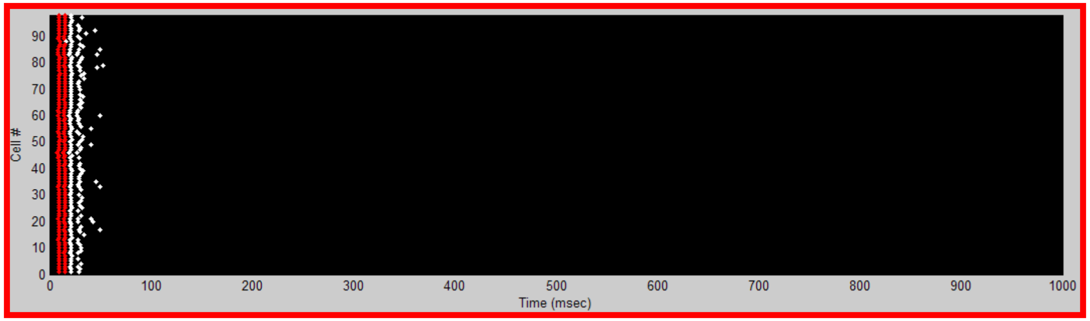


3. RAIN Concepts

➢ Next, we add recurrent inhibition via E:I and I:E synapses...

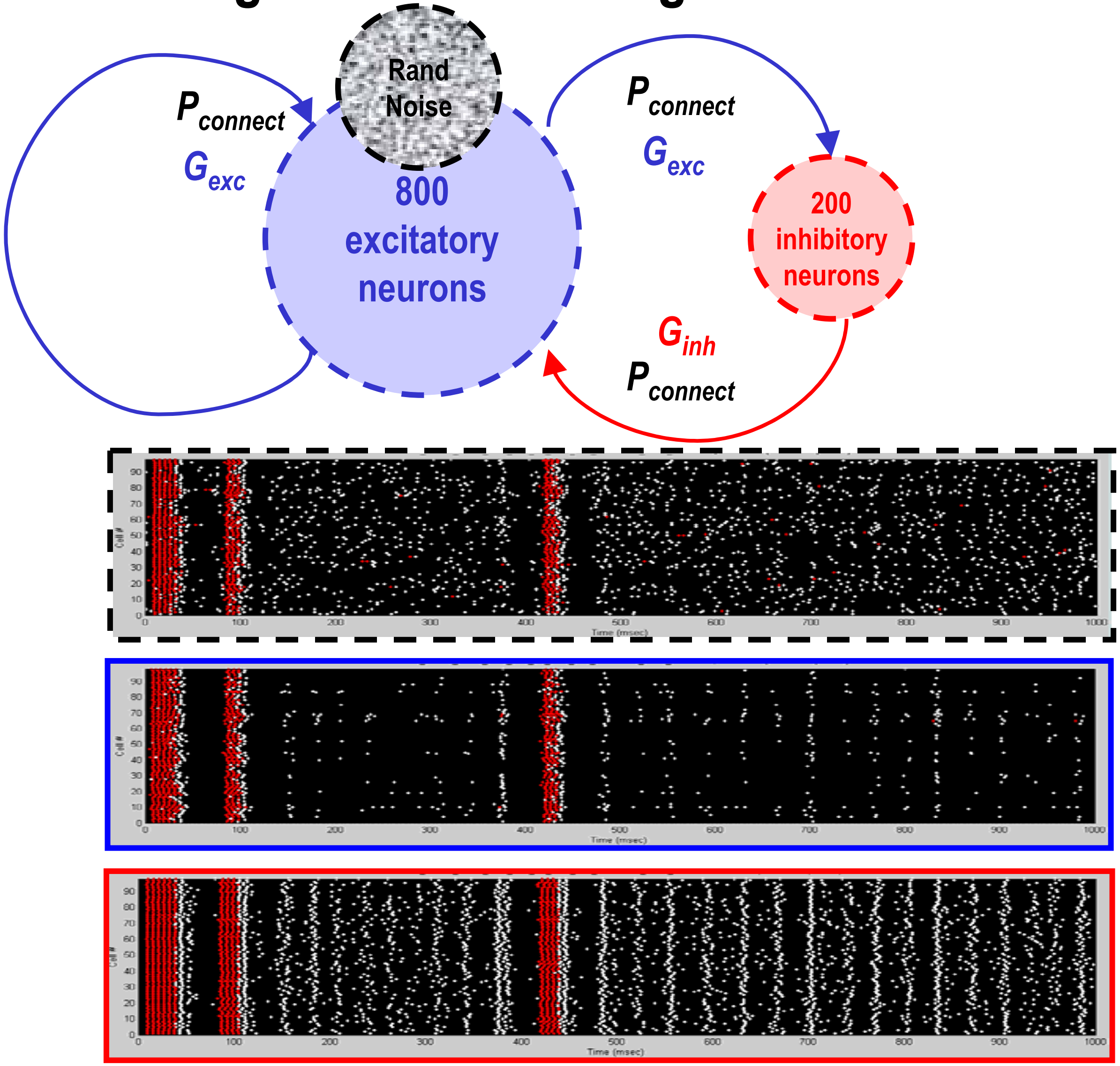






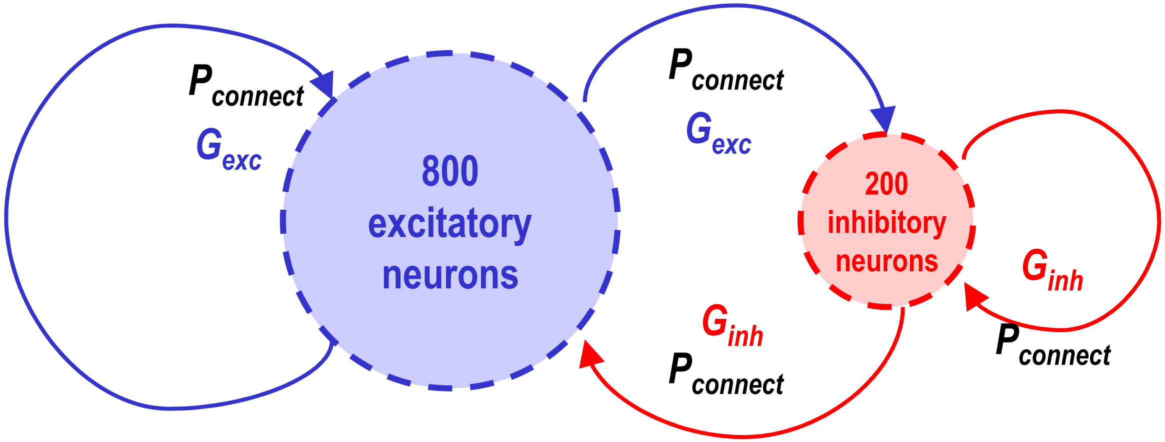
3. RAIN Concepts

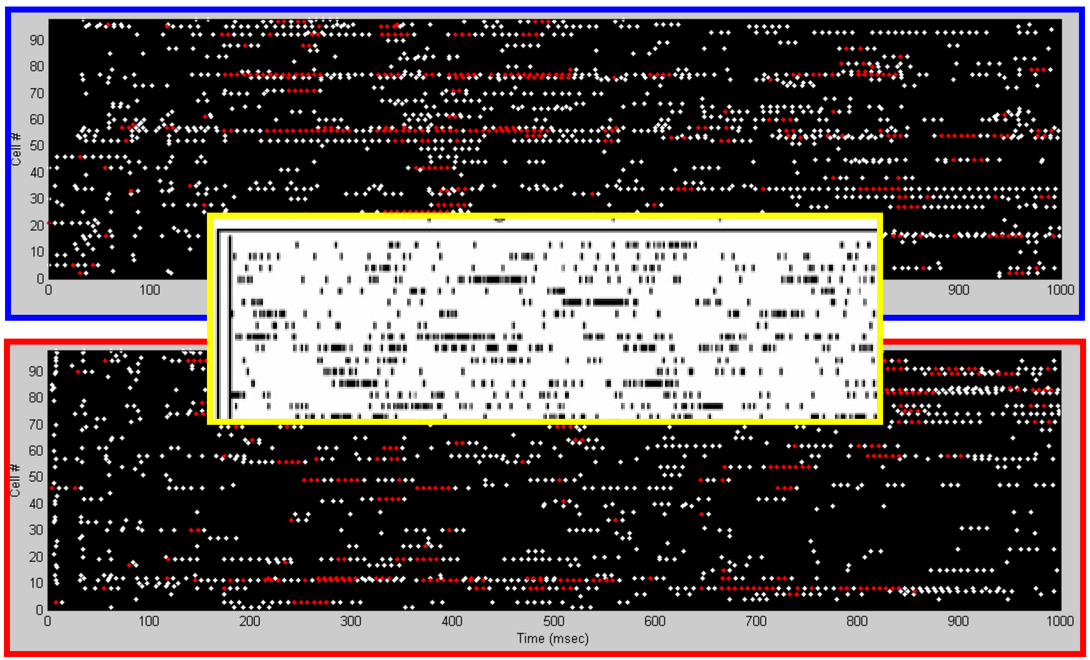
- How could we get sustained firing?



