Dynamical Information Processing in a Neuronal Microcircuit

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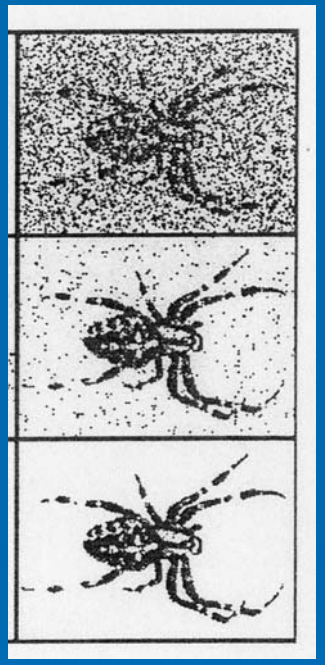
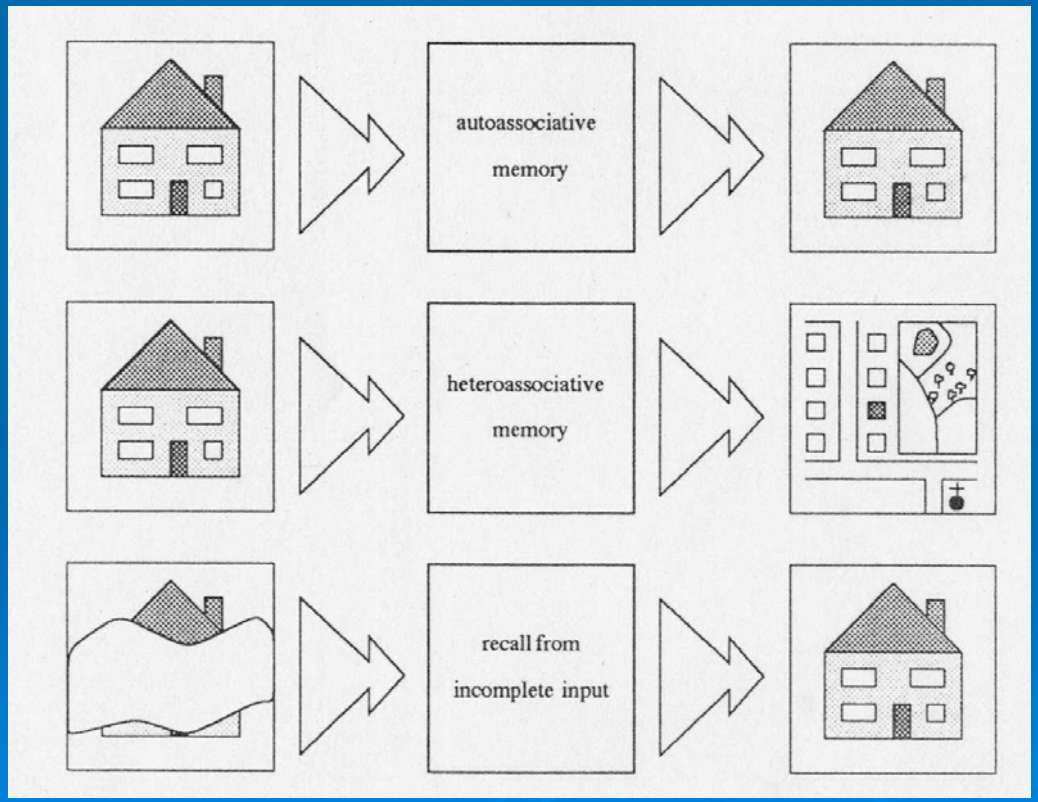
Neurobiology to Cognition

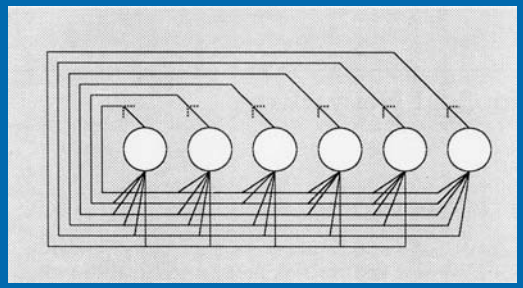
- Associative memory
  - Information storage and recall
- Information coding
  - Patterns of neuronal activity
- Pattern storage and recall
  - Learning rules
  - Threshold setting
- Neuronal dynamics

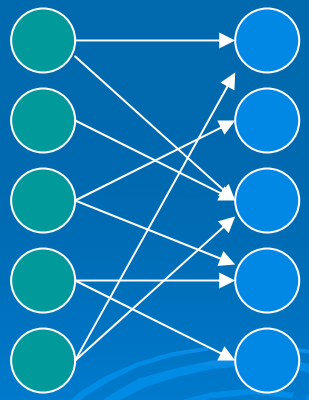


Associative Memory

- Auto- and hetero-associative







Storage By Hebbian Learning

- Binary patterns

  [1 1 0 0 0 1 0 1 1 1 0]

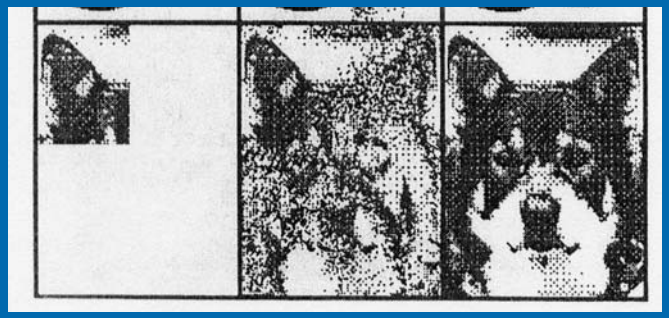
- Correlation between pre- and postsynaptic activity

$$dW_{ij} = x_i x_j$$

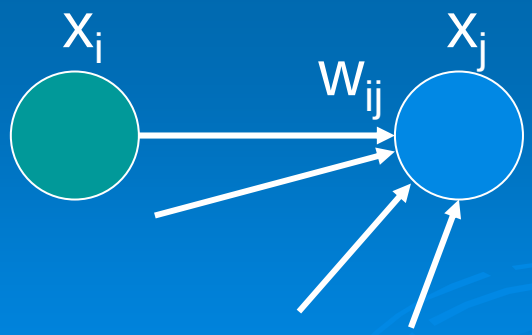
Recall by Threshold Setting

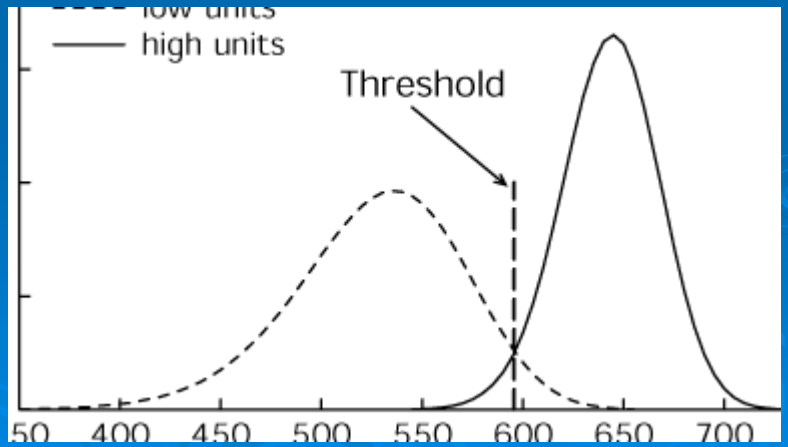
- Partial or noisy cue

  [1 1 0 0 0 0 0 0 0 0 0 0]

