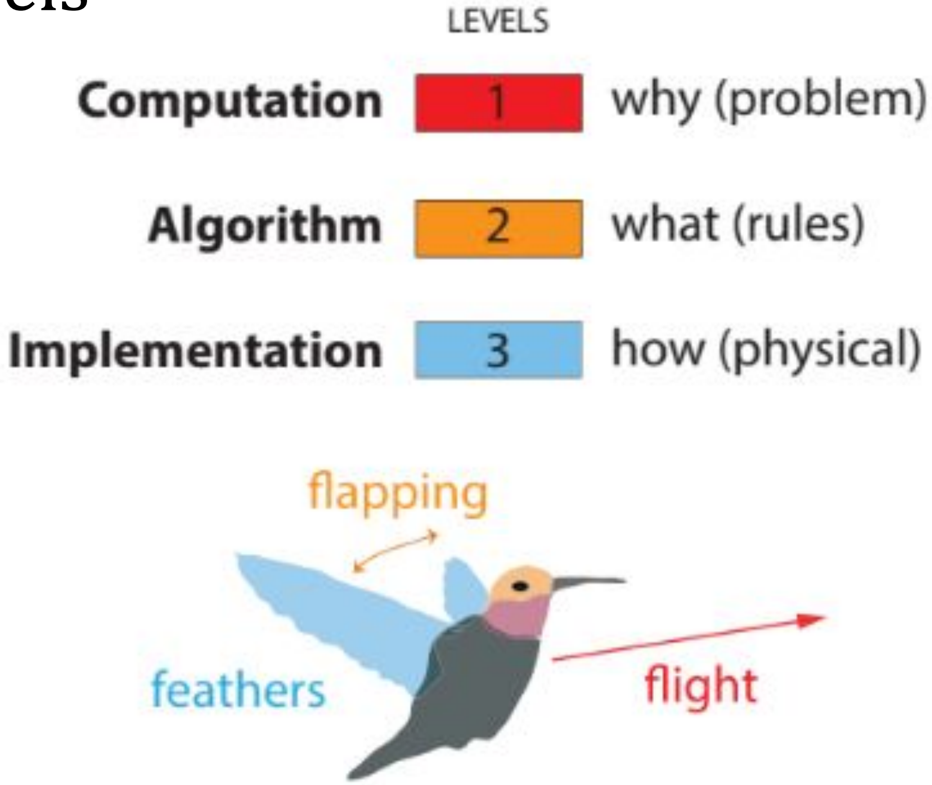
Computation and the Fly Brain

COMS 6998 Guest Lecture
10.3.2018

J. Portes jpp2139@

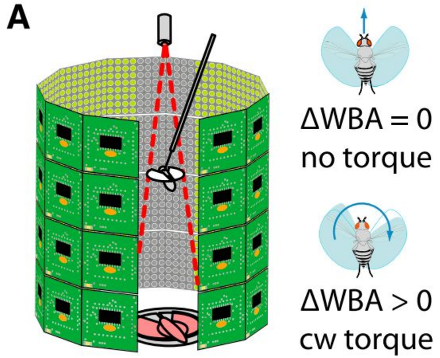
Marr’s 3 Levels



Krakauer, John W., et al. "Neuroscience needs behavior: correcting a reductionist bias." *Neuron* 93.3 (2017): 480-490.

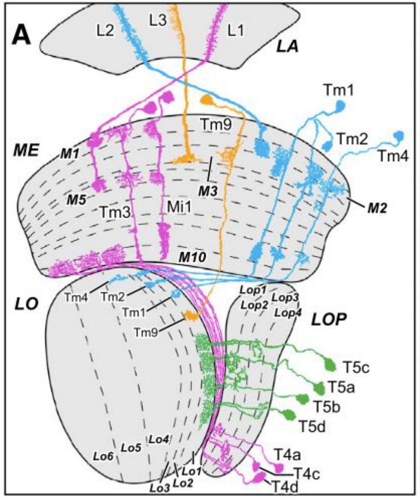
Why the Fly?