3. RAIN Concepts

➢ **But what if we instead add recurrent inhibition of inhibition?**



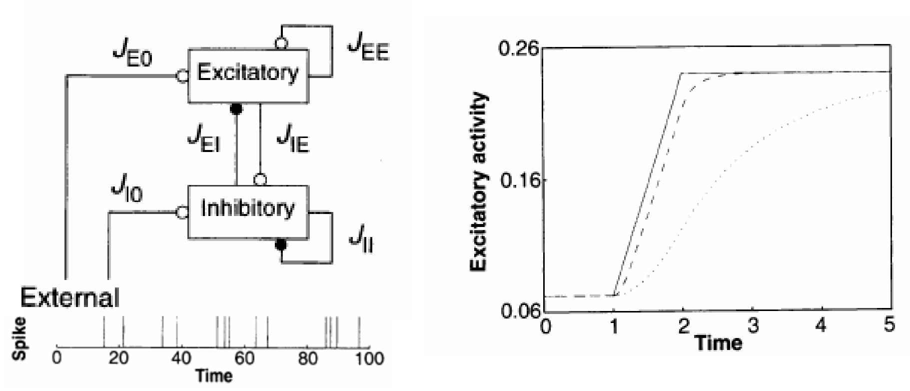


3. RAIN Concepts

➢ Work of others

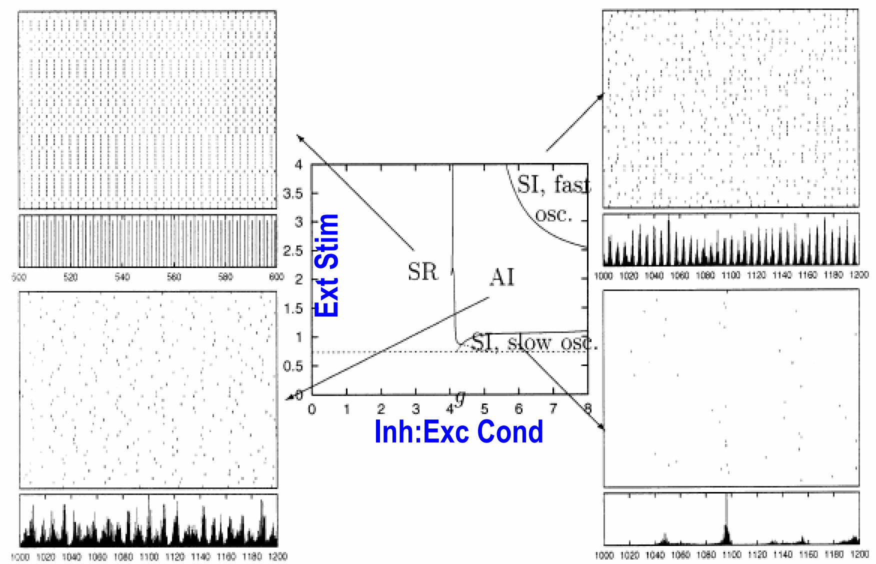
- ✓ van Vreeswijk, C. & Sompolinsky, H. (1996)

  Chaos in neuronal networks with balanced excitatory and inhibitory activity. *Science* 315: 973–976



- ✓ Brunel, N. (2000)

  Dynamics of networks of randomly connected excitatory and inhibitory spiking neurons. *J. Physiol. (Paris)* 94: 445– 463

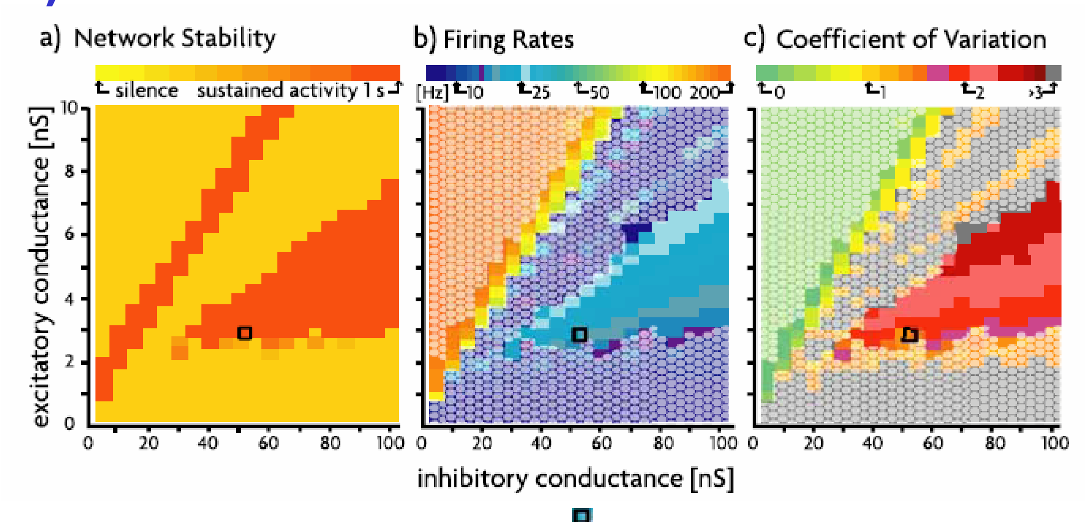


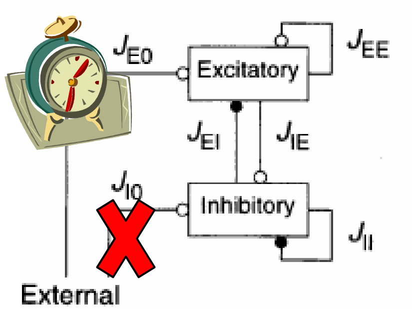
3. RAIN Concepts

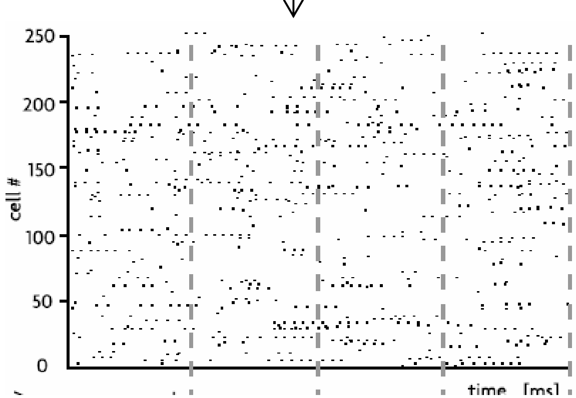
➢ Work of others (cont'd)

✓ Vogels, T. P. & Abbott, L. F. (2005)

Signal propagation and logic gating in networks of integrate-and-fire neurons. *J. Neurosci.* 25: 10786-95.