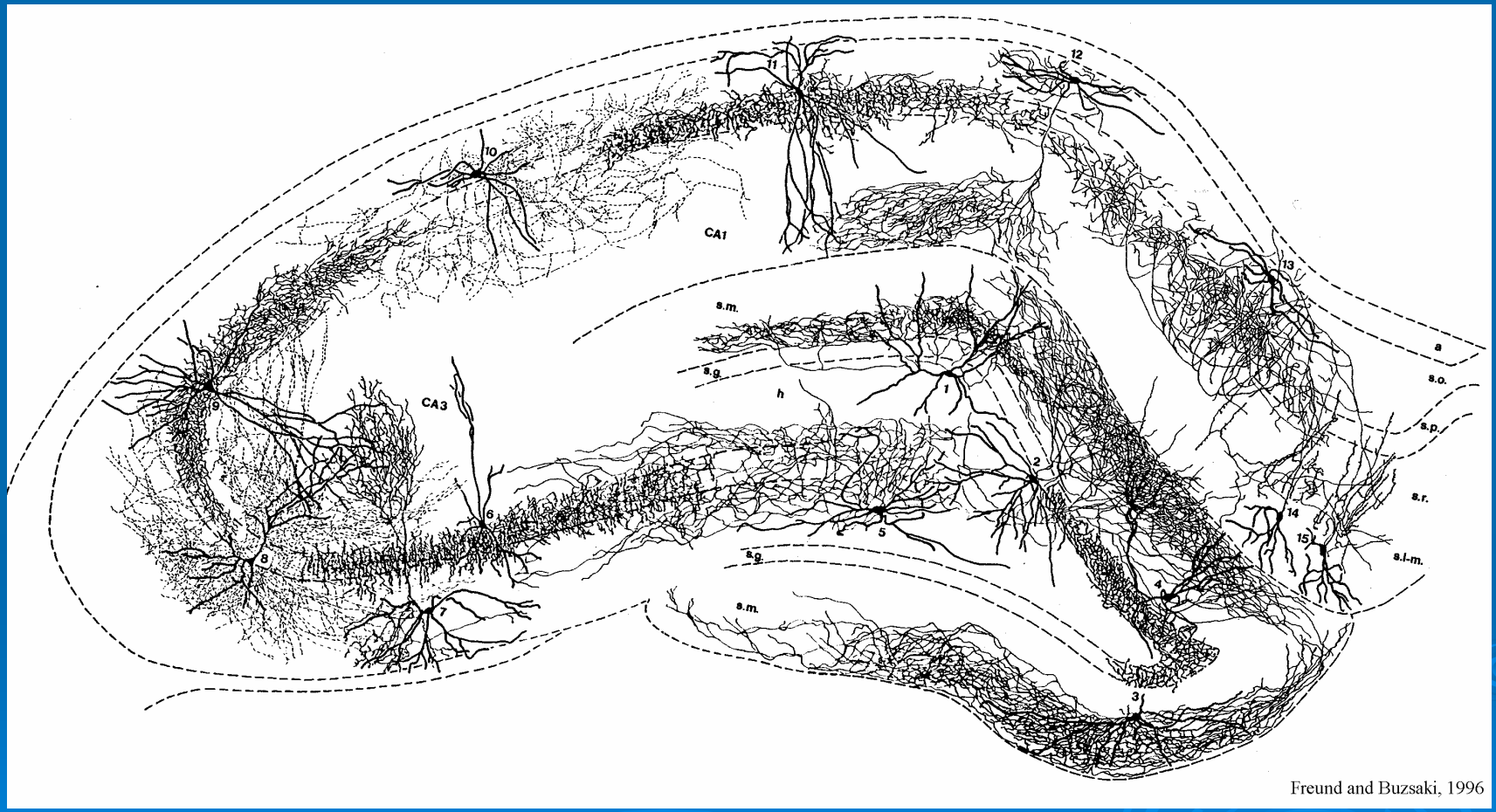


- Neurons made active on the basis of their summed input





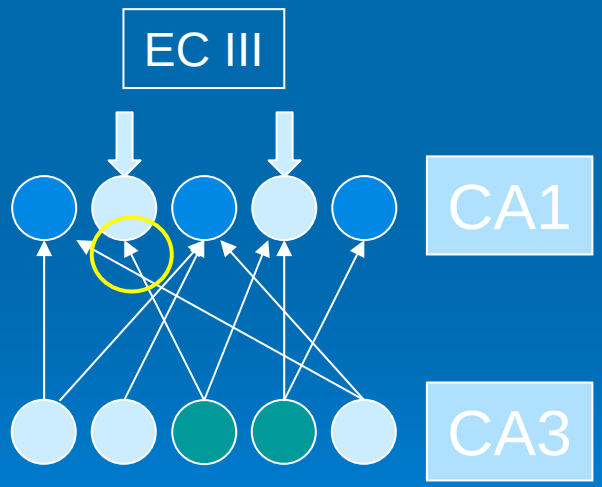
The Hippocampus

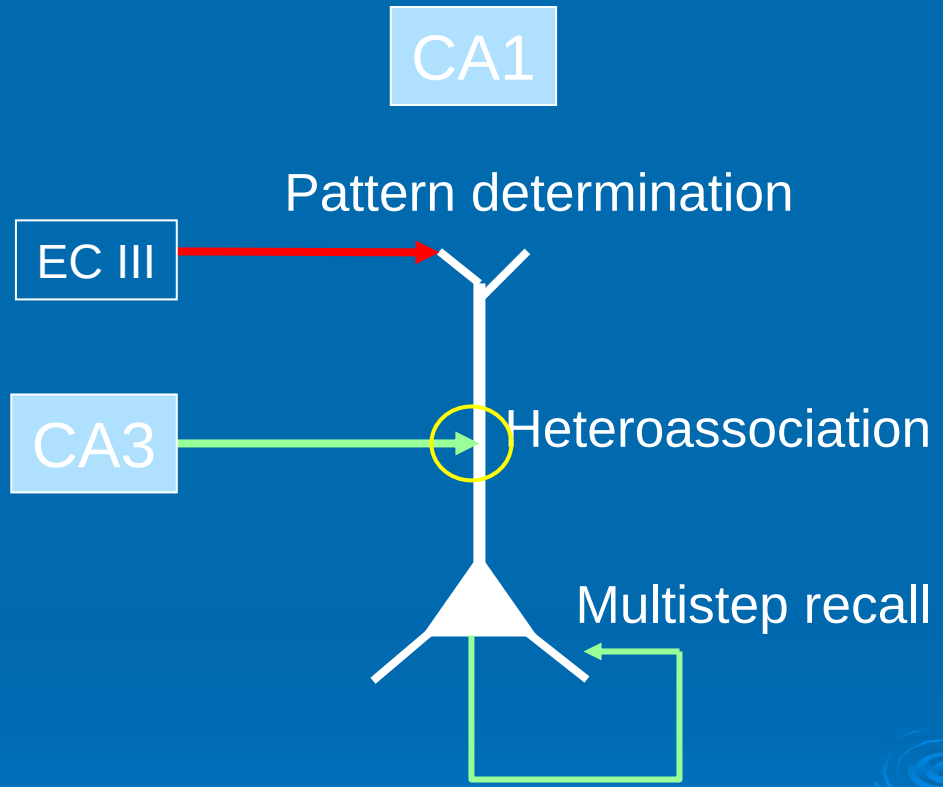


Freund and Buzsaki, 1996

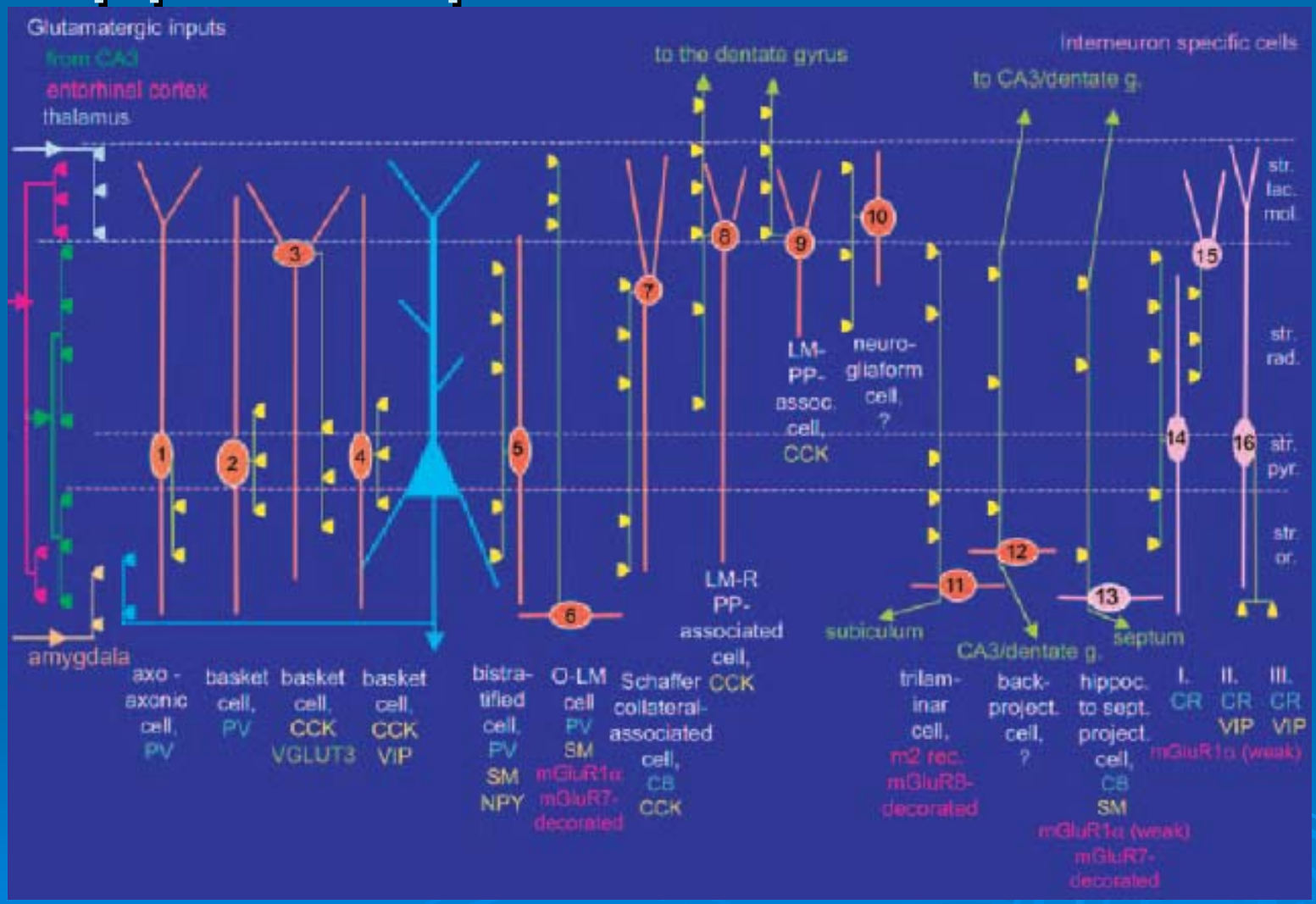
Associative Memory in CA1

- Networks of pyramidal neurones





Hippocampal CA1 Microcircuit



