Dynamics of storage and recall in associative memories

What can we learn from cortical control structures?

2. Hippocampal Microcircuit

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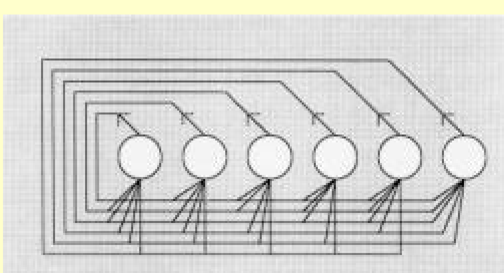
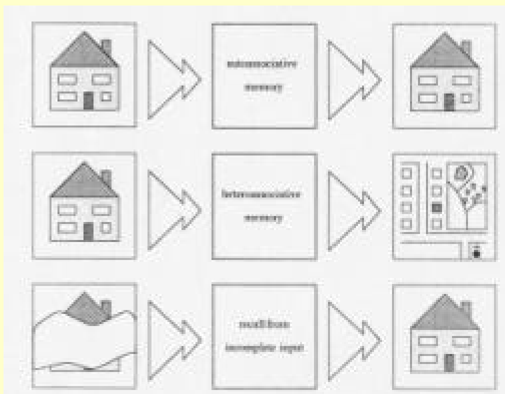
Associative Memory

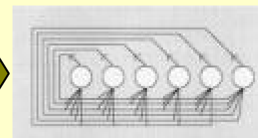
- Content addressable

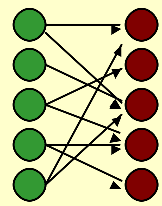


Types of Associative Memory

- Auto- and hetero-associative





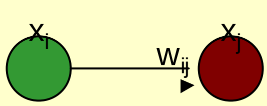


Storage By Hebbian Learning

- Binary patterns

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

- Correlation between pre- and postsynaptic activity



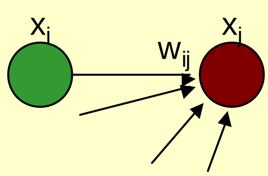
$dW_{ij} = x_i x_j$

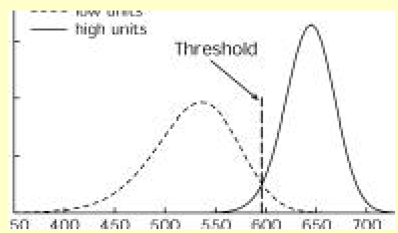
Recall by Threshold Setting

- Partial or noisy cue

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

- Neurons made active on the basis of their summed input





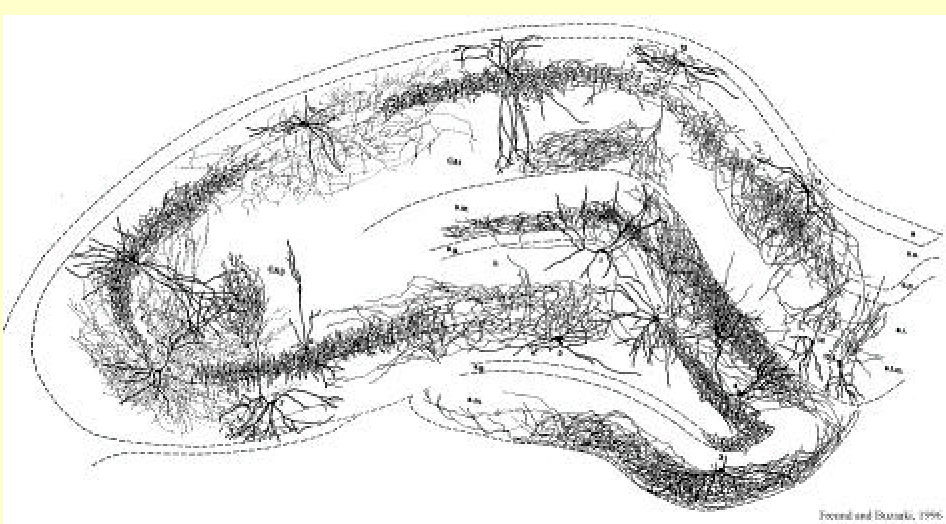
Dynamics of Recall

- Heteroassociative may be single step
  - single update of all neurons
- Autoassociative may be multistep
- Sequence storage and recall