Behavioral Data



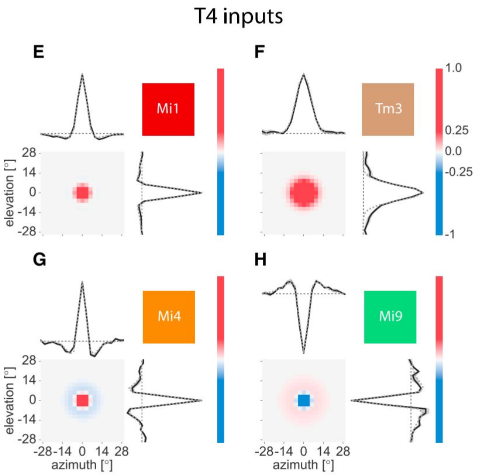
Tuthill et al. 2013

Anatomical Data



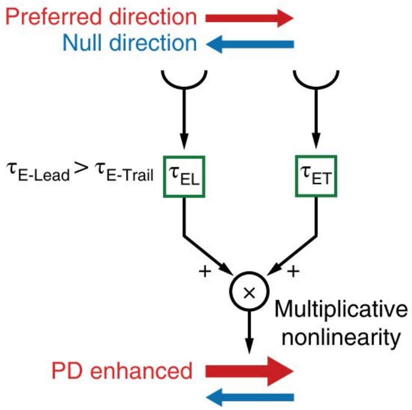
Shinomiya et al. 2014

Physiological Data

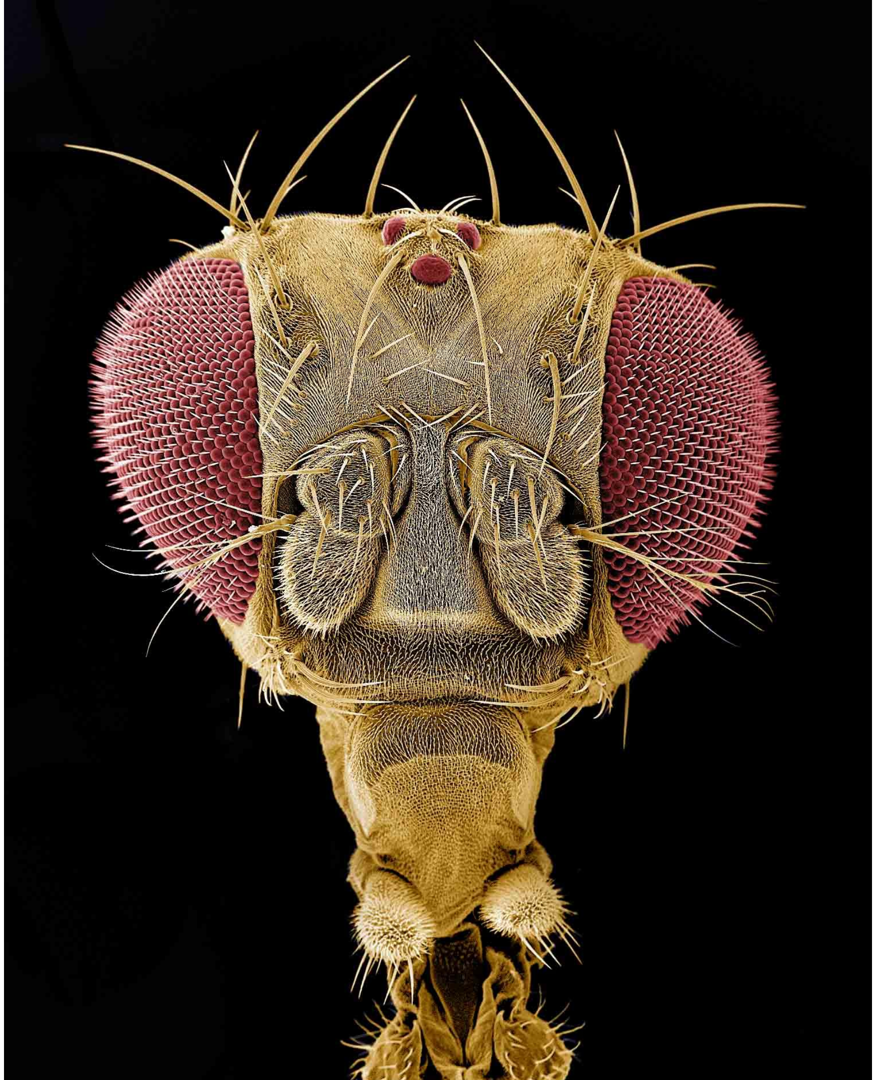


Arenz et al. 2017

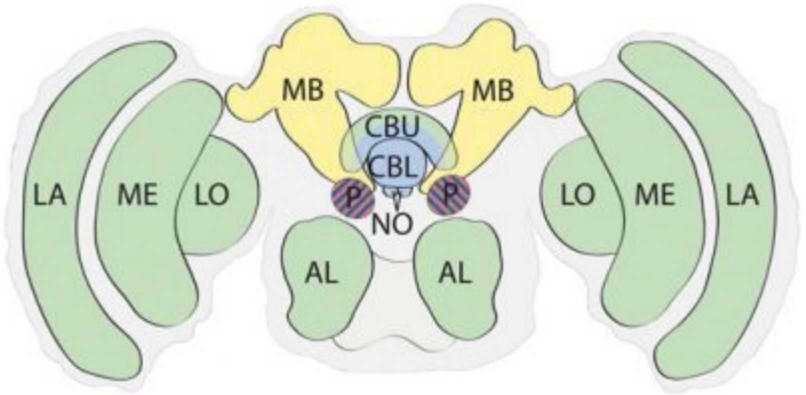
Conceptual Frameworks

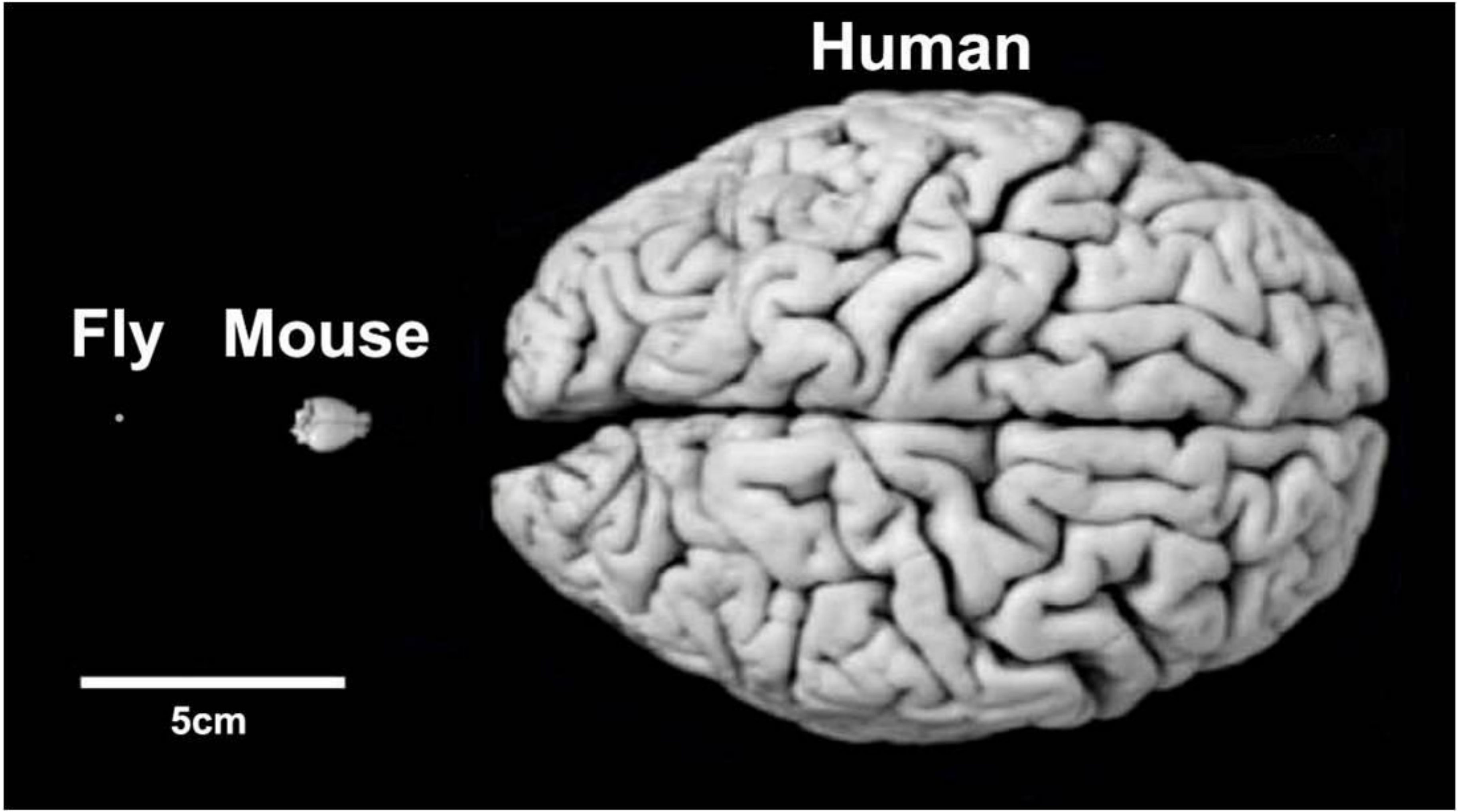


Gruntman et al. 2018



~100,000 Neurons




Human
Fly
Mouse
5cm

Fly Behavior - Aggression

https://www.youtube.com/watch?time_continue=1&v=gEh_y5GvH6A

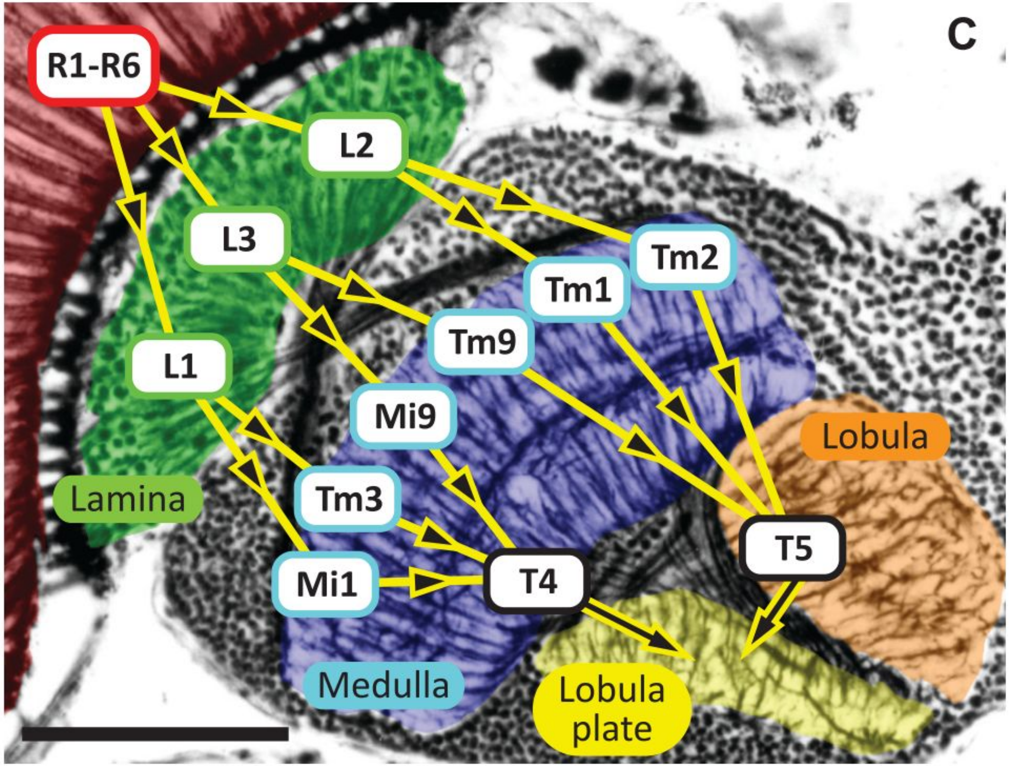
Fly Behavior - Escape Behavior

https://www.youtube.com/watch?v=J-HmfRIe5xM

Fly Behavior - Courtship

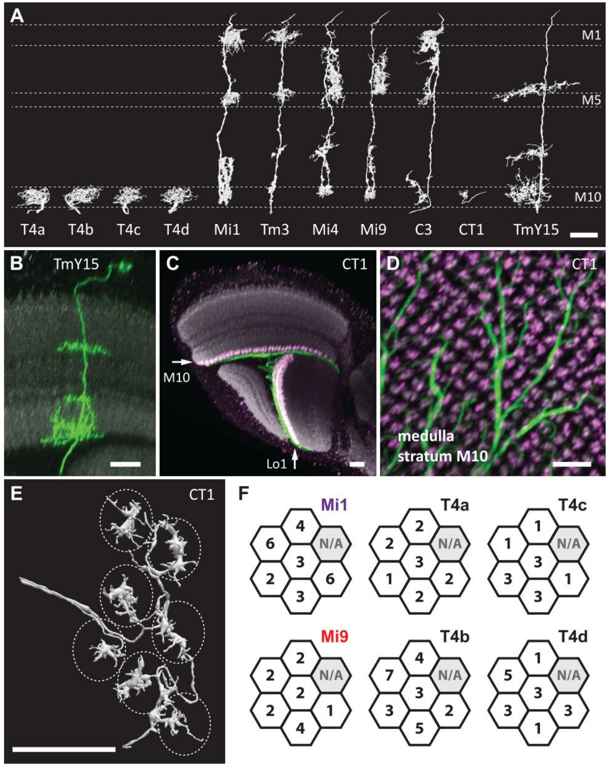
https://www.youtube.com/watch?time_continue=1&v=B-iK2D1mC10

Fly Connectomics - The Visual System



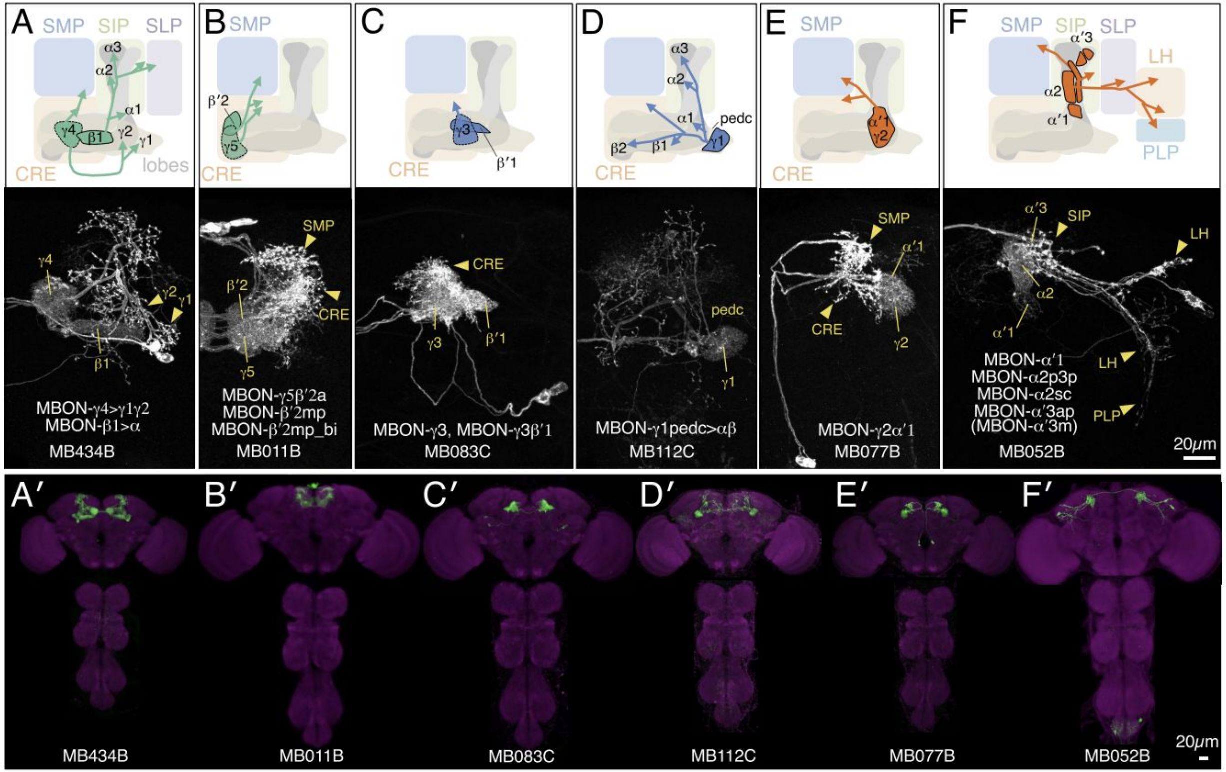
Takemura et al. eLife 2017

Fly Connectomics - The Visual System



Takemura et al. eLife 2017

Fly Connectomics - The Mushroom Body



Aso, Yoshinori, et al. "The neuronal architecture of the mushroom body provides a logic for associative learning." *Elife* 3 (2014): e04577.

Marr’s 3 Levels

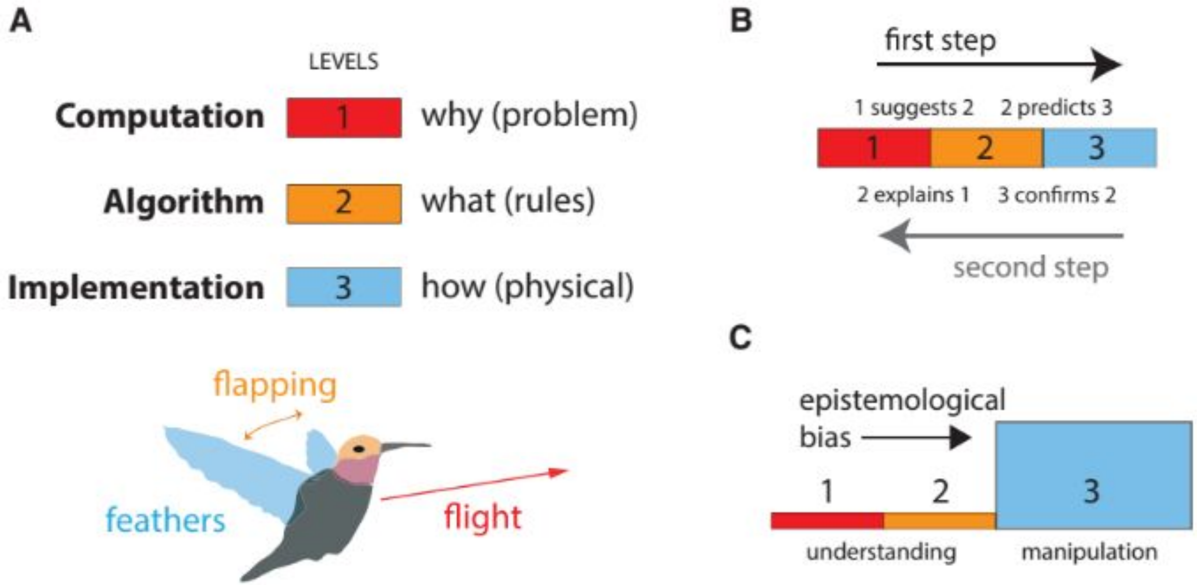


Figure 2. Marr’s Three Levels of Analysis
(A) A bird attempts to fly (goal) by flapping its wings (algorithmic realization) whose aerodynamics depend on the features of its feathers (physical implementation). Feathers “have something to do” with flight and flapping, but what level of understanding do we achieve if we dissect the properties of the feathers alone? Bats fly but don’t have feathers, and birds can fly without flapping.
(B) The relationship between the three levels is not arbitrary; step 1 comes before step 2: the algorithmic level of understanding is essential to interpret its mechanistic implementation. Step 2: implementation level work feeds back to inform the algorithmic level.
(C) An epistemological bias toward manipulation-based view of understanding induced by technology (black filled arrow).

Krakauer, John W., et al. "Neuroscience needs behavior: correcting a reductionist bias." *Neuron* 93.3 (2017): 480-490.