Somogyi & Klausberger, J. Physiol. 562, 2005

Neuronal Cell Types

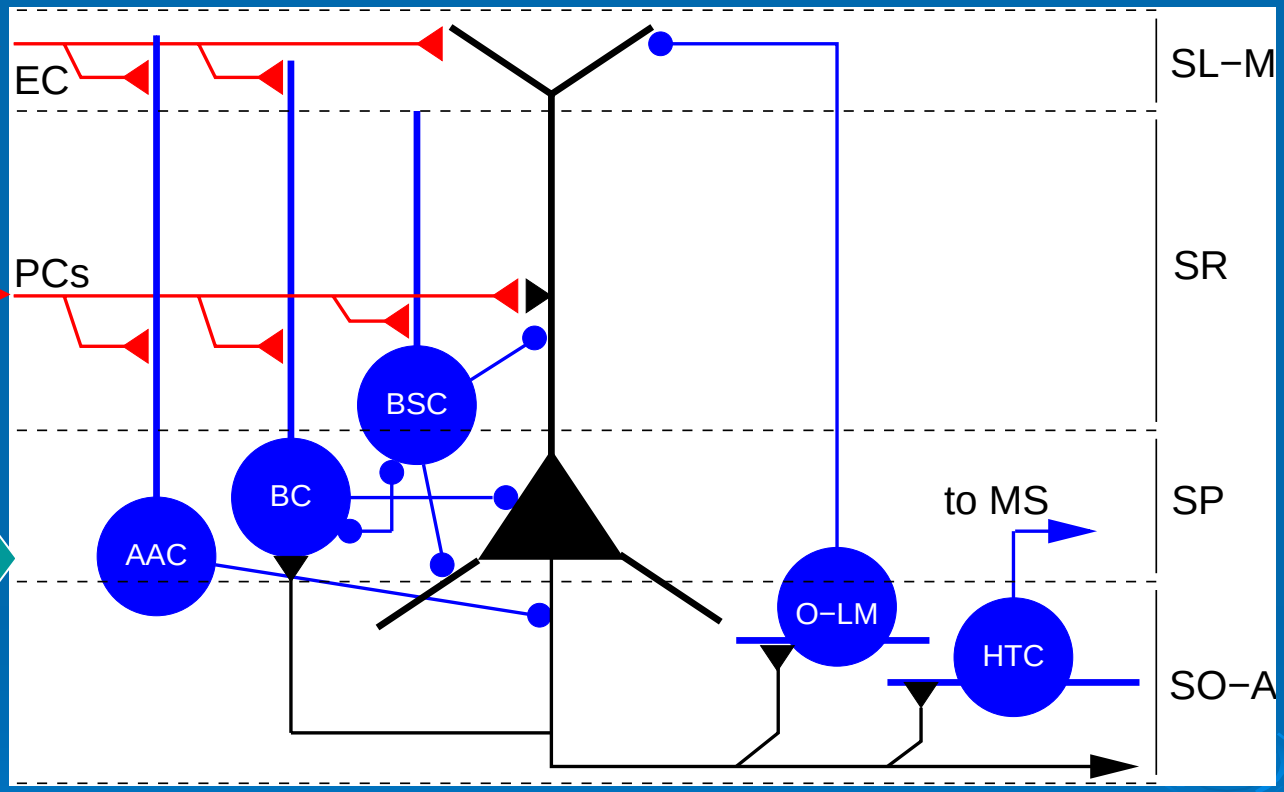
- Single excitatory neurone – pyramidal cell
- 16 types of inhibitory interneurone
  - Morphology and connectivity
  - Firing properties
  - Pharmacology
    - Same morphology but different pharmacology
    - Same function in different context e.g. mood?

