ROBOBEES

A CONVERGENCE OF BODY, BRAIN, AND COLONY

Matt Welsh
Harvard University

Northeastern
Centeye
NSF
HARVARD School of Engineering and Applied Sciences
WYSS INSTITUTE
Museum of Science

WHAT THE HECK?

THE PROBLEM

- 30% of world's food supply pollinated by honeybees
- Big problem if they go away

COLONY COLLAPSE DISORDER

"In the winter of 2006, a strange phenomenon fell upon honeybee hives across the country. Without a trace, millions of bees vanished from their hives, leaving billions of dollars of crops at risk and potentially threatening our food supply."

http://www.pbs.org/wnet/nature/episodes/silence-of-the-bees/introduction/38/

PUT ANOTHER WAY...

PUT ANOTHER WAY...

PUT ANOTHER WAY...

PUT ANOTHER WAY...

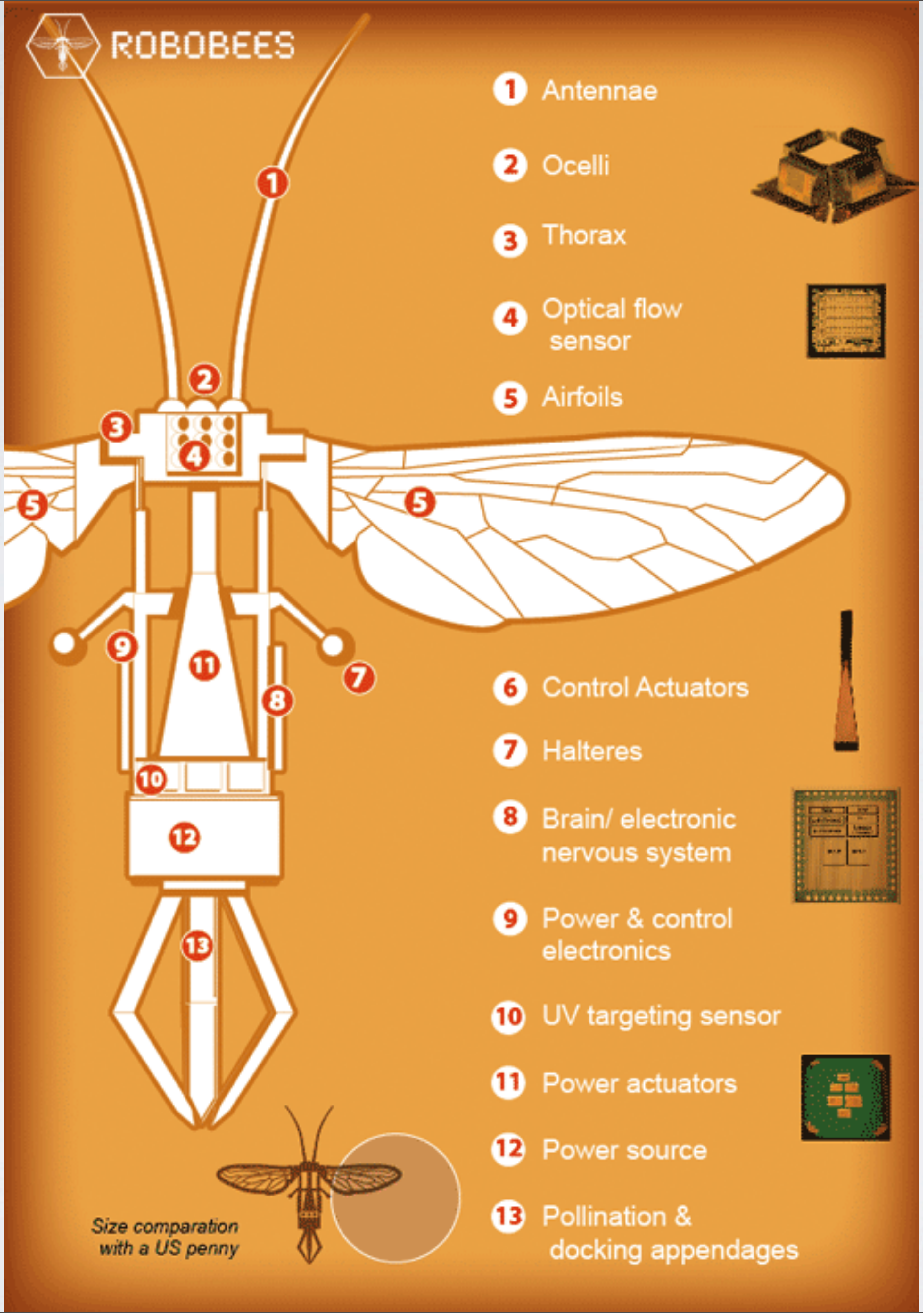
PUT ANOTHER WAY...

PUT ANOTHER WAY...

PUT ANOTHER WAY...

