BIOENG-456

Controlling Behavior in Animals and Robots

Prof. Pavan Ramdya
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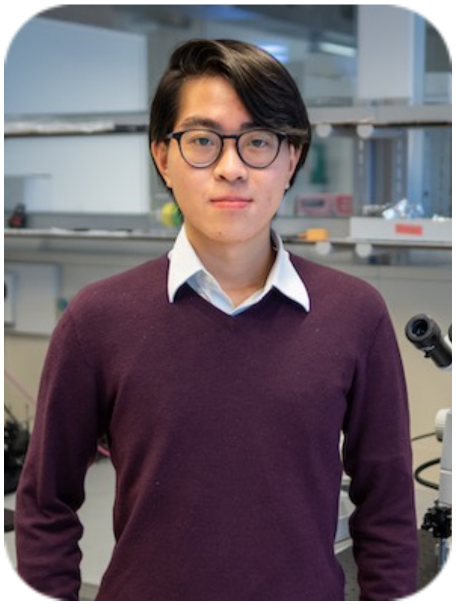
Teaching Assistants

Tommy Lam



Dominic Dall'Osto

Alfred Stimpfling

Course goals

Acquire an **integrative understanding** of bioinspired **control algorithms** for **autonomous behavior**.

An area called '**NeuroAI**'
"use insights from neuroscience to catalyze the development of next-generation artificial intelligence."

Lectures and exercises overview

Room MED 2 2423

Weeks 1-6

Students will give 30 min **oral presentations** on **primary literature** and learn through hands-on **computational simulations (Python/MuJoCo)**

Approximate timing:

13:15 - 13:45 Introduction to the lecture and exercise topic (Pr. Ramdya)

13:45 - 14:10 Paper presentation & discussion (Student group 1)

14:10 - 14:20 Break

14:20 - 14:45 Paper presentation & discussion (Student group 2)

14:45 - 15:00 Break

15:00 - 15:10 Revision of previous week's exercise (TA)

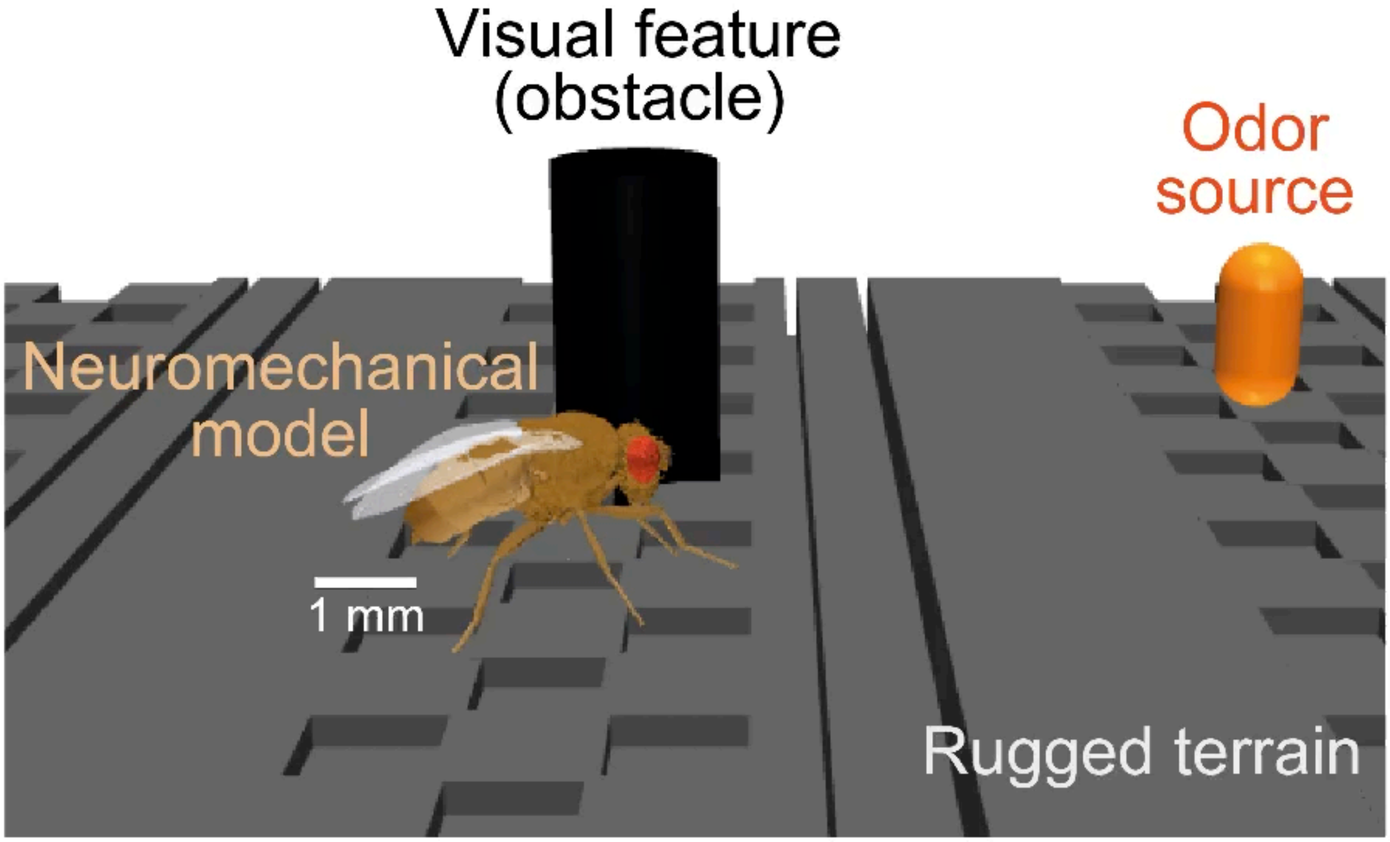
15:10 - 15:20 Introduction to the exercise topic (TA)

15:20 - 18:00 Paced but independent computational exercise

Exercises

'NeuroMechFly'

A neuromechanical simulation of the fly, *Drosophila melanogaster*



Week-by-week overview (Weeks 1-6)

Room MED 2 2423

https://moodle.epfl.ch/course/view.php?id=15802\
Password: cobar

Midterm exam (Week 7)

Room MED 2 2423

Mostly short answers

Based on (Weeks 1-6)

- Short lecture (study slides)
- Paper presentations (study Questions-to-Consider and slides and paper)
- Exercises (do them)

Mini-project overview

Room MED 2 2423

Weeks 8-14

Student groups will design sensorimotor controllers for their own behaviors in **simulations** of the fly, **write** a report and **present** their findings to the class.

Approximate timeline:

Week 8: Introduction to the mini-project

Week 8 - 11: Write Python code to build sensorimotor controllers

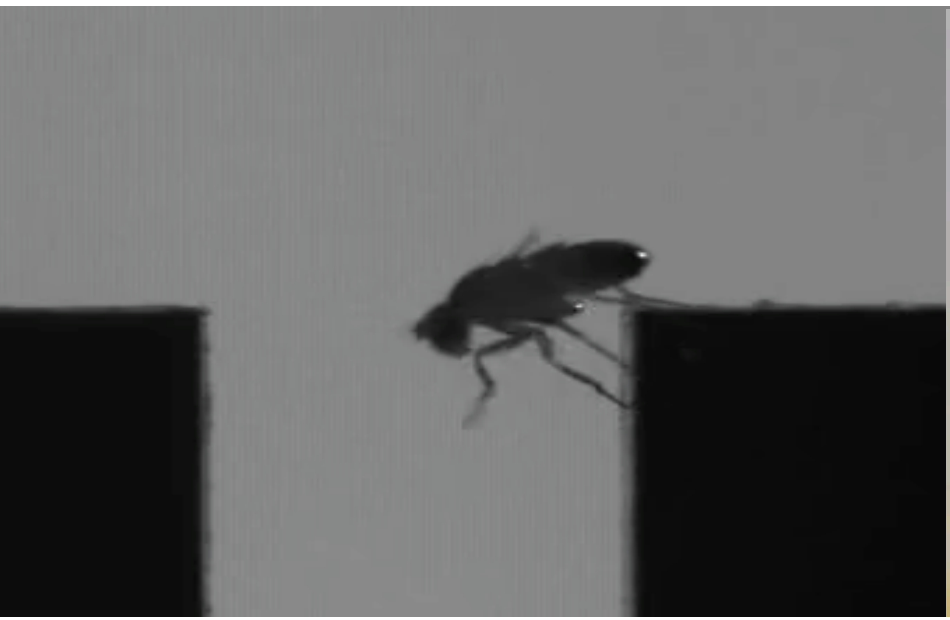
Week 12: Write report

Week 13: Finalize report and prepare presentations

Week 14: Present mini-project results to the class

This year's miniproject topic

Hierarchical *sensorimotor* control



This year's miniproject topic

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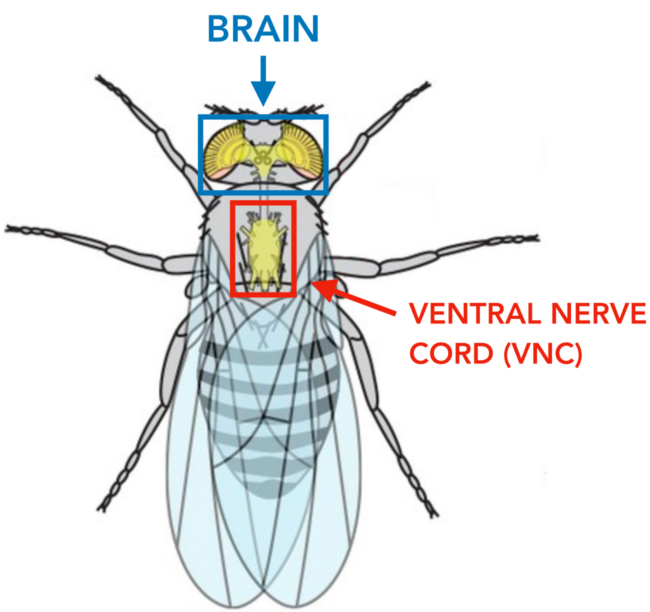
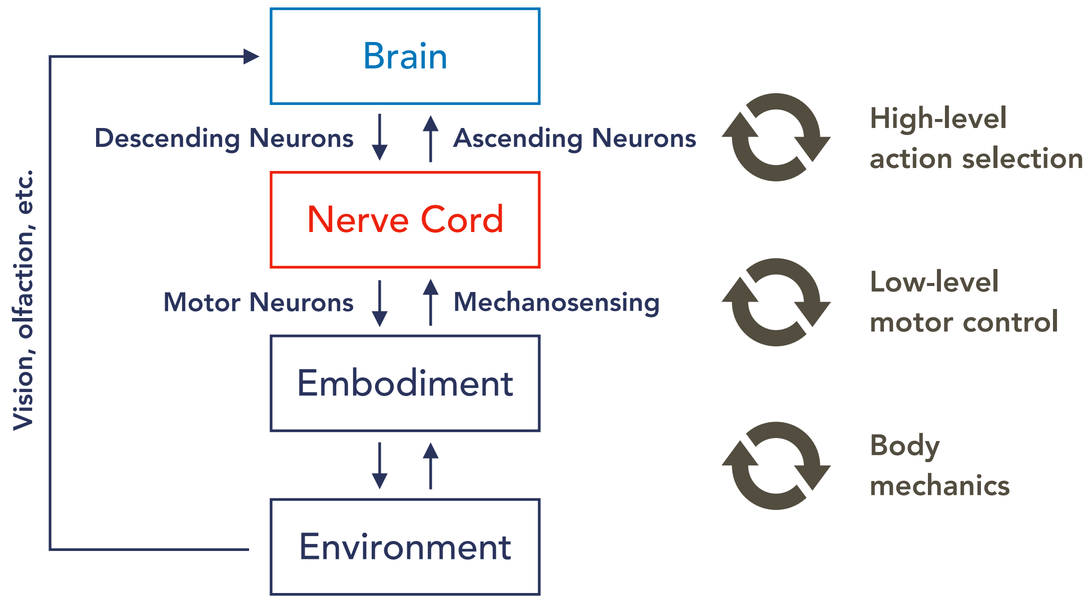
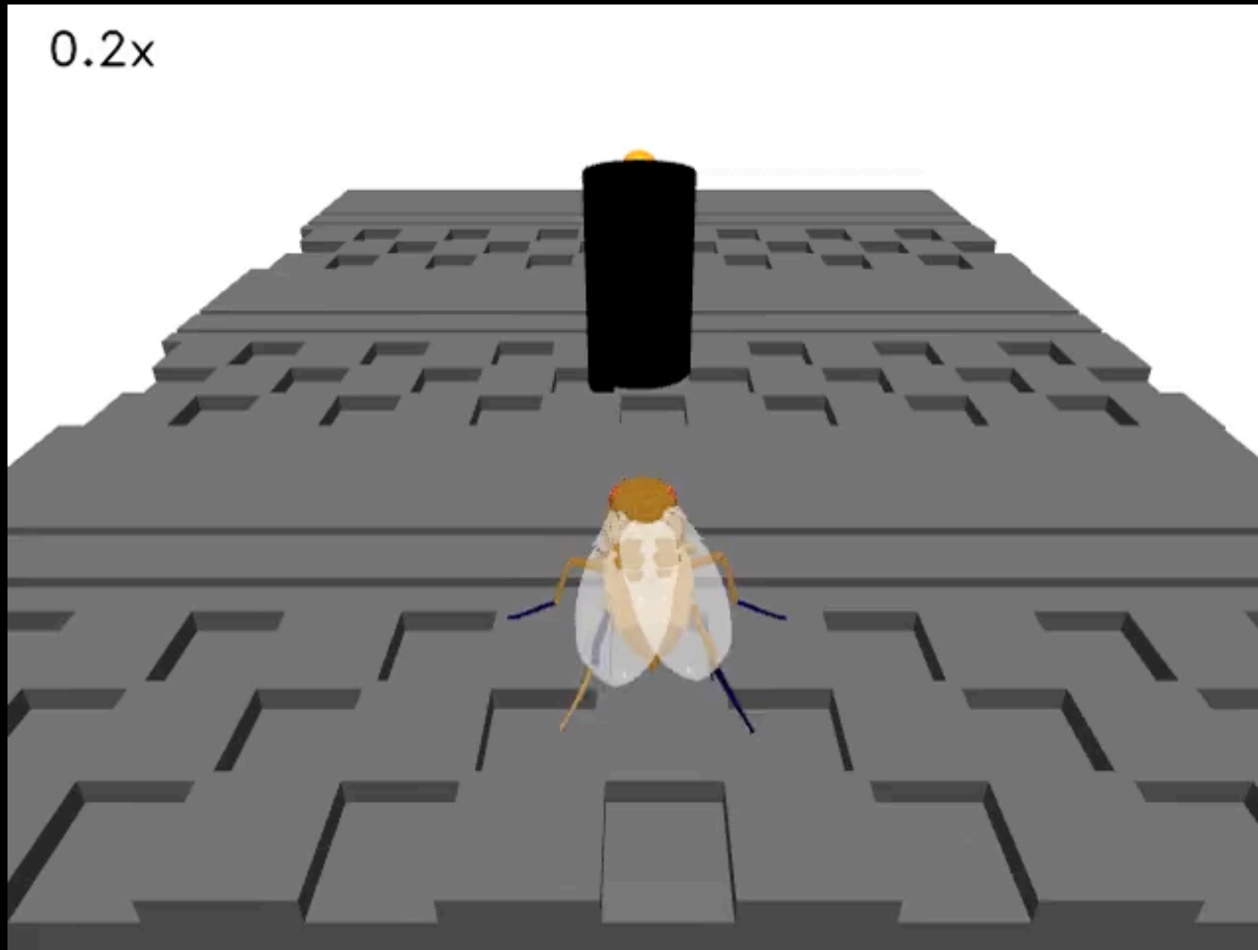


