SAND2013-9462C

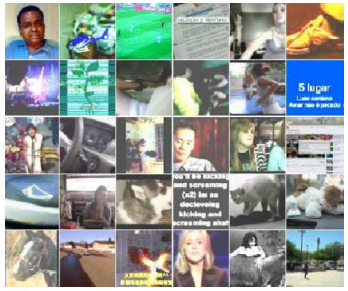
Neurogenesis Inspired Computing

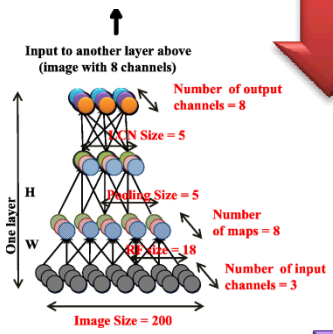
Brad Aimone

Sandia National Laboratories

Cutting edge of modern artificial intelligence – Deep Learning @ Google

10,000,000
YouTube Videos





“Google Brain”

1 billion connections
16,000 CPU cores
Several days
~25,000 kWatt*hours

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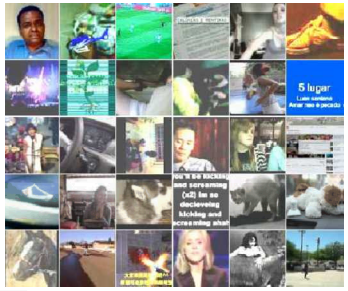

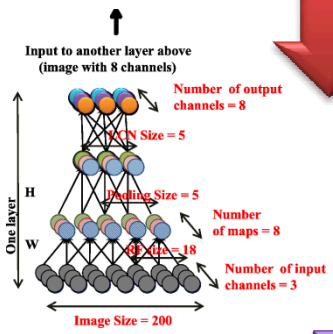

“Google Brain”

1 billion connections
16,000 CPU cores
Several days
~25,000 kWatt*hours

“Marcus”

- Far less than 10,000,000 YouTube videos
- 4 months training; vast majority in sleep state
- 72 kWatt*hours

Why can we barely match the cognitive function of a 4 month old?

- *Wrong algorithms*
  - Artificial neural networks are simple; basically linear algebra with non-linear filters
  - Brain has much greater scale, complexity of anatomy, variable dynamics, etc
- *Wrong data*
  - Little or no context
  - Behavioral relevance is rarely accounted for
- *Wrong hardware*
  - Computers use a simple architecture
  - "Tyranny of wires" makes connectivity of brain impossible
  - Learning is not trivial on silicon

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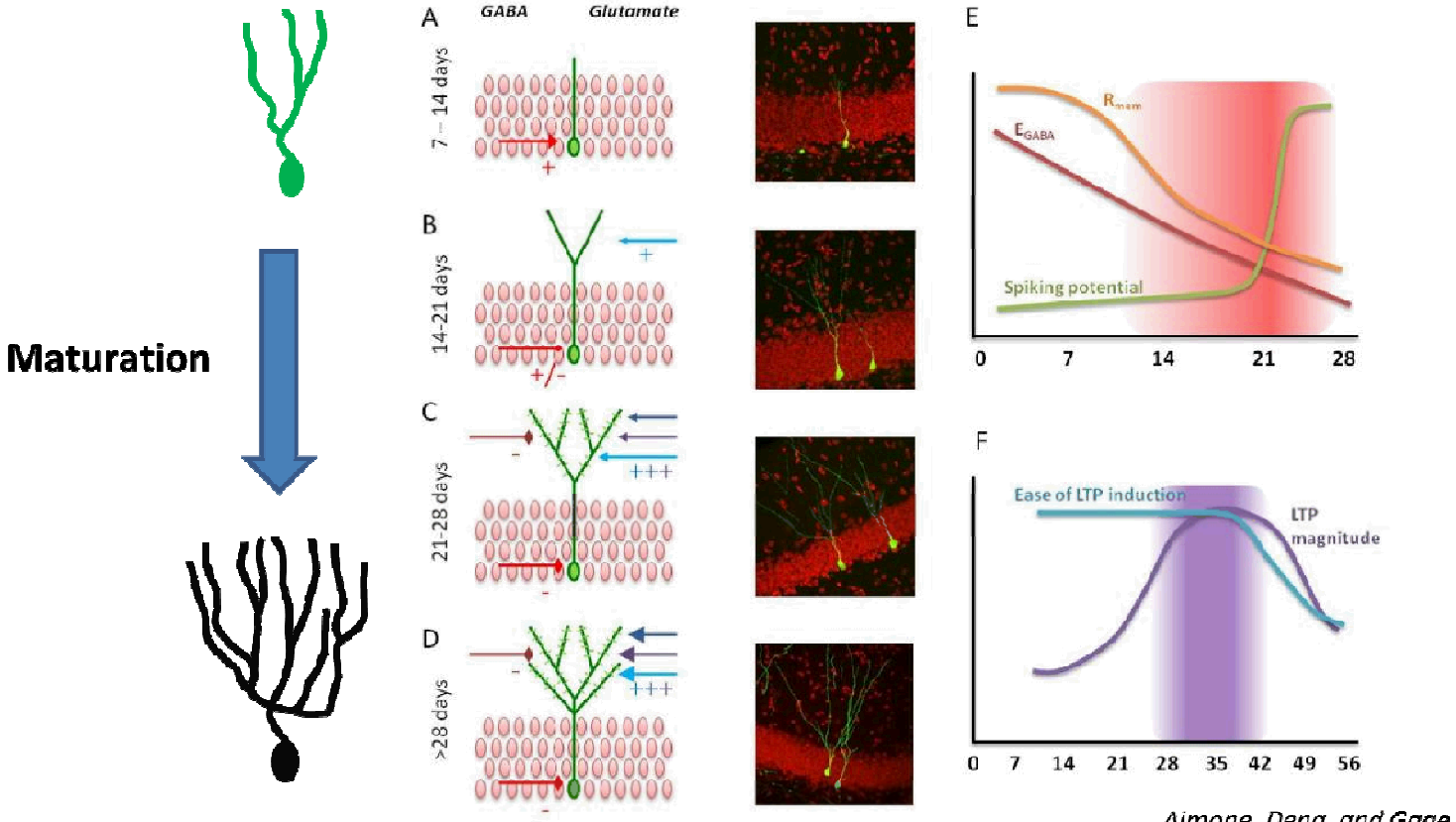
Neurogenesis through a different lens

- Adult neurogenesis is a clever solution to big AI problem
  - Limited structural plasticity is brain's solution to *stability-plasticity dilemma*
- Context dependent "latent" capacity for learning is a very powerful approach

Neurogenesis Process

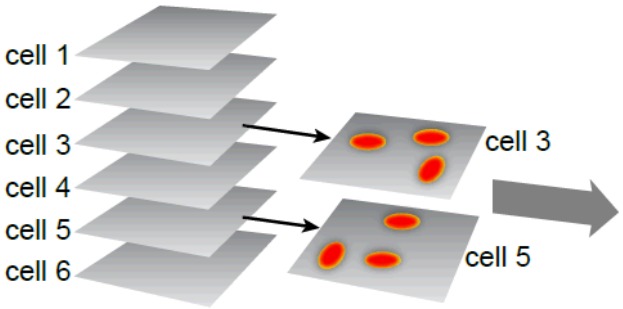


Aimone, Deng, and Gage
Trends in Cog. Sci. 2010

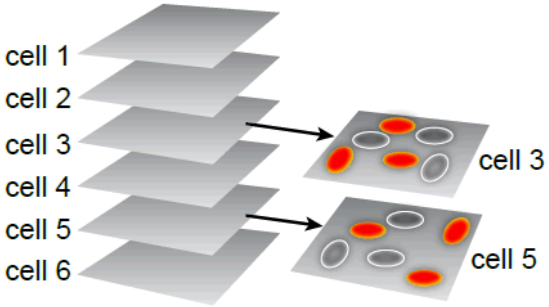
How to leverage this in future computing?

- Algorithms
  - Need stronger formal characterization
- Training
  - Longer term perspective of what neurogenesis is really doing
- Devices
  - What would constitute neurogenesis on a chip?

What is pattern separation?



Subset of GCs show multiple place fields in one context.