Simplified CA1 Microcircuit

Feedforward excitation

Feedforward / recurrent excitation

Feedforward inhibition



Paulsen & Moser, TINS 21:273-278, 1998

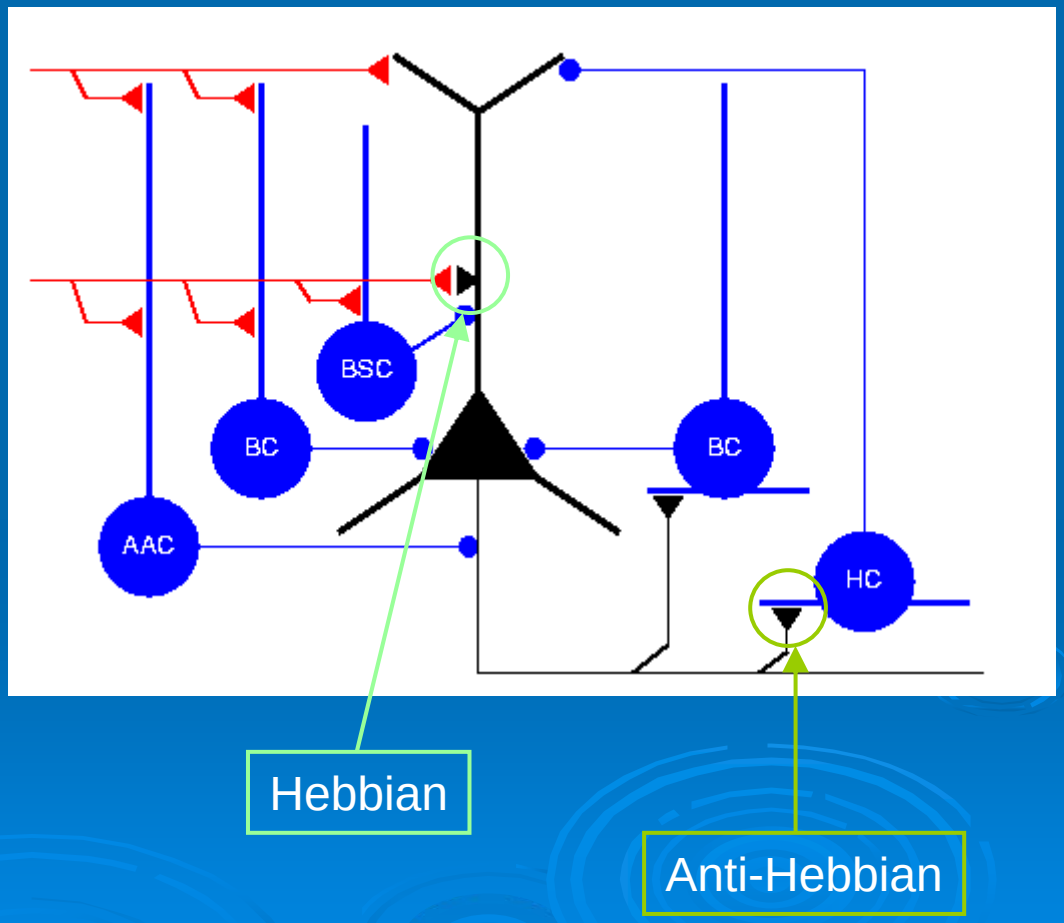
Feedback inhibition

Functions of the Microcircuit

- Rhythm generation
  - Temporal reference signals
  - Synchronisation of PC activity
- Control of PC output
  - General control of network excitability
  - Threshold setting for pattern recall
- Control of synaptic plasticity
  - Storage (learning) and recall modes
  - Spatial and temporal control of internal PC signals
    - BPAPs and calcium spikes

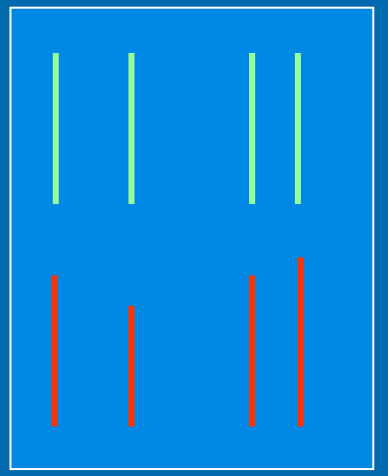
Synaptic Plasticity – Long Term

- LTP / LTD
  - NDMA dependent
  - Synapse specific
  - Hebbian
- Non-Hebbian
  - Presynaptic activity but not postsynaptic
  - Lamsa et al, Science 315:1262, 2007



Synaptic Plasticity – Short Term

- Milliseconds to minutes
- Facilitation
  - Increase in release probability
- Depression
  - Vesicle depletion
  - Receptor desensitization
- Target neurone specific