Namiki et al, 2018, *eLife*



Neuromechfly.org

Lobato-Ríos et al., *Nature Methods* 2022

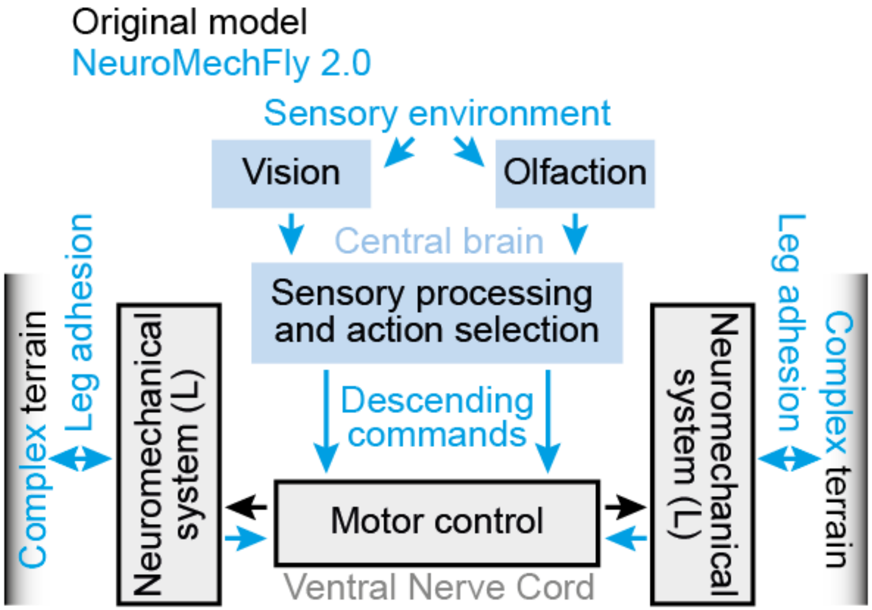


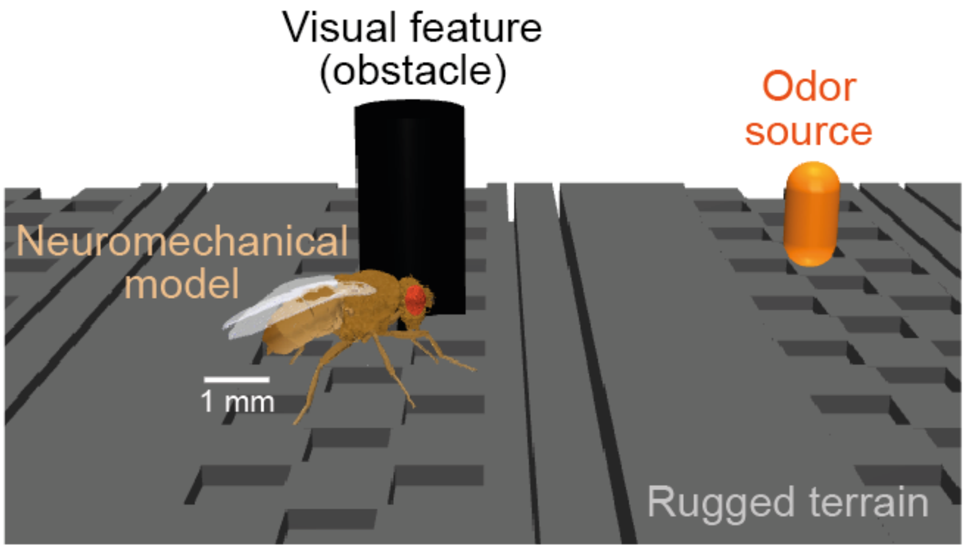
Left antenna and max. palp

Right antenna and max. palp

Wang-Chen et al., *Nature Methods 2024*

You will use NeuroMechFly to design **controllers** to address a multimodal task

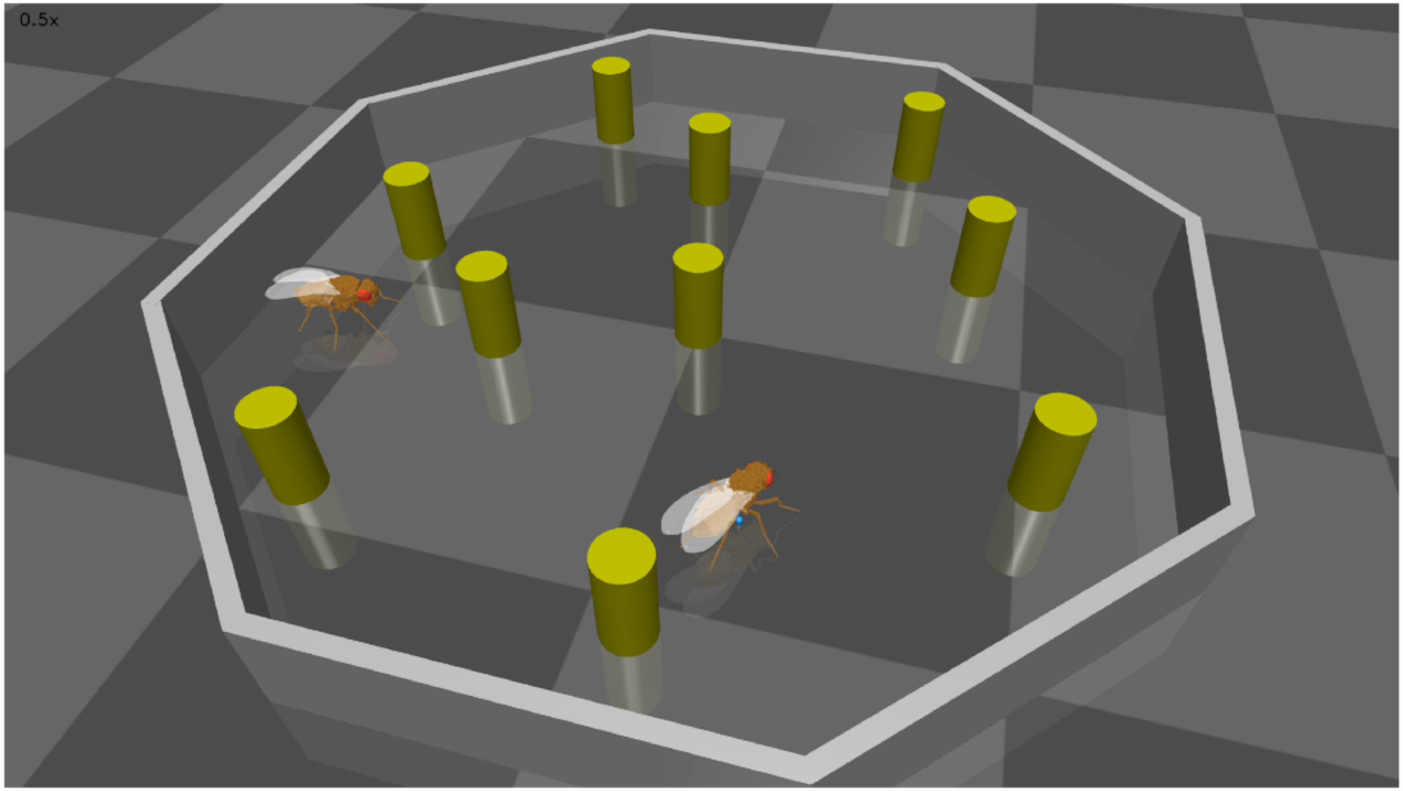


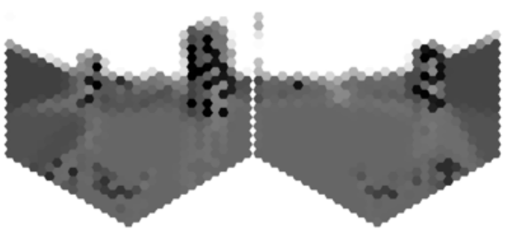


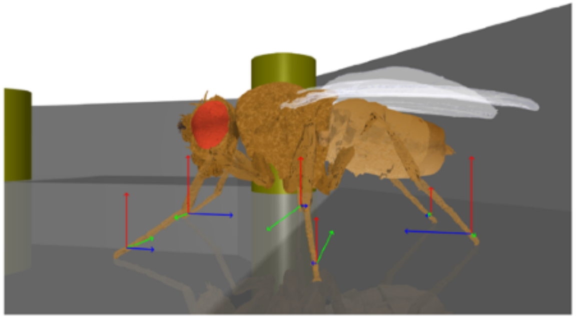
www.neuromechfly.org

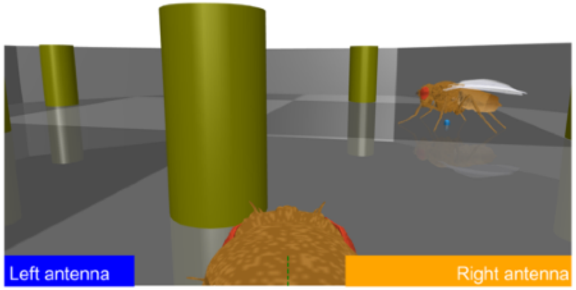
Wang-Chen et al., *Nature Methods 2024*

Mini project: Exploring multisensory integration through a chasing task in a complex environment