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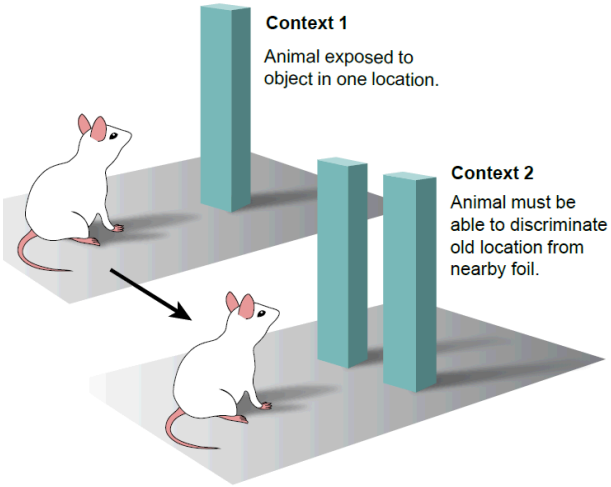
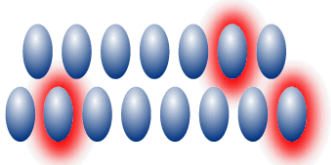
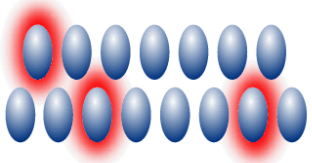


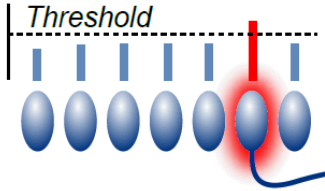


Sparse set of GCs represent one context.

Context 2

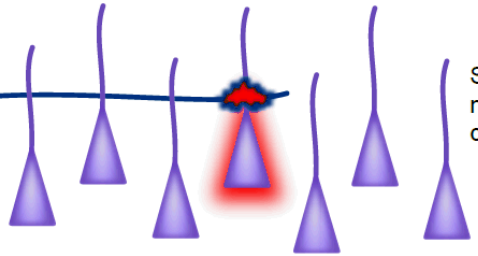


Orthogonal set of GCs represent different context.



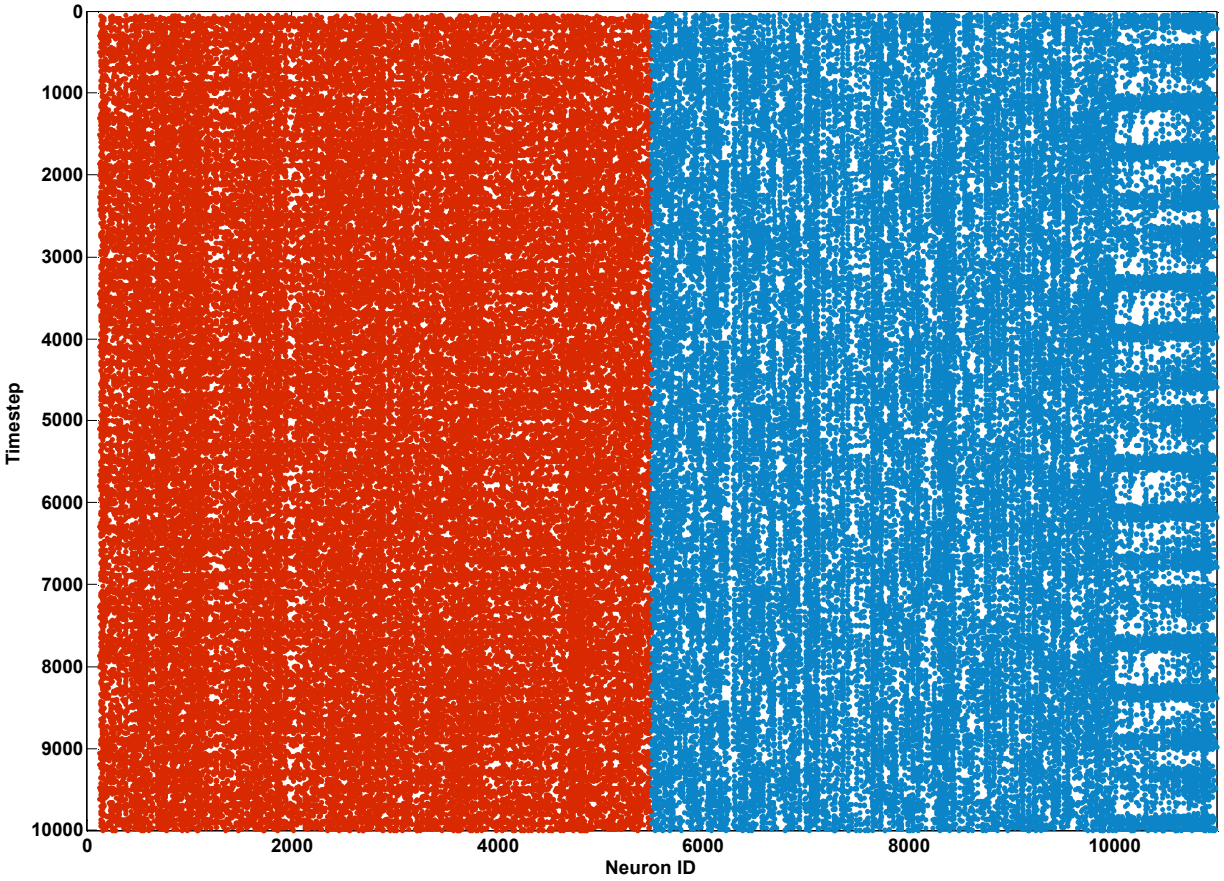
High inhibition in DG limits firing to only most excited GCs.

Mossy fiber output only targets sparse set of downstream CA3 neurons

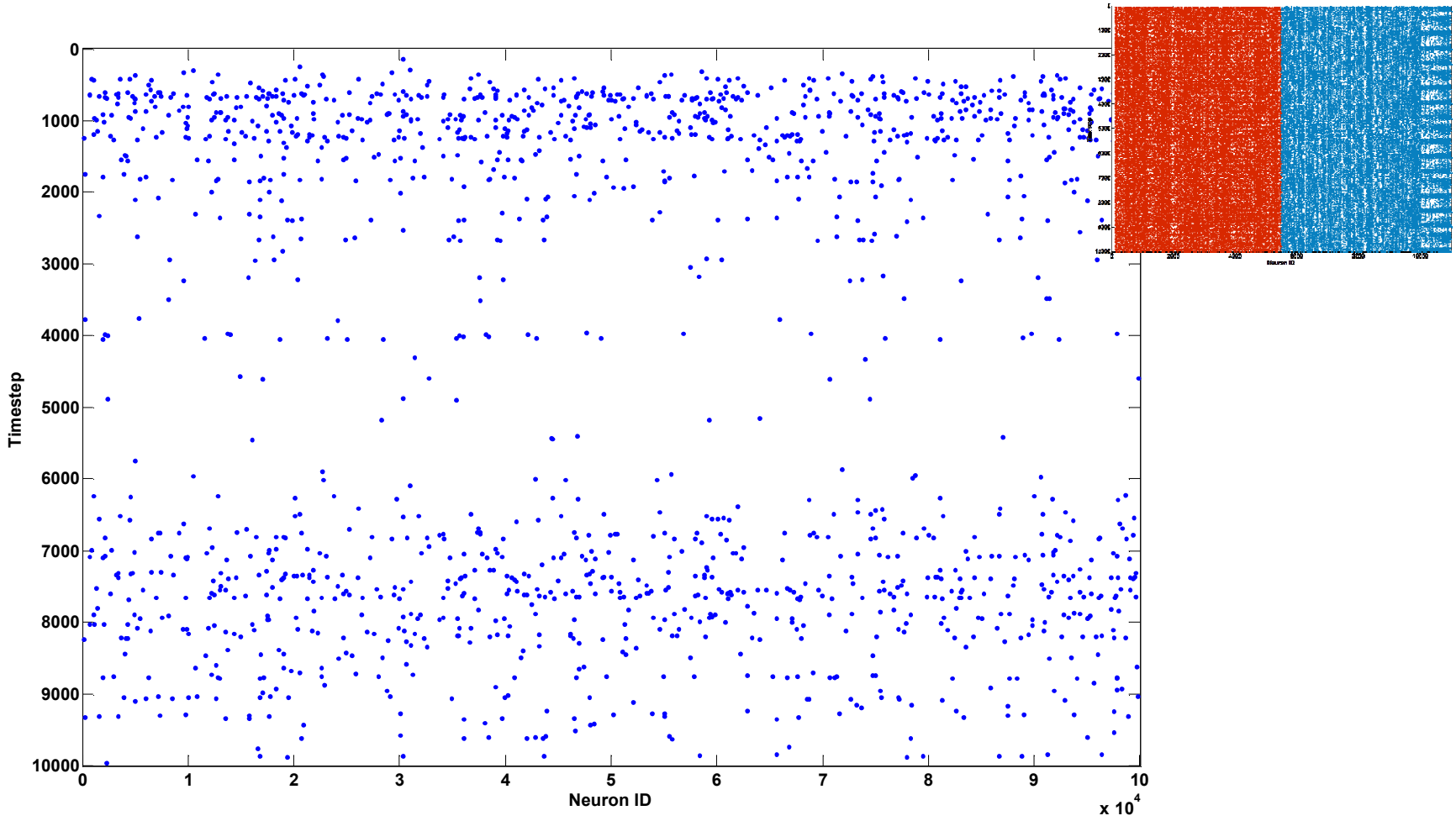


Sparse set of CA3 neurons now selected to encode cortical inputs.