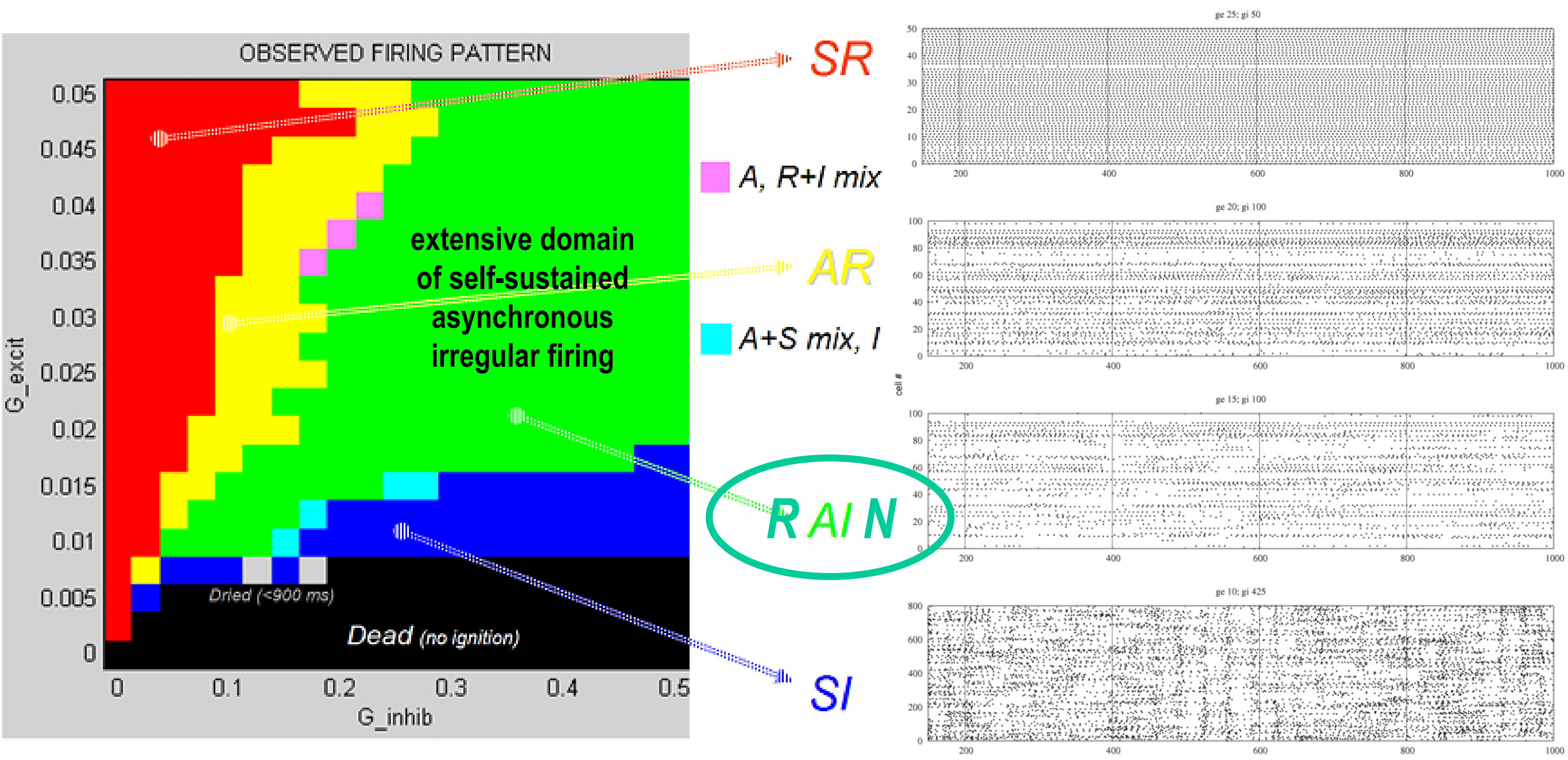






3. RAIN Concepts

- **“Negative-pulse ignited” firing phase diagram: G_{exc} vs. G_{inh}**
  - based on a combination of firing statistics, 4 consistent domains are discovered as excitatory and inhibitory conductances are covaried in separate experiments



3. RAIN Concepts

➢ Effect of Membrane Ion Channels

Figure 1: Excit [Base no K+] and Inhib [Base no K+] [Km=0.025] [Ka=1.0] [Kahp=0.007]

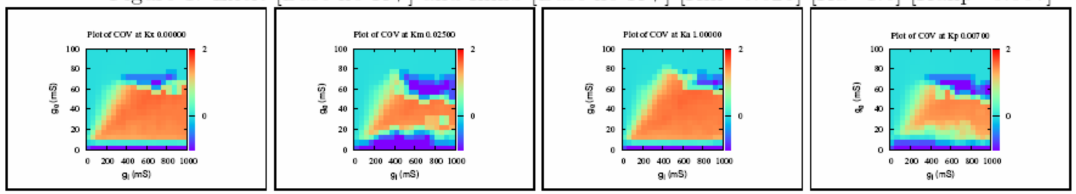


Figure 2: Excit [Km=0.015] and Inhib [Base no K+] [Km=0.025] [Ka=1.0] [Kahp=0.007]

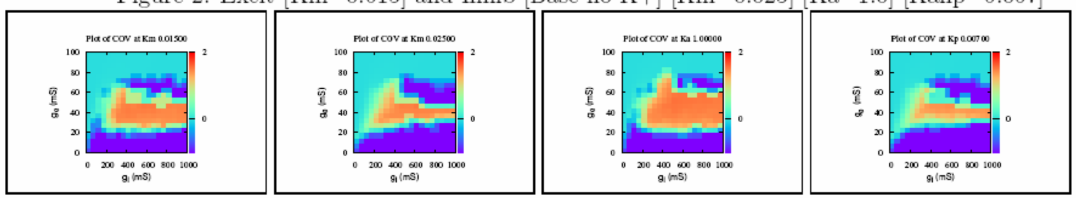


Figure 3: Excit [Ka=6.000] and Inhib [Base no K+] [Km=0.025] [Ka=1.0] [Kahp=0.007]

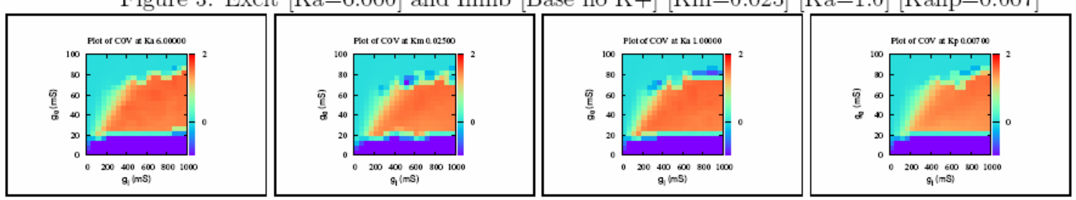
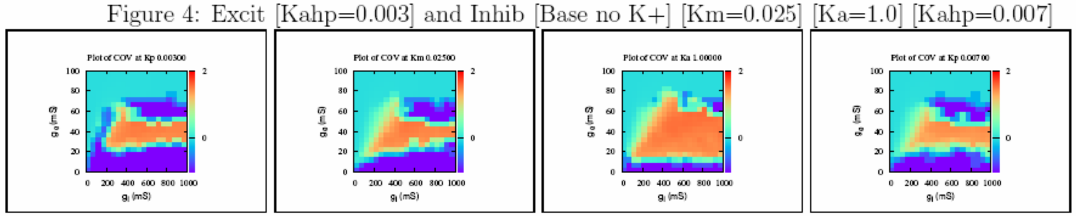
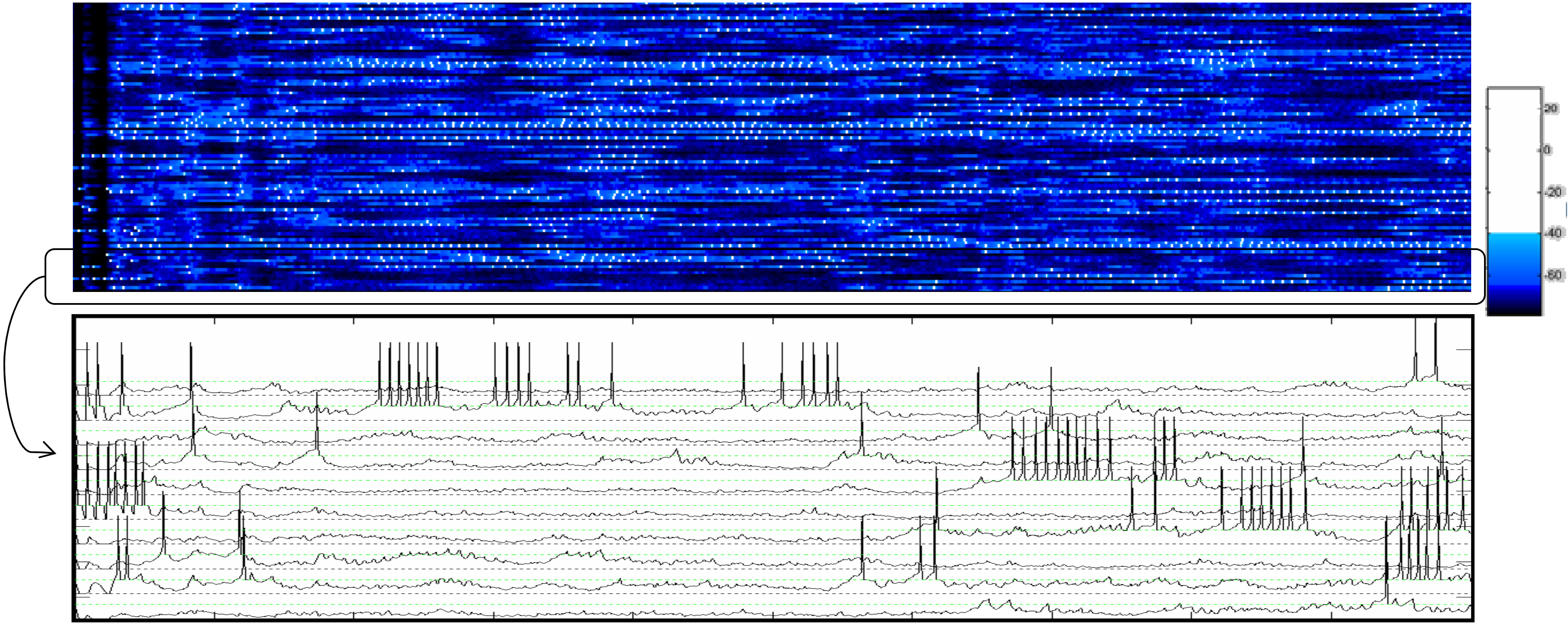