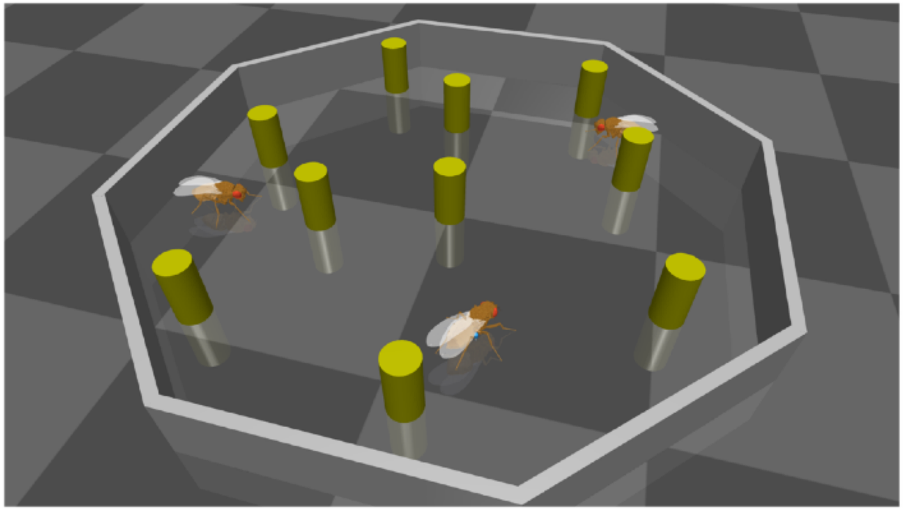




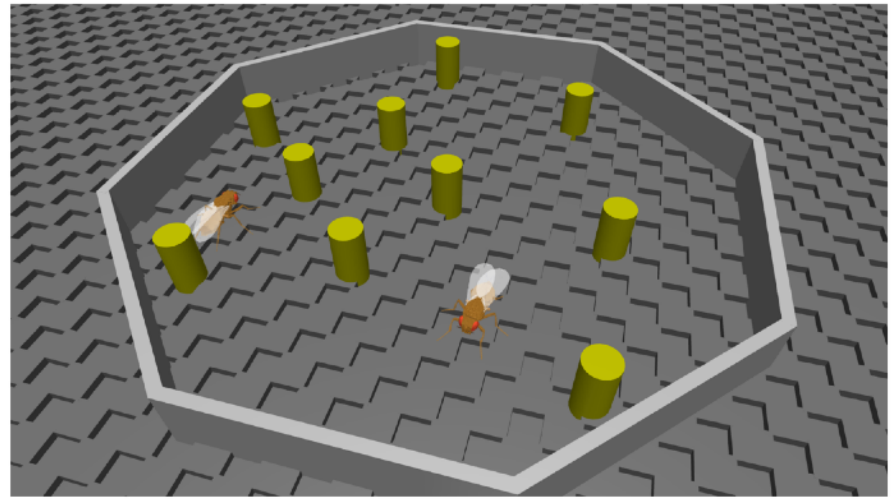


Mini project bonus

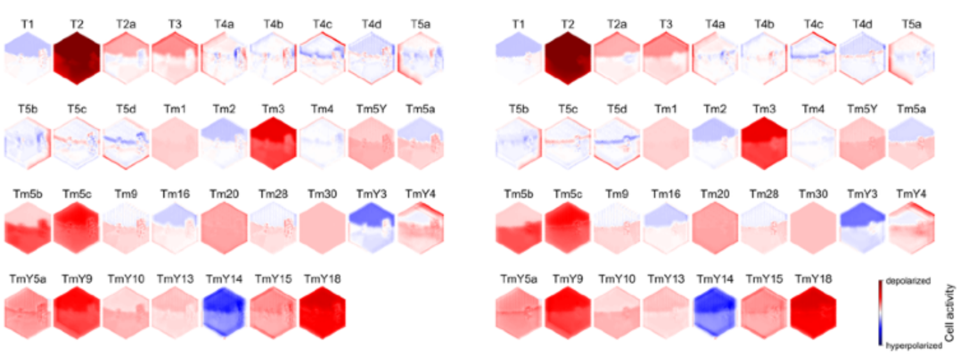
Multiple flies with different odorant barcodes



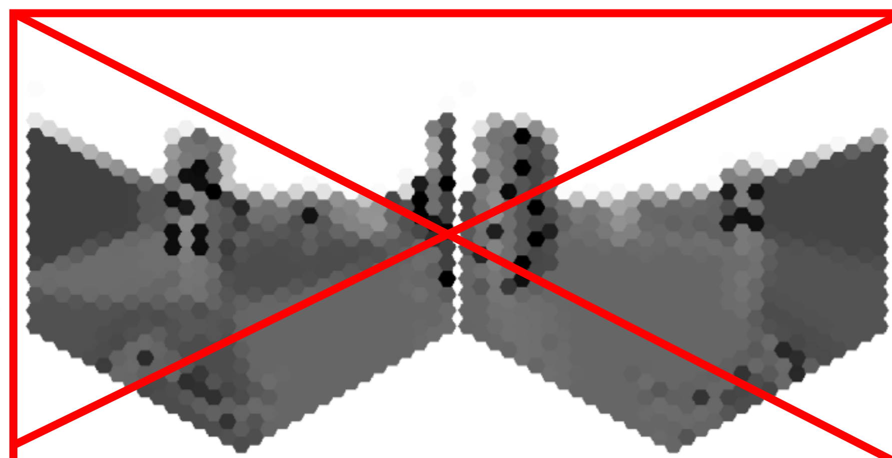
Complex terrain



Connectome constrained vision



No vision



Course prerequisites

Required: Programming experience in Python or C/C++

Nice to have: Neuroscience coursework

What is a neuron?

How is information transmitted by neurons?

What is a nervous system composed of?
(e.g., cortical domains, subcortical areas, spinal cord)

Groups

Paper presentation groups of 2-3 students determined in **Week 2**

Mini-project groups of 2-3 students determined in **Week 6**

Groups

Paper presentation groups of 2-3 students determined in **Week 2**

Mini-project groups of 2-3 students determined in **Week 6**

Student backgrounds

Masters in Robotics

Masters in Life Sciences Engineering

Masters in Neuro-X

Groups

Paper presentation groups of 2-3 students determined in **Week 2**

Mini-project groups of 2-3 students determined in **Week 6**

Student backgrounds

Masters in Robotics

Masters in Neuro-X

Masters in Life Sciences Engineering

Why an interdisciplinary, team-oriented course?

Solve problems in a group setting

Manage resources (complementary areas of competence)

Robotics students exposed to challenges and approaches in biology

Bioeng. students exposed to challenges and approaches in robotics

Course grading

"Continuous grading":

20% Primary literature presentation (shared by presentation **group**)

When: during **weeks 2-6**

Criteria: Understand paper; clear, concise presentation; questions

40% Written exam on literature and exercise concepts (**individual** grade)

When: Week 7

Criteria: Written and multiple choice answers (no documents)

40% Mini-project, report, and presentation (shared by project **group**)

When: during **weeks 8-14**

Criteria: Working style, clear, concise, and comprehensive

Any questions?

Journal club presentations…

Journal Club Presentations

Description

20 min **oral presentation** on a work of **primary neuroscientific literature**.
Followed by 5 min of question-led discussion

Purpose

Convey scientific material to fellow classmates

Open discussion about the material

Learn how to read, distill, and clearly convey a scientific article

Practice public speaking and answering questions

How to Read a Paper

S. Keshav
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ABSTRACT

Researchers spend a great deal of time reading research papers. However, this skill is rarely taught, leading to much wasted effort. This article outlines a practical and efficient *three-pass method* for reading research papers. I also describe how to use this method to do a literature survey.

Categories and Subject Descriptors: A.1 [Introductory and Survey]

General Terms: Documentation.

Keywords: Paper, Reading, Hints.

1. INTRODUCTION

Researchers must read papers for several reasons: to review them for a conference or a class, to keep current in their field, or for a literature survey of a new field. A typical researcher will likely spend hundreds of hours every year reading papers.

Learning to efficiently read a paper is a critical but rarely taught skill. Beginning graduate students, therefore, must learn on their own using trial and error. Students waste much effort in the process and are frequently driven to frustration.

For many years I have used a simple approach to efficiently read papers. This paper describes the 'three-pass' approach and its use in doing a literature survey.

2. THE THREE-PASS APPROACH

The key idea is that you should read the paper in up to three passes, instead of starting at the beginning and plowing your way to the end. Each pass accomplishes specific goals and builds upon the previous pass: The *first* pass gives you a general idea about the paper. The *second* pass lets you grasp the paper's content, but not its details. The *third* pass helps you understand the paper in depth.

2.1 The first pass

The first pass is a quick scan to get a bird's-eye view of the paper. You can also decide whether you need to do any more passes. This pass should take about five to ten minutes and consists of the following steps:

1. Carefully read the title, abstract, and introduction
2. Read the section and sub-section headings, but ignore everything else
3. Read the conclusions
4. Glance over the references, mentally ticking off the ones you've already read

At the end of the first pass, you should be able to answer the *five Cs*:

1. *Category*: What type of paper is this? A measurement paper? An analysis of an existing system? A description of a research prototype?
2. *Context*: Which other papers is it related to? Which theoretical bases were used to analyze the problem?
3. *Correctness*: Do the assumptions appear to be valid?
4. *Contributions*: What are the paper's main contributions?
5. *Clarity*: Is the paper well written?

Using this information, you may choose not to read further. This could be because the paper doesn't interest you, or you don't know enough about the area to understand the paper, or that the authors make invalid assumptions. The first pass is adequate for papers that aren't in your research area, but may someday prove relevant.

Incidentally, when you write a paper, you can expect most reviewers (and readers) to make only one pass over it. Take care to choose coherent section and sub-section titles and to write concise and comprehensive abstracts. If a reviewer cannot understand the gist after one pass, the paper will likely be rejected; if a reader cannot understand the highlights of the paper after five minutes, the paper will likely never be read.

2.2 The second pass

In the second pass, read the paper with greater care, but ignore details such as proofs. It helps to jot down the key points, or to make comments in the margins, as you read.

1. Look carefully at the figures, diagrams and other illustrations in the paper. Pay special attention to graphs. Are the axes properly labeled? Are results shown with error bars, so that conclusions are statistically significant? Common mistakes like these will separate rushed, shoddy work from the truly excellent.
2. Remember to mark relevant unread references for further reading (this is a good way to learn more about the background of the paper).

Preparing a presentation

Independently

Read the paper (all group members)

Find and discuss relevant background materials

With your group (self-organized)

Discuss the paper and background materials

Identify 3 important concepts from the paper

Identify 3 questions or concerns about the paper

Delegate responsibilities for making slides and presenting the material

In class

Present the paper, important concepts, and questions

Presentation (~20 minutes)

Slide 1: Title of paper, authors, journal, date

Introduction to the "big picture" question(s)

Background material (e.g., previous papers)

Approach taken by the paper

Answer 'Questions to consider'

Figures **3, 1, 5**… description and explanation

Conclusions made by the authors

Three most important concepts to draw from the paper

Three questions or concerns about the paper

Answer open questions from class and professor

Presentation sign-up

Week 2 Moodle Questionnaire: indicate your top 3 partners

Week 2

Two volunteer groups (3 each) are needed
to present 2 simple articles describing NeuroMechFly

Any questions?

Who would benefit most (**or not**) from this course

Next:
How will we use flies to develop an intuition for controlling autonomous behavior…

Goals of modern neuroscience

Fundamental understanding
of the human or animal brain

Medicine
heal or prevent disease
in *human* brains

"NeuroAI"
build biologically-inspired
artificial/robotic systems

Bioengineering
improve human
capabilities

Model organisms in neuroscience

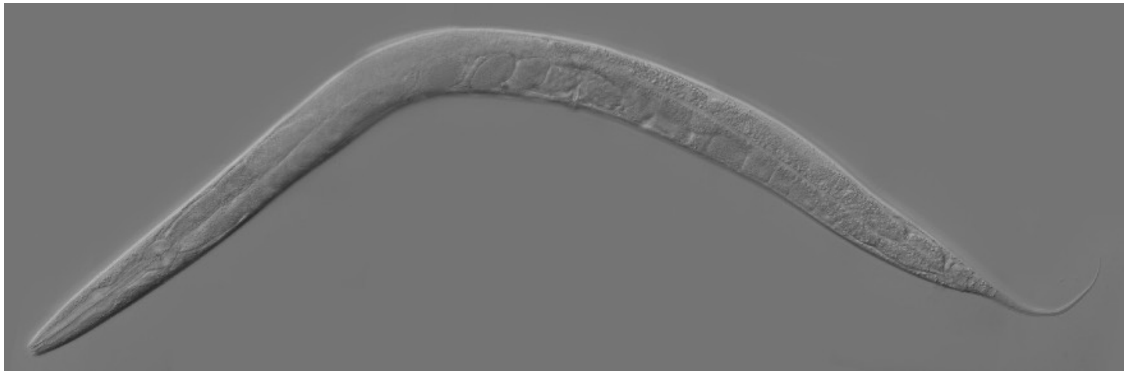
What is a "model organism"?