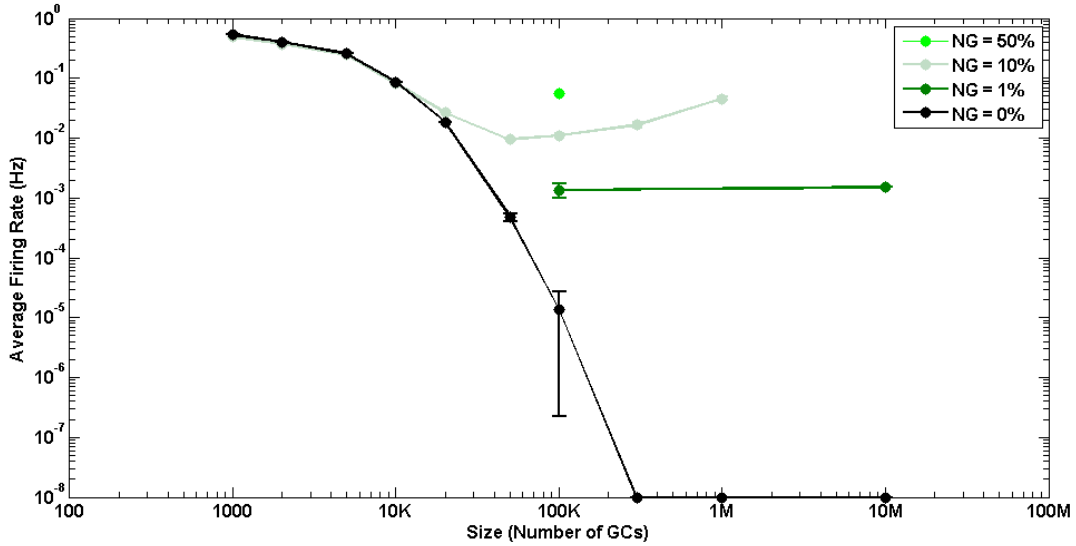
Activity of network – EC Inputs



Activity of network – GC Outputs

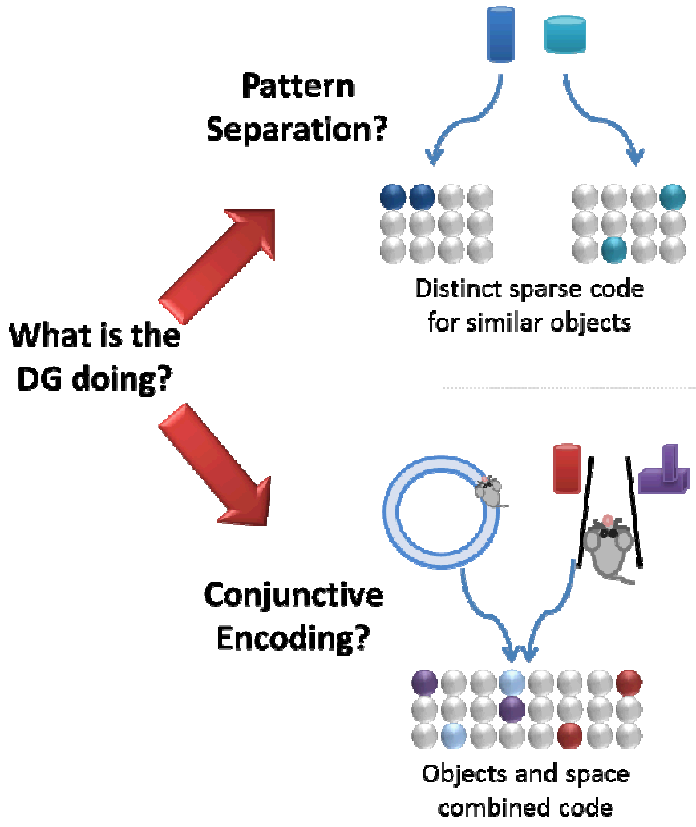


Lack of neurogenesis in large networks correlates with much lower activity



- Neurogenesis networks show activity to novel information at much higher scales
- As we approach human scales, mature neurons appear essentially silent in response to novel information
- Signal (immature) to noise (mature) is amplified in larger networks

Metrics for understanding NG model



- Pairwise correlation / dot product

$$Sim_{t1,t2} = \frac{\|f_{GC,t1} \cdot f_{GC,t2}\|}{\|f_{GC,t1}\|\|f_{GC,t2}\|}$$

- Average covariance

$$\sigma_{t1,t2} = \sum_{GC} (f_{GC,t1} - f_{t1}) \cdot (f_{GC,t2} - f_{t2})$$

How to combine over observations?

- **Linear compressability**

$$\kappa_{GC} = \sum_{i=1..d} (\sigma_i - \lambda_i) \Big/ \sum_{i=1..d} \sigma_i$$

- Average firing rate

$$f_{GC} = 1/N_{GC} \sum_{GC} N_{spikes}/T$$

- Total variance

$$\sigma_{GC} = \sum_{T} \sigma_{GC,T}$$

- Information Content

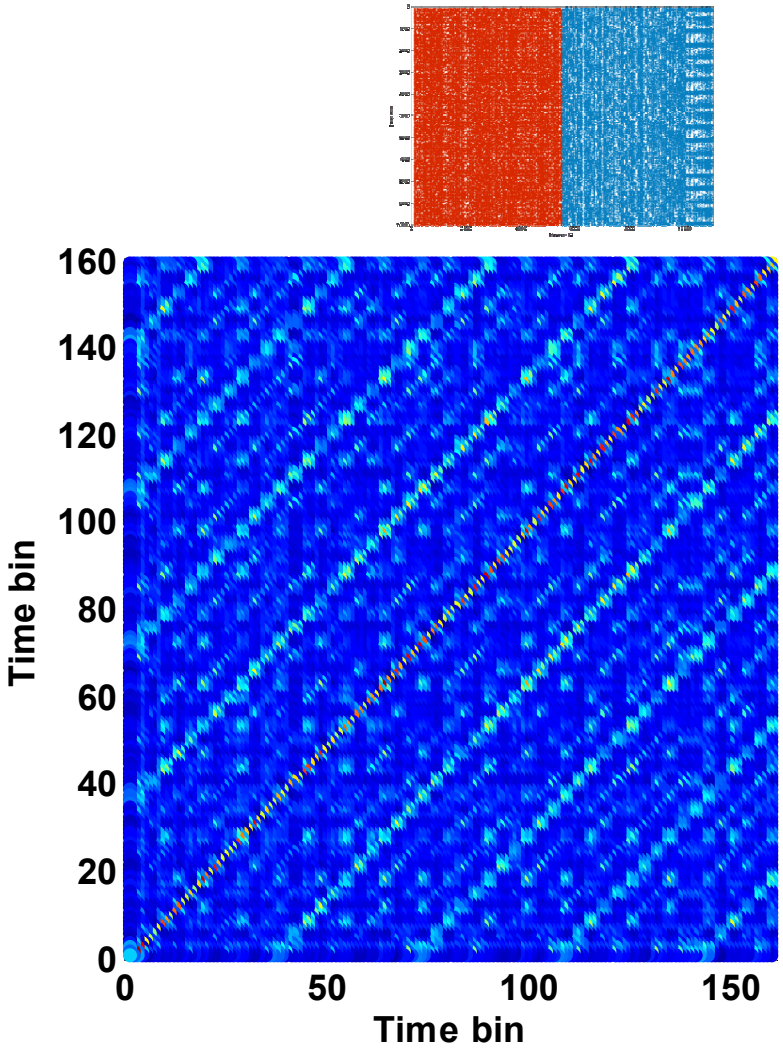
$$I = \sum_{ctx} p_{ctx}{}^{t}/_{t} \log_2 {}^{t}/_{t}$$