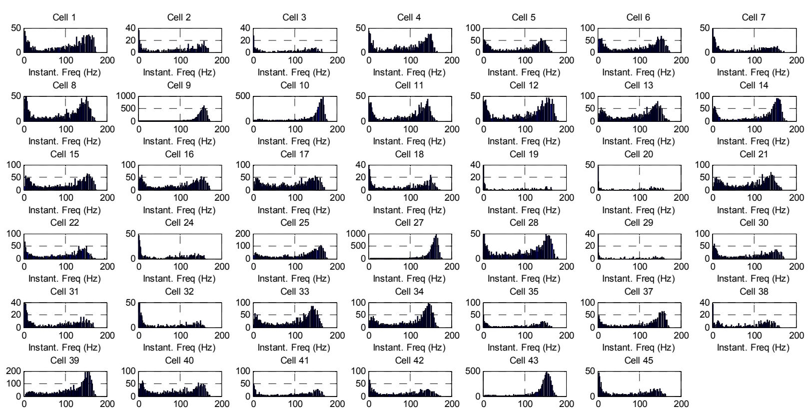
Figure 4: Excit [Kahp=0.003] and Inhib [Base no K+] [Km=0.025] [Ka=1.0] [Kahp=0.007]



3. RAIN Concepts

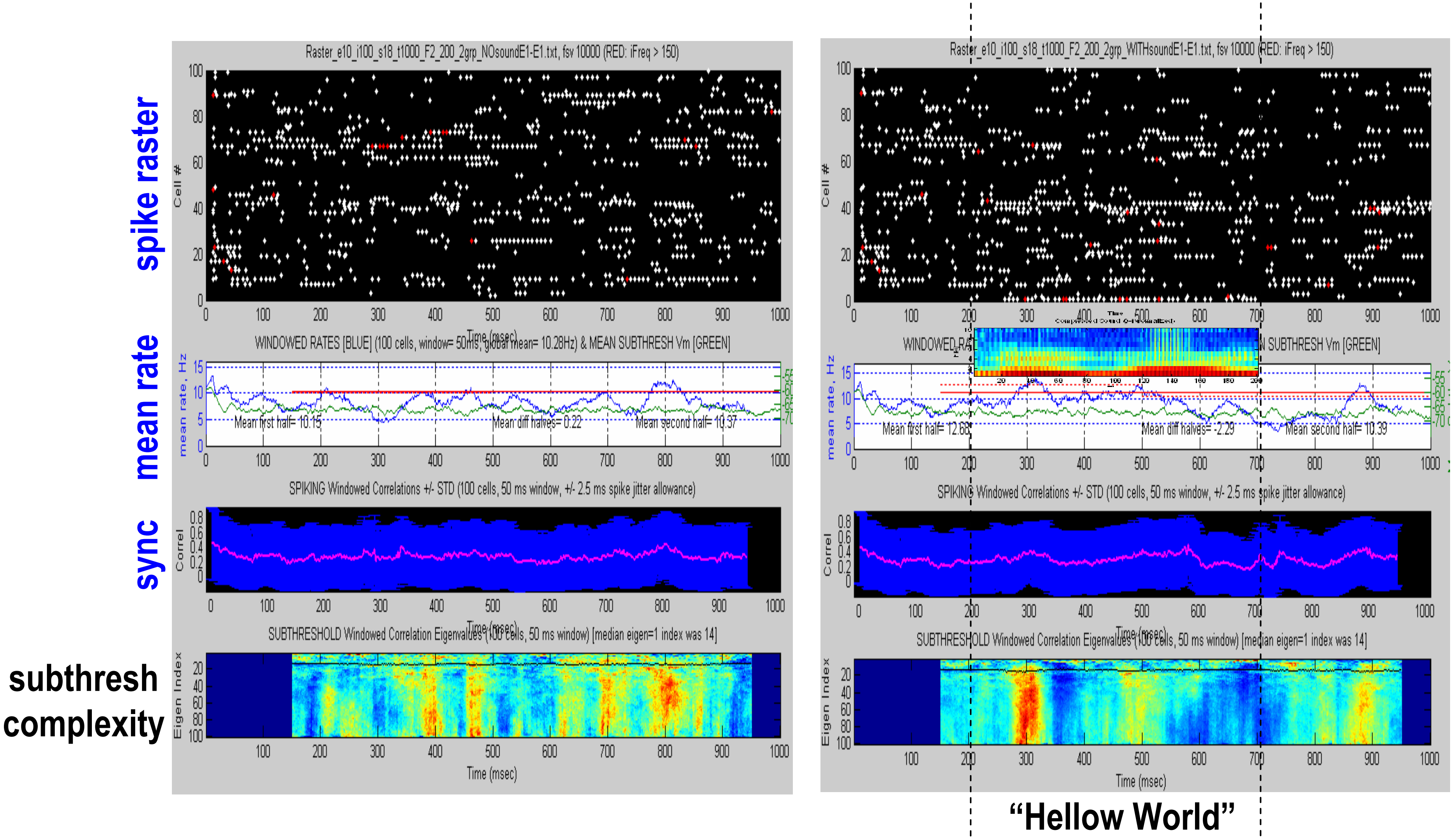
➢ Firing characteristics





3. Progress to Date

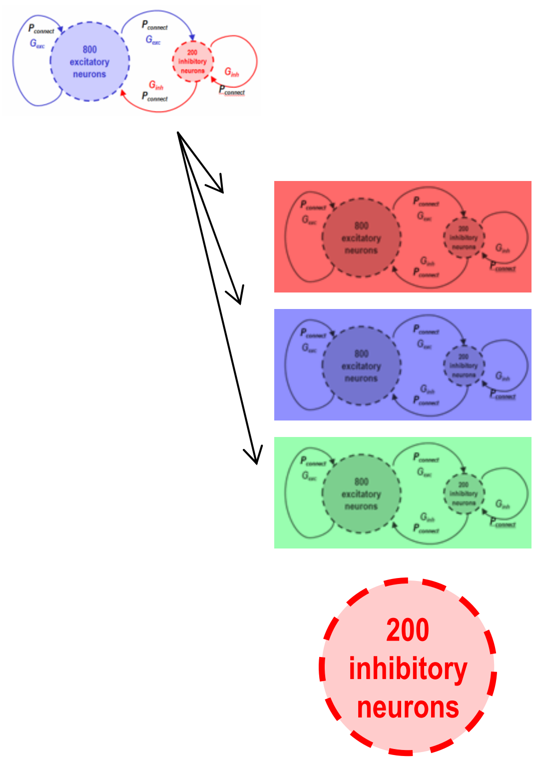
- **Subthreshold correlation complexity** **(eigenvalue distribution):**