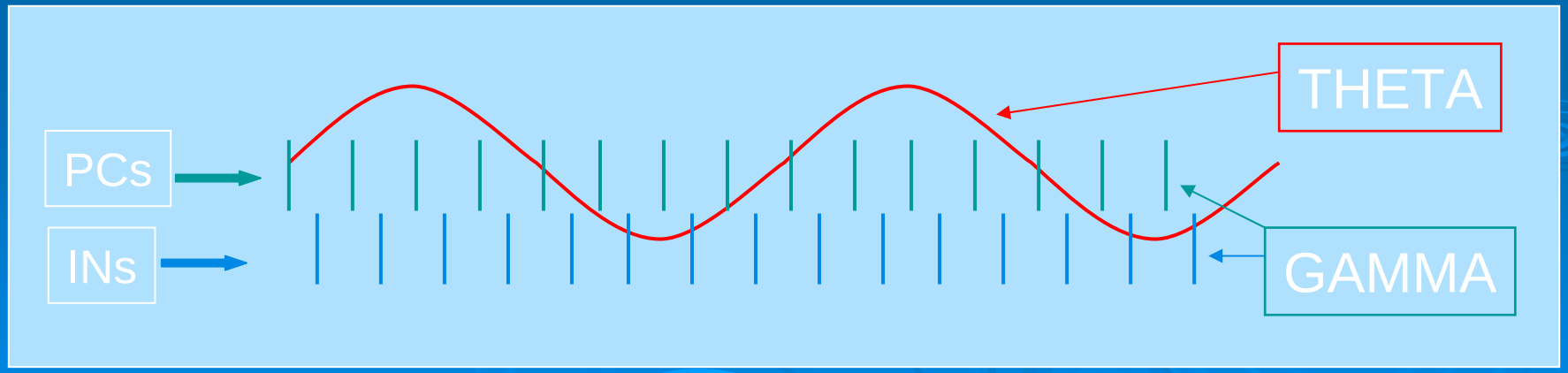


Behavioural Network States

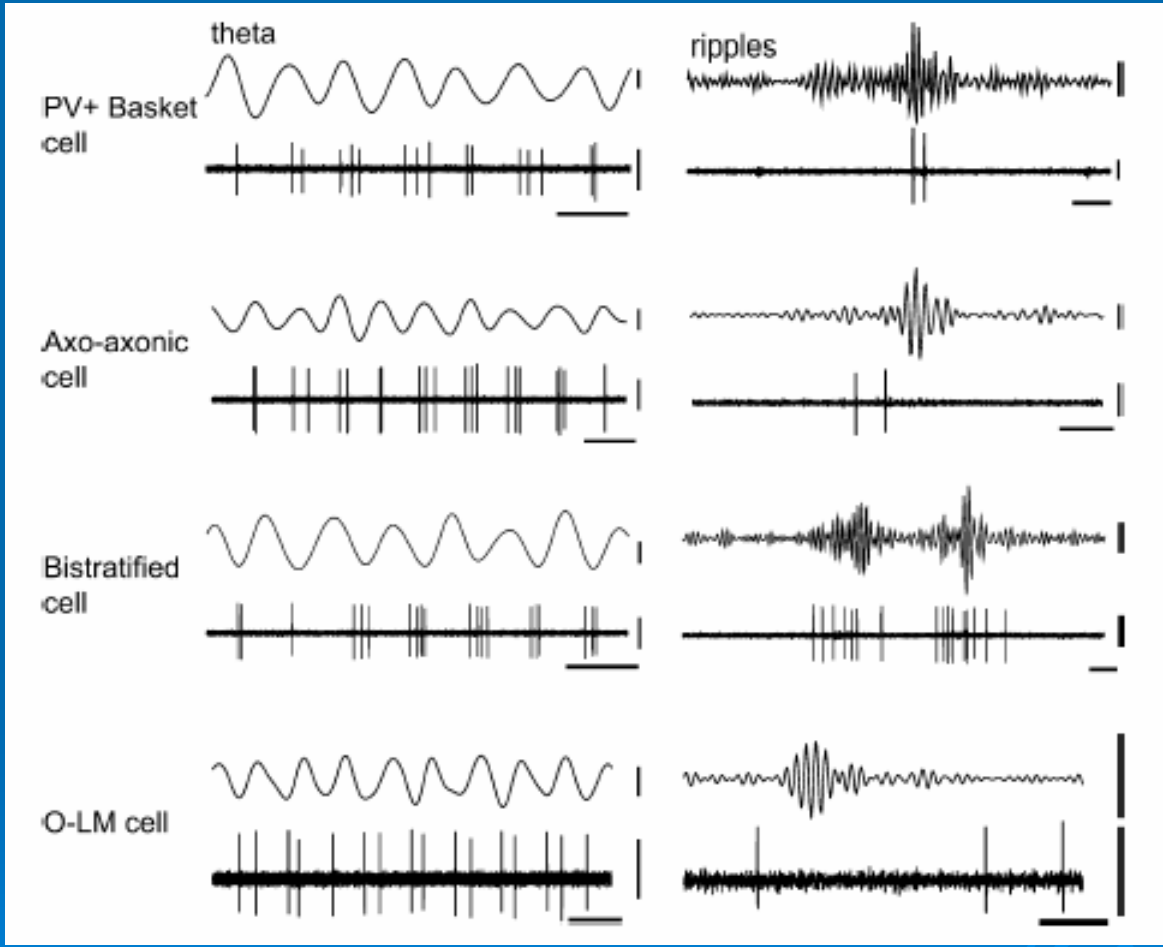
- Passive behaviour
  - No sensory input
  - Slow-wave sleep; consummatory
  - EEG punctuated by sharp waves (120-200Hz)
- Active behaviour
  - Sensory input
  - Exploration of environment
  - Theta (4-10Hz) and gamma (30-80Hz)

Rhythm Generation

- Theta and gamma
  - External pacemakers such as medial septum
  - Internal circuit dynamics
    - Feedback inhibition and synaptic dynamics
  - Coincident