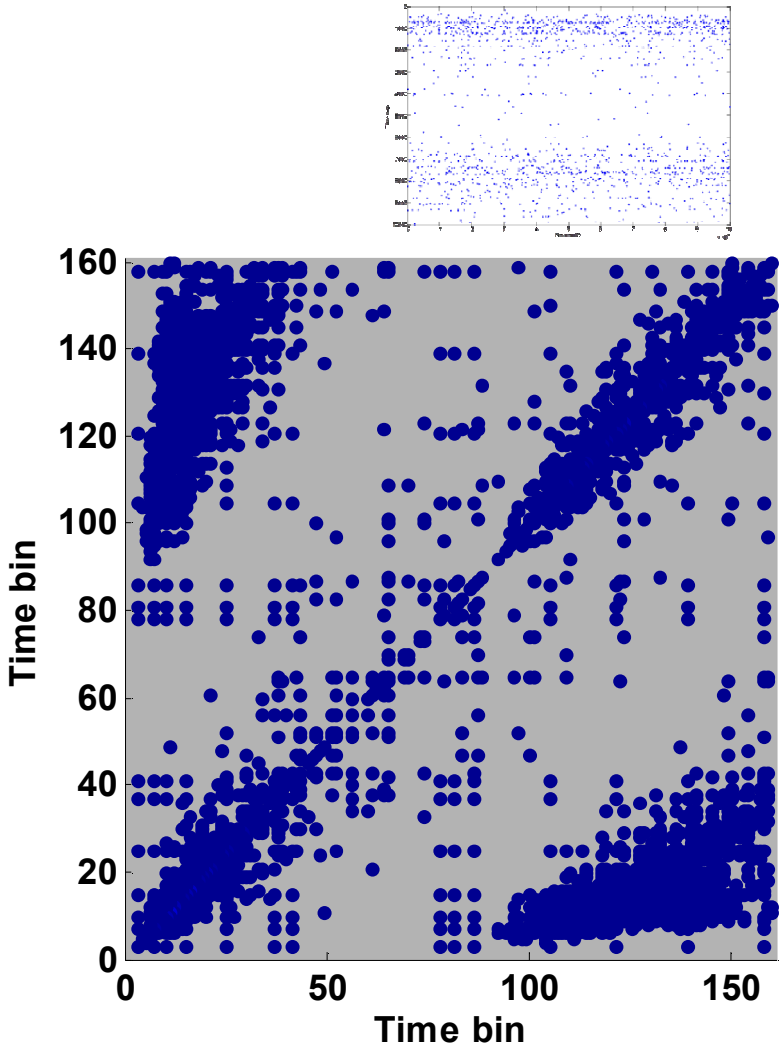
How to combine over neurons?

- **Independent variance**

$$\varphi_{GC} = \sigma_{GC} \times \kappa_{\lambda}$$

Information processing in large networks





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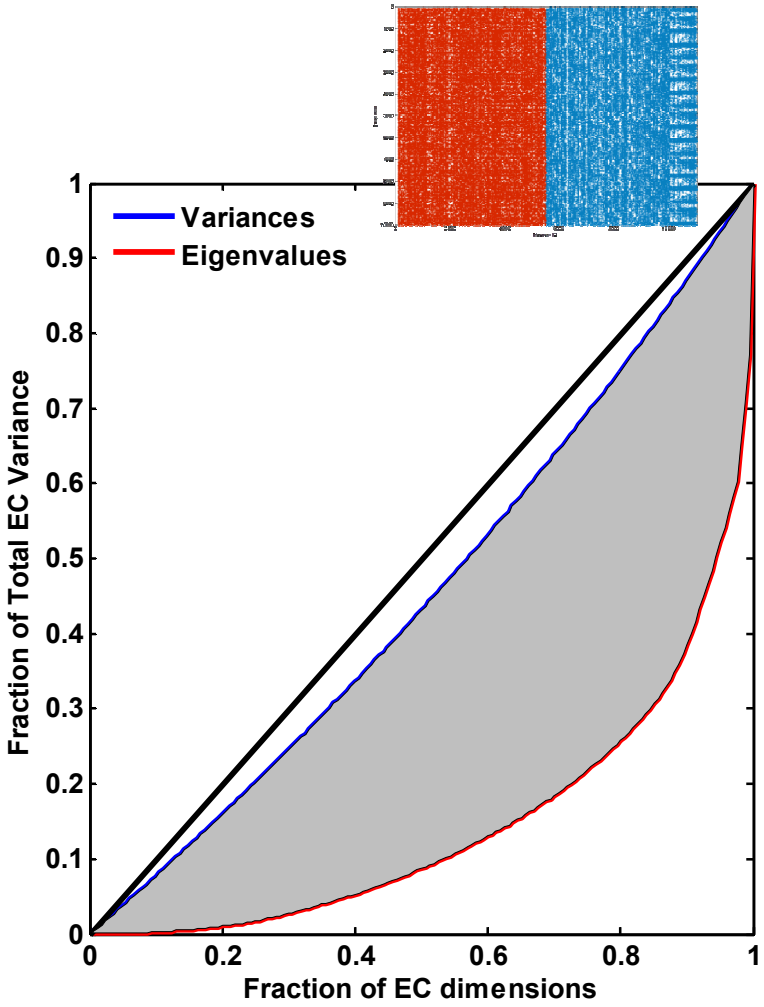
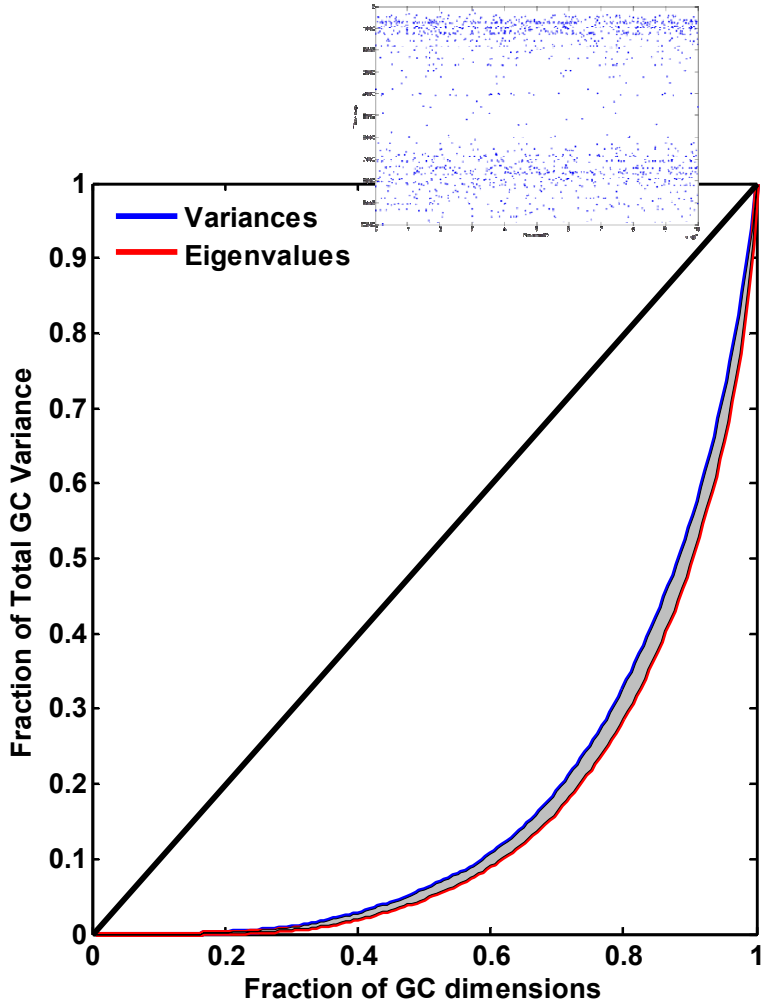
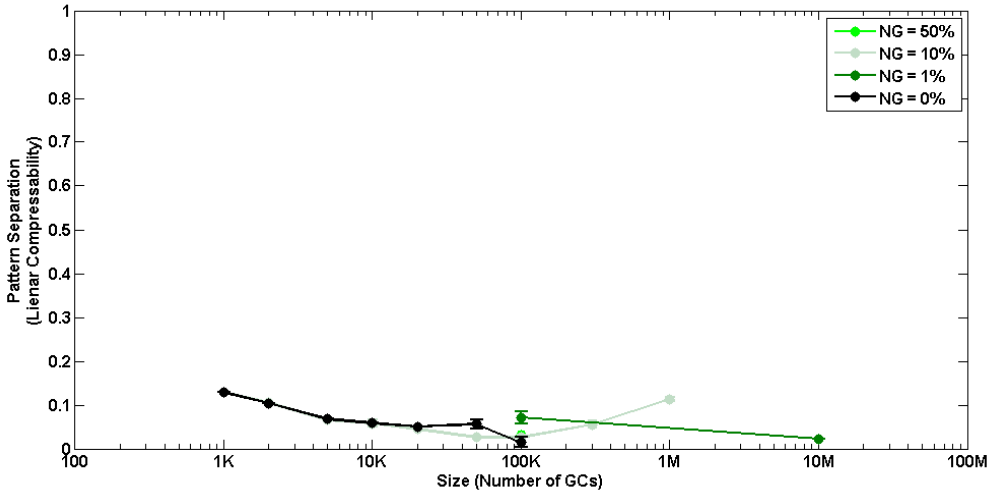
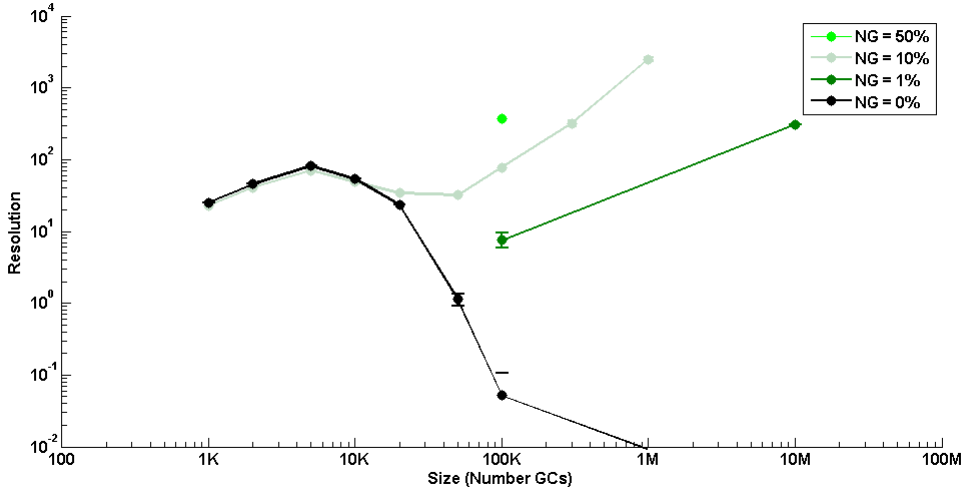