ANN Models vs Neurobiology

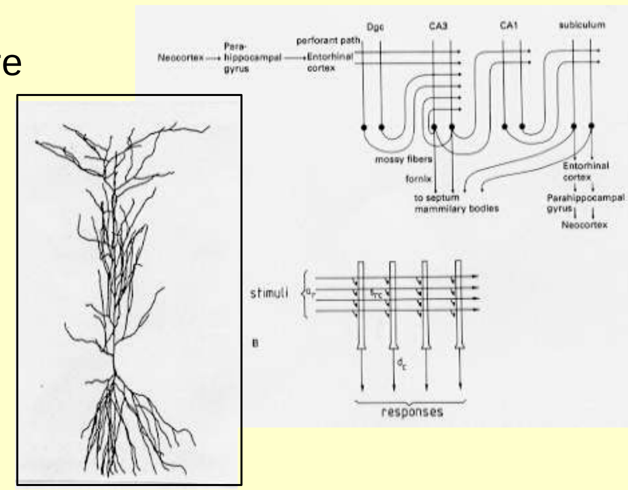
- ANNs
  - separate storage and recall phases
  - single neuron both excitatory and inhibitory
  - strictly clocked operation
- Neural circuits
  - dynamic phasing of storage and recall
  - principal excitatory cells and diverse classes of inhibitory cells
  - synchronous spiking as pattern coding?

The Hippocampus

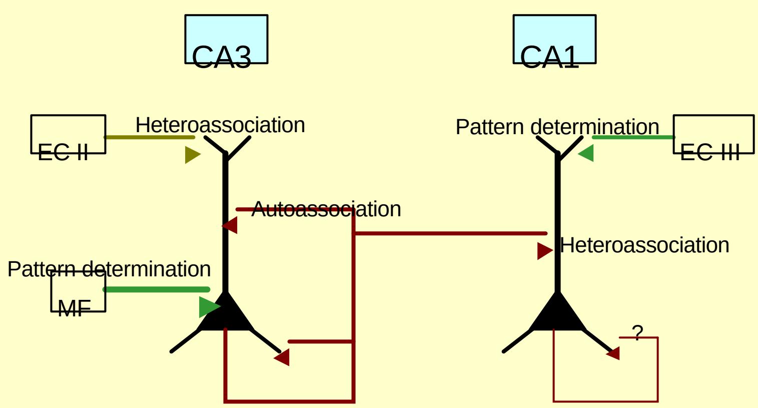


Networks of Principal Cells

- Pyramidal neurons are principal excitatory cells

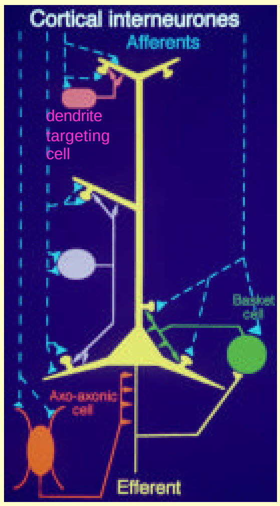


Auto- & Heteroassociative Networks

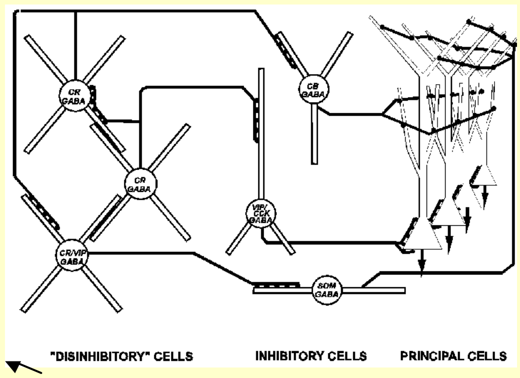


Hippocampal Microcircuit

Control synaptic excitatory input to cell



Control action potential output of cell



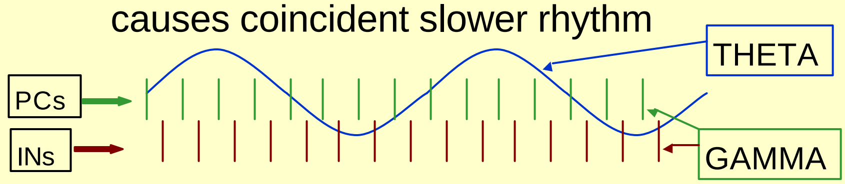
Control integration of synaptic inputs

Functions of the Microcircuit

- Rhythm generation
  - temporal reference signals
  - synchronisation of PC activity
- Controlling plasticity
  - storage (learning) and recall modes
  - spatial and temporal control of internal PC signals
    - BPAPs and calcium spikes
- Threshold setting for PC output
  - recall mode
  - general control of network excitability