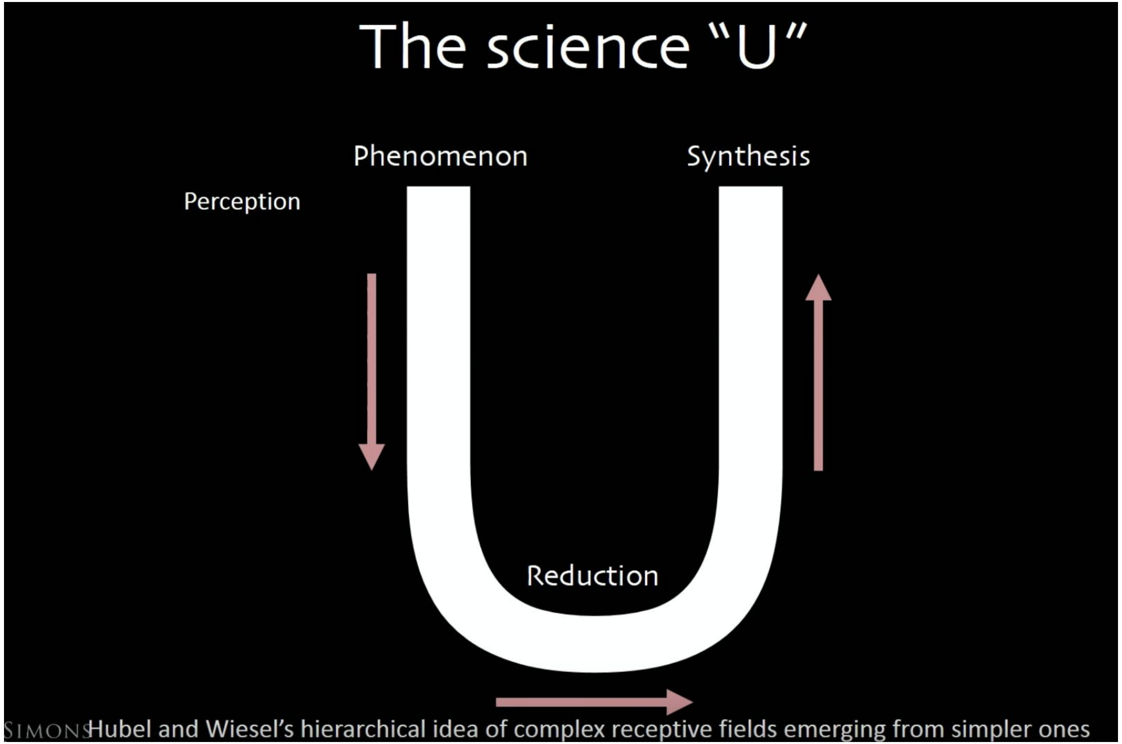
Outline - Canonical Computations in the Fly

1. Memory/Learning (MUSHROOM BODY)
   a. Classical Conditioning
2. Navigation (CENTRAL COMPLEX)
   a. Path Integration?
3. Vision (OPTIC LOBE)
   a. Motion Detection
   b. Optical Flow
   c. Object Detection?

Goals for Lecture

- Convey basic algorithms
- Connect to HW4 → Lichtman Connectome Lectures (https://www.youtube.com/watch?v=R2US2yVO4us&t=1s)
- Possibly inspire ideas for class projects

Lichtman Lecture



https://www.youtube.com/watch?v=R2US2yVO4us&t=1s

Fundamental Axioms of Neurobiology (Cajal's lasting influence)

- Neuron doctrine (n. is basic unit)
- Stereotyped cell types
- Law of dynamic polarization
- Canonical circuits

https://www.youtube.com/watch?v=R2US2yVO4us&t=1s

The Aspiration of Connectomics is to explore these fundamental axioms

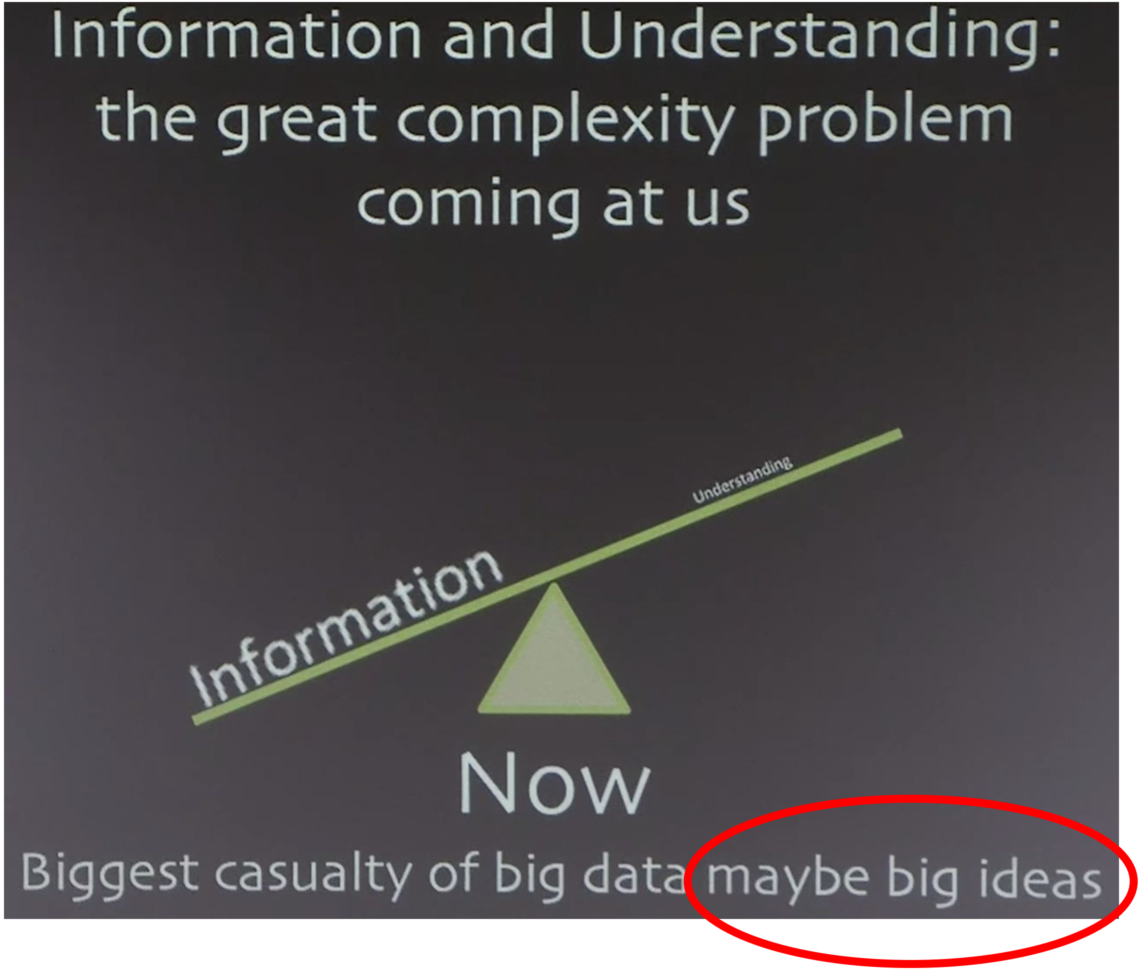
- Goal to discover *all* the cell types (at least as manifested in variations in shape and connectivity)
- Goal to acquire complete canonical circuits at the level of synaspes (as opposed to the hyper-sparse cartoons neuroscientists draw) to get physical instantiations of behaviors
- But might another goal be to *look* at the ultrastructural data per se to seek new biological regularities (rather than just use it to make a wiring diagram)?

In principle, c. is a <u>bottom-up</u> approach; it shows what is there physically in the brain independent of what theories exist.

SIMONS INSTITUTE
for the Theory of Computing

Swanson and Lichtman, Ann Rev Neurosci , 2016
Morgan and Lichtman, Nat Meth, 2015

https://www.youtube.com/watch?v=R2US2yVO4us&t=1s



Totally disagree

https://www.youtube.com/watch?v=R2US2yVO4us&t=1s

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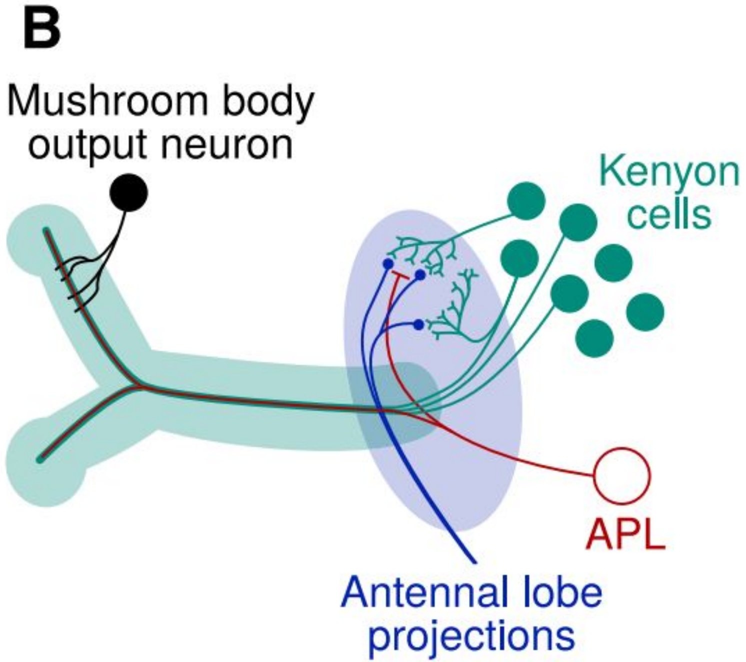
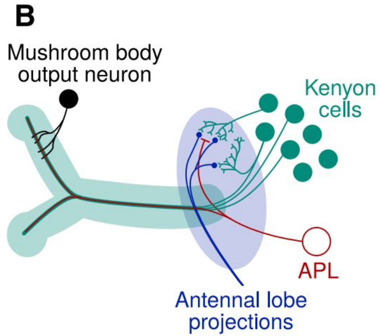
What does the Mushroom Body Do?

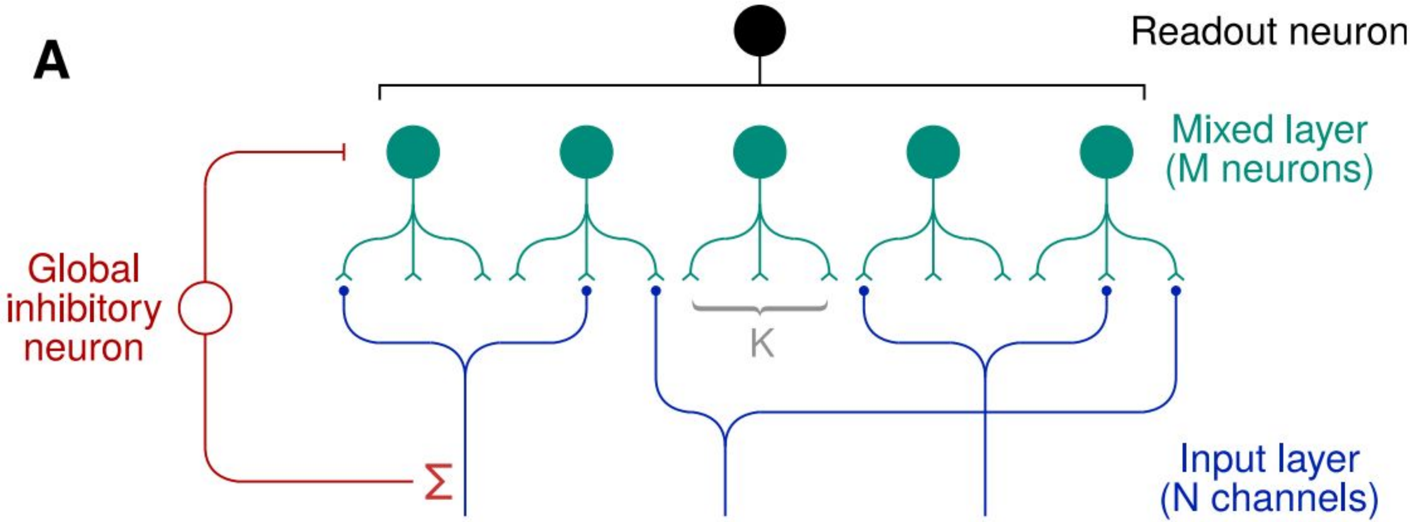


Litwin-Kumar, Ashok, et al. "Optimal degrees of synaptic connectivity." *Neuron* 93.5 (2017): 1153-1164.