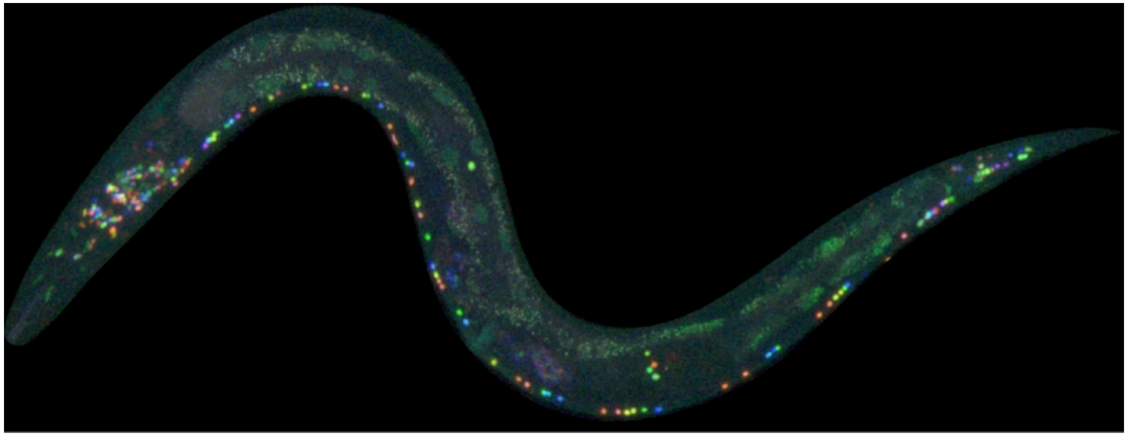
What typically makes model organisms advantageous for experiments?

How can we decide which model organisms are worth using *for a particular goal*?

Model organisms in neuroscience

Worms
(*C. elegans*)

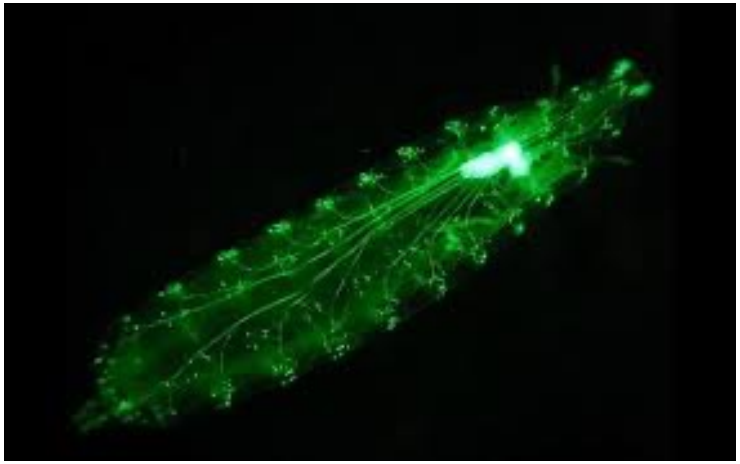




- 302 neurons
- Full connectome
- Transgenic animals

Model organisms in neuroscience

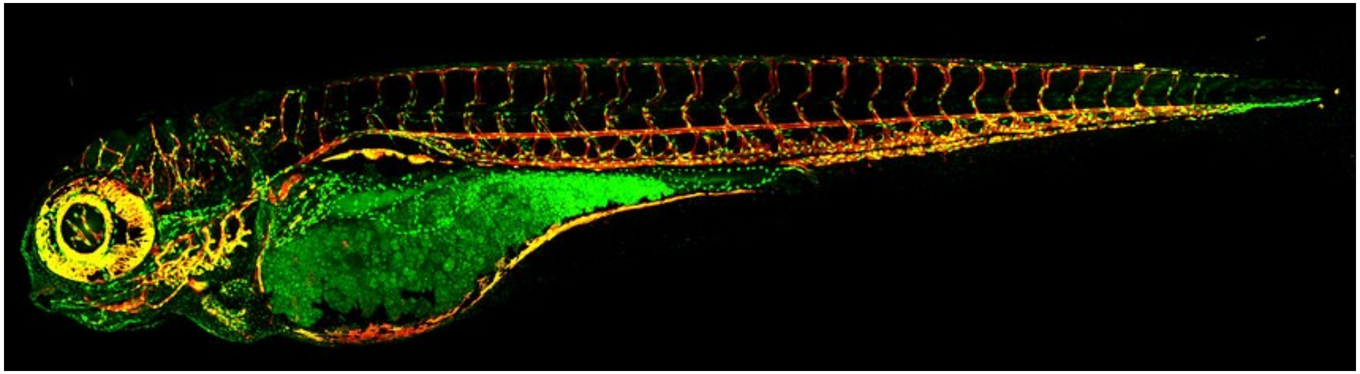
Fly larvae
(*D. melanogaster*)



- ~15,000 neurons
- Full connectome
- Transgenic animals

Model organisms in neuroscience

Zebrafish larvae
(*D. rerio*)



- ~100,000 neurons
- Partial connectome
- Some transgenic animals

Model organisms in neuroscience

Adult flies (*D. melanogaster*)

- ~150,000 neurons
- Complete connectome
- Many transgenic animals

Model organisms in neuroscience

Mice
(*M. musculus*)

- ~100,000,000 neurons
- Small regions have connectome
- Transgenic animals

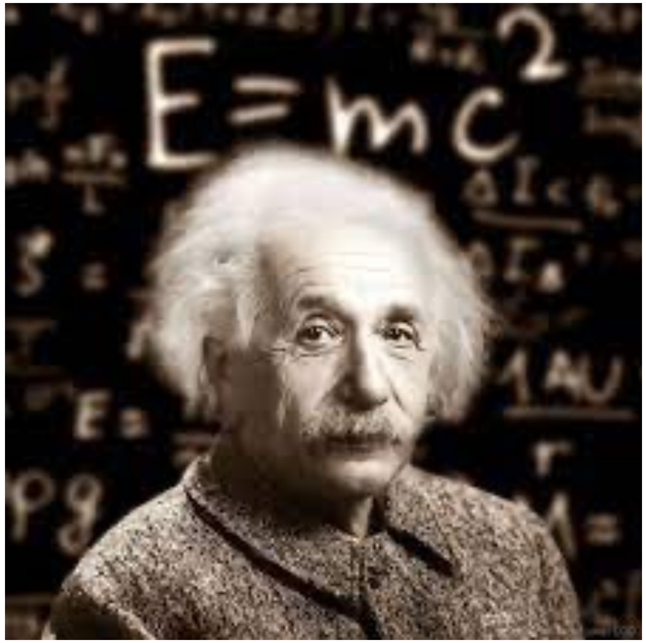
Model organisms in neuroscience

Monkeys

- ~500,000,000 neurons
- No connectome
- Few transgenic animals

Model organisms in neuroscience

Humans



- ~1,000,000,000 neurons
- No connectome
- No transgenics yet

Which model(s) would you use (and why)?

Fundamental understanding
of the human or animal brain

Medicine
heal or prevent disease
in *human* brains

"NeuroAI"
build biologically-inspired
artificial/robotic systems

Bioengineering
improve human
capabilities

Ethics in NeuroAI

What are some ethical considerations?

What is the compromise between ethics and science?

How can we decide which experiments are worth doing?

Sustainability

What is sustainability in the context of NeuroAI?

Why should we be more sustainable in NeuroAI?

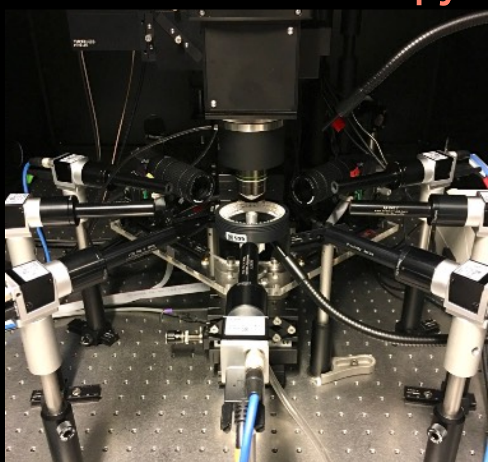
How can we become more sustainable in NeuroAI?

My choice: study adult flies to develop NeuroAI

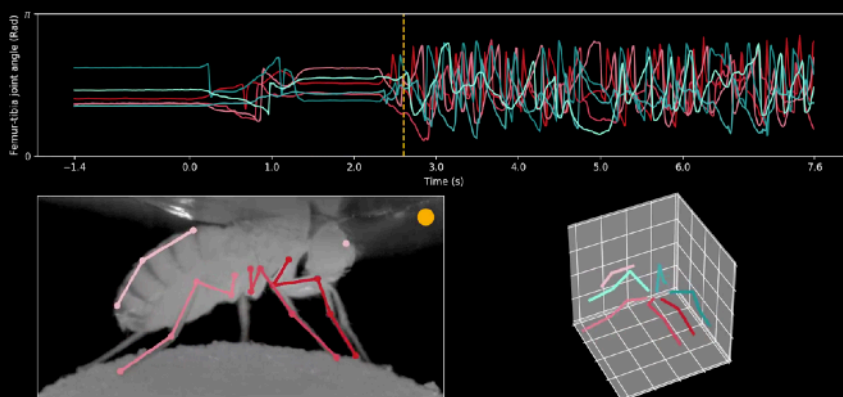
Vision

1. Use *Drosophila* to ***understand*** how the brain represents the self and the world
2. Use this knowledge to ***design*** better robots
3. Use this knowledge and genetics to ***rewire*** the brain and behavior

Genetics & microscopy

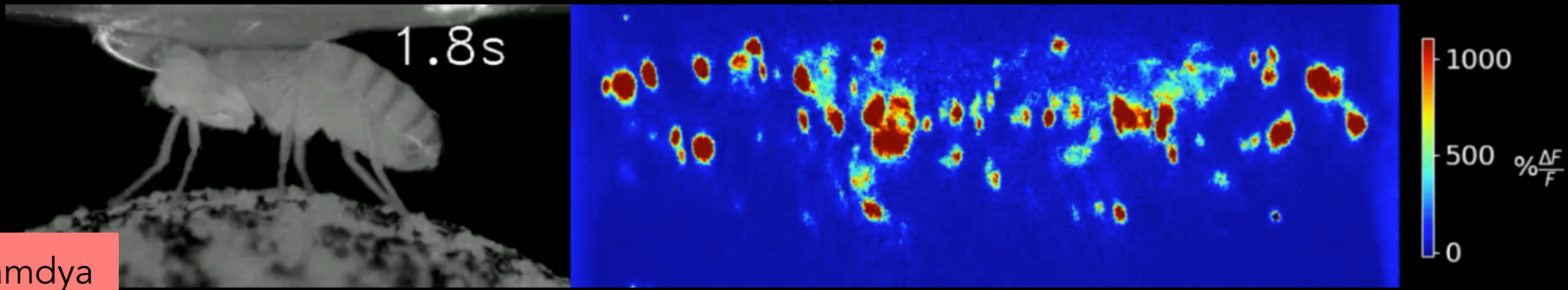


Machine learning



Robotics/modeling

Neural recordings



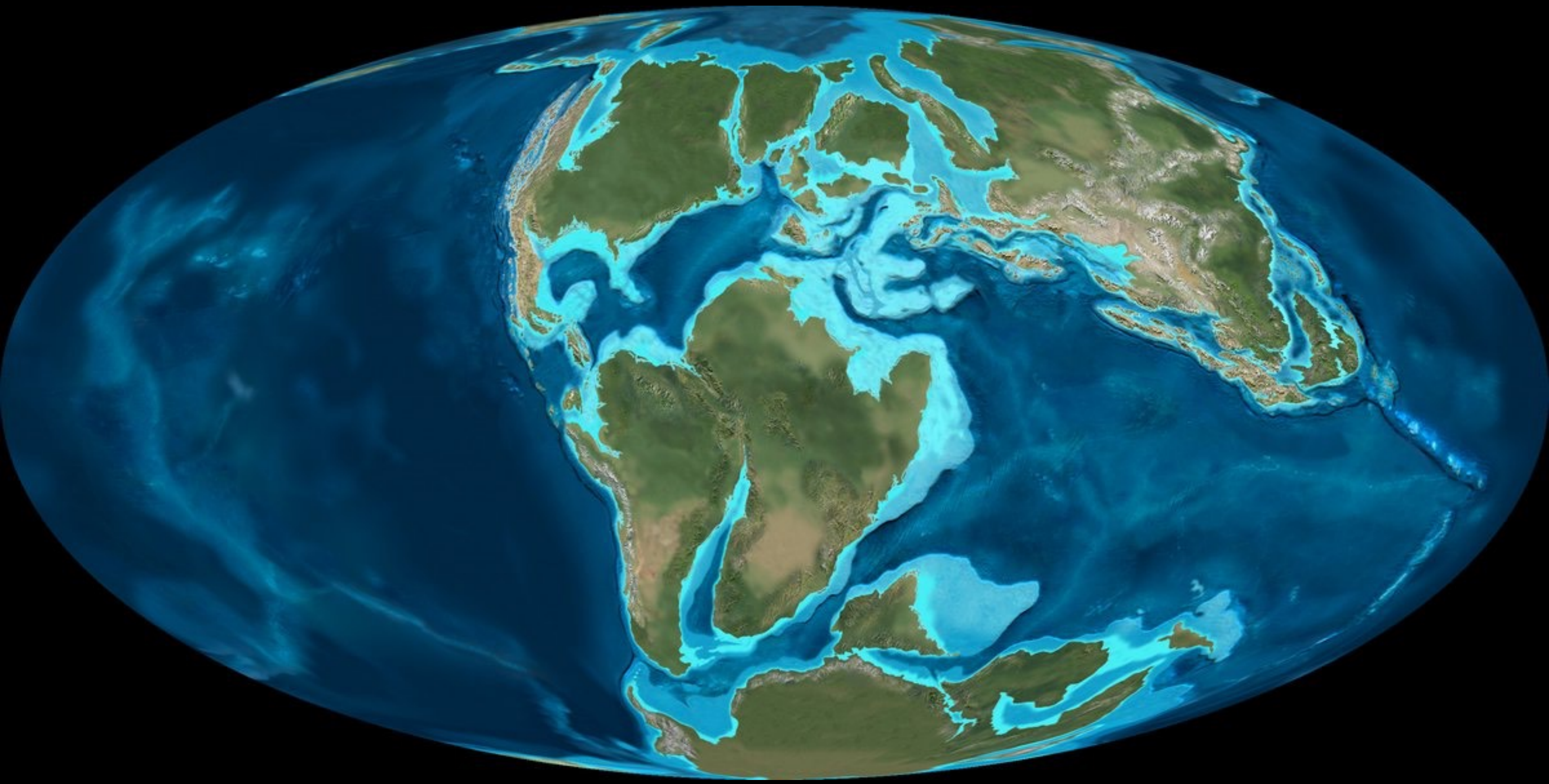
Why use biology to inspire robot design?