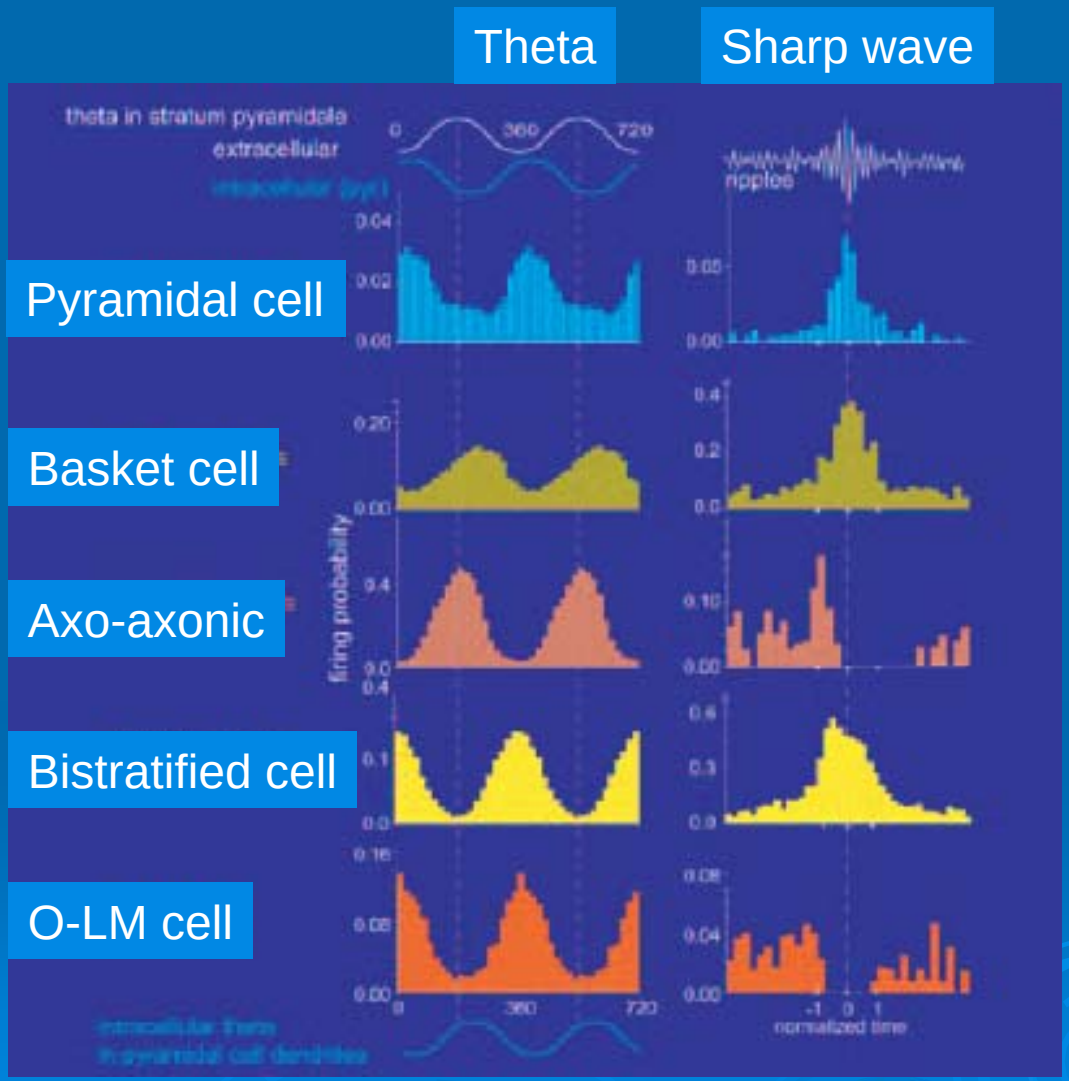


In Vivo Cell Firing Patterns



Somogyi & Klausberger, J. Physiol. 562, 2005

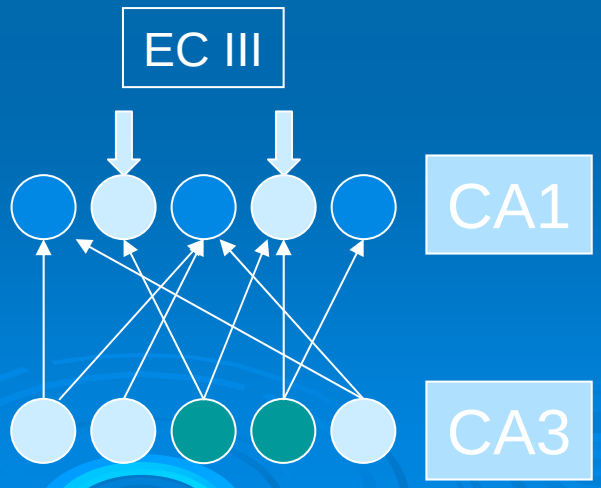
Average Cell Activity



Somogyi & Klausberger, J. Physiol. 562, 2005

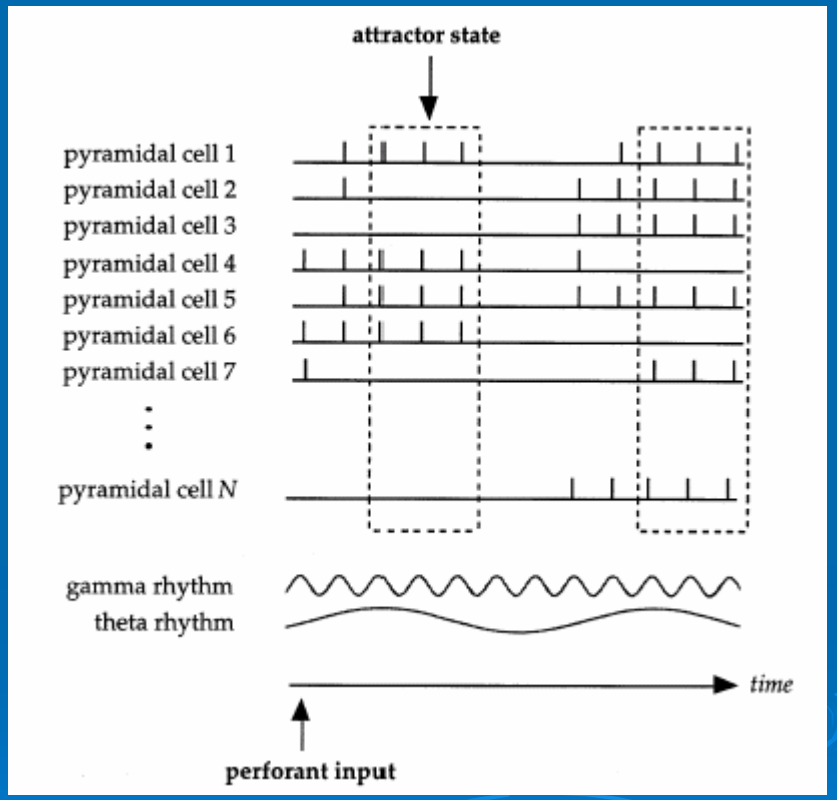
Associative Memory

- Can we relate associative memory function with microcircuit behaviour?
  - Spatio-temporal pattern coding
  - Conditions for pattern storage
  - Conditions for pattern recall
  - Are storage and recall mutually exclusive?



Oscillations and AM

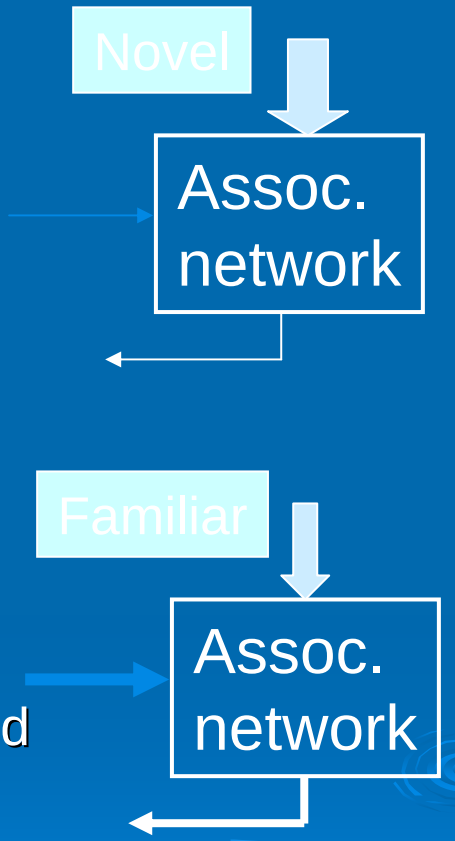
- Gamma rhythm (30-80Hz)
  - internal clock
  - memory pattern is active PCs on a gamma cycle
  - recall takes place at gamma frequency
- Theta rhythm (5-12Hz)
  - phases learning and recall
  - recall compressed to a theta cycle



Menschik & Finkel, Artif. Intell. Med. 13:99-121, 1998

Setting the Network State

- Self-regulation of storage and recall
- Exploring a novel environment promotes storage
  - Novel patterns lead to low CA1 output
  - Cholinergic input from medial septum is strong, promoting conditions for plasticity
- Familiar environment encourages recall
  - CA1 output is strong, leading to inhibition of medial septum
  - Cholinergic input and hence plasticity is reduced
- Modulation on time scale of seconds



CA1: Hasselmo & Schnell, J. Neurosci. 14:3898-3914, 1994
CA3: Hasselmo, Schnell & Barkai, J. Neurosci. 15:5249-5262, 1995