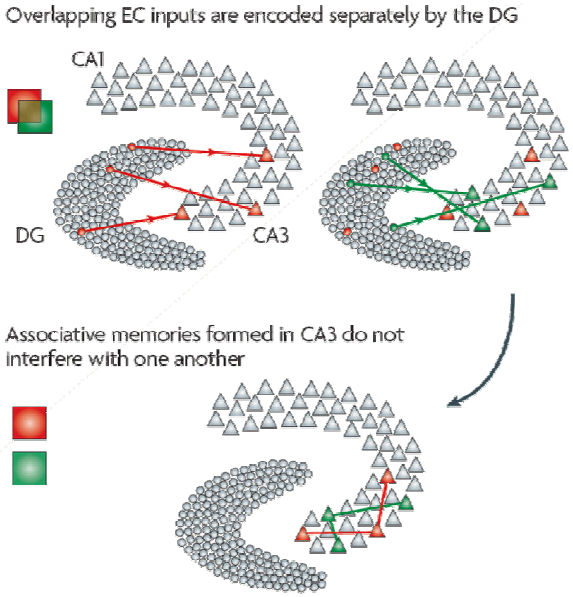


Neurogenesis maintains compressibility and increases total representation



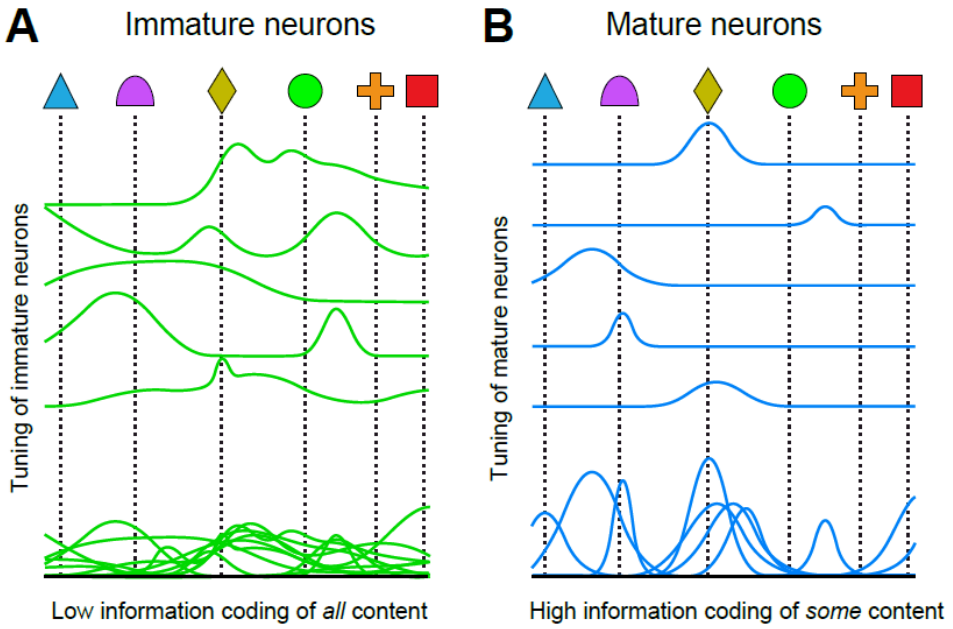


So which is right?

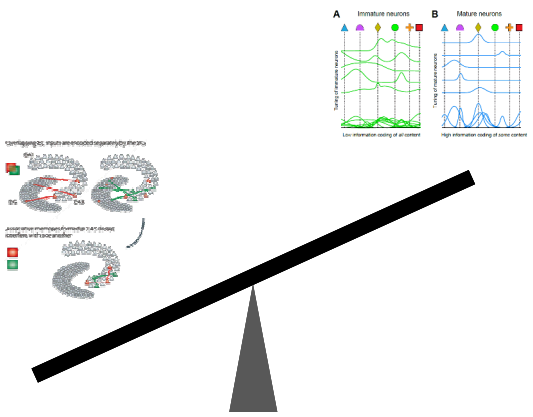


Pattern separation?

Or memory resolution?

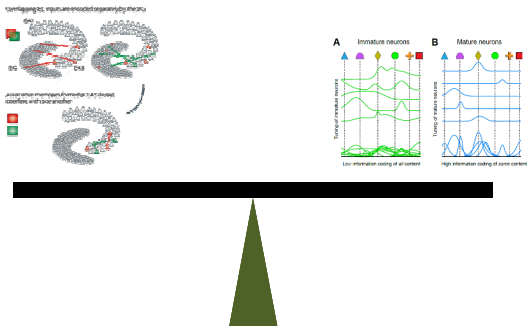


Neurogenesis strikes a balance



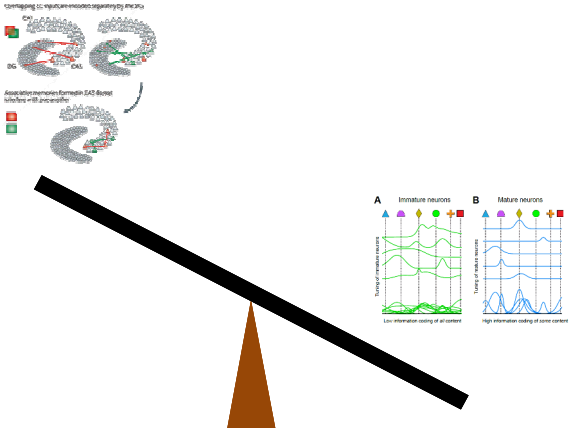
No neurogenesis yields very little activity

DG representations are separate but very sparse



Neurogenesis increases activity while preserving separation

DG representations increase their resolution but avoid interference



Increasing activity directly ruins pattern separation

DG representations are dense and informative but potentially interfere with each other