Classical Conditioning

Mushroom Body as a site of plasticity and learning





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Path integration – a network model

Thomas Wittmann, Helmut Schwegler

Zentrum für Kognitionswissenschaften, Institut für Theoretische Physik, Universität Bremen, D-28334 Bremen, Germany

Received: 25 April 1995 / Accepted in revised form: 30 May 1995

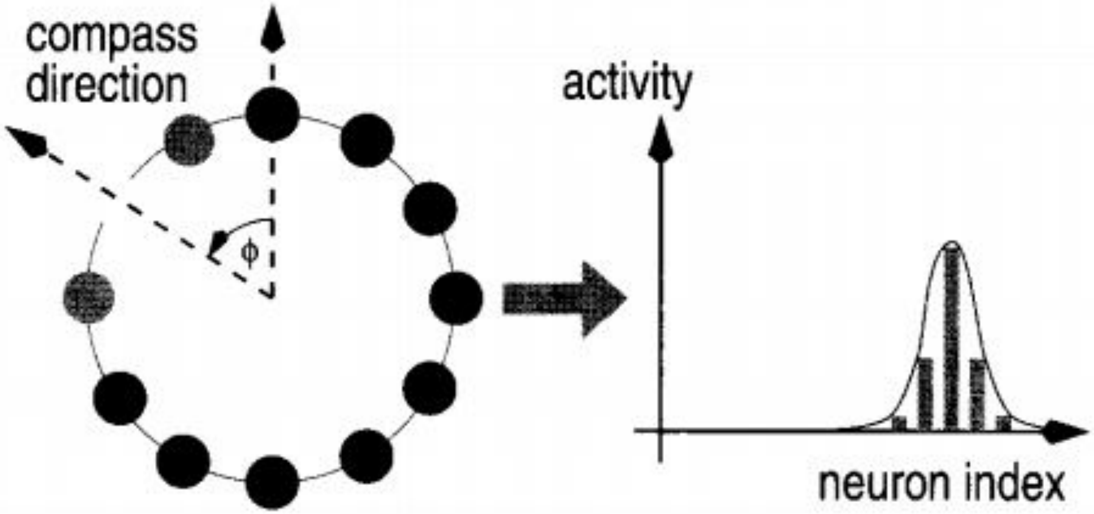


Fig. 3. Representation of compass direction as an activity pattern on a circular group of neurons

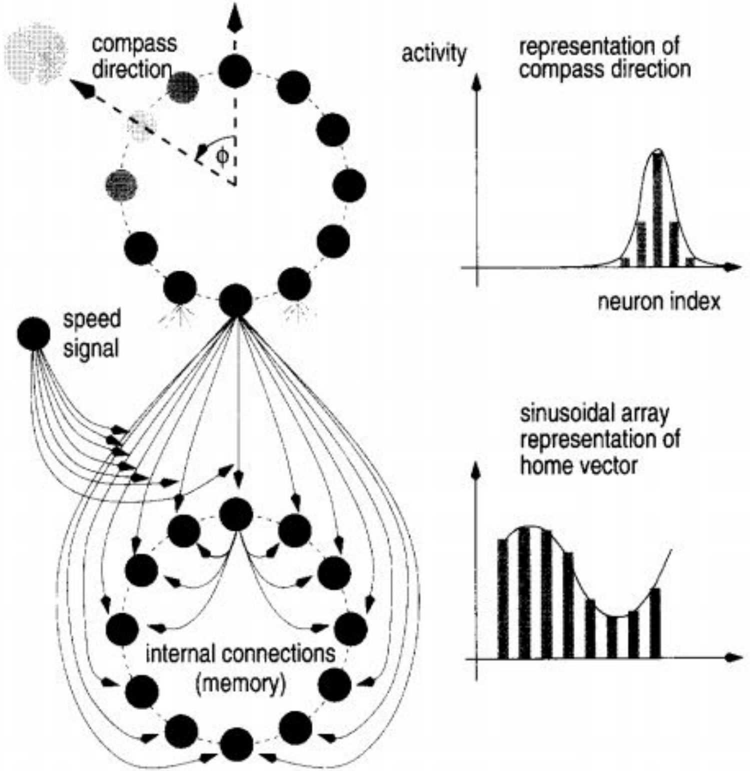


Fig. 4. Summary of the model. The compass direction is encoded as an activity pattern on a dedicated neuron group; this pattern is transformed into a sinusoidal array encoding by connections (8) and added to the vector computed so far. For consideration of speed the connections between both neuron groups have to be modulated by a speed signal

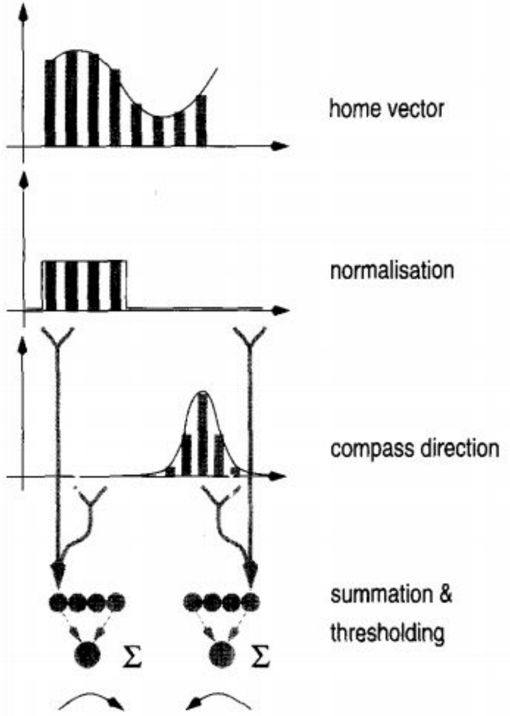
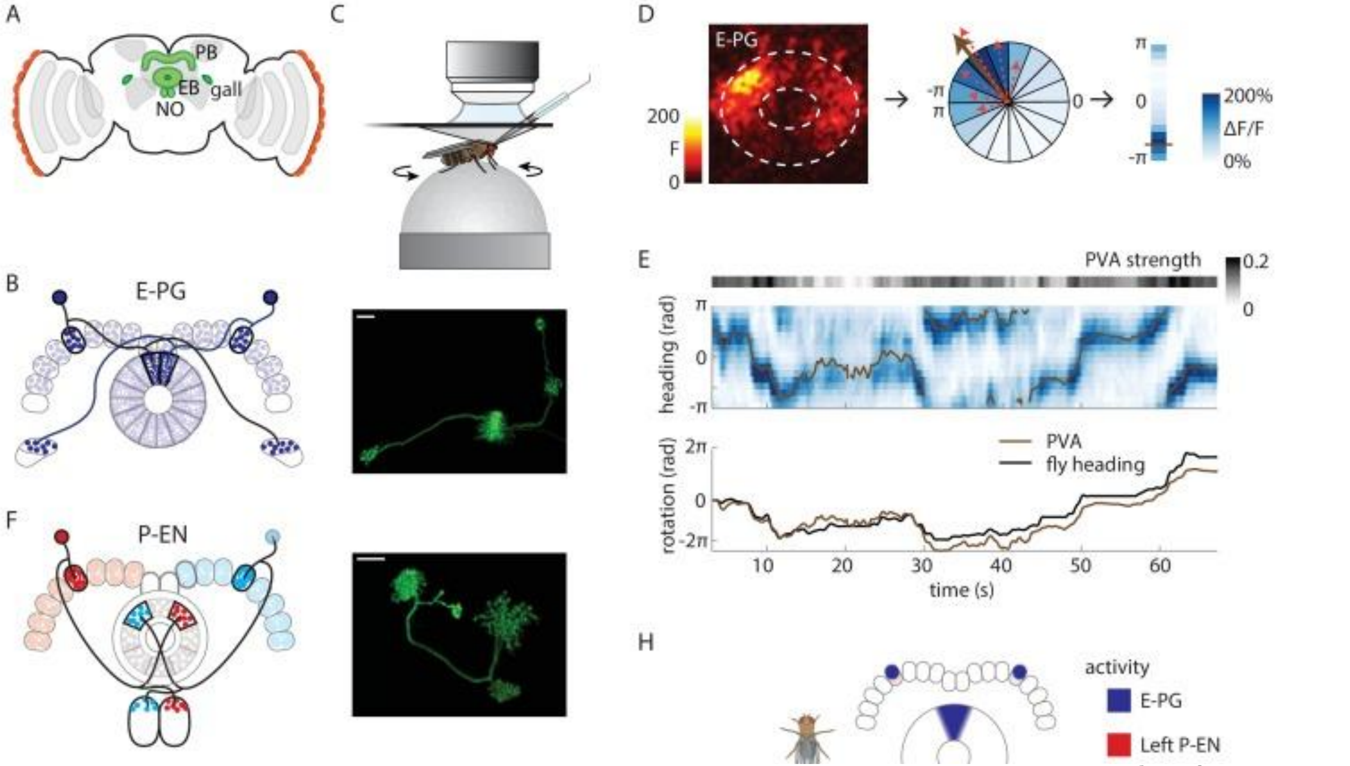


Fig. 5. Read-out mechanism. A turn signal that turns the animal into the homewards direction can be derived by comparison of the sinusoidal array representation of the home vector and the encoding of the compass direction; if the maxima of both patterns are at corresponding positions the animal is oriented homeward. A turn signal is generated by neurons that are sensitive to a certain displacement of the maximum on one neuron group with respect to the other

Fly Ring Attractor!

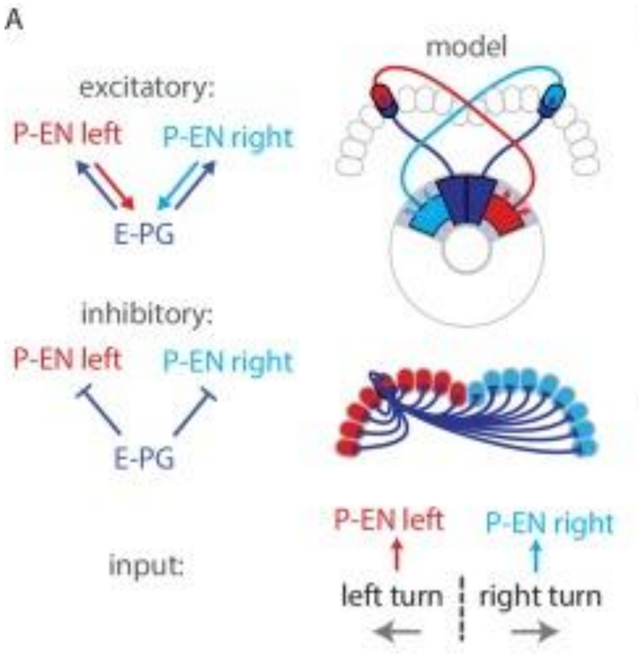
(although not quite path integration)



Turner-Evans et al. eLife 2017, SS Kim et al. Science 2017

The Model (in words)

- Our model consists of **three populations** of neurons corresponding to the E-PG neurons, the P-EN neurons for the left side and the P-EN neurons for the right side.
- We assume that the **E-PG neurons make excitatory synapses onto the P-EN** neurons and that the **P-EN neurons**, in turn, **make excitatory synapses onto the E-PG** neurons.
- Finally, we assume **global inhibition,** a necessary requirement for obtaining localized bumps of activity.



Turner-Evans et al. eLife 2017

The Model (in math)

E($\boldsymbol{\theta}$,t): firing rate for E-PG neurons
P($\boldsymbol{\theta}$,t): firing rate for P-EN neurons (l = left, r = right)

K: kernel describing connectivity in ellipsoid body (circular!)

$$eq:model \tau \frac{dE(\theta_i,t)}{dt} = -E(\theta_i,t) + \left[\alpha \sum_{N(i)} P_l(\theta_{N(i)},t) K_l(\theta_i - \theta_{N(i)})\right]_+$$

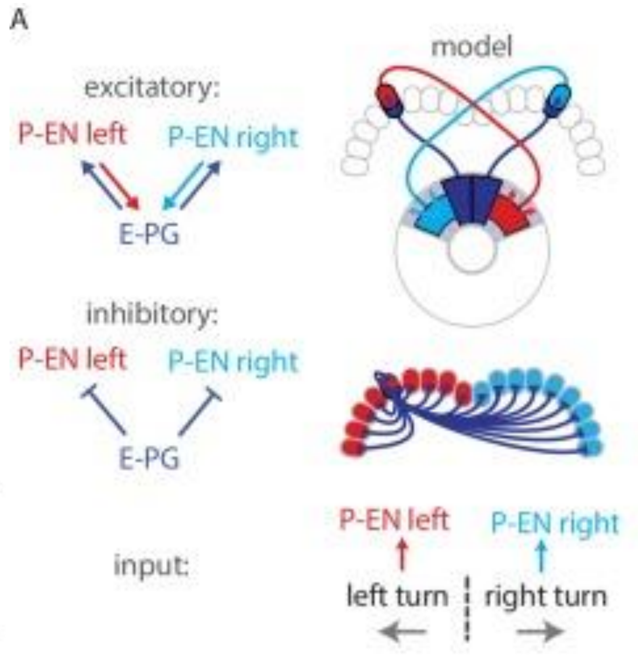
$$\tau \frac{dE(\theta_j,t)}{dt} = -E(\theta_j,t) + \left[\alpha \sum_{N(j)} P_r(\theta_{N(j)},t) K_r(\theta_j - \theta_{N(j)})\right]_+$$

$$\tau_p \frac{dP_l(\theta_k,t)}{dt} = -P_l(\theta_k,t) + \left[\frac{\alpha}{3} \sum_{m \in \mathcal{N}_k^l} E(\theta_m,t) - \frac{\beta}{N} \sum_n E(\theta_n,t) + 1 + v_+\right]_+$$

$$\tau_p \frac{dP_r(\theta_k,t)}{dt} = -P_r(\theta_k,t) + \left[\frac{\alpha}{3} \sum_{m \in \mathcal{N}_k^r} E(\theta_m,t) - \frac{\beta}{N} \sum_n E(\theta_n,t) + 1 + v_-\right]_+$$

Local excitation

Global inhibition



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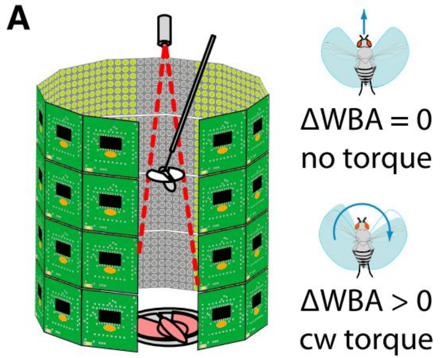
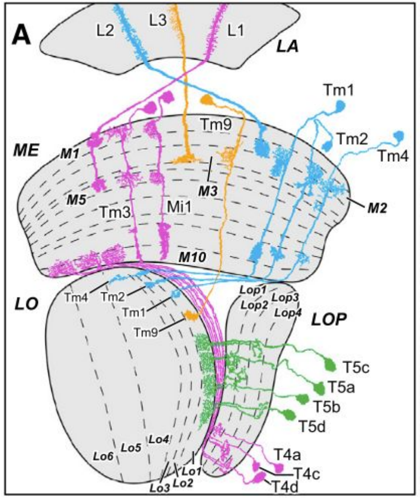
Fly Motion Detection: a well constrained, well defined problem...