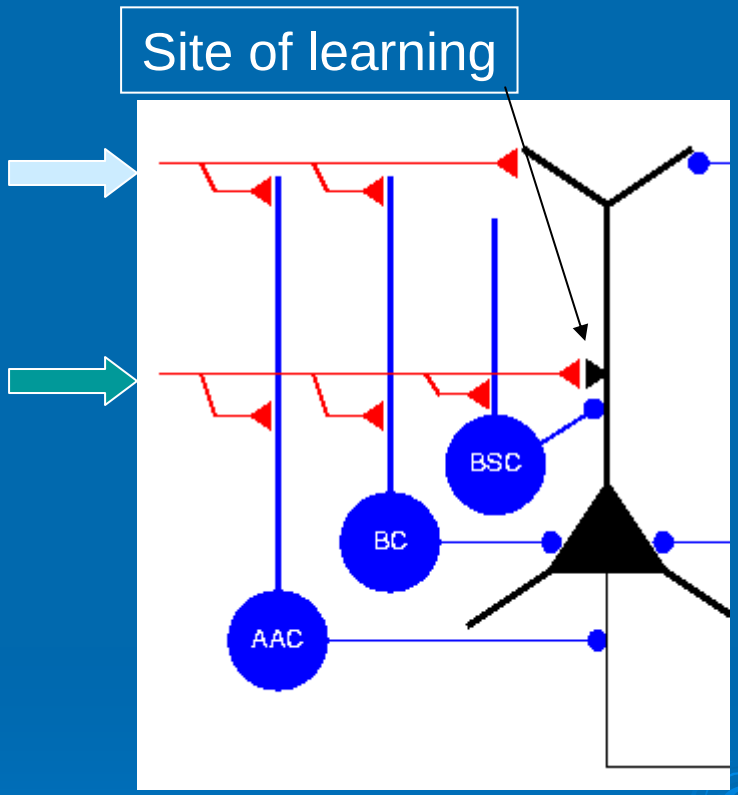
Rapid Phasing of Plasticity

- One theta cycle divided into storage and recall
- $GABA_B$-mediated inhibition from medial septum
  - modulated at theta rhythm
  - when *strong* transmission in associative pathways is inhibited and learning is promoted
  - when *weak* associative pathways provide recall

Hasselmo et. al. Neural Comp. 14, 2002

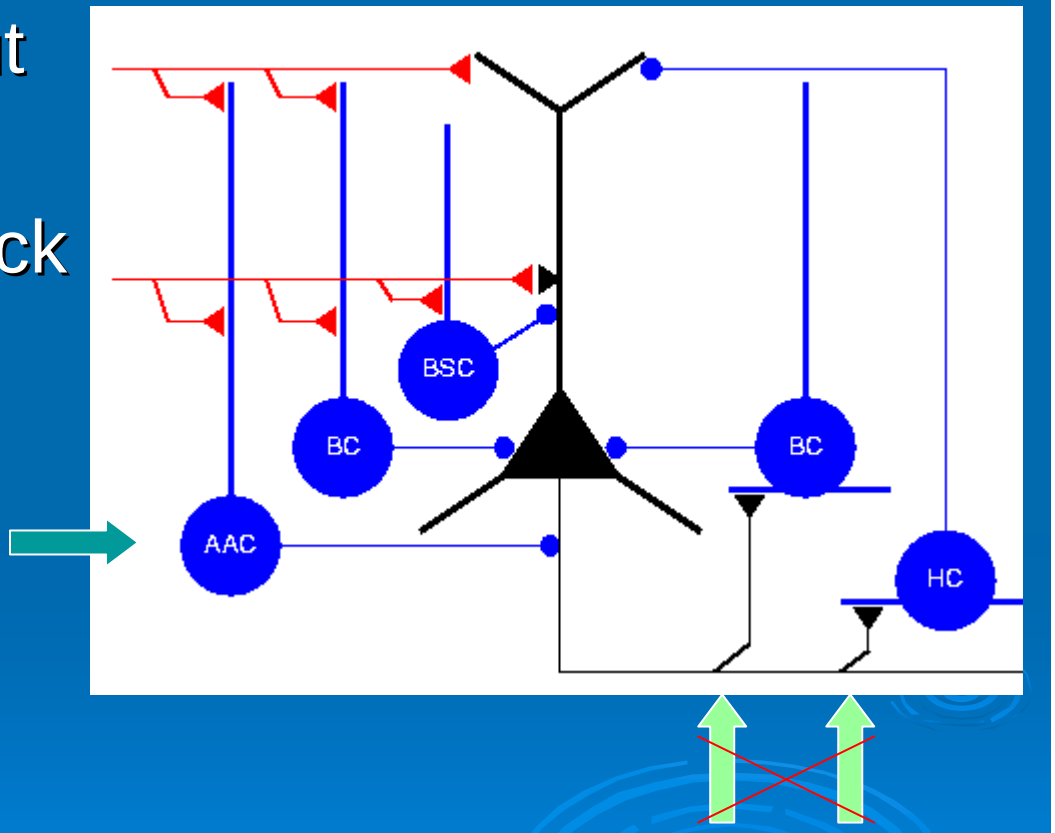
Excitatory Pathways

- Storage
  - Distal pathway establishes which principle cells belong to pattern
  - Proximal pathway is input pattern for association
- Recall
  - Proximal pathway provides partial or noisy cue



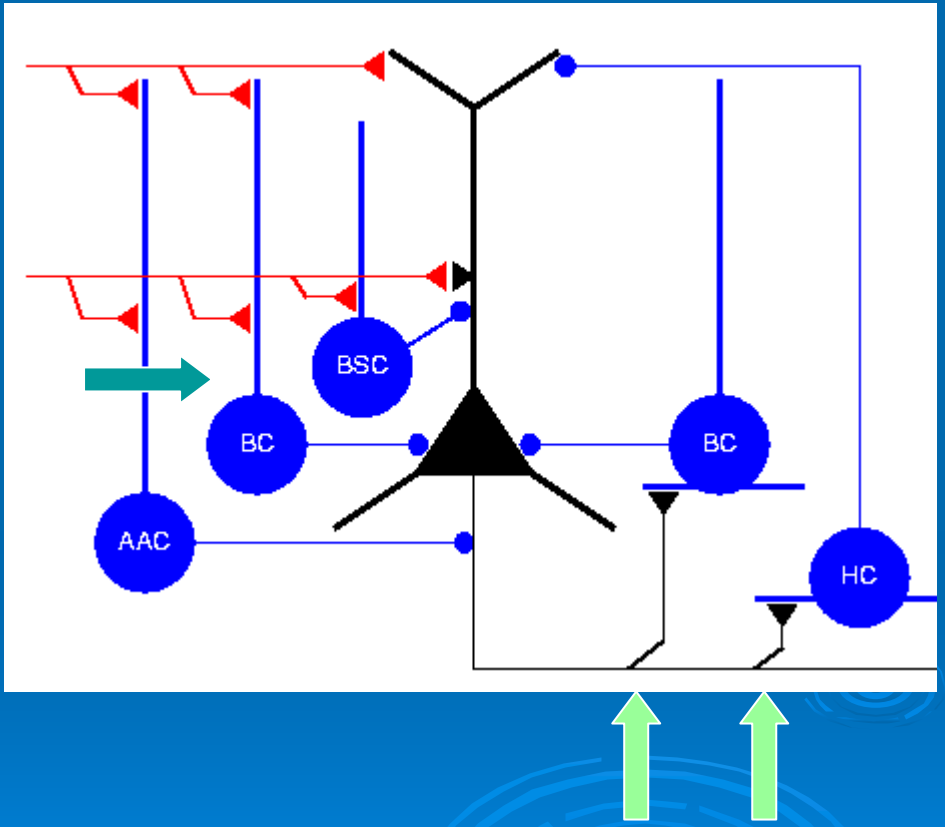
Inhibitory Pathways - Storage

- AAC blocks PC output
  - recall not required
- Consequently feedback inhibition blocked
  - may interfere with synaptic plasticity
  - should not inhibit patterned input