THE SOLUTION

- Micro-sized robotic bees!
- Funded through $10M NSF Expeditions in Computing grant
- Ten faculty at Harvard, one at Northeastern, collaborators at Centeye, Inc.
- Collaboration across many areas:
  Computer Science, Electrical Engineering, Biology, Applied Math, Mechanical Engineering


ROBOBEES
1 Antennae
2 Ocelli
3 Thorax
4 Optical flow sensor
5 Airfoils
6 Control Actuators
7 Halteres
8 Brain/ electronic nervous system
9 Power & control electronics
10 UV targeting sensor
11 Power actuators
12 Power source
13 Pollination & docking appendages
Size comparation with a US penny

THE TEAM

HARVARD
School of Engineering
and Applied Sciences

WYSS INSTITUTE

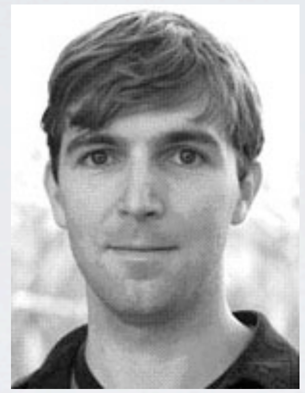
Northeastern

Centeye

Gu-Yeon Wei

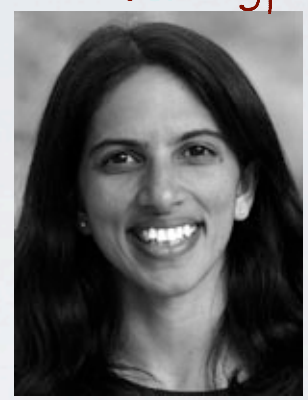
VLSI

Rob Wood



Microrobotics

Radhika Nagpal



Distributed Control

Joe Ayers

Neurobiology
Biorobotics

Stacey Combes

Insect biology

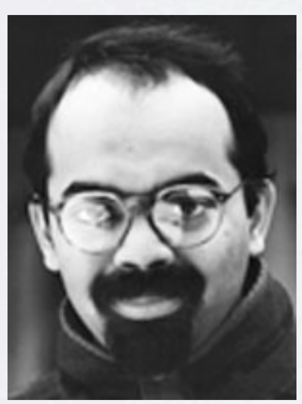
David Brooks

Low-power architecture

Programming languages

Greg Morrisett

L. Mahadevan



Bio-materials

Todd Zickler

Vision

Geof Barrows

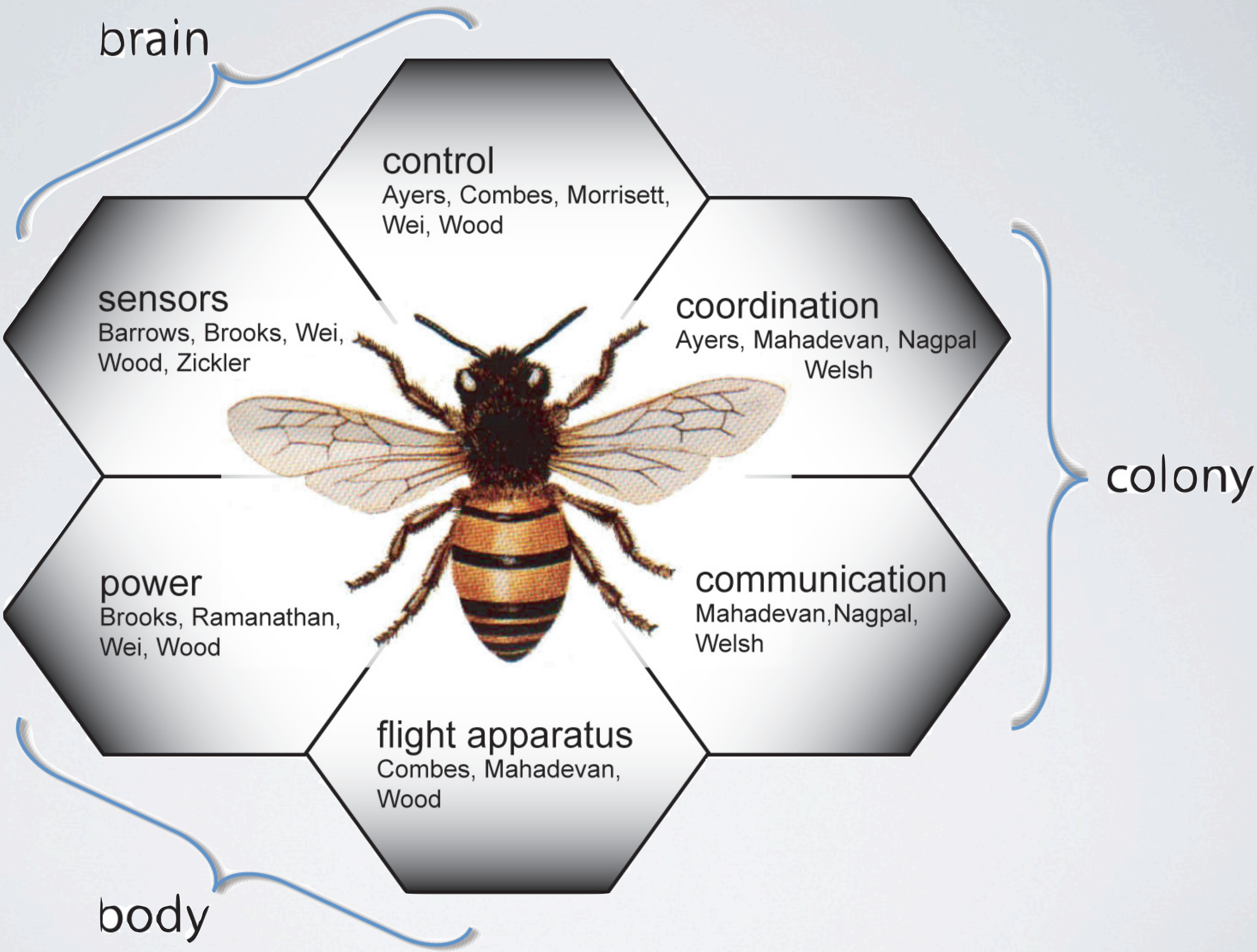
Vision sensors

Some Guy

Mascot

Micro fuel cells

Shriram Ramanathan



brain
control
Ayers, Combes, Morrisett,
Wei, Wood
sensors
Barrows, Brooks, Wei,
Wood, Zickler
coordination
Ayers, Mahadevan, Nagpal
Welsh
colony
power
Brooks, Ramanathan,
Wei, Wood
communication
Mahadevan,Nagpal,
Welsh
flight apparatus
Combes, Mahadevan,
Wood
body