Behavioral Data



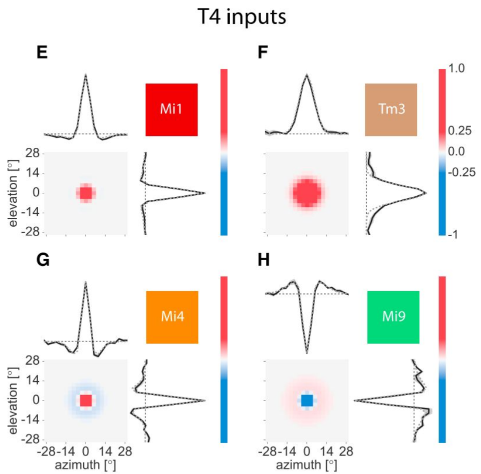
Tuthill et al. 2013

Anatomical Data



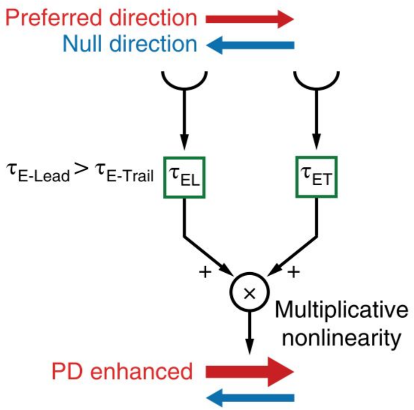
Shinomiya et al. 2014

Physiological Data



Arenz et al. 2017

Conceptual Frameworks



Gruntman et al. 2018

The Problem:

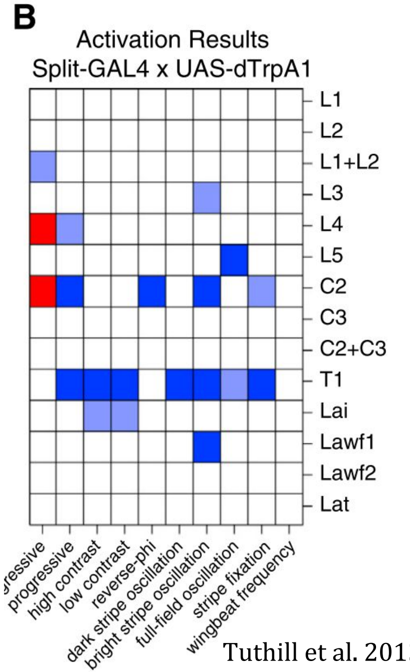
*"...Nevertheless, as a field, we cannot claim to have **"solved" elementary motion detection.** We cannot satisfactorily answer the question, **How do flies compute motion?** There exists no model that describes the elementary motion detection algorithm and its mechanistic implementation by **specific neurons, synapses, molecules, and circuits**."*

Yang & Clandinin

Elementary Motion Detection in Drosophila: Algorithms and Mechanisms (2018)

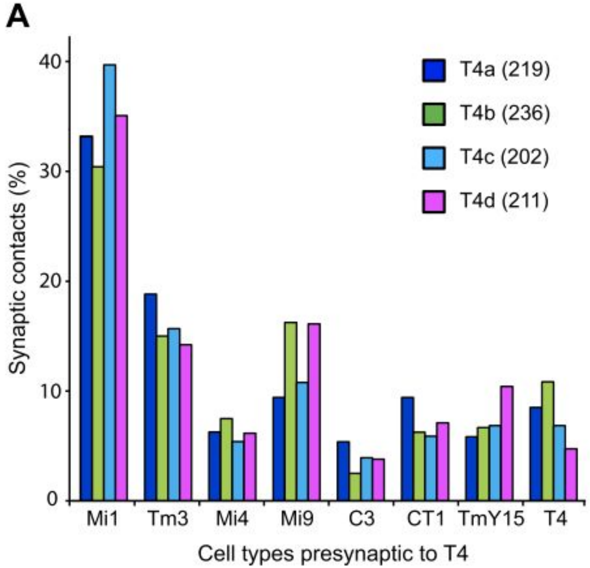
Why?

Some Data is hard to interpret/contradictory



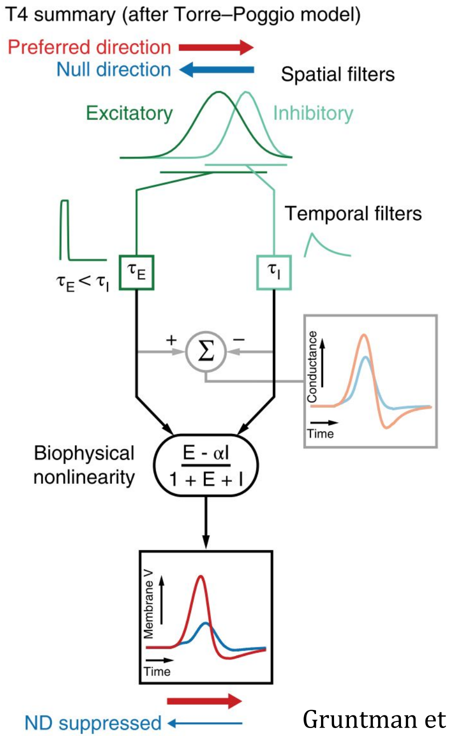
Tuthill et al. 2013

Some data is very new!