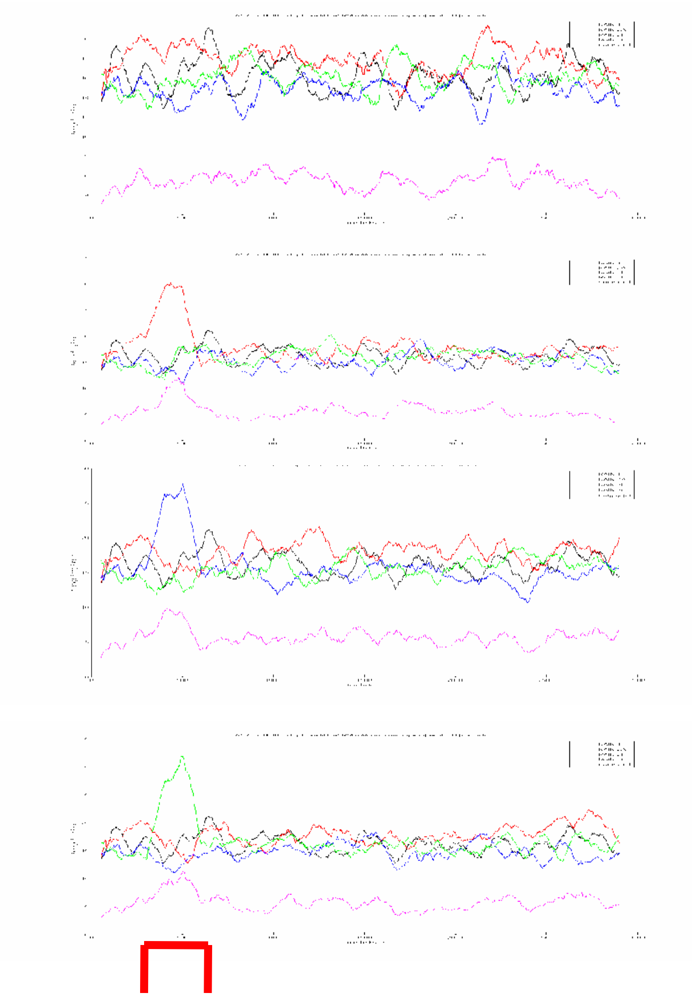


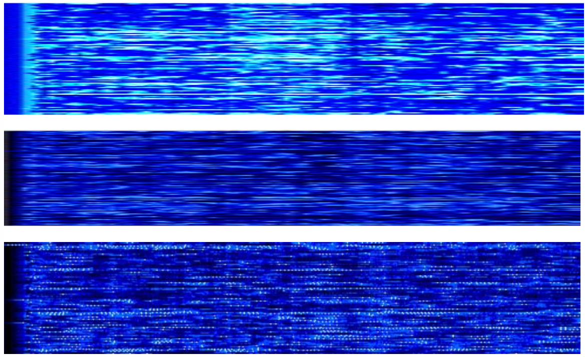
"Hellow World"
@ 200-700 ms
into 4 of 800 exc cells

3. Progress to Date

➢ Multi-RAIN “Transient Winner-Take-Most”

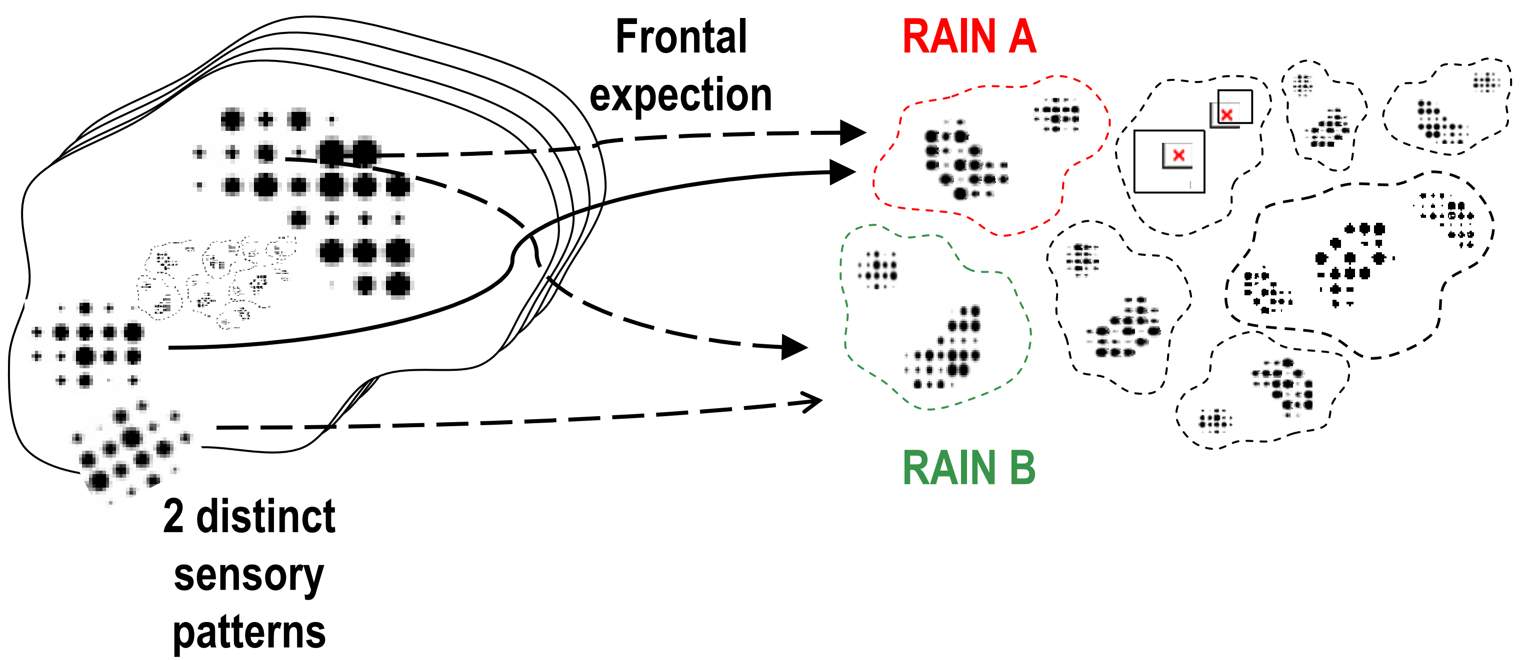






3. Progress to Date

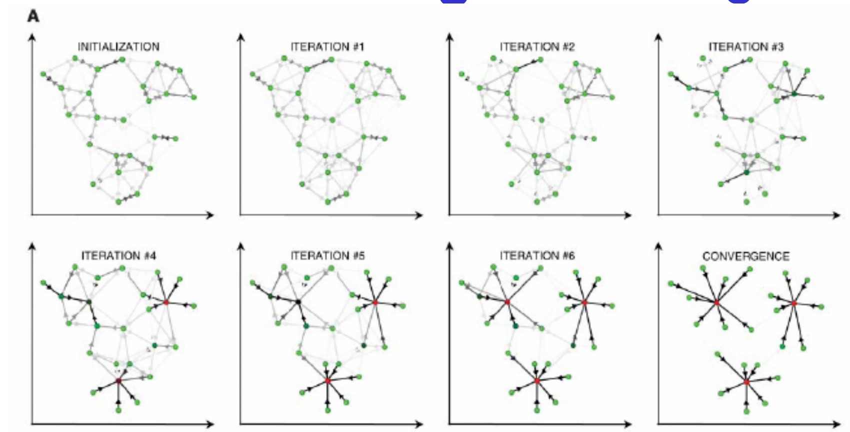
- **Multi-RAIN Discriminate Hebbian Learning: clustering**



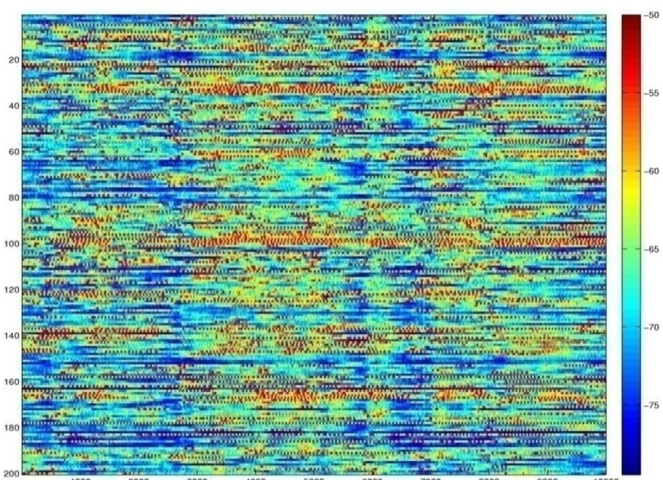
3. Progress to Date

➢ **Multi-RAIN Discriminate Hebbian Learning: clustering**

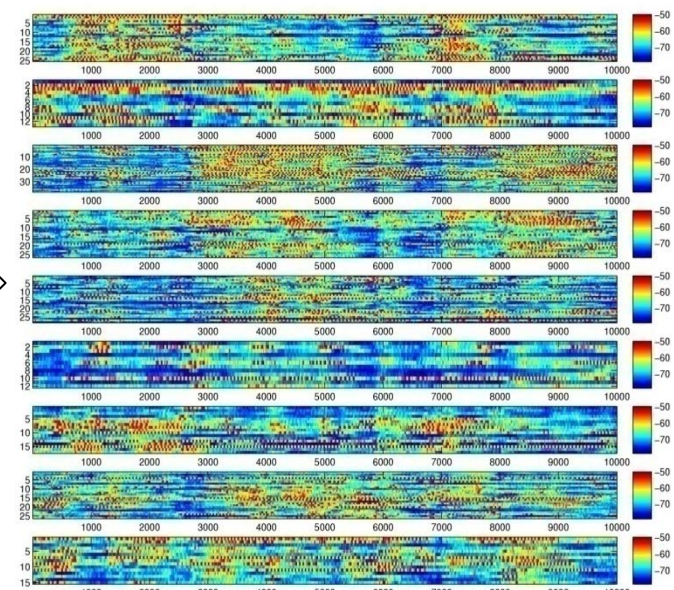
Frey, B.J., Delbert, D. (2007) Clustering by Passing Messages Between Data Points *Science* 315: 973–976