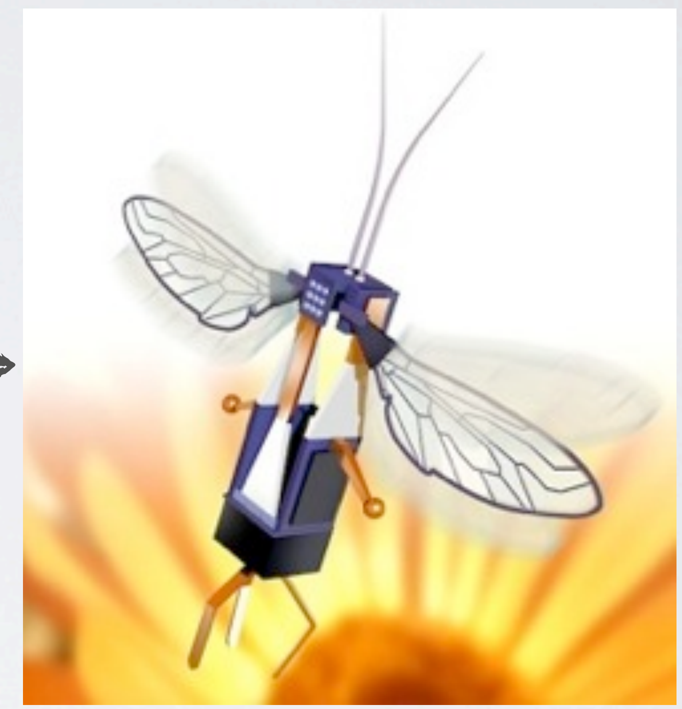
MORE THAN JUST POLLINATION

- Environmental mapping: air pollution and more
- Search and rescue
- Exploring collapsed buildings, mines, caves, volcanoes?
- "Interesting" military and surveillance applications

BIO-INSPIRATION OR BIO-MIMICRY?