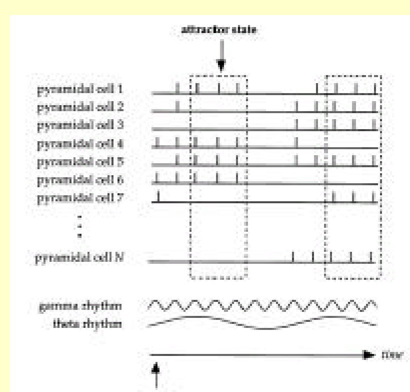
Dynamics of Operation

- Gamma rhythm (30-80Hz)
  - circuit dynamics of feedback inhibition leads to rhythmic firing of PCs and INs
- Theta rhythm (5-12Hz)
  - external inhibitory and modulatory input causes coincident slower rhythm



Roles for Oscillations

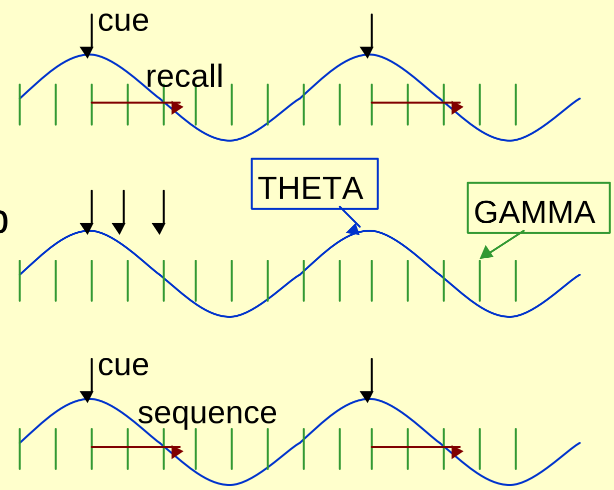
- Gamma rhythm (30-80Hz)
  - internal clock
  - memory pattern is active PCs on a gamma cycle
  - recall takes place at gamma frequency
- Theta rhythm (5-12Hz)
  - phases learning and recall
  - recall compressed to a theta cycle



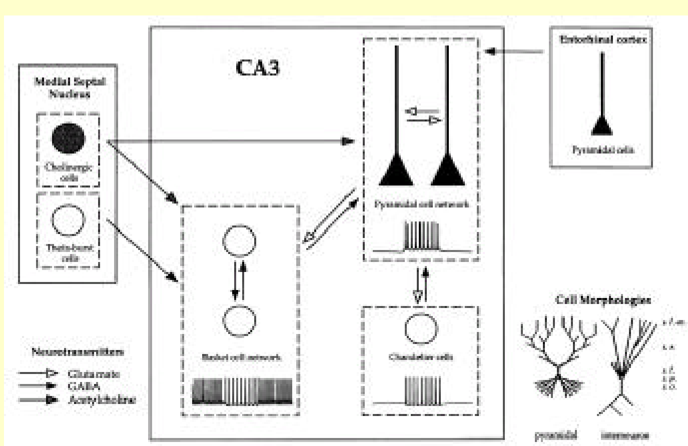
Menschik & Finkel, Artif. Intell. Med. 13:99-121, 1998

Associative Recall

- Multistep
- Single step
- Sequence



Autoassociative Example



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

Network Construction

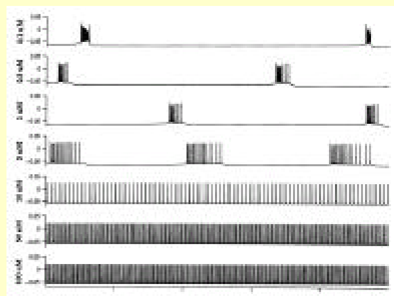
- 64 PCs, 64 chandelier cells (AAC), 8 basket cells
- PC -> PC and PC->AAC->PC connection strengths determined by Hopfield net
  - positive weights scale PC AMPA/NMDA synapses
  - negative weights scale AAC $GABA_A$ synapses
- Basket cells project all-to-all to each other & PCs
  - driven by PCs and provide gamma band oscillations
  - firing modulated at theta rhythm by input from septum
- EC input provides recall cue on each theta cycle