Boston Dynamics 2021

Insect neurobiology: an ancient puzzle

120 Million Year Old orthopteran in Brazilian limestone Grimaldi & Engel

Insect neurobiology: an ancient puzzle



Late Cretaceous period Earth (125 MYA)

https://australian.musem

Insects dominate the planet

Yet insects are on the decline

Where have all the insects gone?

Surveys in German nature reserves point to a dramatic decline in insect biomass

10 MAY 2017 • BY GRETCHEN VOGEL

Science

Why insect populations are plummeting—and why it matters

A new study suggests that 40 percent of insect species are in decline, a sobering finding that has jarred researchers worldwide.

BY **DOUGLAS MAIN**

NATIONAL GEOGRAPHIC

PUBLISHED FEBRUARY 14, 2019 • 8 MIN READ

Climate change and farming driving insect decline

BBC NEWS

20 April 2022

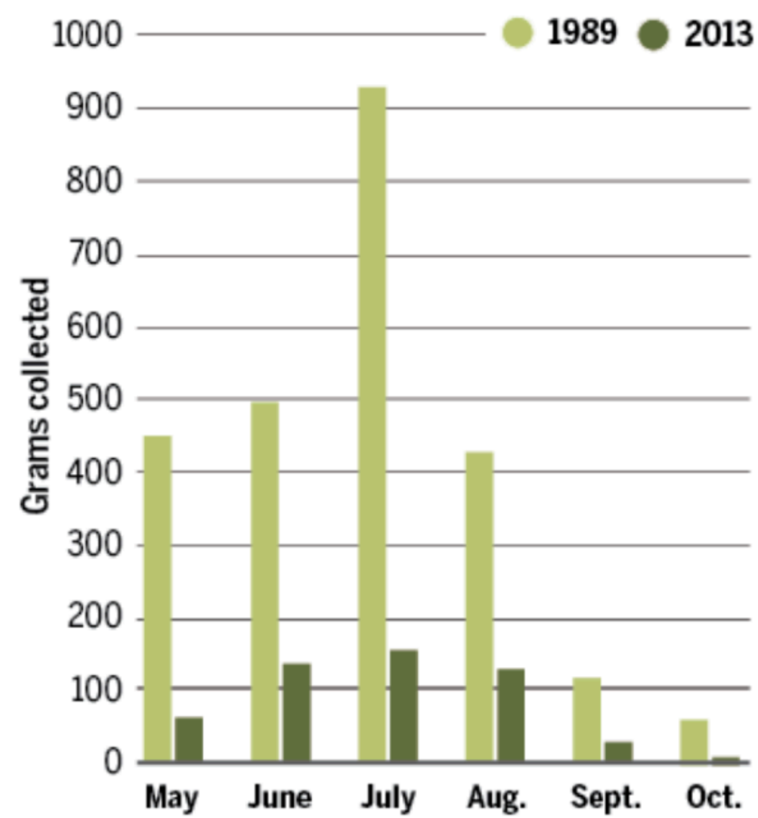
Climate change

The world's insect population is in decline — and that's bad news for humans

npr

February 24, 2022 · 1:09 PM ET
Heard on Fresh Air

The mass of insects collected by monitoring traps in the Orbroicher Bruch nature reserve in northwest Germany dropped by 78% in 24 years.



How can insects inspire robot design?

SCIENCE ROBOTICS | REVIEW

ARTIFICIAL INTELLIGENCE

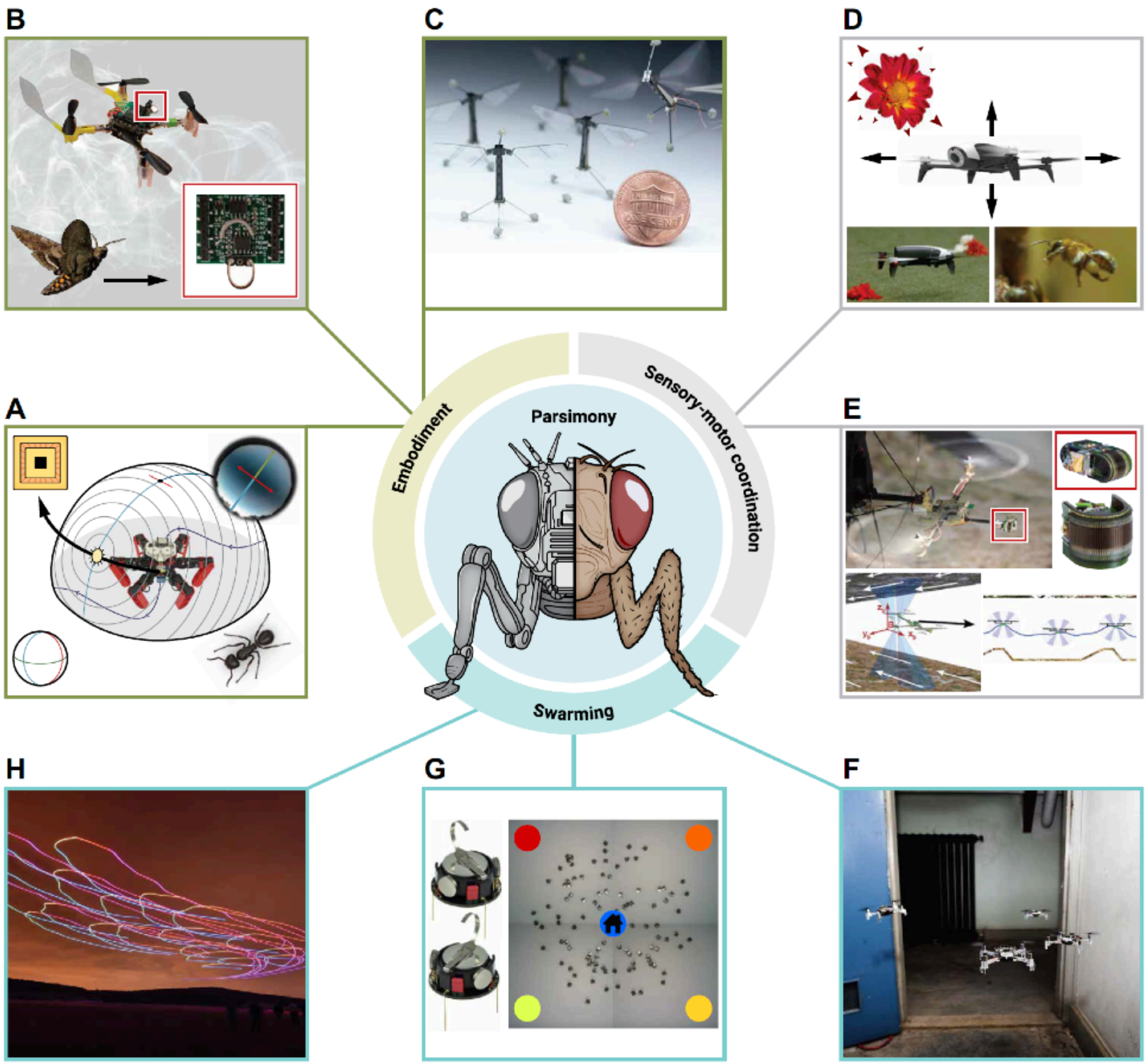
Insect-inspired AI for autonomous robots

G. C. H. E. de Croon[1]*, J. J. G. Dupeyroux[1], S. B. Fuller[2], J. A. R. Marshall[3,4]

Autonomous robots are expected to perform a wide range of sophisticated tasks in complex, unknown environments. However, available onboard computing capabilities and algorithms represent a considerable obstacle to reaching higher levels of autonomy, especially as robots get smaller and the end of Moore's law approaches. Here, we argue that inspiration from insect intelligence is a promising alternative to classic methods in robotics for the artificial intelligence (AI) needed for the autonomy of small, mobile robots. The advantage of insect intelligence stems from its resource efficiency (or parsimony) especially in terms of power and mass. First, we discuss the main aspects of insect intelligence underlying this parsimony: embodiment, sensory-motor coordination, and swarming. Then, we take stock of where insect-inspired AI stands as an alternative to other approaches to important robotic tasks such as navigation and identify open challenges on the road to its more widespread adoption. Last, we reflect on the types of processors that are suitable for implementing insect-inspired AI, from more traditional ones such as microcontrollers and field-programmable gate arrays to unconventional neuromorphic processors. We argue that even for neuromorphic processors, one should not simply apply existing AI algorithms but exploit insights from natural insect intelligence to get maximally efficient AI for robot autonomy.

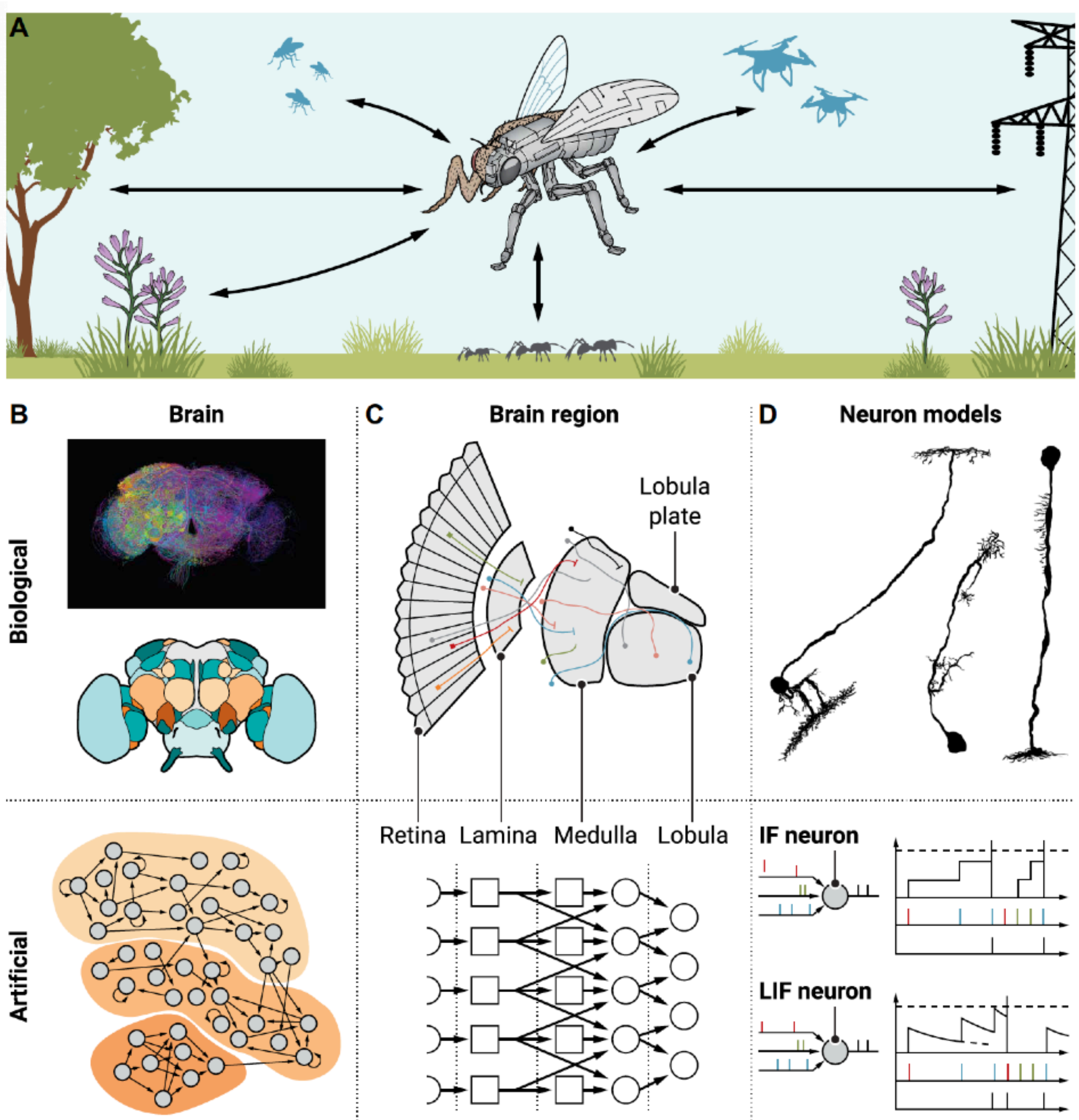
de Croon et al., *Science Robotics*, 2022

How can insects inspire robot design?



de Croon et al., *Science Robotics*, 2022

How can insects inspire robot design?



de Croon et al., *Science Robotics*, 2022

How can insects inspire robot design?