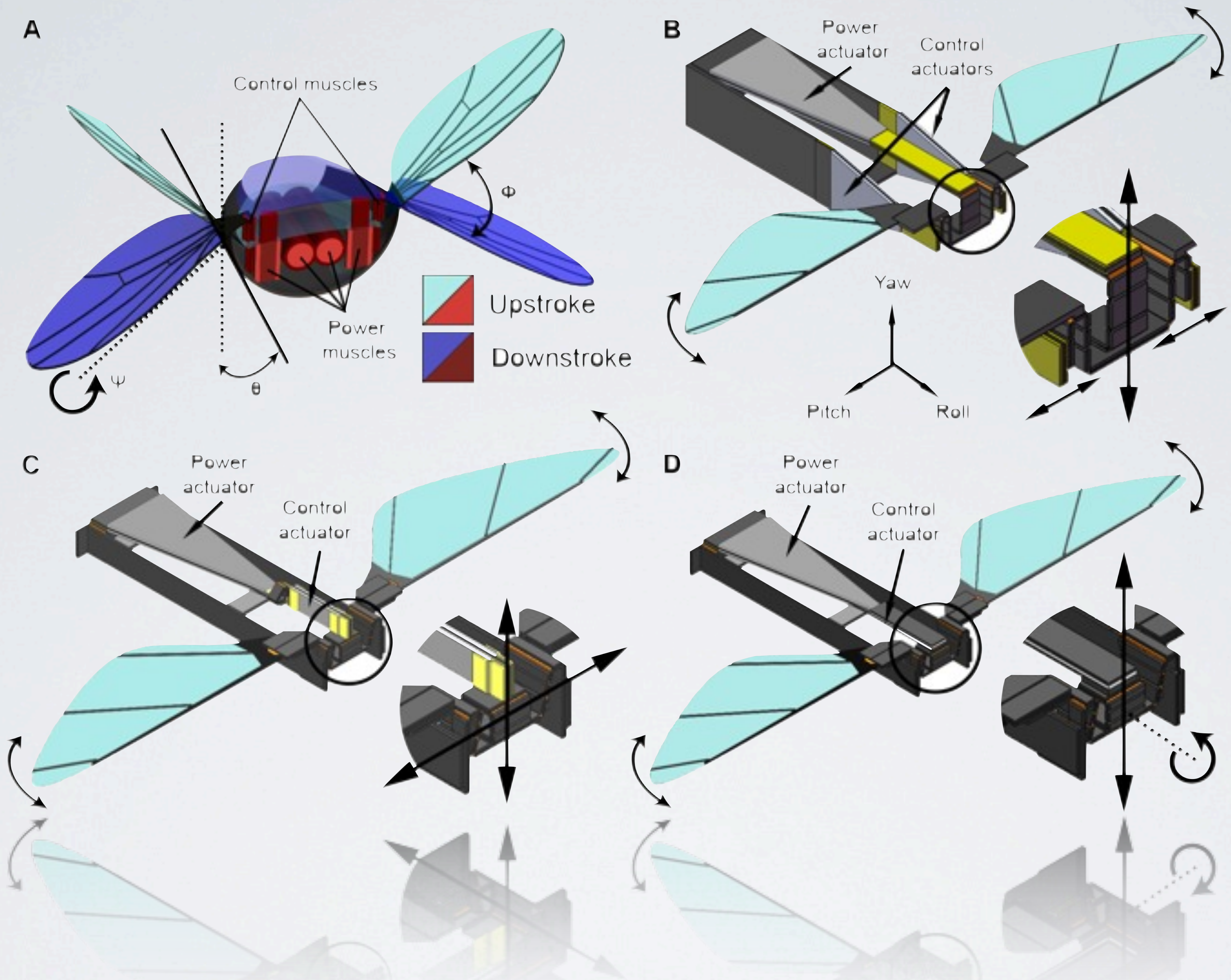
Nature

Engineering



- Build better machines by understanding nature
- Better understand nature by building machines

Chapter One: The Body



HOW DO THEY FLY?

WHY CHOOSE BEES FOR FLIGHT BIOINSPIRATION?