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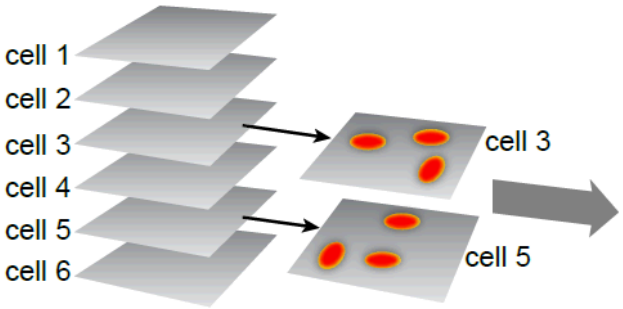

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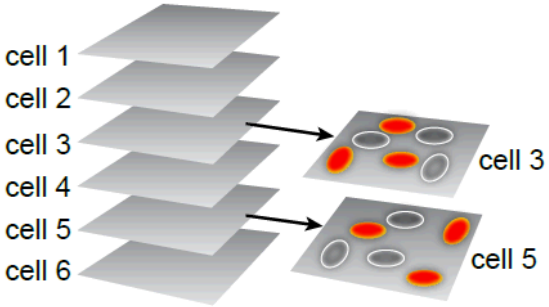

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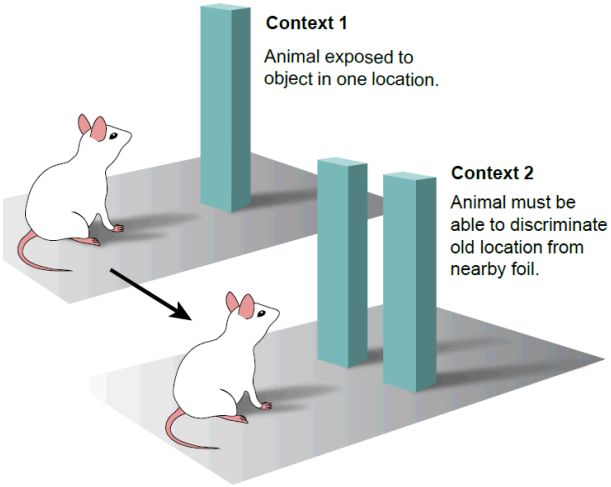

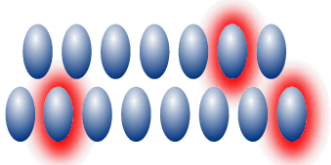

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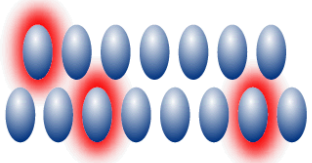

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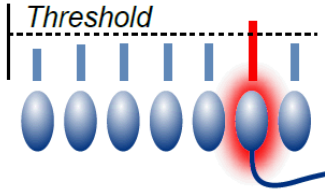

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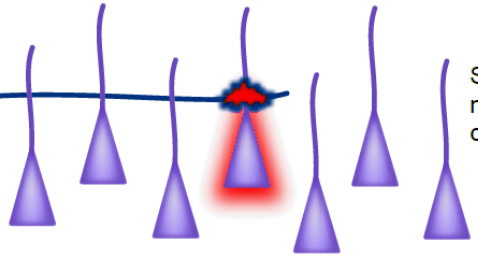
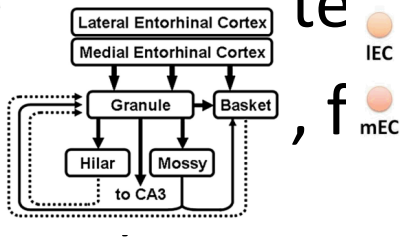
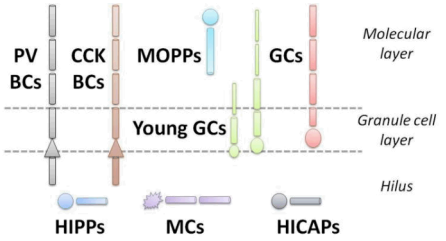


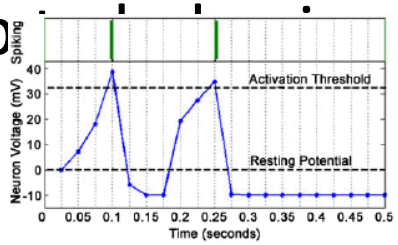
Sparse set of CA3 neurons now selected to encode cortical inputs.

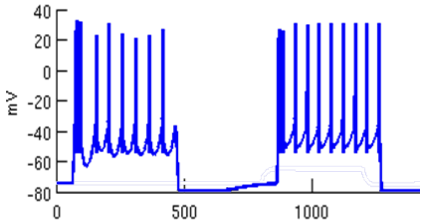
Limitations of past modeling work

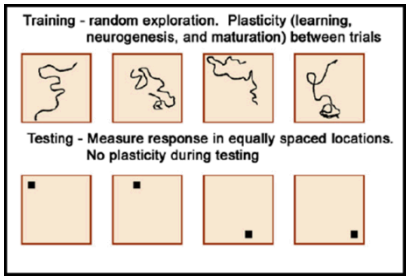
- Between abstract and high fidelity
  - Time not particularly well represented
  - Details of DG architecture, f
    inhibition, modulatory in
  - Experiment doesn't map