Cholinergic Modulation

- Multiple effects on PCs and INs
  - muscarinic and nicotinic receptors
- Increased cell excitability
  - suppression of K currents
- Decrease in synaptic transmission
  - presynaptic inhibition in particular pathways
- Increased synaptic plasticity
  - facilitated NMDA response
  - enhanced BPAPS due to suppression of KA

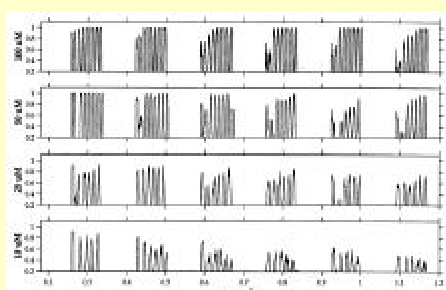
ACh In Menshik & Finkel Model

- Constant level during recall
- Reduces intrinsic Ca and AHP currents
- Increases PC and BC excitability
  - depolarizing current
- Reduces strength of recurrent collaterals
- Mediates transition from bursting to spiking
  - bursting for learning?



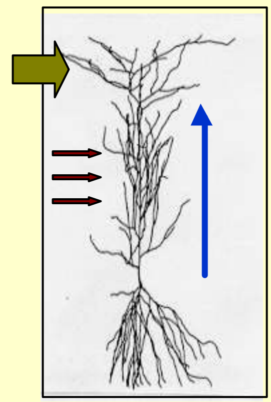
Recall Performance

- New cues on theta cycles
- Recall from noisy cue within 3-5 gamma cycles
- PC reset by BCs during second half of theta
- Decreasing ACh lowers gamma frequency and disrupts recall



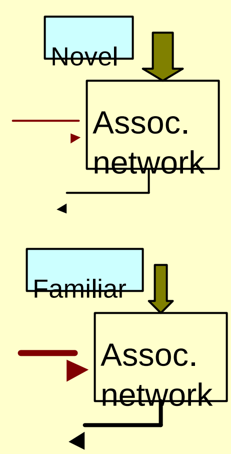
Storage Mode

- Activity determined by external input
- Learned connections should be suppressed
  - minimise interference from previous patterns
- But these connections should still be plastic
- Cholinergic modulation achieves this state
  - but compare Menschik & Finkel



Phasing Storage and Recall

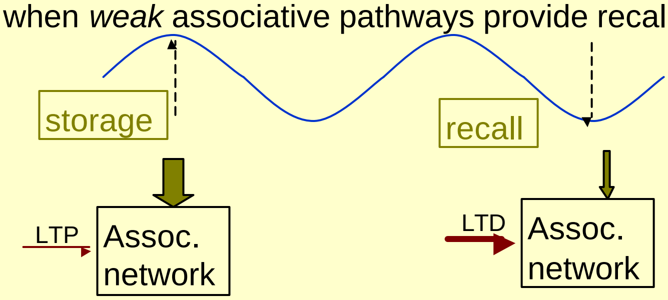
- Feedback regulation of ACh input as a function of activity
  - novel patterns lead to low activity and strong ACh modulation which promotes plasticity
  - familiar patterns lead to high activity which decreases modulation, promoting recall and inhibiting plasticity
- Demonstrated with rate (not spike) based models of auto- and heteroassociative memory based on CA3 and CA1
  - not rhythmic operation
- 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