- High payload

  > able to carry loads ≅ body weight

- High flapping frequency (~230 Hz)*

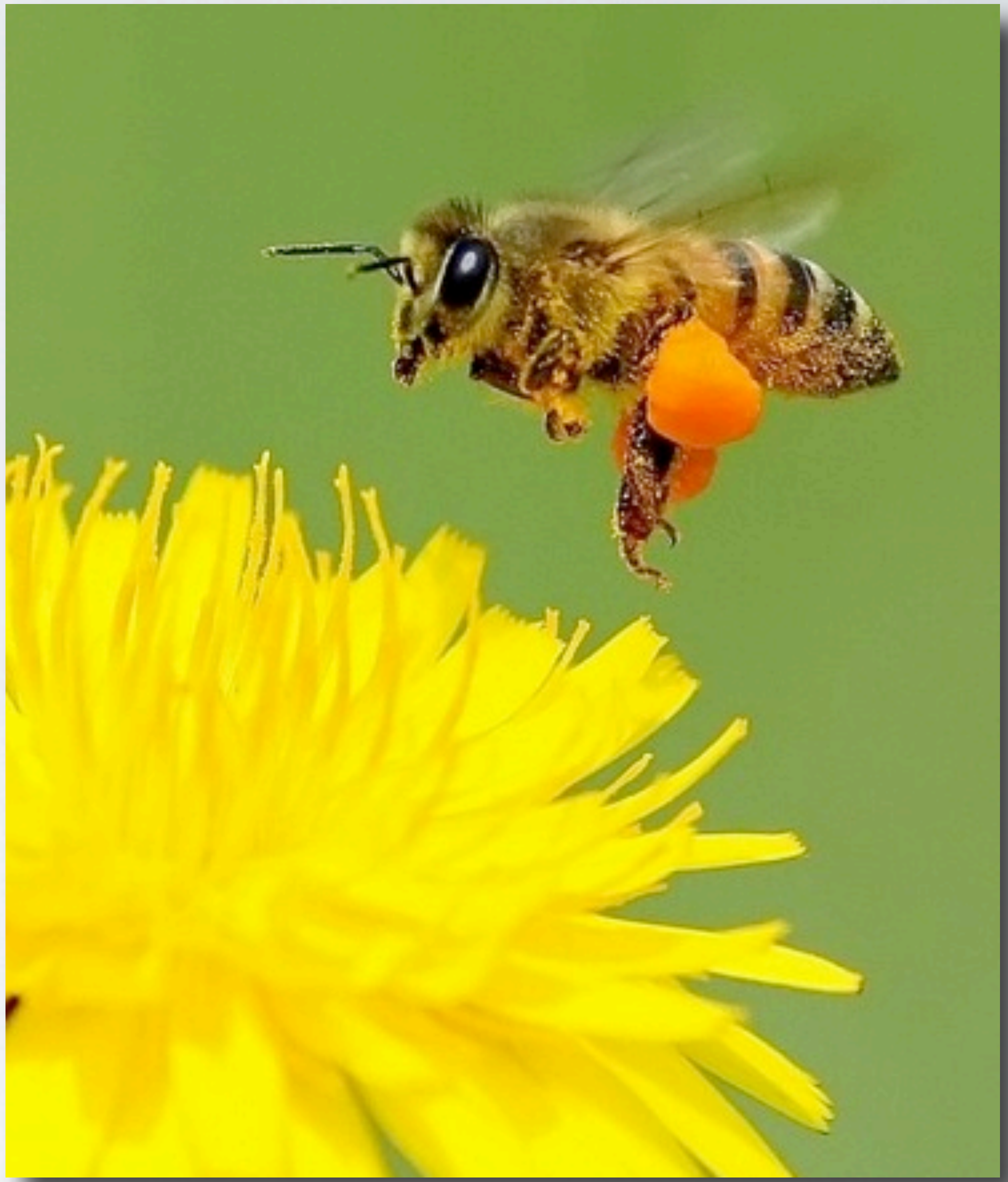
- Low stroke amplitude

  (~90° at hovering, increase up to 130°)*

- Non-wing control mechanisms

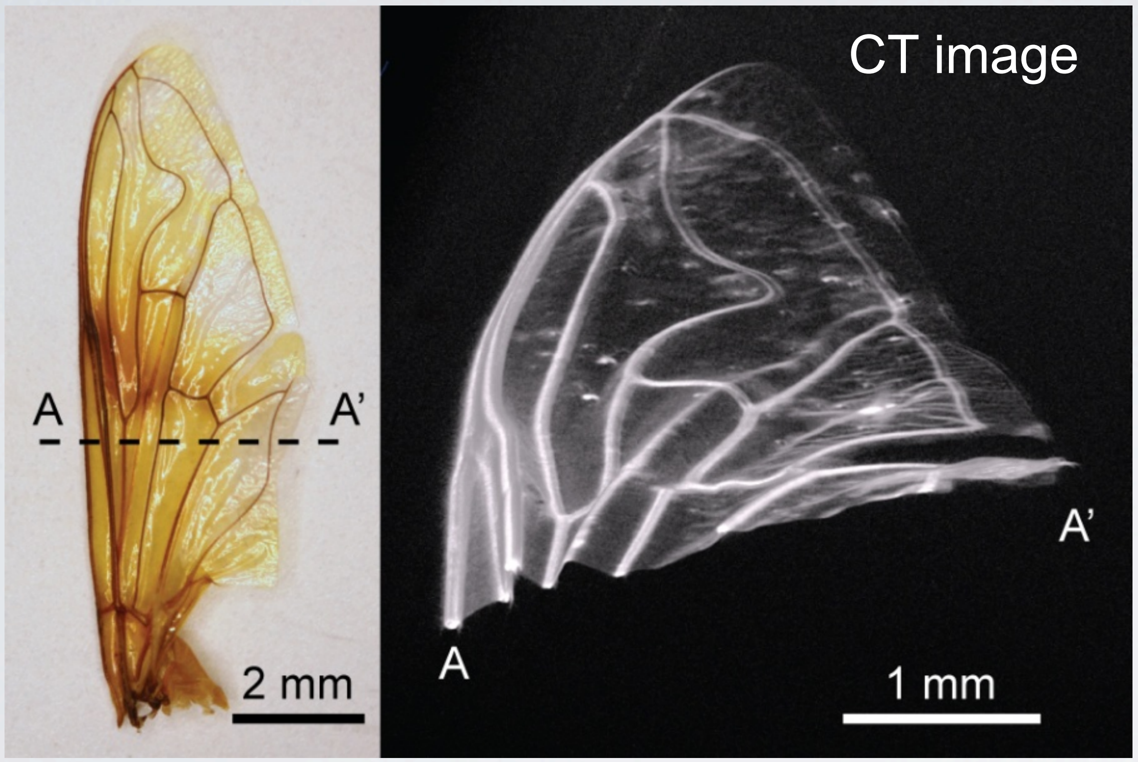
  > extend hind legs for stability†

- Able to fly in turbulent conditions†



(*Altschuler et al., 2005, *PNAS;*
†*Combes and Dudley, 2009, PNAS*)

BIOMIMETIC MICRO WINGS



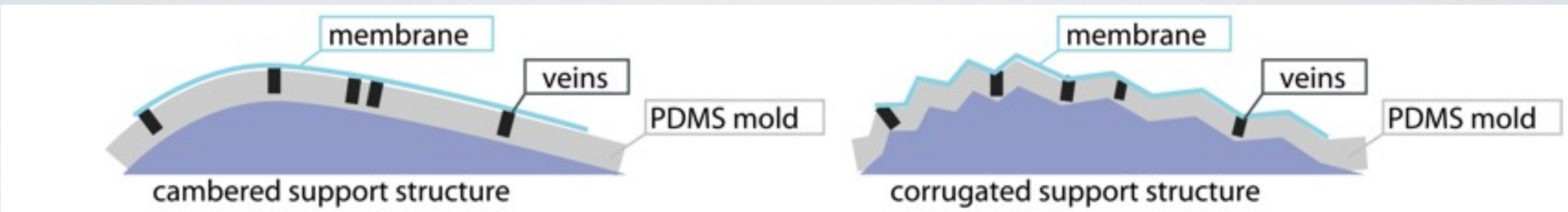
Morphology of natural wing (hover fly)


3D plastic micro wing [Tanaka *et al.*, in press]

- Engineer wings that mimic natural wing morphology
  - High stiffness, light weight, structural control of wing deformation
- Enables parametric experiments to better understand the functional morphology of insect wings

[Wood]