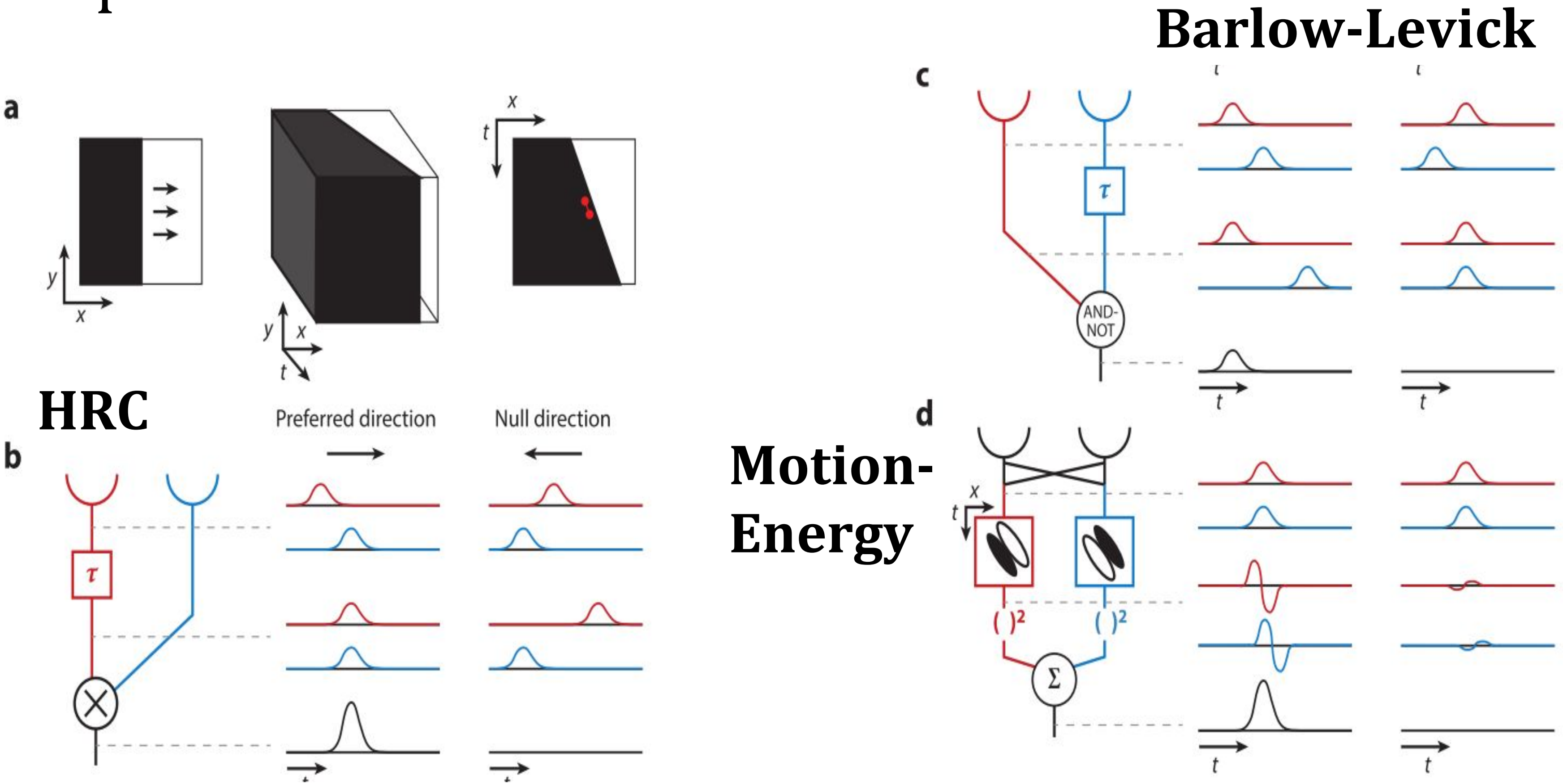
Takemura et al. 2017

No consensus on models

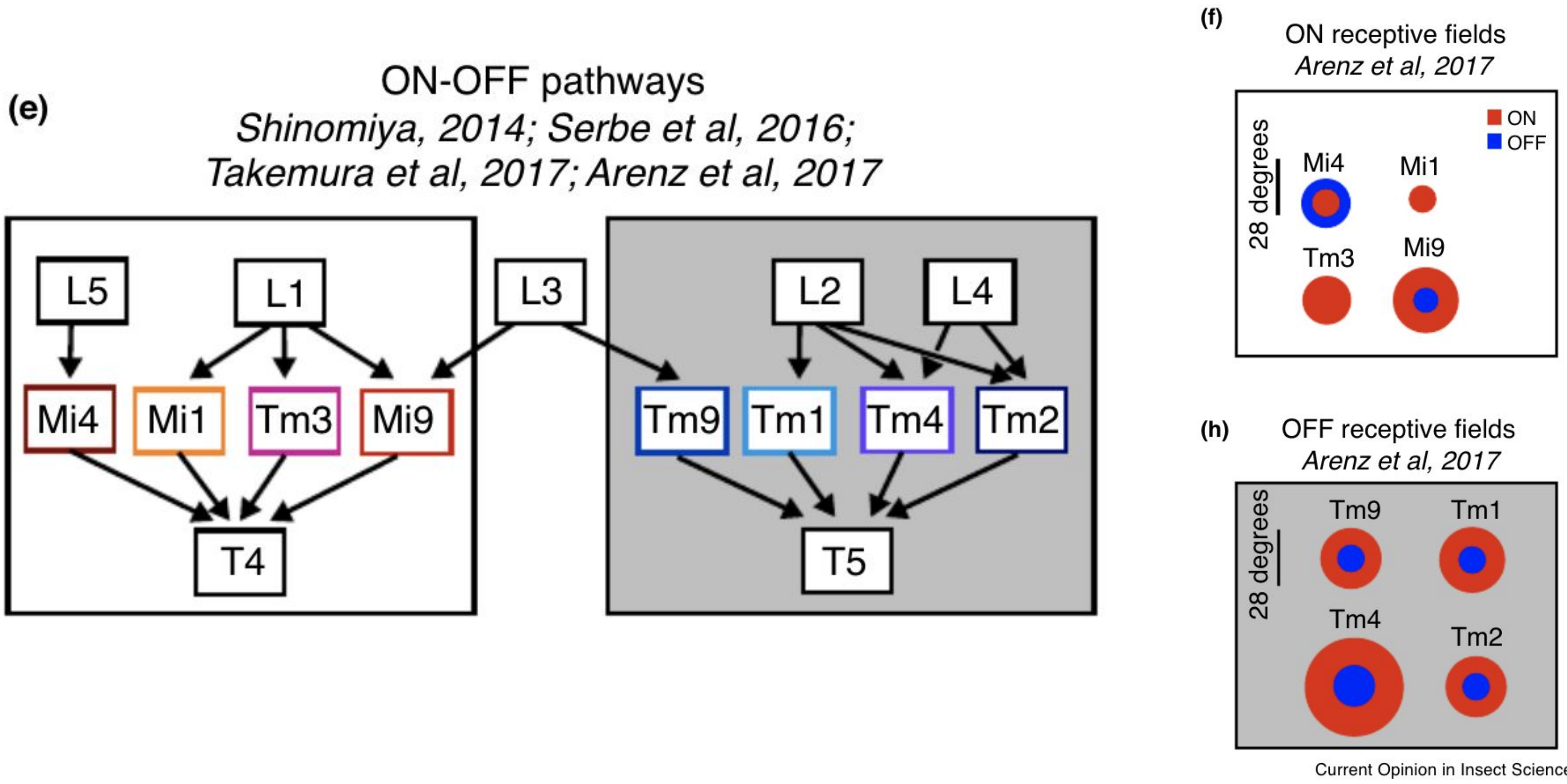


Gruntman et al. 2018

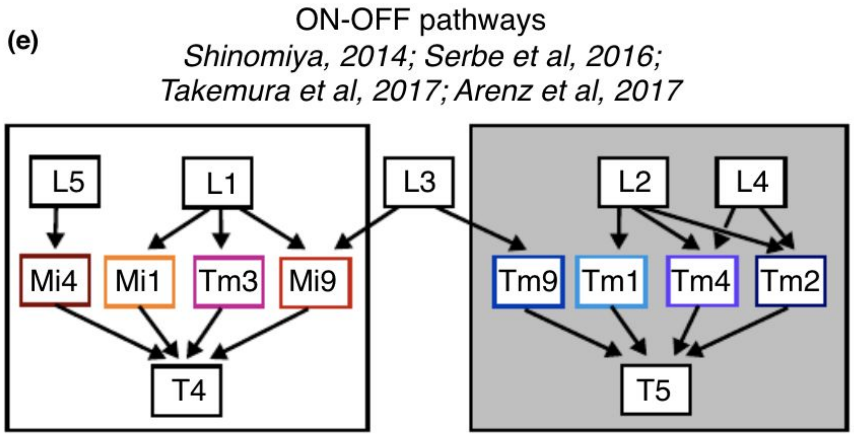
Simple Models for Motion Detection

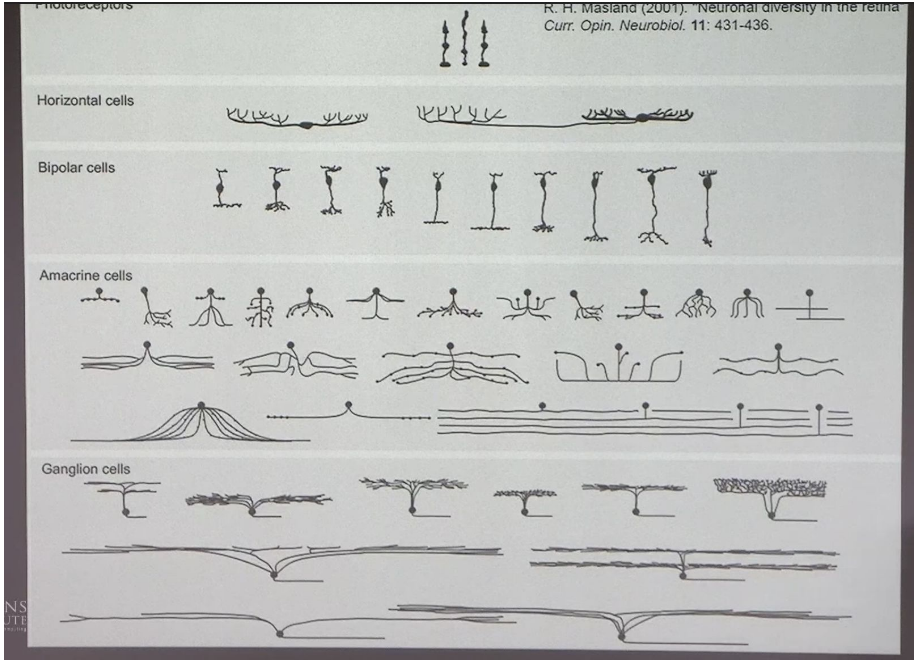


ON and OFF Pathways in the Fly



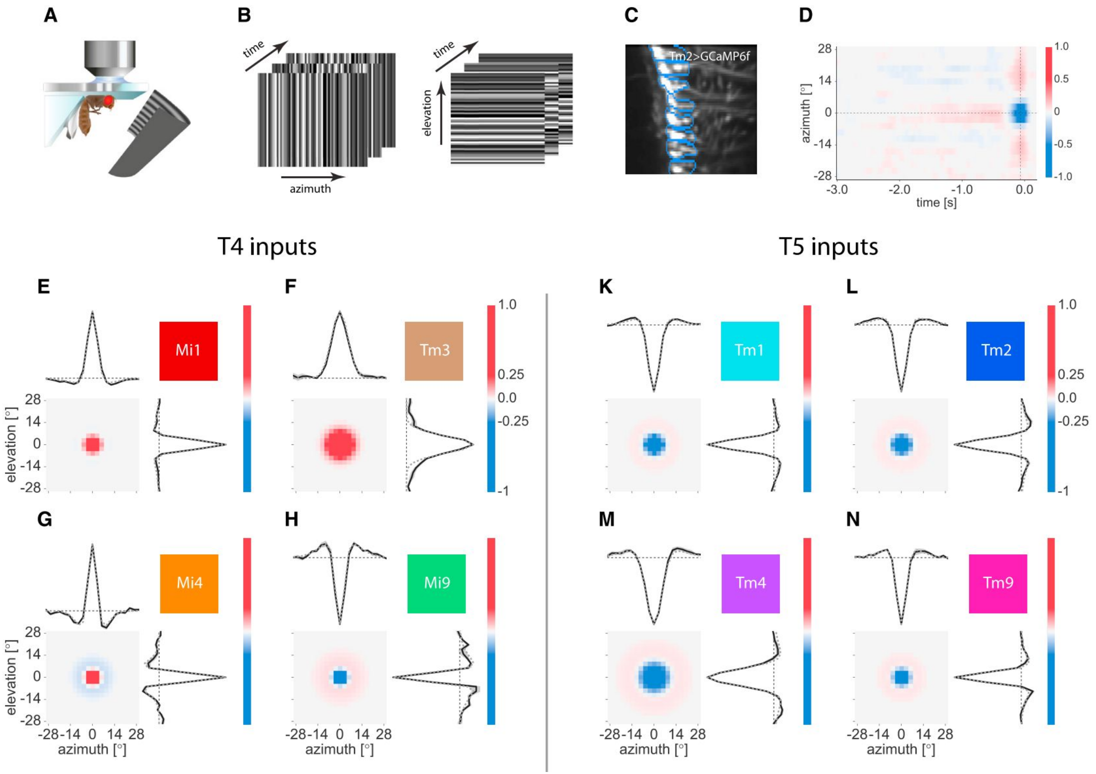
Dyakova et al. 2017, Current Opinion in Insect Science





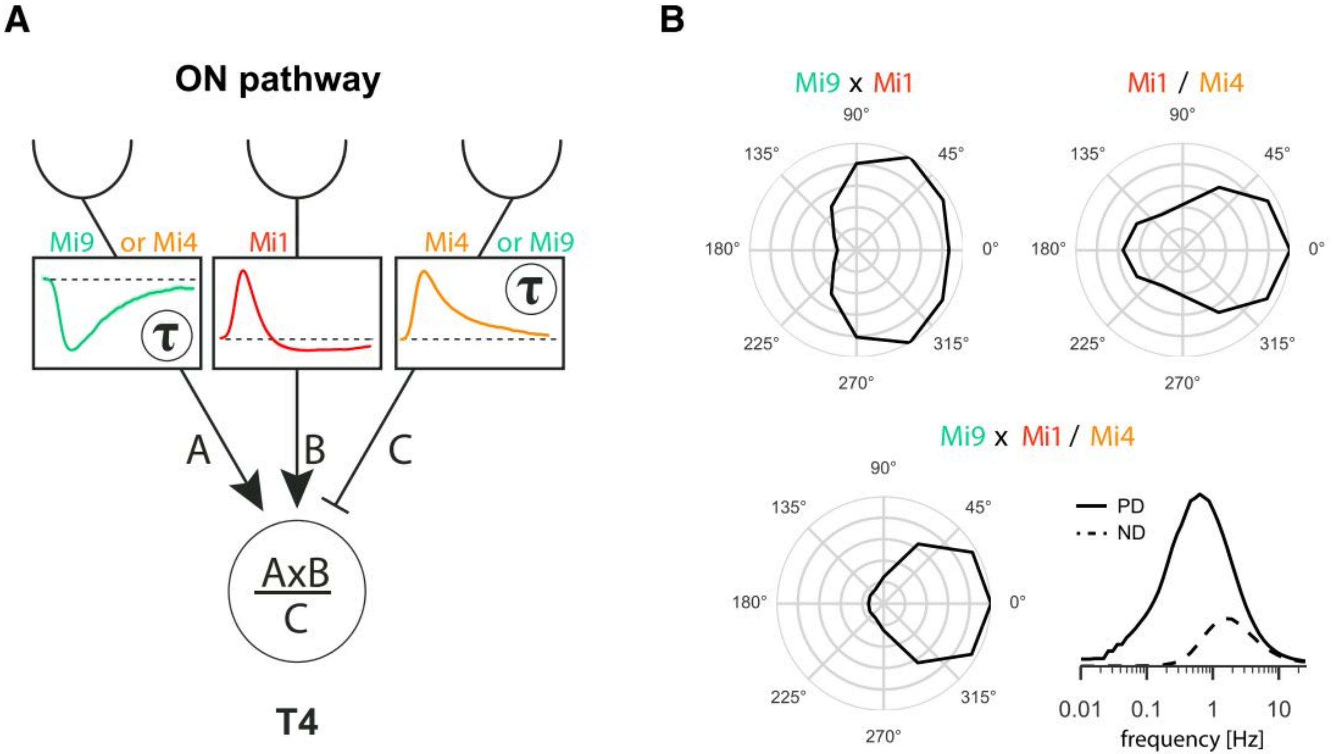
https://www.youtube.com/watch?v=R2US2yVO4us&t=1s

Functional Properties of Cells



Arenz, Alexander, et al. "The temporal tuning of the Drosophila motion detectors is determined by the dynamics of their input elements." Current Biology 27.7 (2017): 929-944.

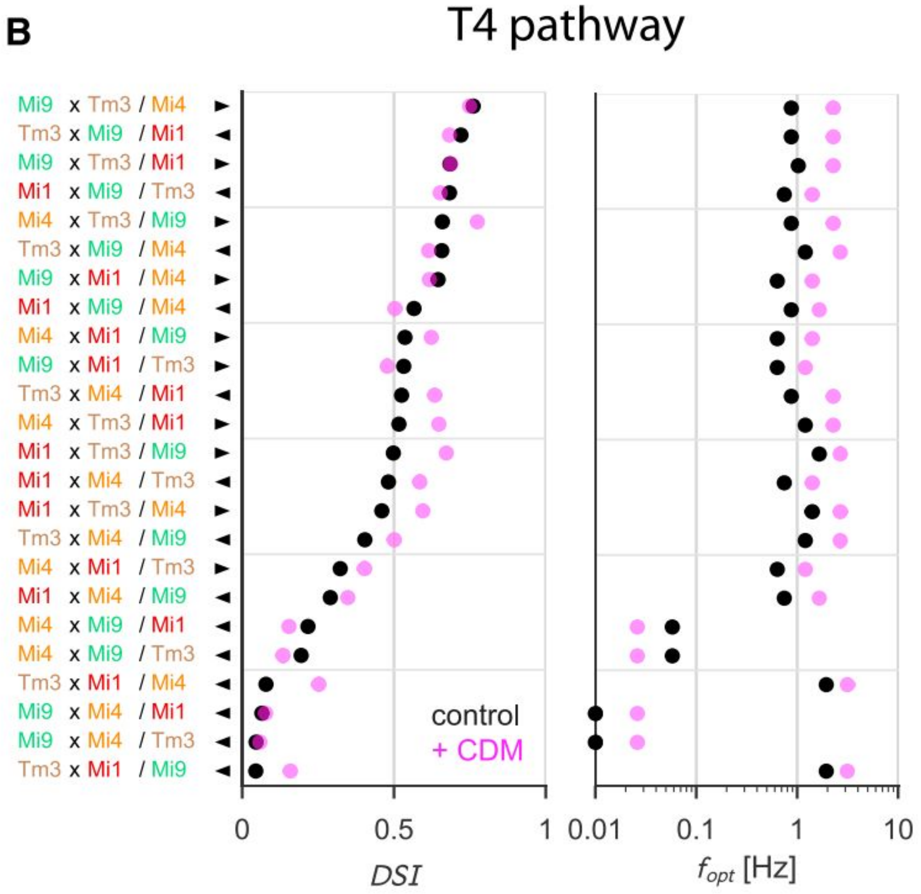
A Simple Model (HRC and BL inspired)



Arenz, Alexander, et al. "The temporal tuning of the Drosophila motion detectors is determined by the dynamics of their input elements." Current Biology 27.7 (2017): 929-944.