Smart prosthetics

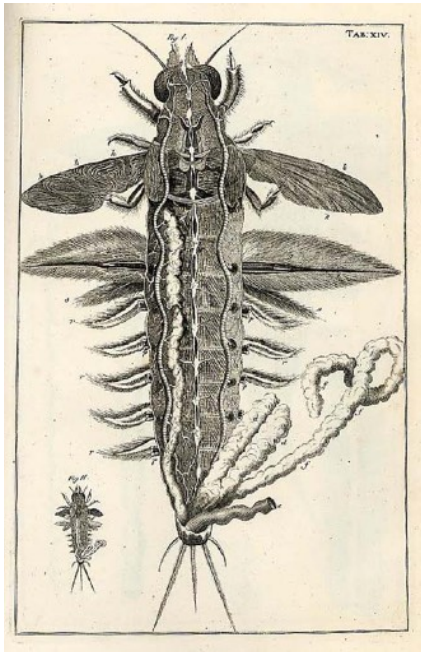
Industrial robots

Atutonomous robots

How can insects inspire robot design?

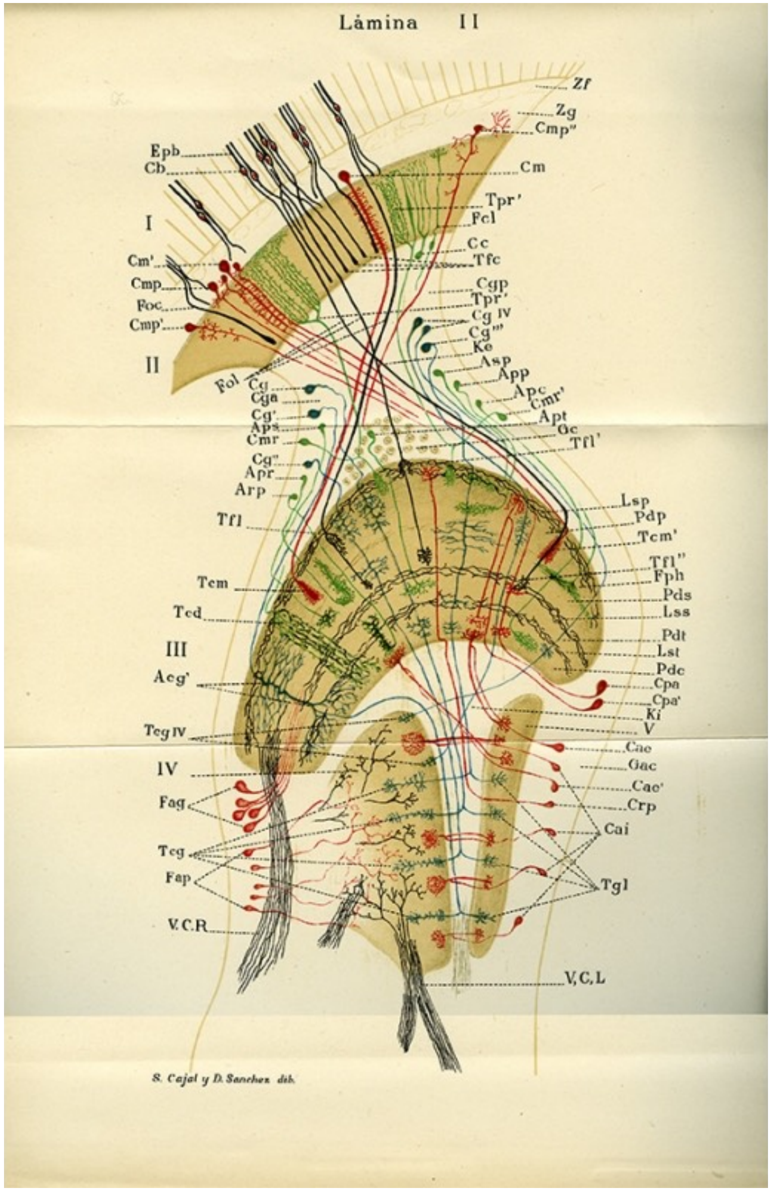
Insect biodiversity project

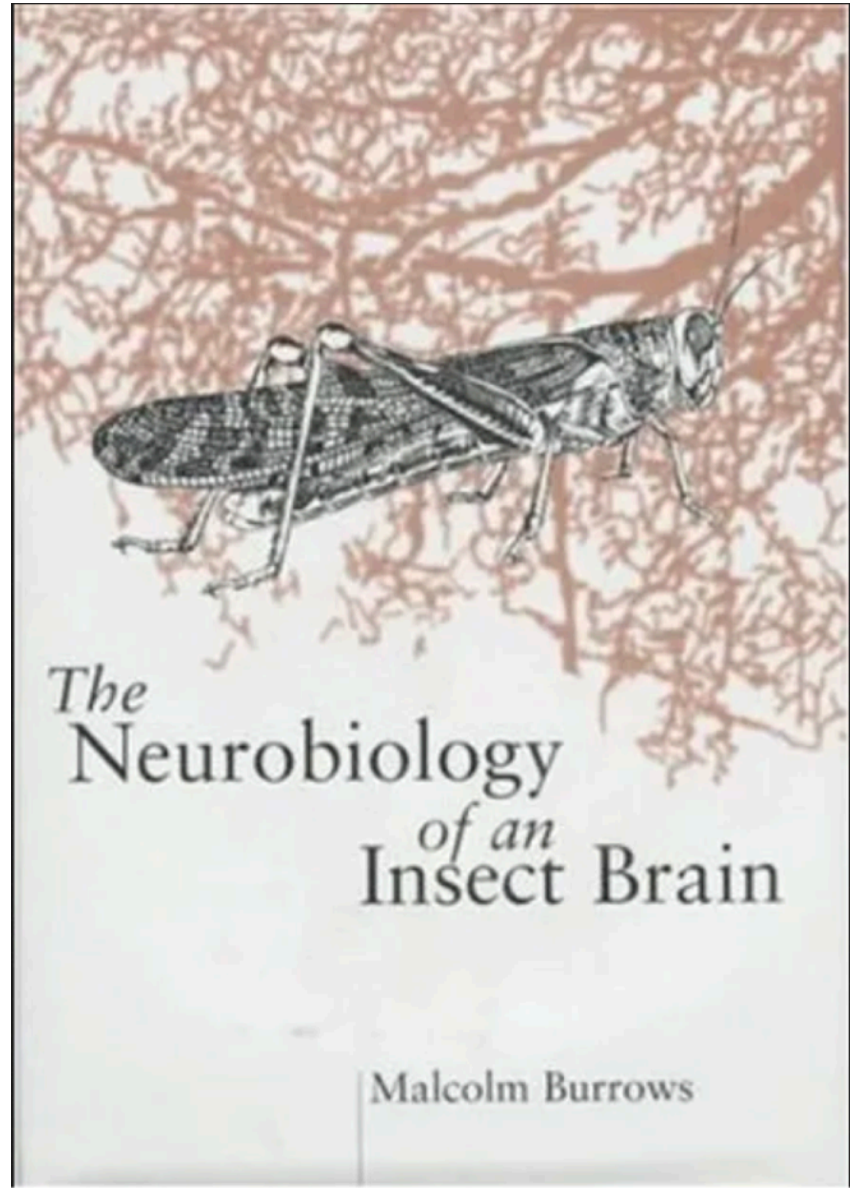
Insects have been studied for centuries



Swammerdam's Historia Insectorum Generalis (1685)

Insects have been studied for centuries





Santiago Ramón y Cajal

Burrows and others

Insects have inspired robotic control approaches

A neuromechanical simulation of insect walking and transition to turning of the cockroach *Blaberus discoidalis*

Nicholas S. Szczecinski · Amy E. Brown · John A. Bender · Roger D. Quinn · Roy E. Ritzmann