INSECT WING DESIGN: WING CORRUGATION



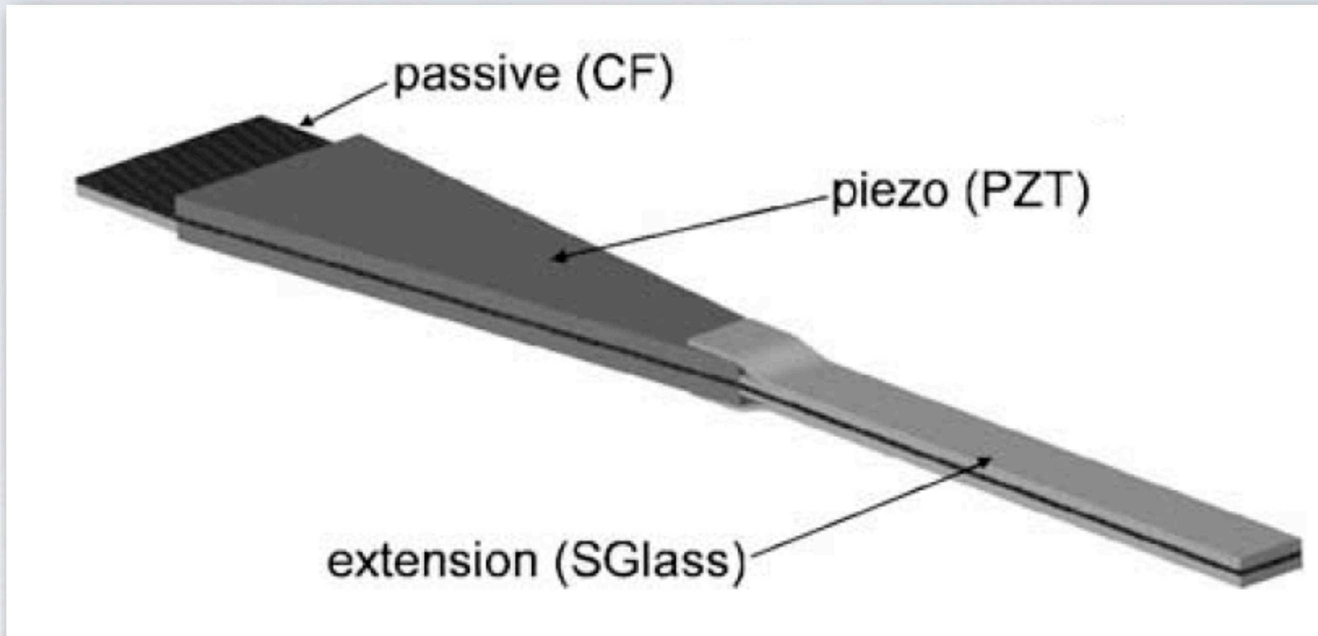
Fabrication method for cambered and/or corrugated artificial wings

- 3-D profile (e.g., corrugation, camber) affects dynamic behavior of wings

  > increases bending stiffness while minimizing weight and permitting wing torsion

[Wood]

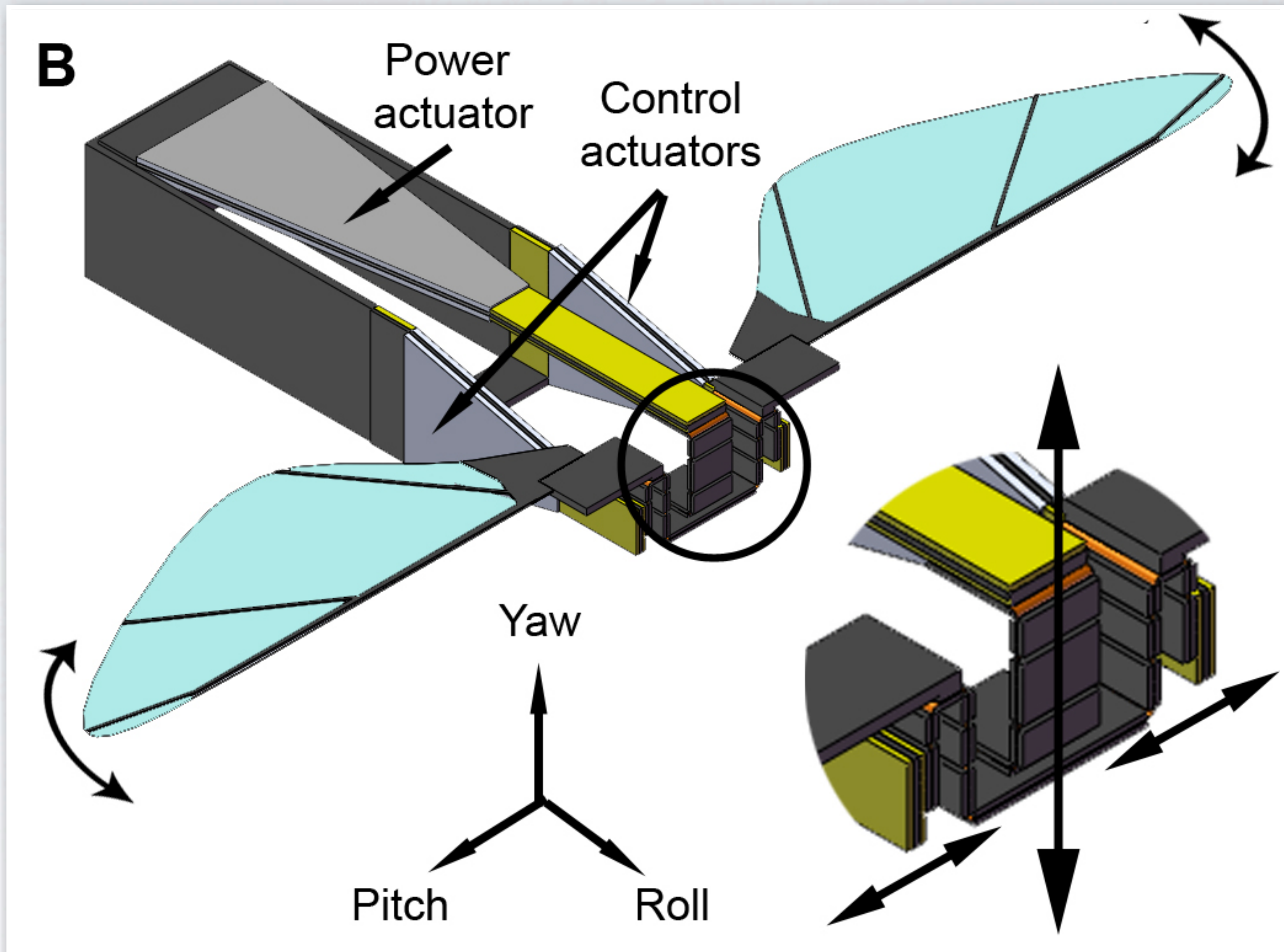
THE MUSCLE



- Piezoelectric actuator
  - 2V produces displacement of ~ 1 micron
  - Needs ~200V for flapping movement of 100 um
  - But a tiny amount of power: tens of mW