Model works with all cell-type combinations…

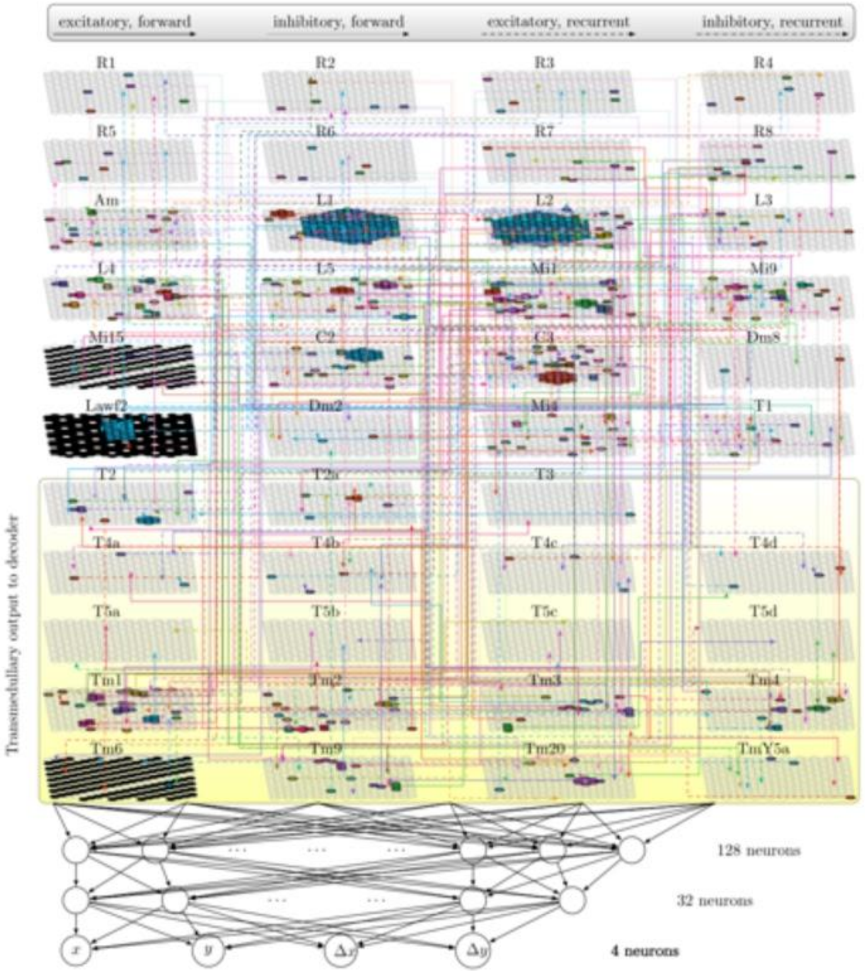
Is this a good model?
Or too simple?



Arenz, Alexander, et al. "The temporal tuning of the Drosophila motion detectors is determined by the dynamics of their input elements." Current Biology 27.7 (2017): 929-944.

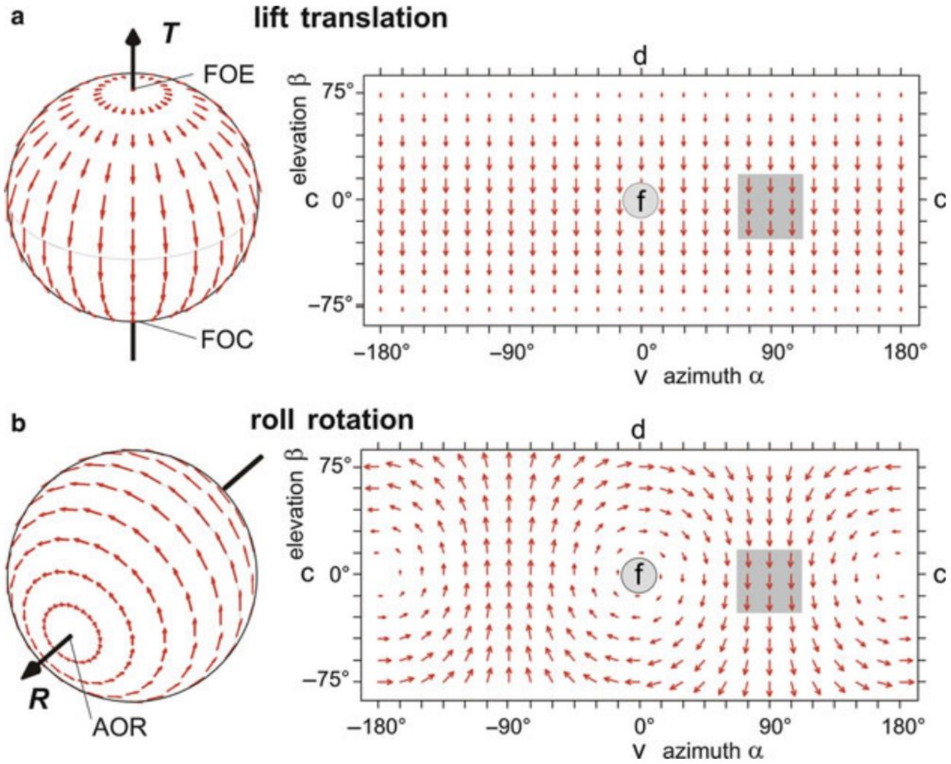
CNN-LSTM + Connectome Approach

Is this a good model? Or too complicated?



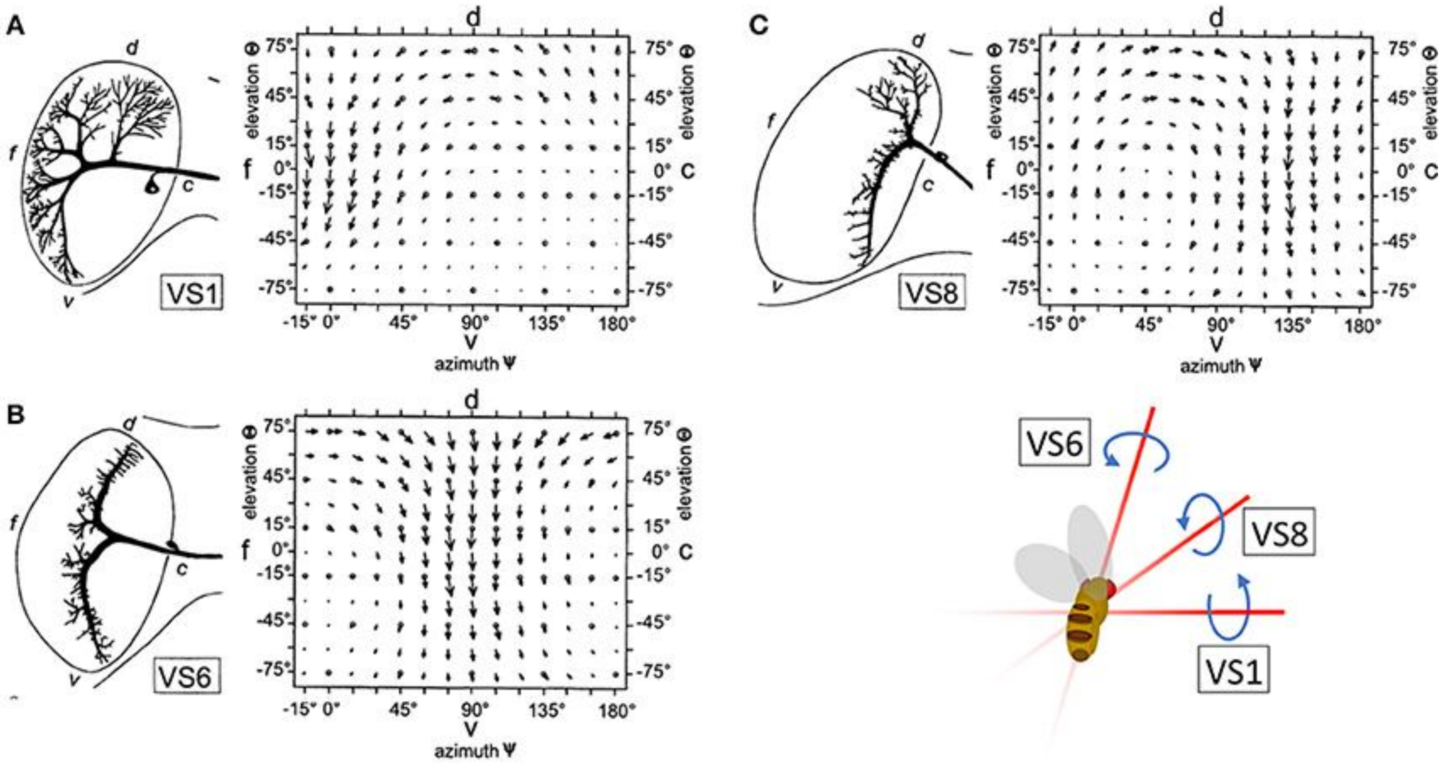
Tschopp, Fabian David, Michael B. Reiser, and Srinivas C. Turaga. "A Connectome Based Hexagonal Lattice Convolutional Network Model of the Drosophila Visual System." arXiv preprint arXiv:1806.04793 (2018).

Optical Flow



Krapp, Holger G. "Optic flow processing." Encyclopedia of Computational Neuroscience (2015): 2156-2175.

Optical Flow Neurons in the Fly



Kohn Heath Behnia 2018

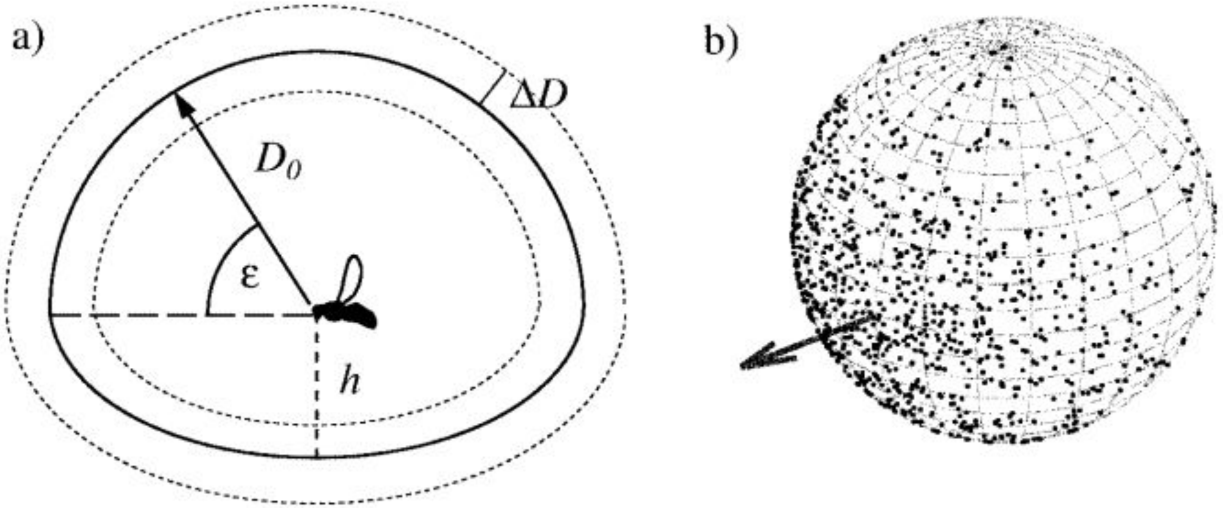
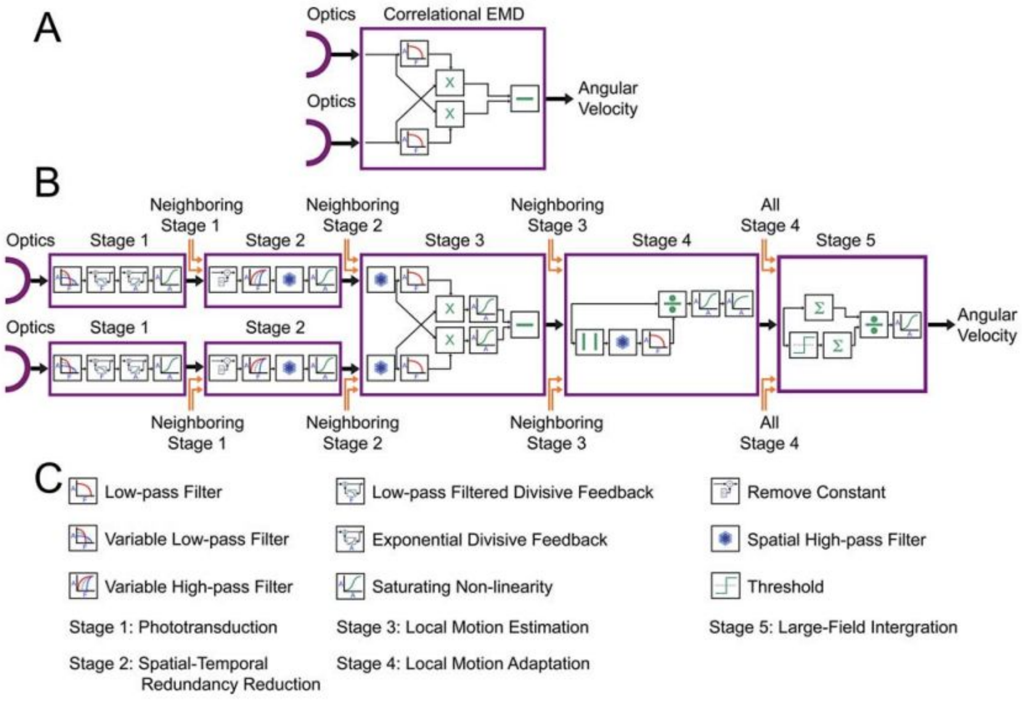