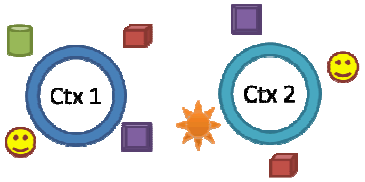






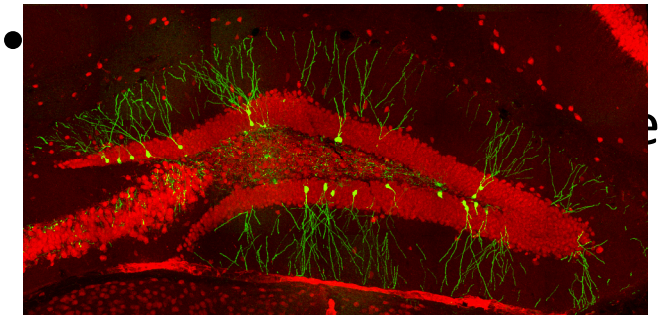






Aimone et al., Neuron 2009

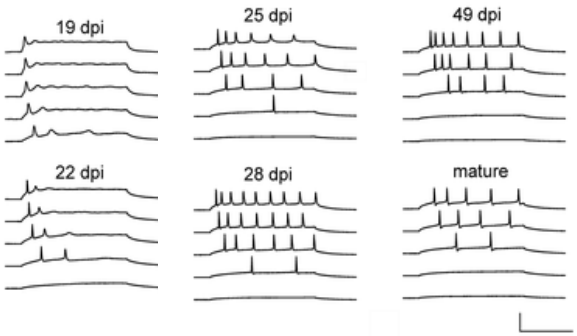
Modeling considerations

- 

  eurons, interneurons, and how they are

  neurons

courtesy Chunmei Zhao

- 

  unique dynamics

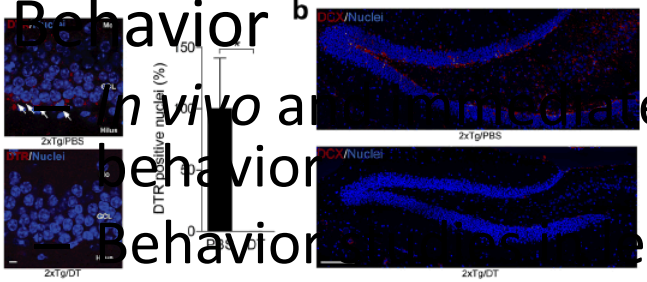
  lts in many different forms of GC

Mongiat et al., 2009

- Behavior

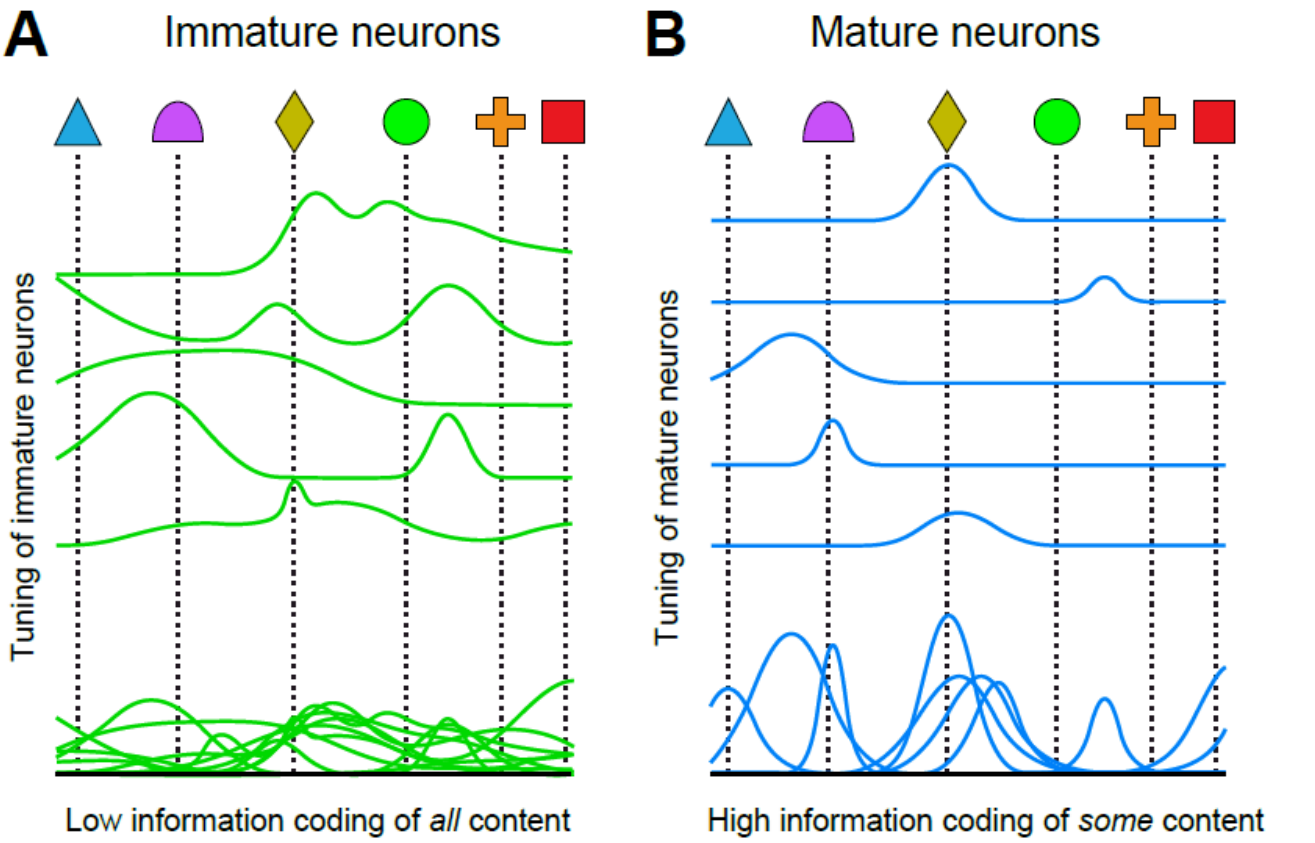
  In vivo ar e early gene studies of neuron behavior

  Behavior esion or knockdown animals



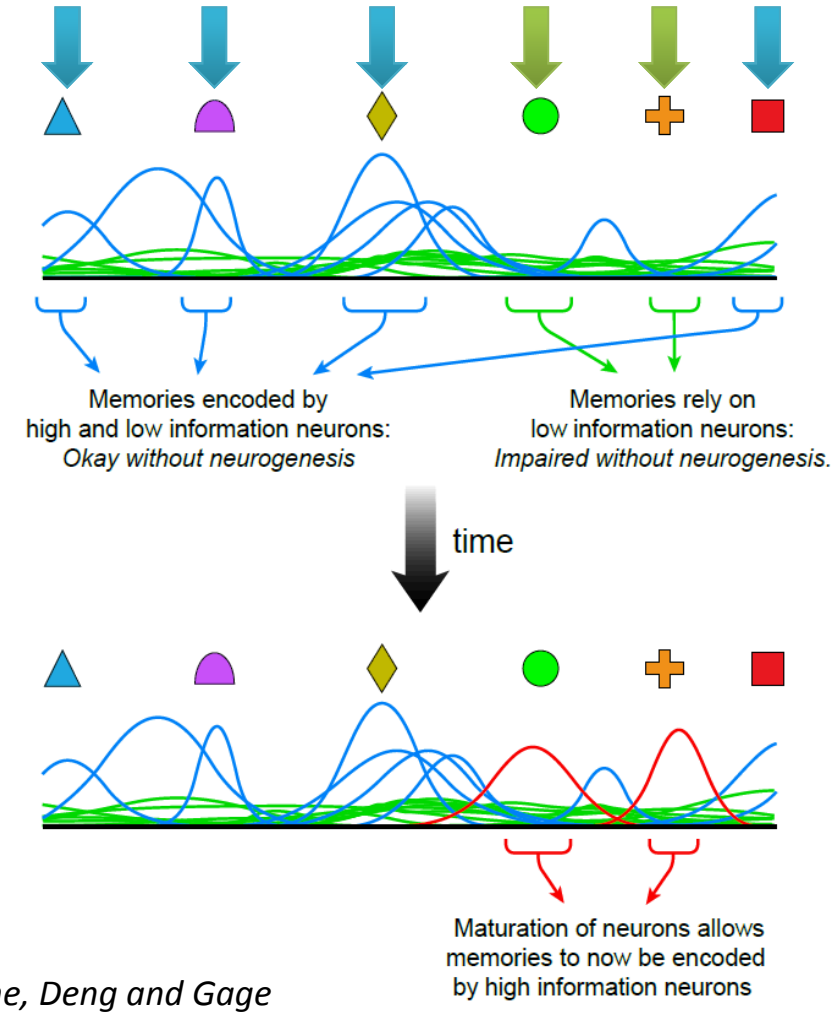
Arruda-Carvalho et al., 2011

Immature and mature neurons encode information differently



Aimone, Deng and Gage
Neuron; 2011

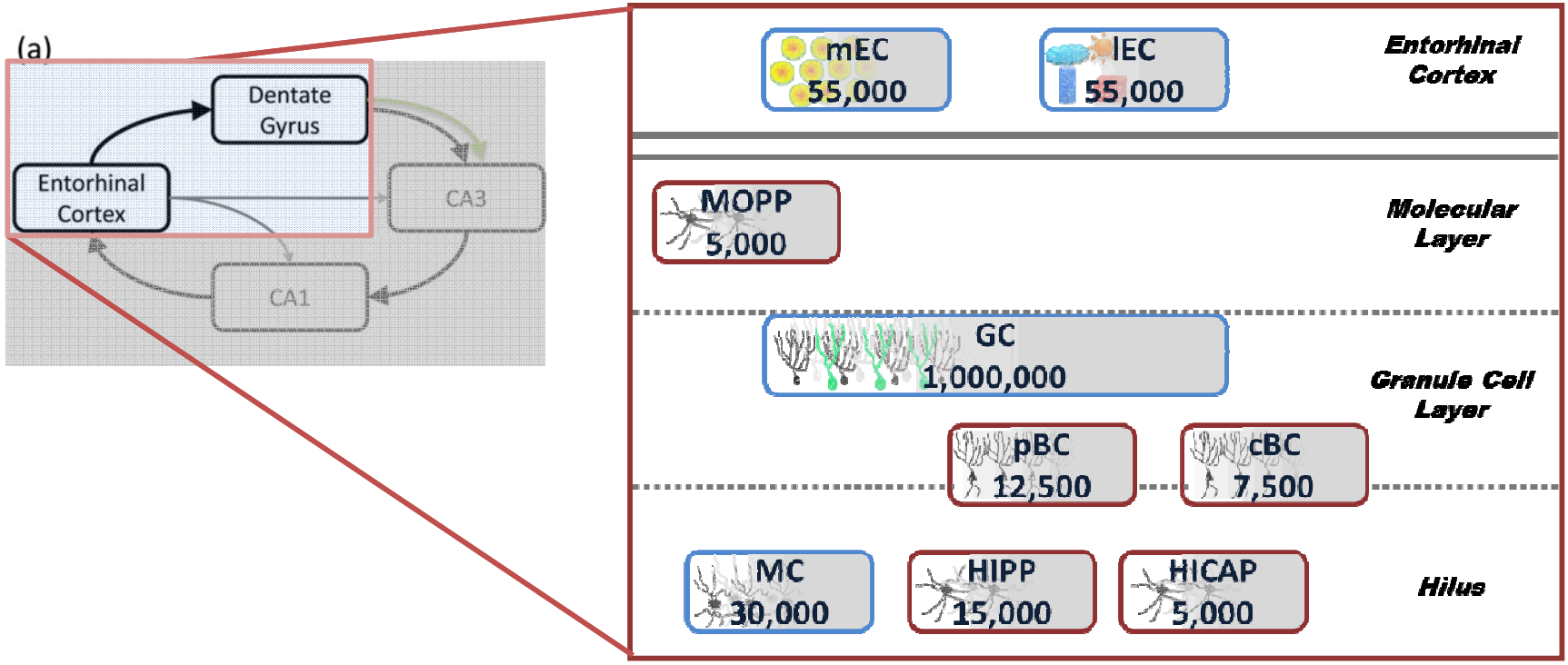
Mixed coding scheme in DG is potentially very powerful