[Wood]

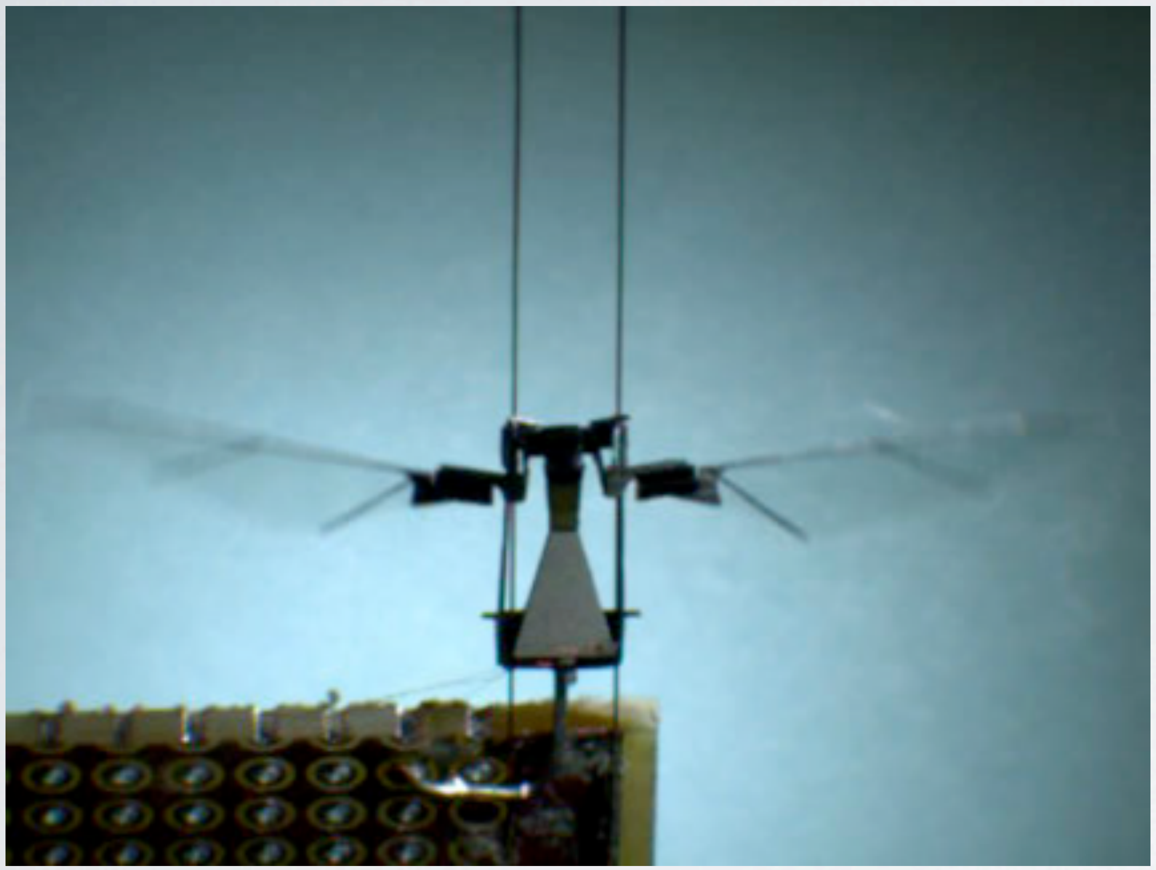
CONTROL ACTUATOR

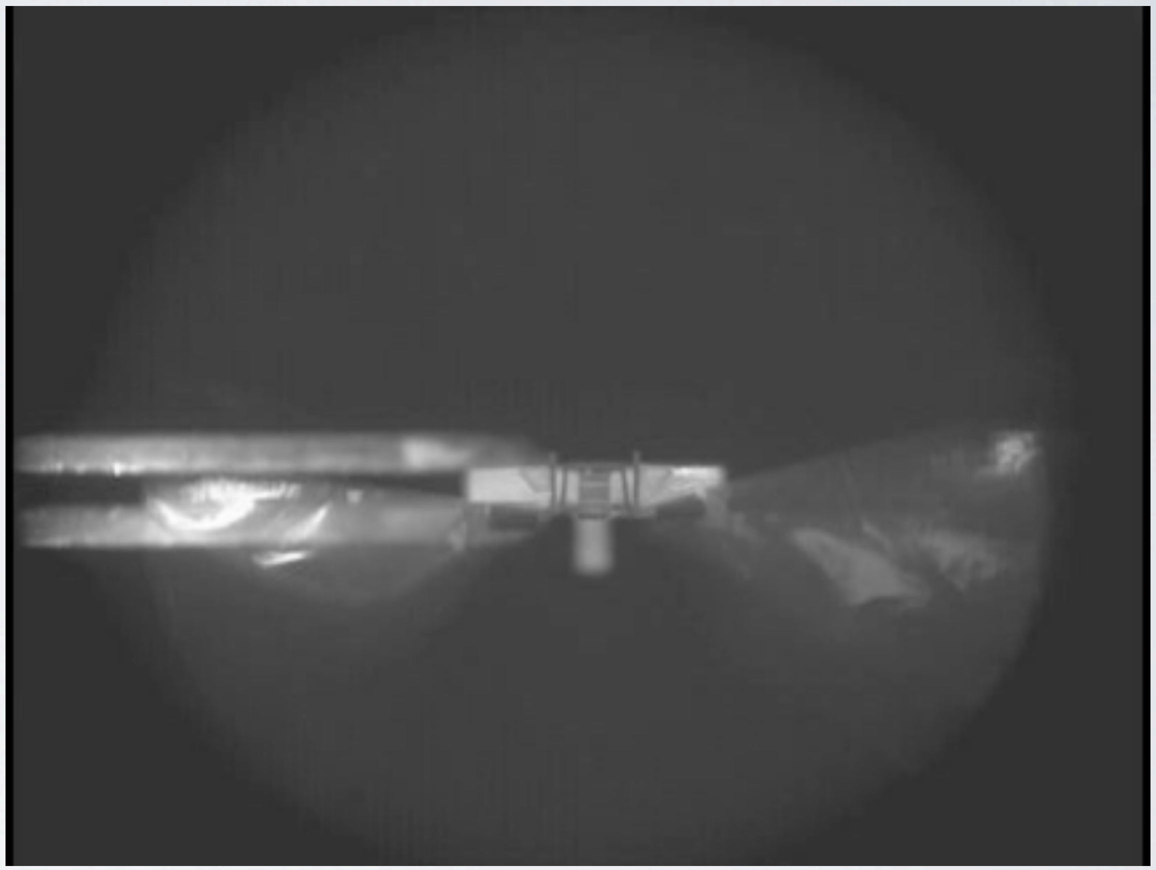


- Thoracic mechanics