Fig. 5. Simplified "world model" of a blowfly flying at an average height h over ground. **a** Anisotropic distribution of the average distances in the visual field. The distance deviation ΔD is assumed to be independent of the viewing direction. **b** one thousand samples generated by the two-dimensional von Mises distribution of the translation directions. The *arrow* indicates the maximum of the distribution that is in the forward direction

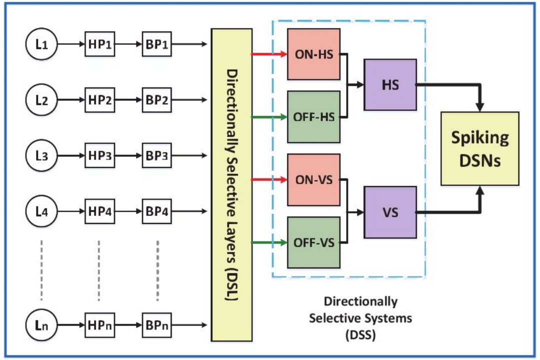
Franz, Matthias O., and Holger G. Krapp. "Wide-field, motion-sensitive neurons and matched filters for optic flow fields." Biological cybernetics 83.3 (2000): 185-197.

Model of Optical Flow in the Fly (2009)

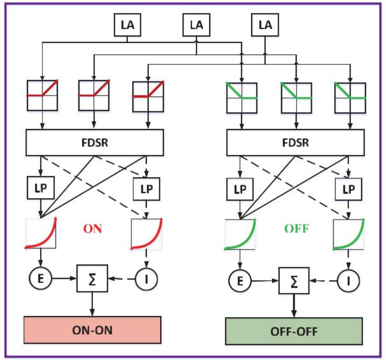


Brinkworth, Russell SA, and David C. O'Carroll. "Robust models for optic flow coding in natural scenes inspired by insect biology." PLoS Computational Biology 5.11 (2009): e1000555.

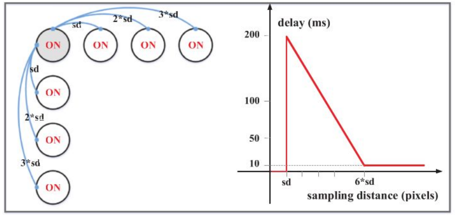
Model of Optical Flow in the Fly (2018) → still old school



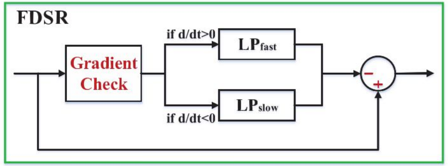
(a) a schema of DSNN



(b) a schema of DSL in DSNN



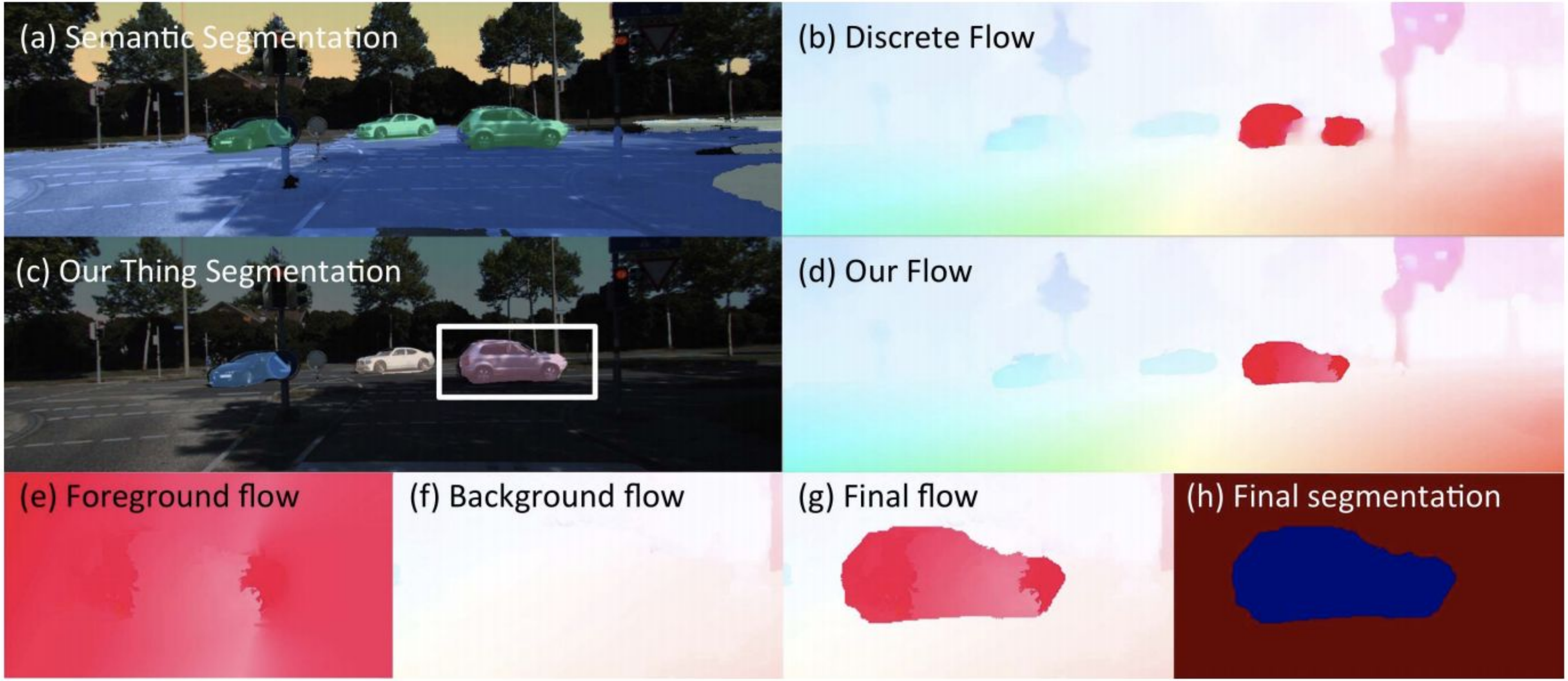
(c) spatiotemporal dynamics in DSL



(d) FDSR mechanism

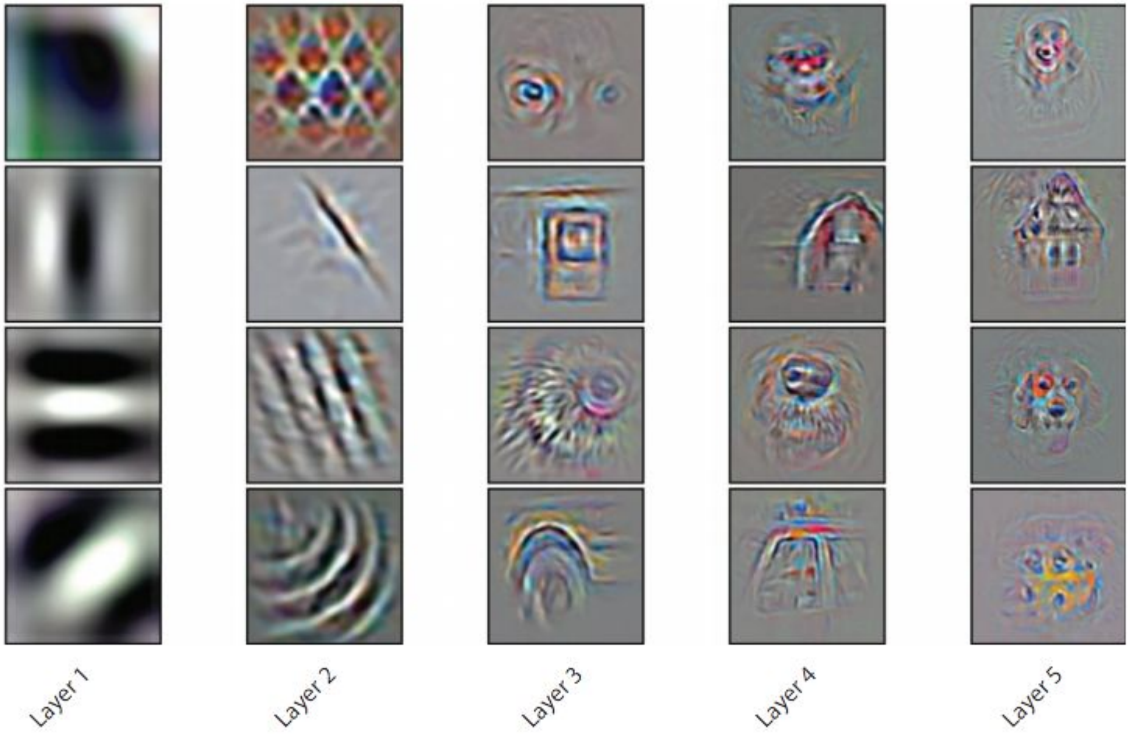
Fu et al. A Directionally Selective Neural Network with Separated ON and OFF Pathways for Translational Motion Perception in a Visually Cluttered Environment arXiv 2018

Optical Flow in CS → Much Better Performance



Chen, Qifeng, and Vladlen Koltun. "Full flow: Optical flow estimation by global optimization over regular grids." Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition. 2016.

Does the Fly "Recognize" Objects?



Kriegeskorte, Nikolaus. "Deep neural networks: a new framework for modeling biological vision and brain information processing." Annual review of vision science 1 (2015): 417-446.

Potential Project Ideas

- Build a MB inspired FF circuit that classifies MNIST
  - Litwin-Kumar, Ashok, et al. "Optimal degrees of synaptic connectivity." *Neuron* 93.5 (2017): 1153-1164.
- Build a MB inspired spiking model
  - https://link.springer.com/content/pdf/10.1007/s00422-008-0241-1.pdf
- Build a Central Complex inspired ring attractor model that performs path integration
  - Turner-Evans et al. eLife 2017, SS Kim et al. Science 2017
- Build a motion detection circuit using HRC and BL and compare performance
  - Arenz, Alexander, et al. "The temporal tuning of the Drosophila motion detectors is determined by the dynamics of their input elements." Current Biology 27.7 (2017): 929-944.
- Use HRC in tensorflow and optimize over natural movies
  - Tschopp, Fabian David, Michael B. Reiser, and Srinivas C. Turaga. "A Connectome Based Hexagonal Lattice Convolutional Network Model of the Drosophila Visual System." arXiv preprint arXiv:1806.04793 (2018).
- Build a Optic Lobe + MB circuit that categorizes images
- Review the class of algorithms that can be performed by the MB
- Summarize the literature on ring attractor algorithms