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



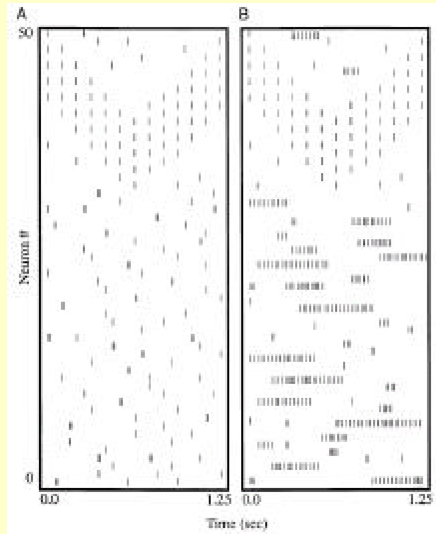
A Sequence Storage Model

- 1000 PCs and 200 INs
  - random connectivity with probability of connection between 15-30% depending on cell types
- Theta frequency inhibition of INs from septum
- Constant ACh modulation increases cell excitability so that on average 15% of PCs fire spontaneously
- Network exhibits gamma/theta activity levels
  - $GABA_B$ inhibition rises and falls with theta
- NMDA synapses of recurrent collaterals undergo LTP
  - proportional to presynaptic activity over 50msecs preceding a postsynaptic spike

~~Wallenstein & Hasselmo, J. Neurophysiol. 78:393-408, 1997~~

Sequence Storage

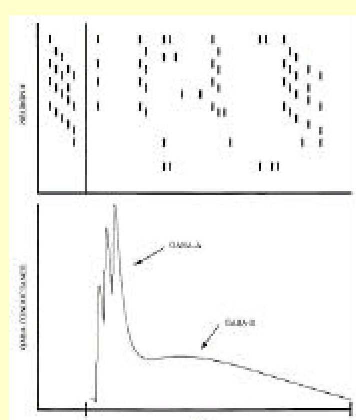
- Input sequence at theta frequency
  - weak recurrent connections prevents interference from previous patterns
  - repeated 5 times
- Emergence of context-sensitive cells
  - connection from afferent-driven PC to random firing PC strengthened if within 50msec time window



Wallenstein & Hasselmo, J. Neurophysiol. 78:393-408, 1997

Sequence Recall

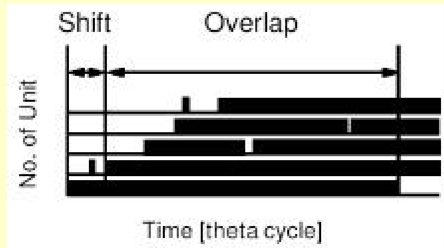
- Input sequence recalled at gamma frequency
- Cue provided late in a theta cycle
  - $GABA_B$ inhibition has decayed
  - recurrent connections are strong



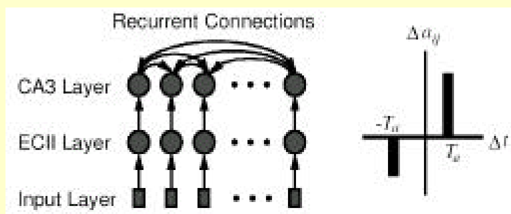
Wallenstein & Hasselmo, J. Neurophysiol. 78:393-408, 1997

Temporal Sequence Compression

- How is a match achieved between behavioural and internal time scales?
  - Input sequence may be much slower than theta
- Model considers temporal compression in EC and sequence learning in CA3

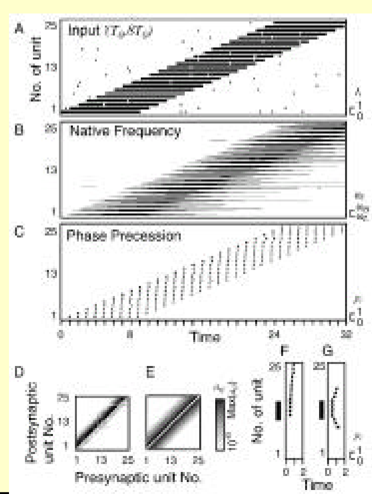


Sato & Yamaguchi, Neural Comp. 15:2379-2397, 2003



Compression (2)

- EC cells fire once per theta cycle
- Intrinsic properties lead to phase advance
  - gamma frequency
- Phase separation suitable for STDP in CA3
- Sequence recalled at gamma frequency



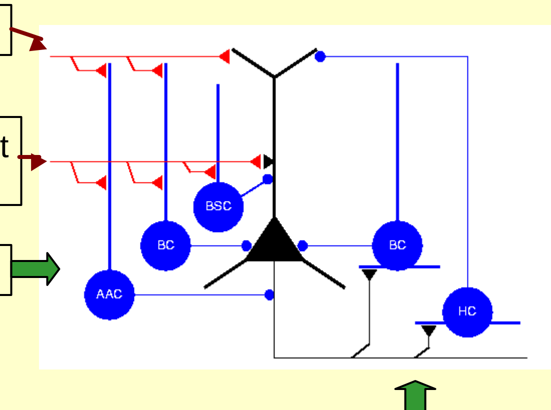
Sato & Yamaguchi, Neural Comp. 15:2379-2397, 2003