200 cell RAIN network



cluster



1 “Key X”

“Key Y” 4

“Lock” 6 7

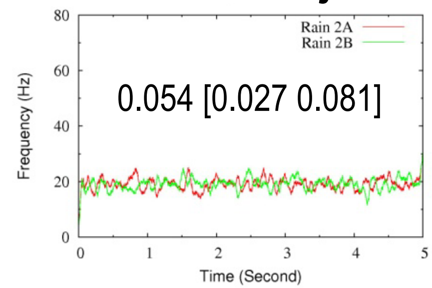
3. Progress to Date

➢ Multi-RAIN Discriminate Hebbian STDP Learning

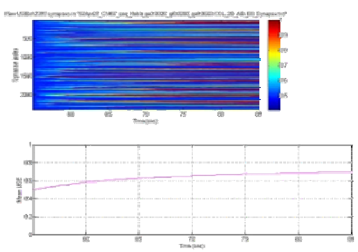
<u>**Rate Diffs (Hz) with 95% Confidence Intervals**</u>

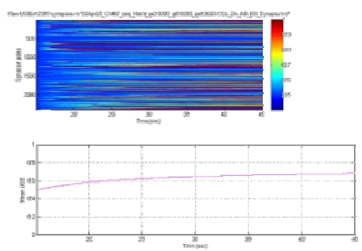
Baseline RAIN A & B activity:

No Pattern Injection

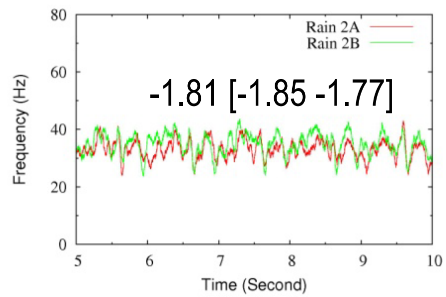


Patterns into RAIN A & B, ***pre-STDP:***

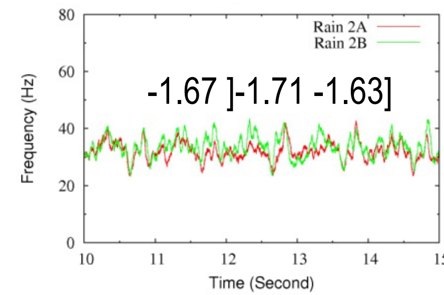




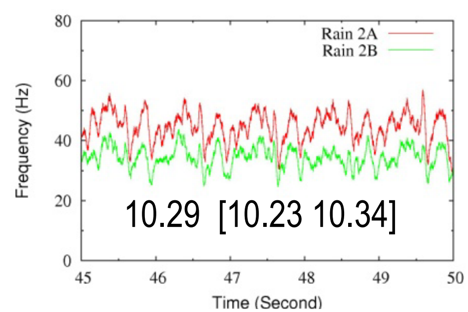
Response to Patt X

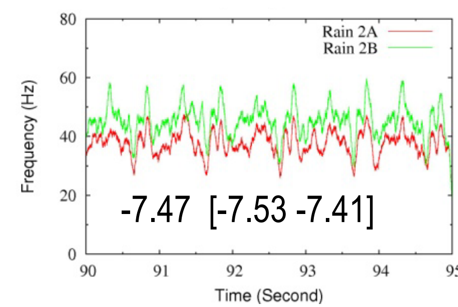


Response to Patt Y



Patterns into RAIN A & B, ***post-STDP:***

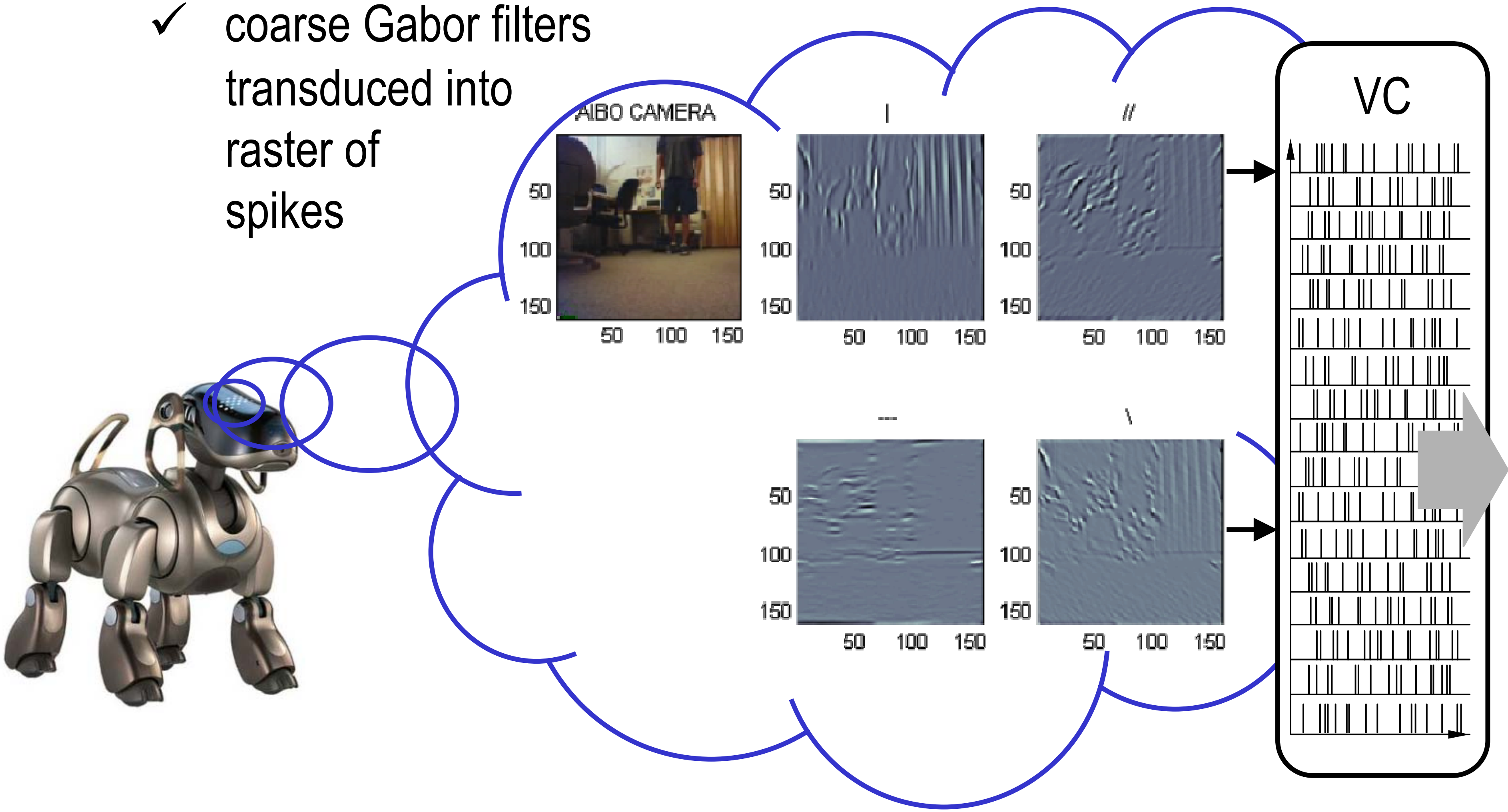




3. Progress to Date

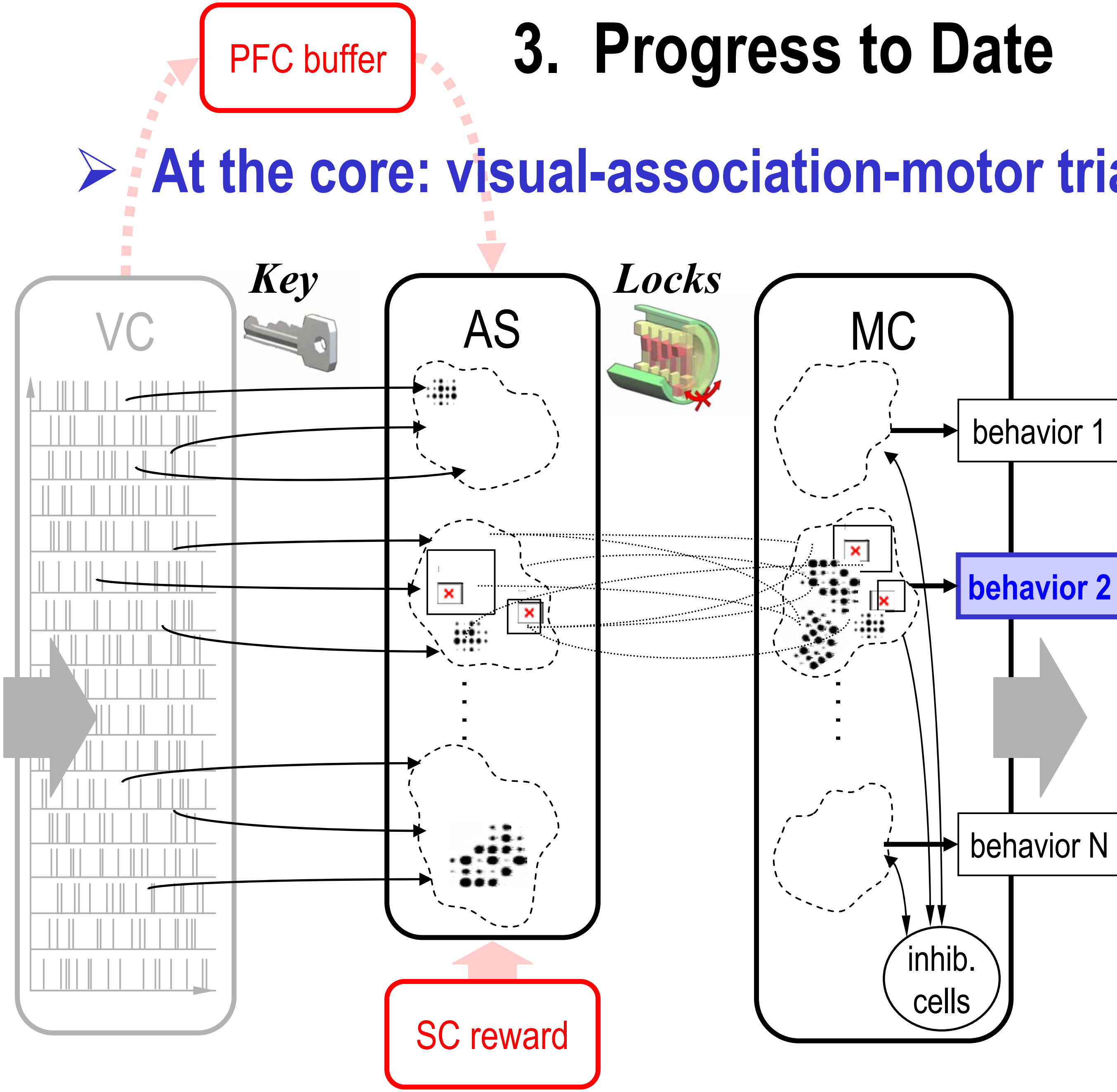
➢ Robot's visual input

- ✓ coarse Gabor filters transduced into raster of spikes



3. Progress to Date

➢ **At the core: visual-association-motor triad**

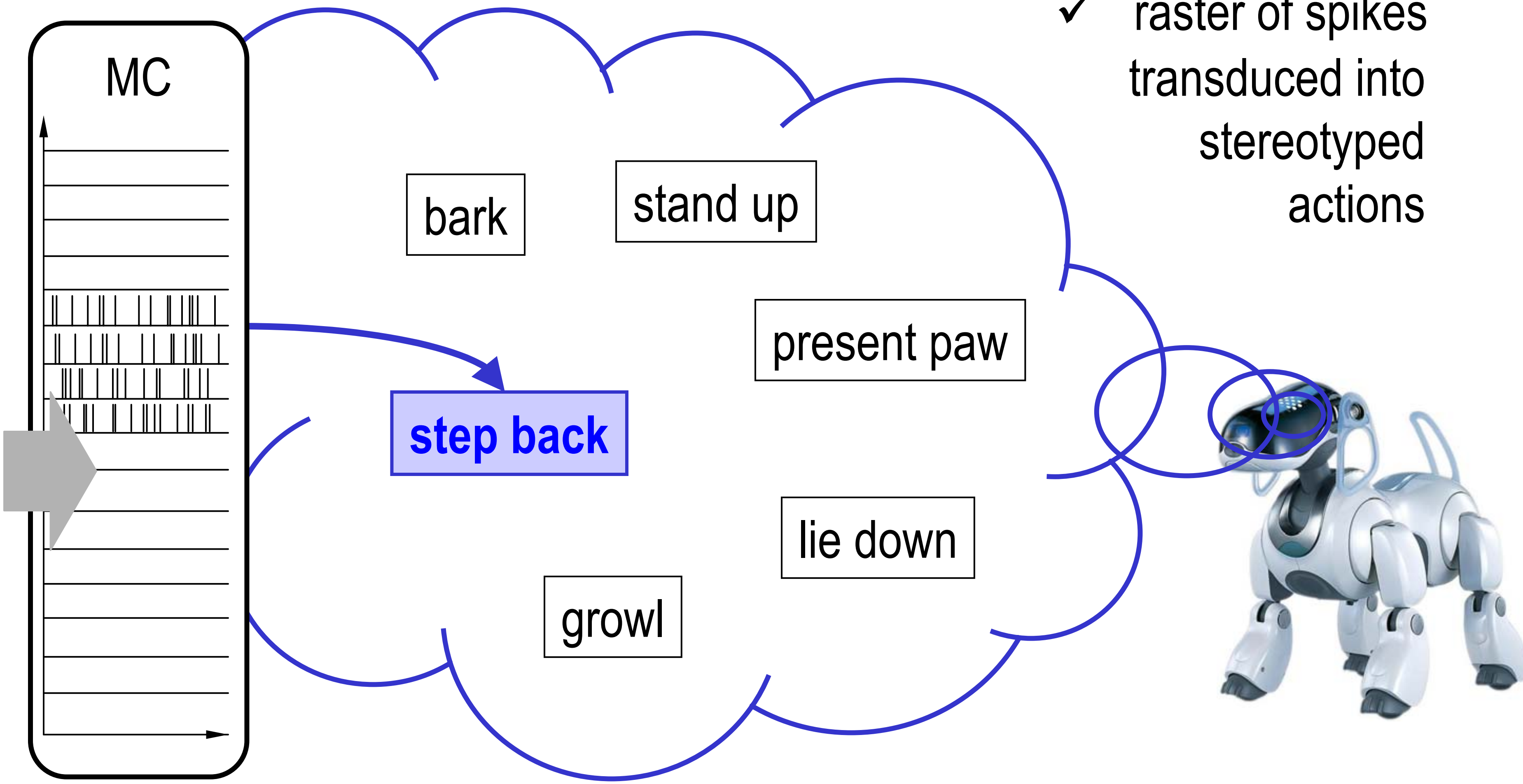


- ✓ the visual cortex (VC) provides the stimulus patterns, or "keys"
- ✓ the association area (AS) holds the complex neuro-dynamics in "locks"
- ✓ the motor cortex (MC) is the AS "readout": it coalesces the activity into winner-take-all

3. Progress to Date

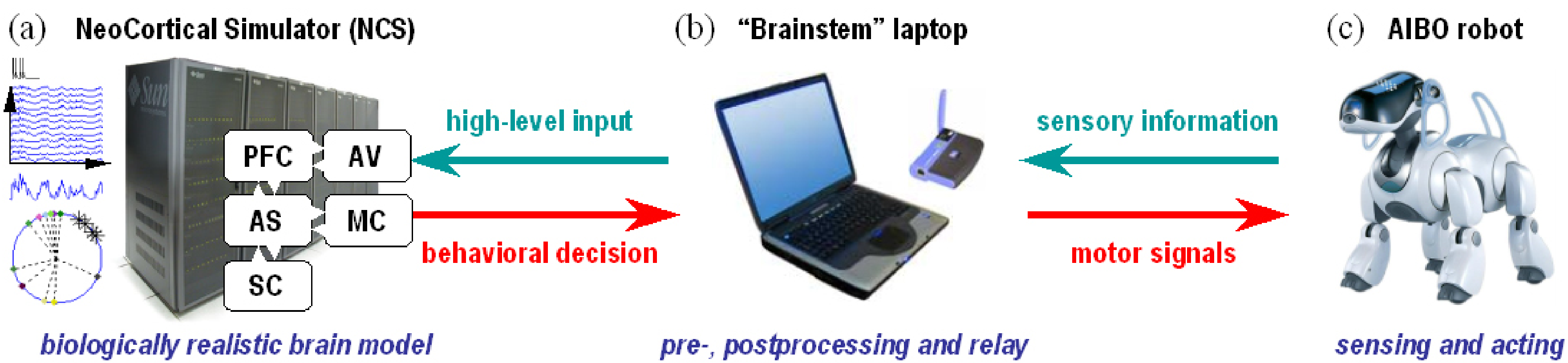
➢ RAIN drives Robot's behavioral output

✓ raster of spikes transduced into stereotyped actions



3. Progress to Date

- **Completed sensorimotor loop between cluster and robot**
  - ✓ initial attempt to implement a real-time, embedded neural robot
  - c) a robot (military sentry, industrial assistant, etc.) interacts with environment and humans via sensors & actuators
  - a) NeoCortical Simulator (NCS) software runs on computer cluster; contains the brain architecture for decision-making and learning
  - b) "brainstem" laptop brokers WiFi connection: transmits multimodal sensory signals to NCS; sends actuator commands to robot



3. Progress to Date

➢ Social robotics paradigm

✓ Typical robot/human interaction and learning scenario

a. resting

b. alerted, observing

c. reacting by offering a paw

d. receiving reward (stroking)

e. angry barking and walking (no reward!)