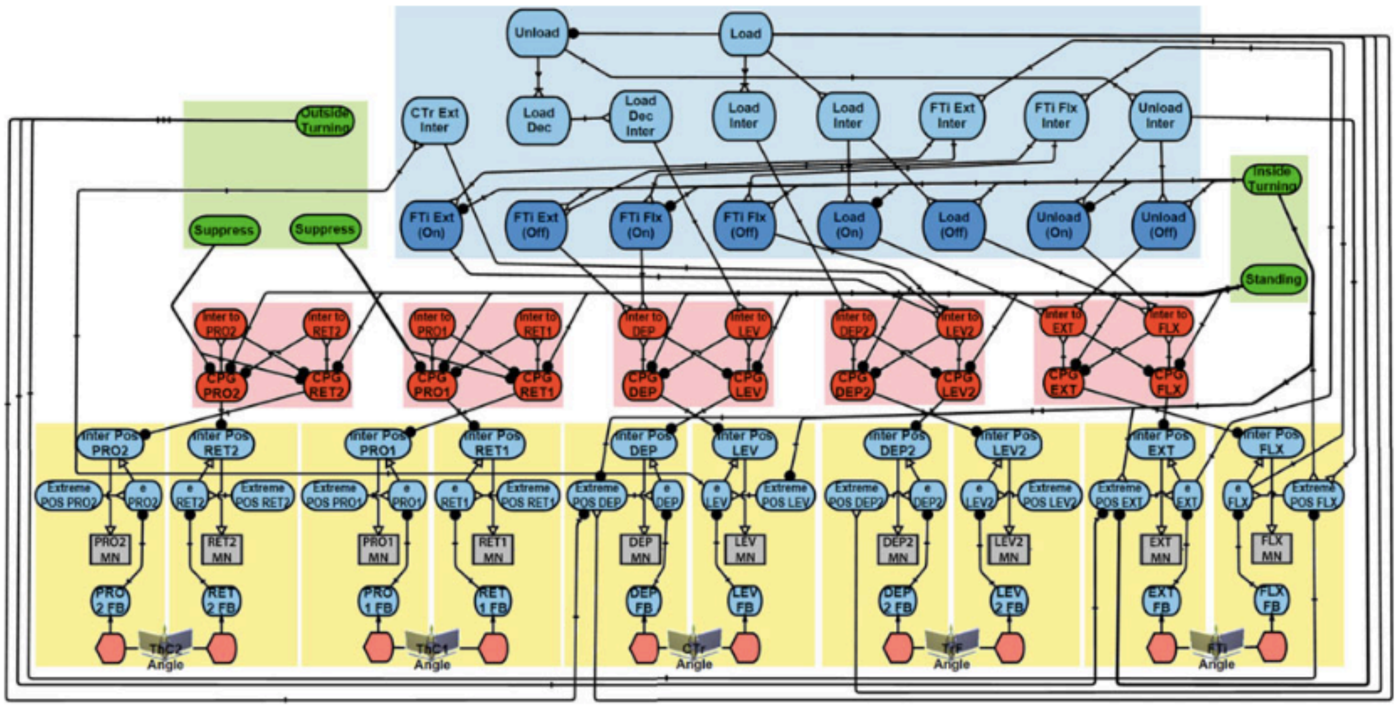
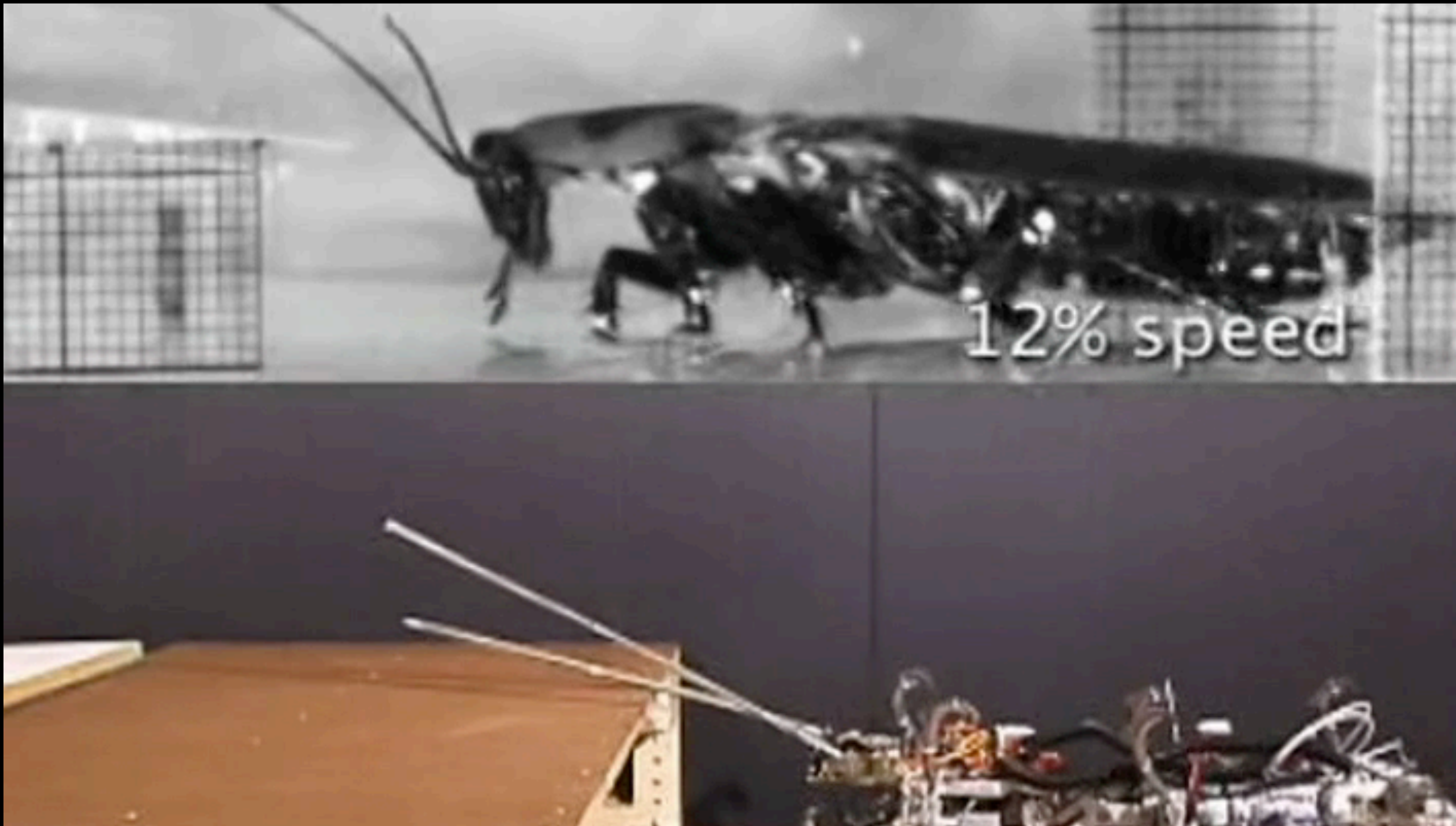


Fig. 1 Low-level network used to control stepping in the middle leg. Sensory information is encoded in sensory neurons (*blue highlighting*). These influence CPG timing at each joint (*red*) to coordinate stepping. CPGs change the gain of muscle control comparators (*yellow*), generating oscillatory motion. The context neurons (*green*) can influence sensory interneurons (*dark blue*) to reverse reflexes and transition to turning. The details of the network function are provided in the text (color figure online)

Szczecinski et al., Biol Cyber 2013

Insects have inspired robotic control approaches



Cockroach vs. Quinn's Whegs II robot

Which insect species should we reverse engineer?

reverse engineer verb

Save Word

reverse engineered; reverse engineering; reverse engineers

Definition of *reverse engineer*

transitive verb

: to disassemble and examine or analyze in detail (a product or device) to discover the concepts involved in manufacture usually in order to produce something similar

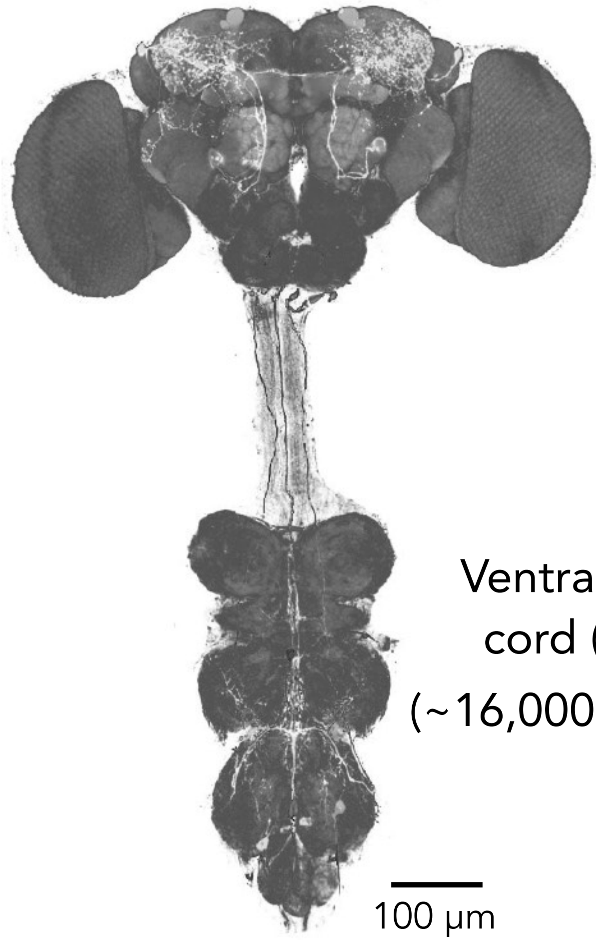
Merriam-Webster Dictionary

Adult flies generate complex behaviors

PBS Digital Studios - Deep Look

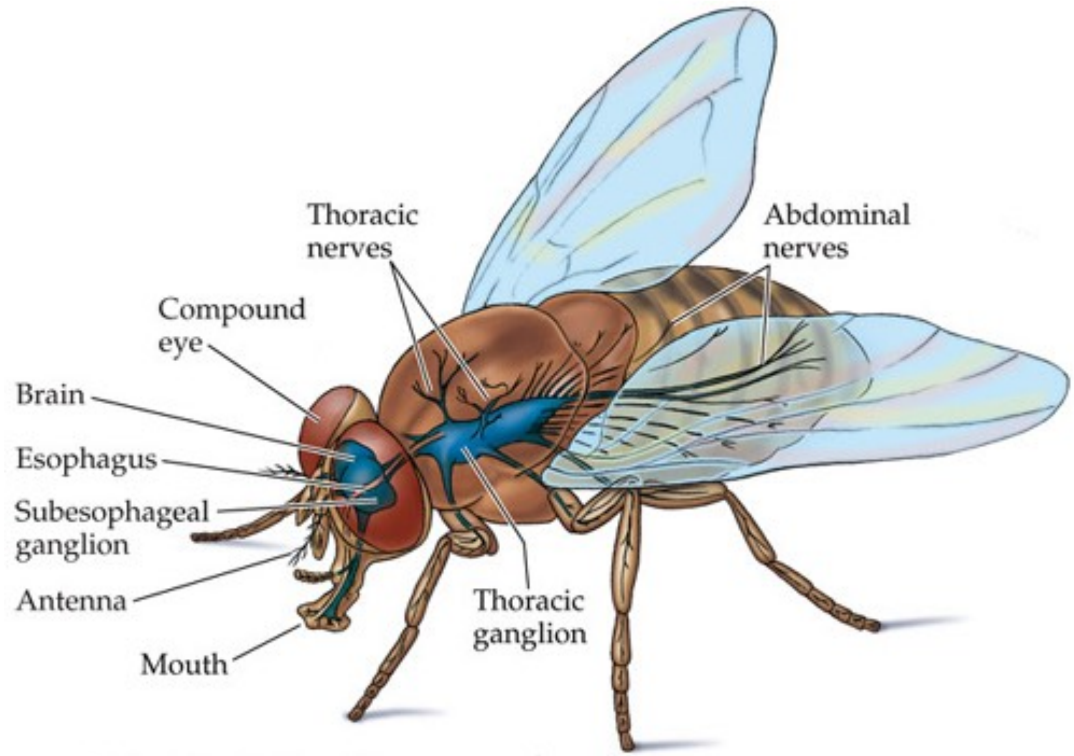
A small and compact nervous system

Brain (~10^5 neurons)



Ventral nerve cord (VNC)

(~16,000 neurons)



Chang & Shih, 2011

Breedlove & Watson, 2013

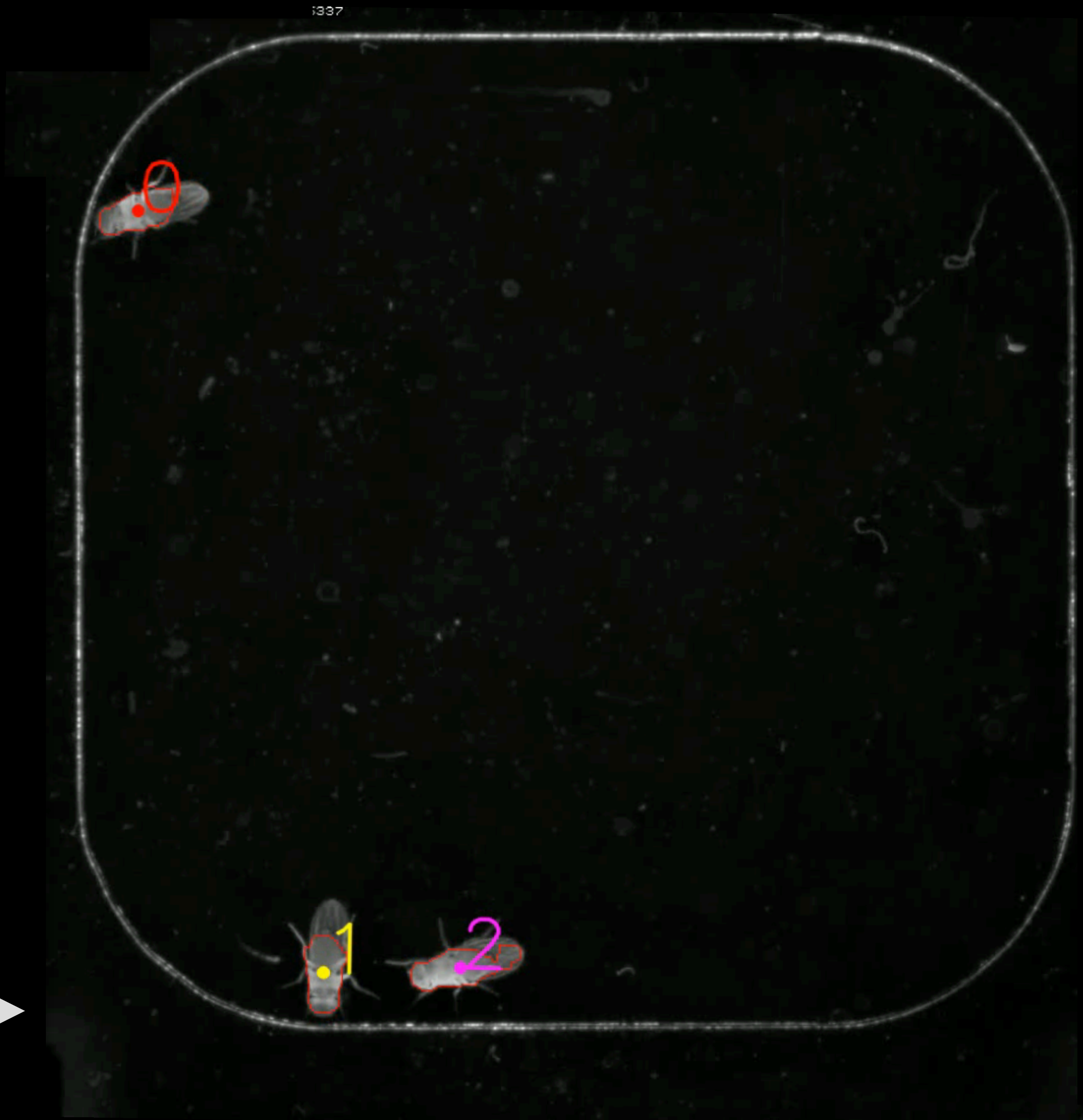
A long history of building genetic tools