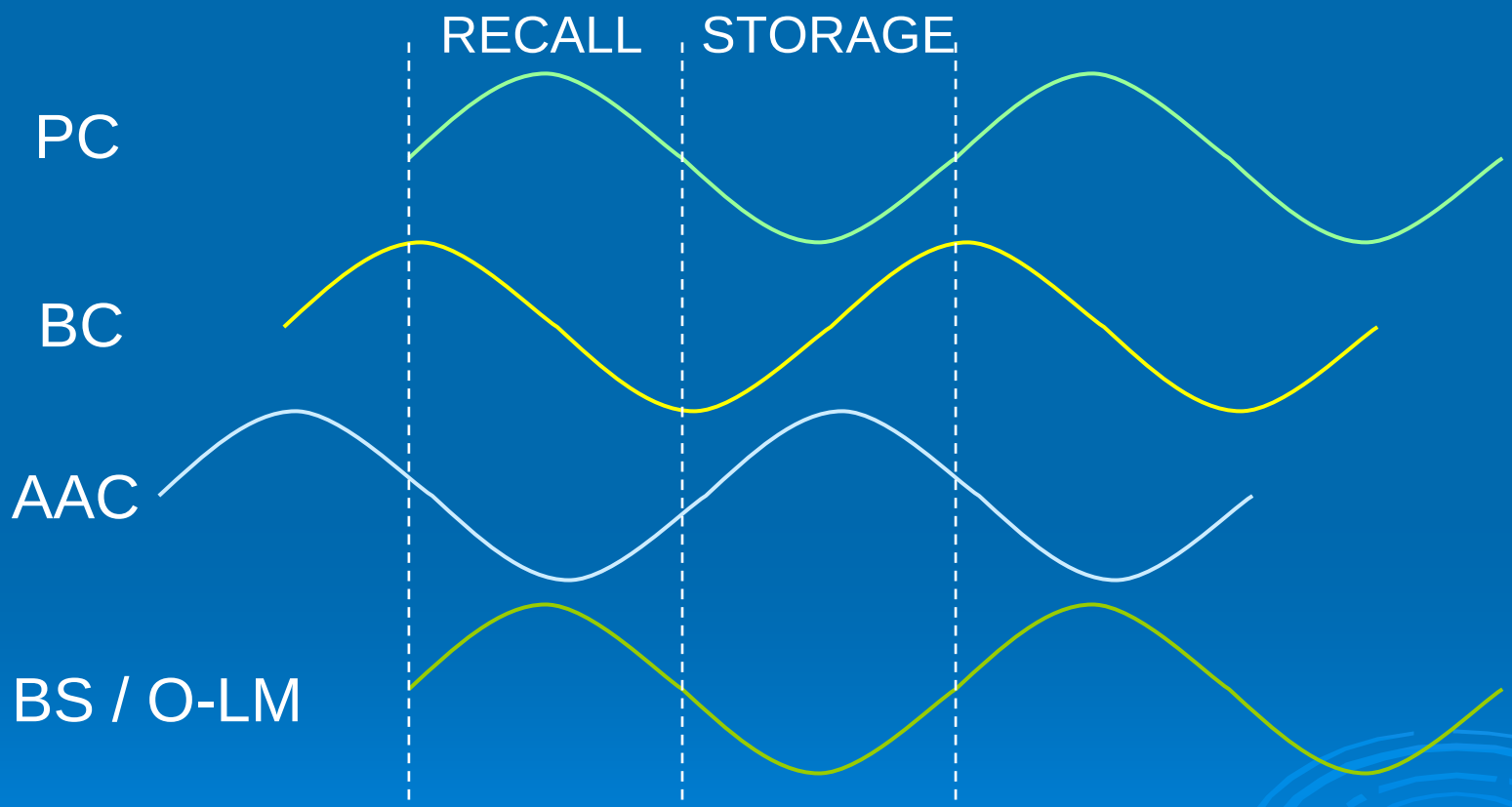


Inhibitory Pathways - Recall

- Feedforward inhibition
  - sets recall threshold via BC and BSC
  - AAC too slow to block output now
- Feedback inhibition
  - resets PC for next pattern via BC
  - blocks stray patterned input via HC (O-LM)



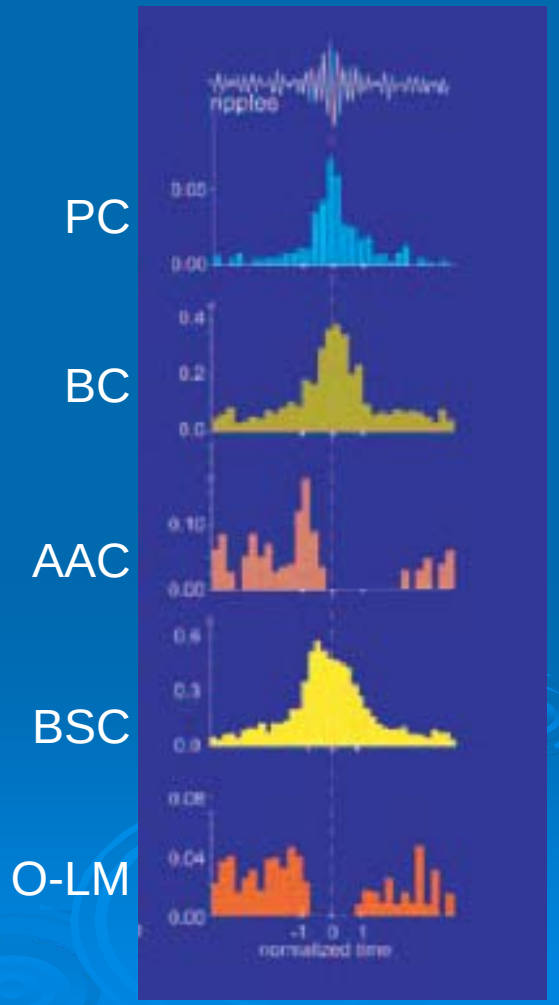
IN Firing Patterns



Klausberger et al, Nature 421:844-848, 2003

IN Firing Patterns - SWR

- Recall of patterns for consolidation
  - Synchronous PC activity
  - Thresholding by BC/BSC
  - AAC silent
  - O-LM silent (?)



The End

- The reality is much more complicated...
  - Variety of cell types
  - Intracellular properties
    - Interaction of inhibition and Ih: rebound excitation
  - Synaptic plasticity
  - Network states and rhythms