Large-Scale Cortical Mesocircuit Dynamics

1. Scope of Work
2. Neurodynamics & Mesocircuit Theory
3. RAIN Concepts & Progress to Date
4. **Future Directions**

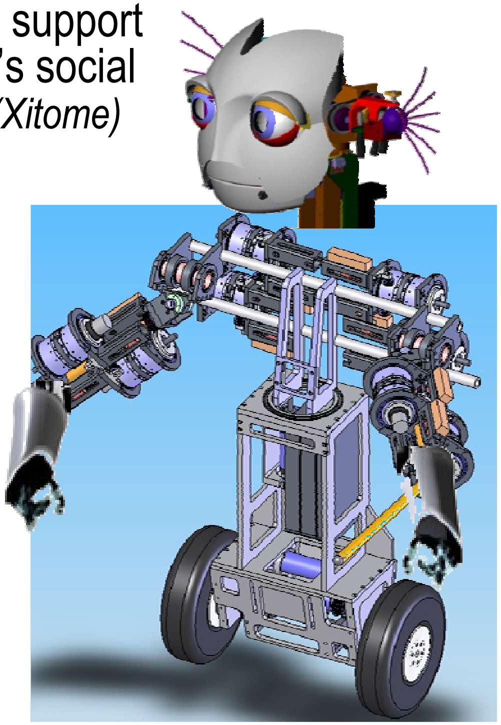
4. Future Directions

Remote-RAIN Brain control of **MDS** (Mobile/Dexterous/Social) Robot

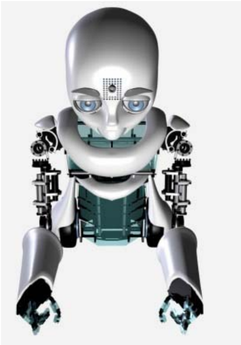
Developed by a collaboration of:

1. **Cynthia Breazeal (MIT Media Lab)**
2. **Xitome (MIT spinoff)**
3. **Rod Grupen (U Mass Amherst)**

Expressive face design to support the robot's social function *(Xitome)*



2 DoF hands with tactile sensing developed at MIT *(based on SDM technique developed by Aaron Dollar and Rob Howe at Harvard)*



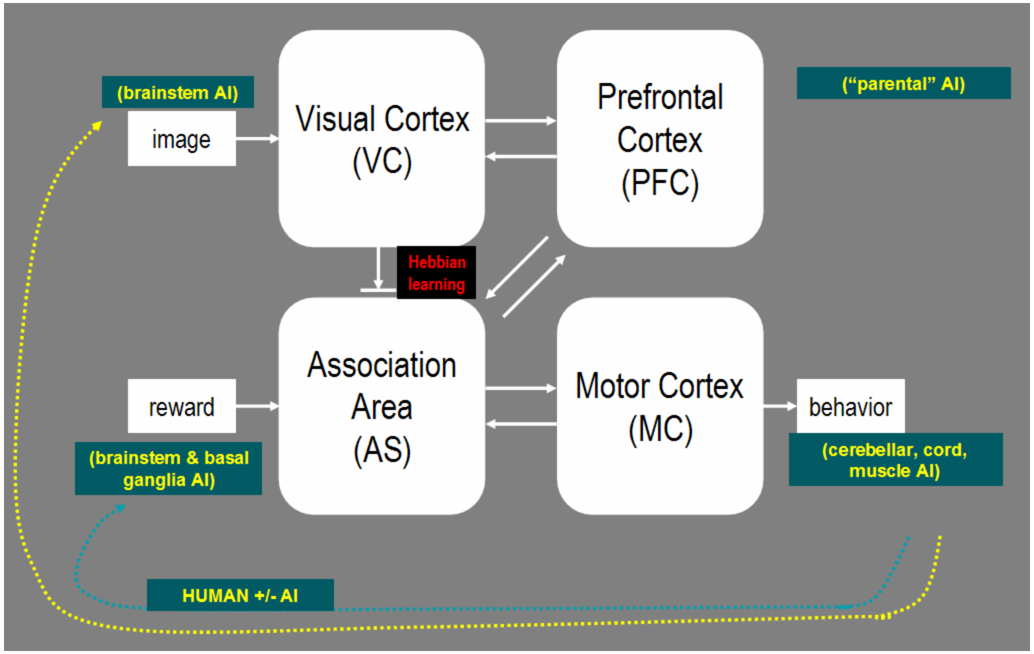
uBot-5 chassis from U Mass—1/2 meter tall

- *11 DoF inverted pendulum mobility base*
- *Trunk rotation and two 4 DoF arms*
- *11-channel embedded FPGA controller*
- *Force and position feedback & series-elastic actuators*
- *API in C++*

4. Future Directions

➢ NCS development & robotics

- optimization of RAIN mesocircuit network design and STDP
- addition of realistic dopamine-reward basal ganglion (subcortical SC) module for reinforcement learning & planning
- humanoid social interactive robotics
- mesocircuit application to other domains (eg, speech & threat recognition)



4. Future Directions

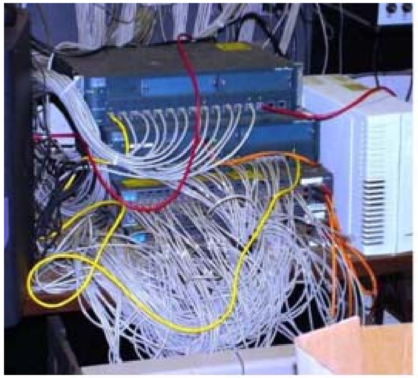
DURIP 2007: optimizing architecture for neural simulation

Additional CPUs:

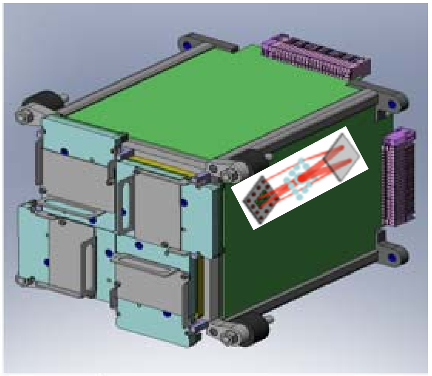
1. Distributed, inexpensive cluster
2. New “less expensive” shared-memory architectures

Faster inter-CPU communication options:

1. Infiniband (switched, theoretically up to 96 Gbit/s throughput)
2. LightFleet’s “Corowave” direct optical interconnect (32-cpu this summer)



Traditional switched Interconnect

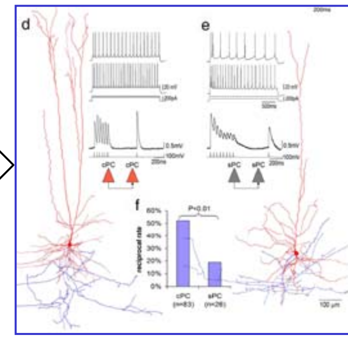


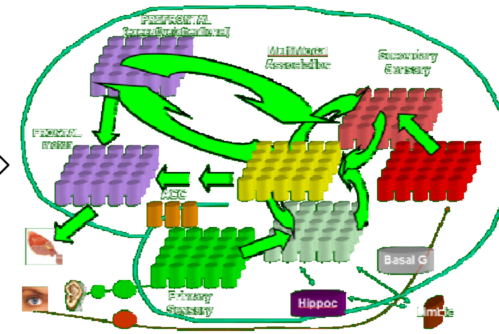
Corowave optical interconnect

4. Future Directions

Collaboration with Mind Brain Institute, EPFL, Lausanne

- **Basic science**: ongoing biological extraction of neural parameters





- **Computer science**:
  1. Use of IBM BlueGene L: 8096-CPU cluster, 22 Trillion Flops
  2. Runs NCS and NEURON (and a hybrid)
  3. Plan to run remote-brain AIBO this summer
  4. & MDS robot by summer 2008

Q & A