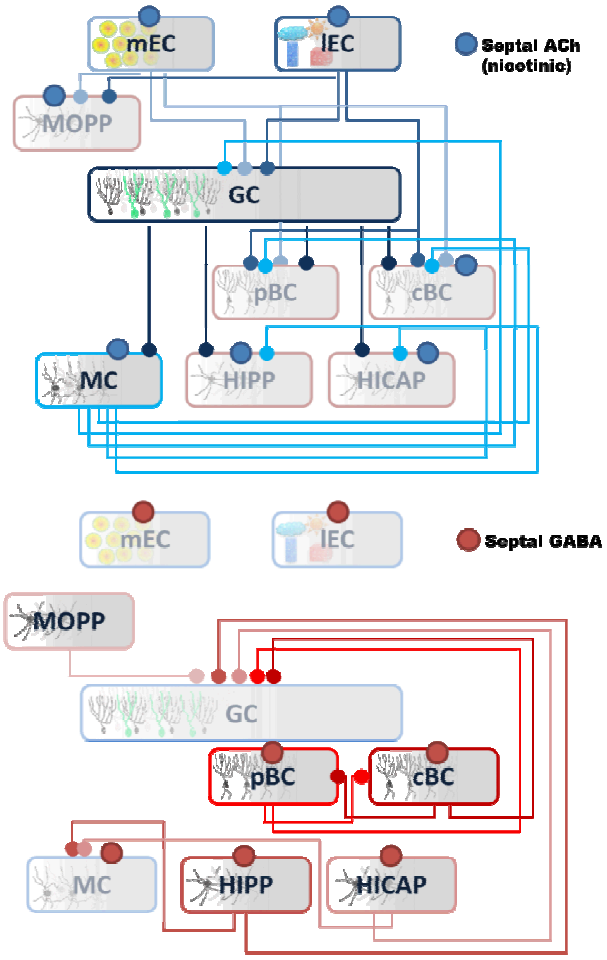
Aimone, Deng and Gage
Neuron; 2011

- Dentate Gyrus performs sparse coding for episodic memories
- Mature neurons are tightly tuned to specific features
  - *Not all events will activate mature neurons*
- Immature neurons are broadly tuned
  - *All events will activate some immature neurons*
- Neurons mature to be specialized to those events later
  - *Coding range of network gets more sophisticated over time*

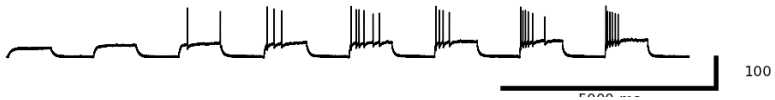
Realistic scale model



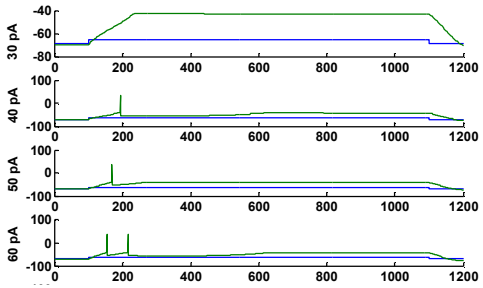
Realistic connectivity and dynamics

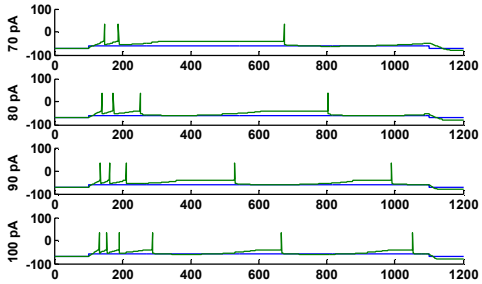


Physiology data

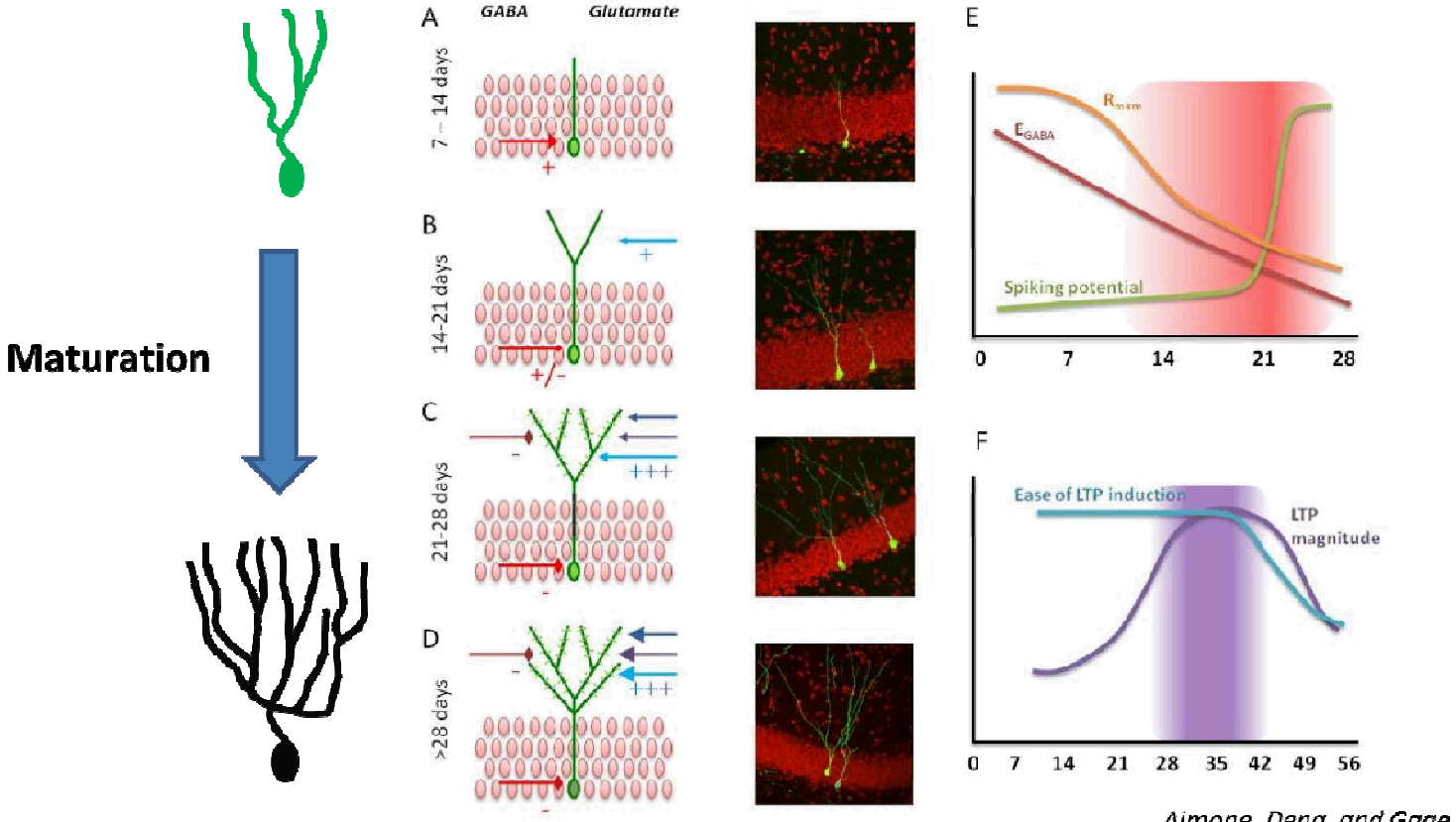


Modeled neuronal dynamics





Neurogenesis Process



Aimone, Deng, and Gage
Trends in Cog. Sci. 2010