Thomas Hunt Morgan laboratory, Columbia University ~1920

Genetic targeting of identifiable cells across animals

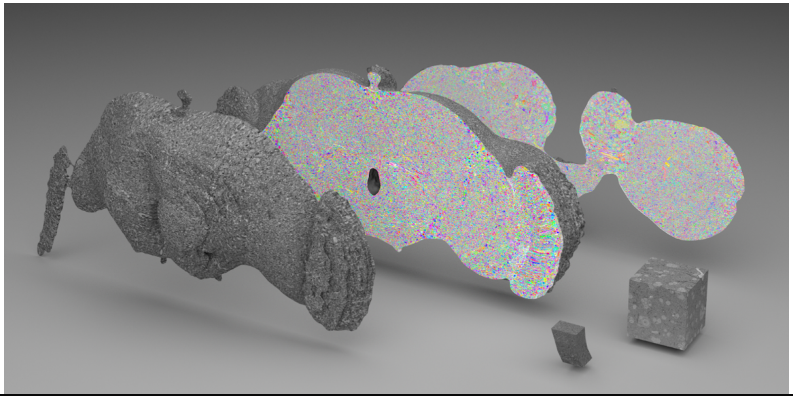
Moonwalker Descending Neurons (4)

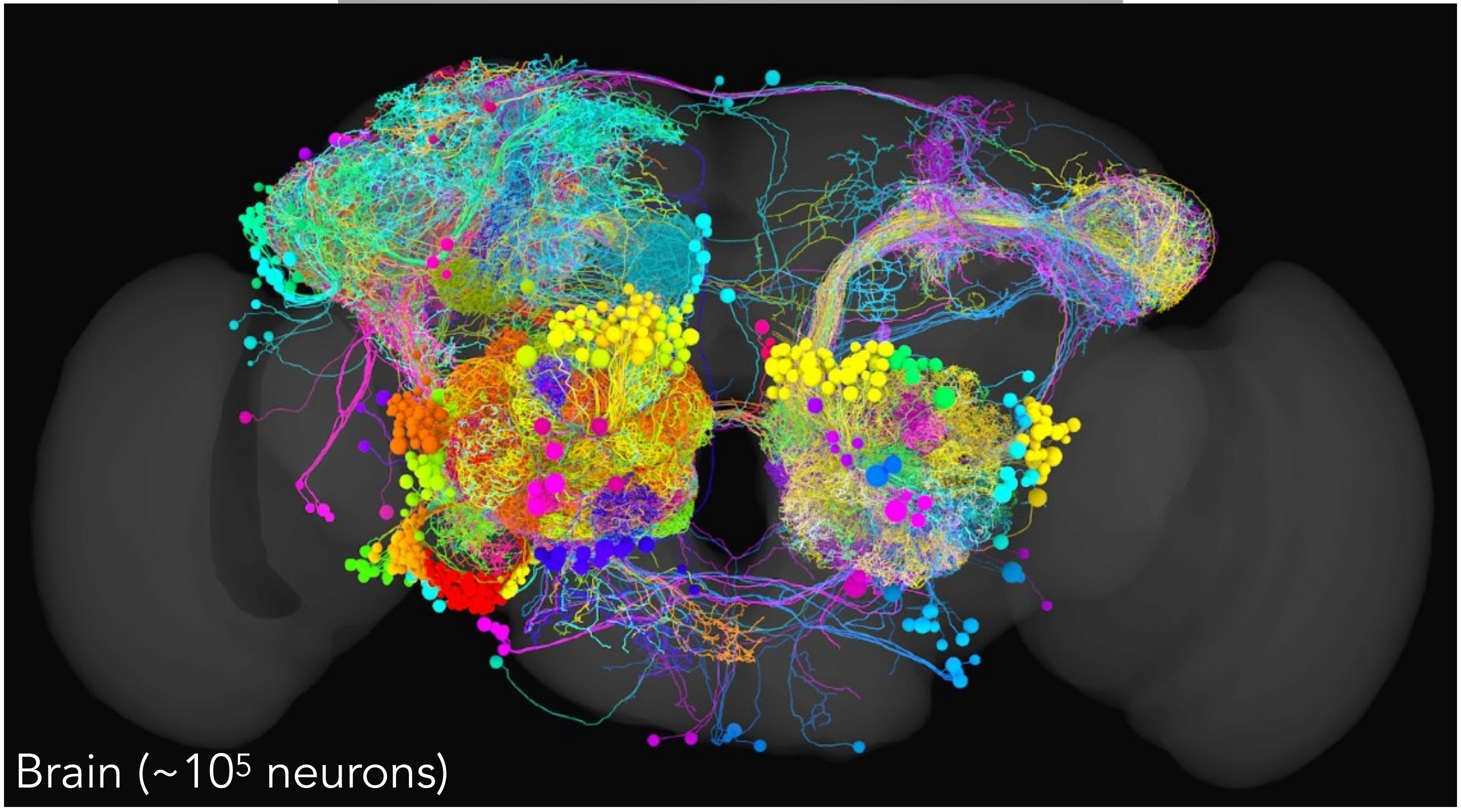
Optogenetic activation of identifiable neurons



Light ON =
neurons activated

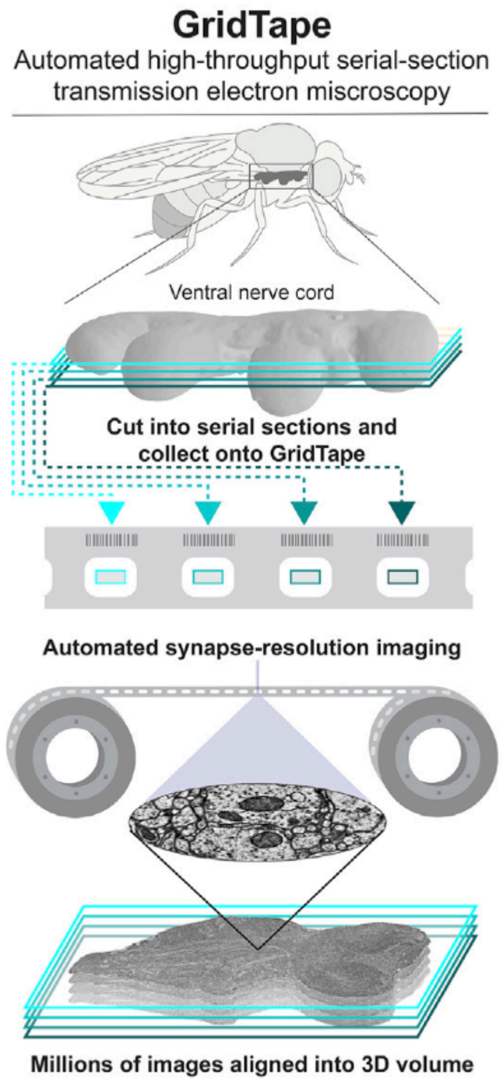
Drosophila brain connectome



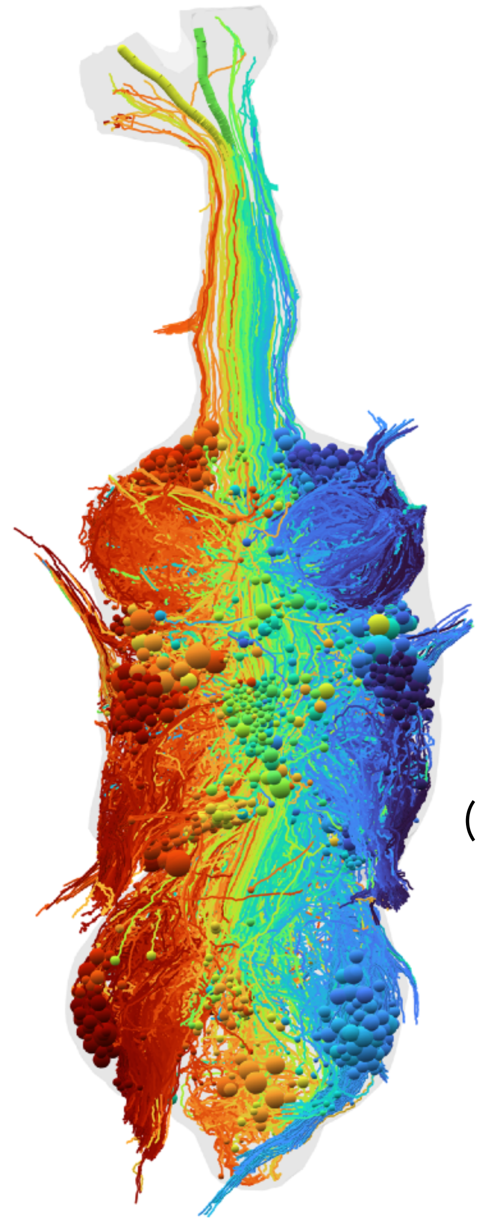


HHMI Janelia Research Campus, LMB Cambridge, Oxford, Google

Drosophila motor system (VNC) connectome



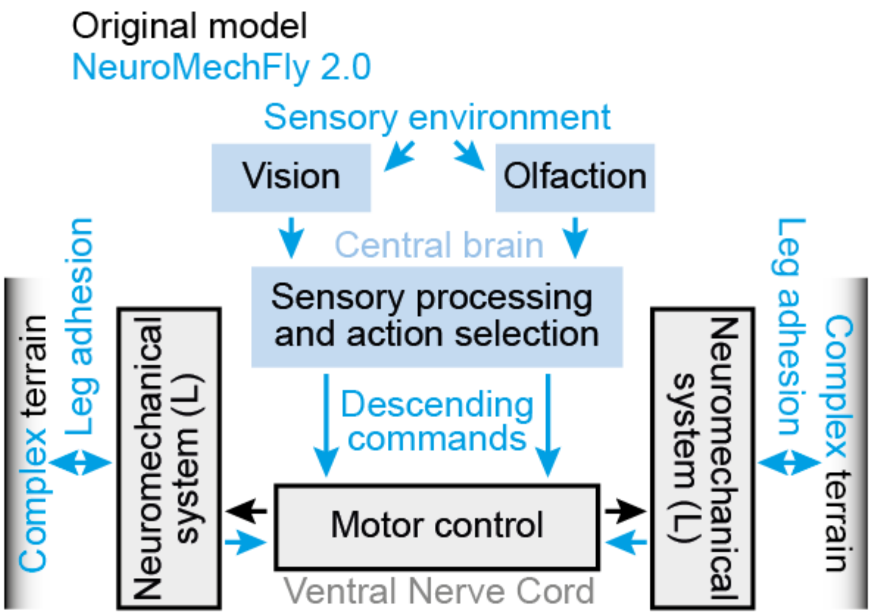
Phelps et al. *Cell* 2021

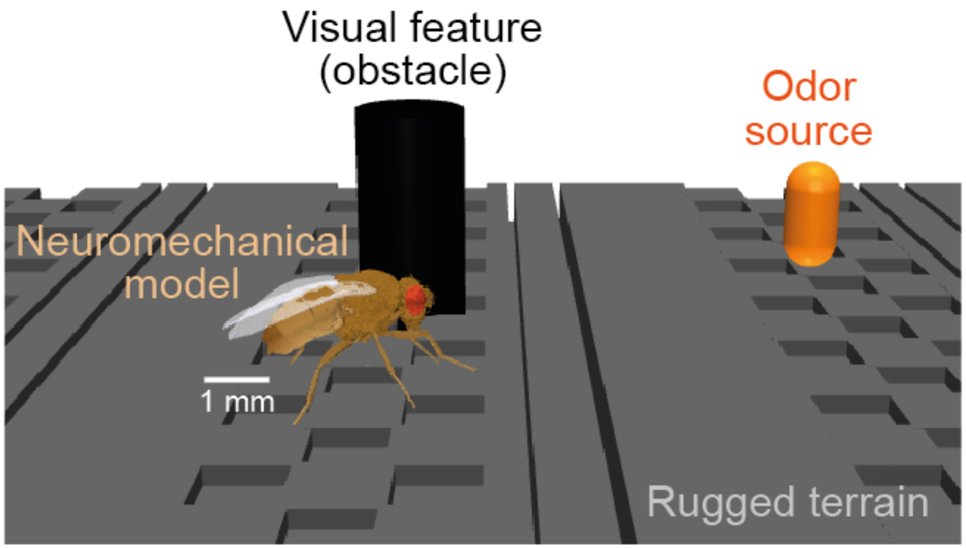


Ventral nerve cord (VNC) (~16,000 neurons)

J. Phelps

NeuroMechFly forms the basis for whole-organism simulation





www.neuromechfly.org

Wang-Chen et al., *Nature Methods 2024*

Any questions?

Let's start the first exercises!
Getting to know NeuroMechFly