The Microcircuit Again

Feedforward excitation

Feedforward / recurrent excitation

Feedforward inhibition



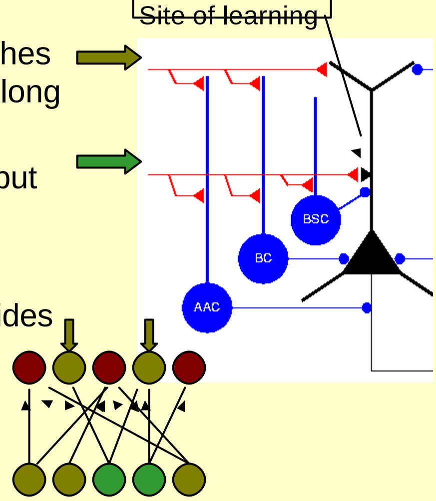
Feedback inhibition

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

Excitatory Pathways - CA1

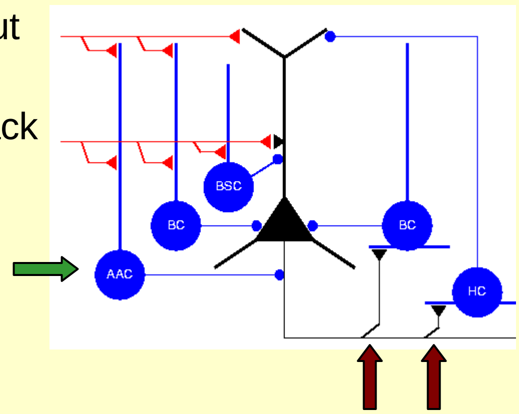
- Storage
  - Distal pathway establishes which principle cells belong to pattern
  - Proximal pathway is input pattern for association
- Recall
  - Proximal pathway provides partial or noisy cue

Site of learning



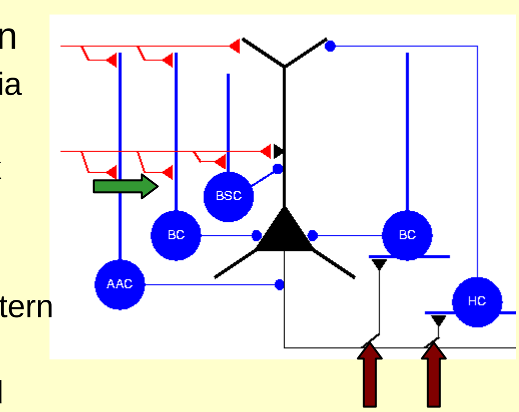
Inhibitory Pathways - Storage

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



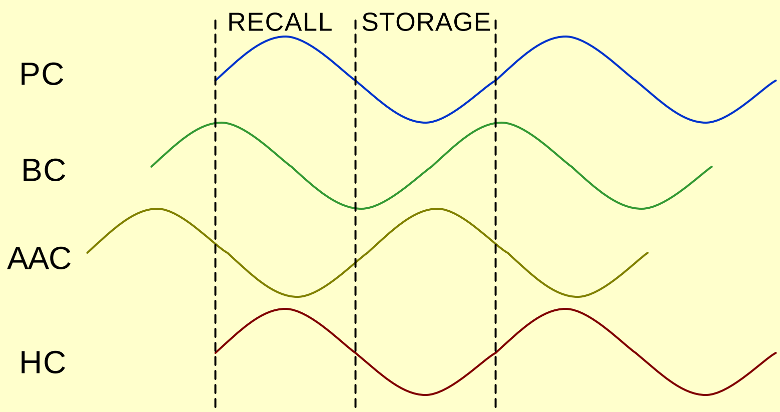
Inhibitory Pathways - Recall

- 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



IN Firing Patterns

- Distinct classes of IN show distinctive activity



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

The End

- BUT the reality is much more complicated...
- Is *theta/gamma* model appropriate?
  - other rhythms in different behavioural states
- Intrinsic neuronal properties
  - modulated to phase storage and recall
  - resonance / stochastic resonance
- What roles do *variations* in network and cellular properties play?