  - Separate power and control actuators

[Wood]

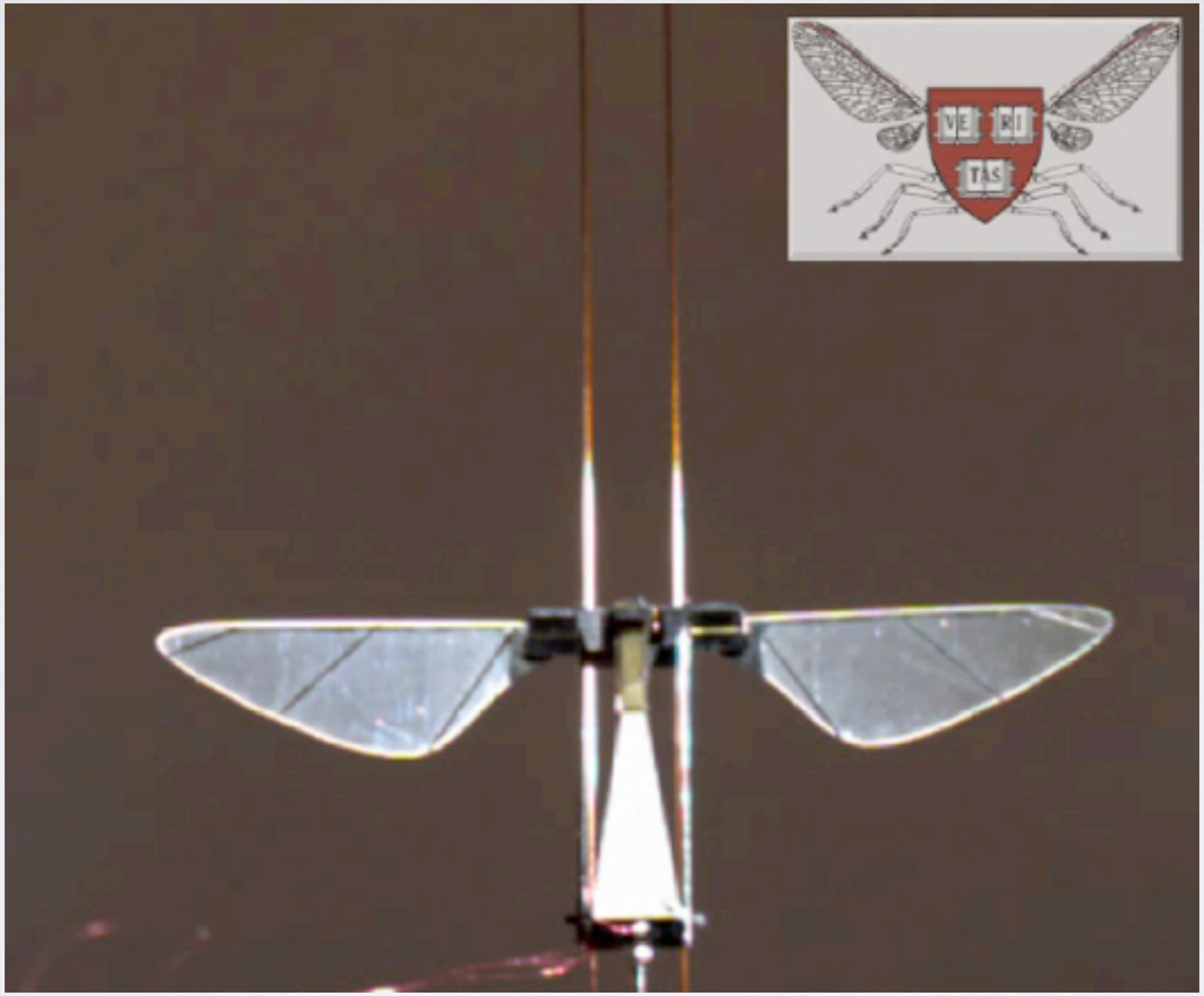
WINGS IN ACTION





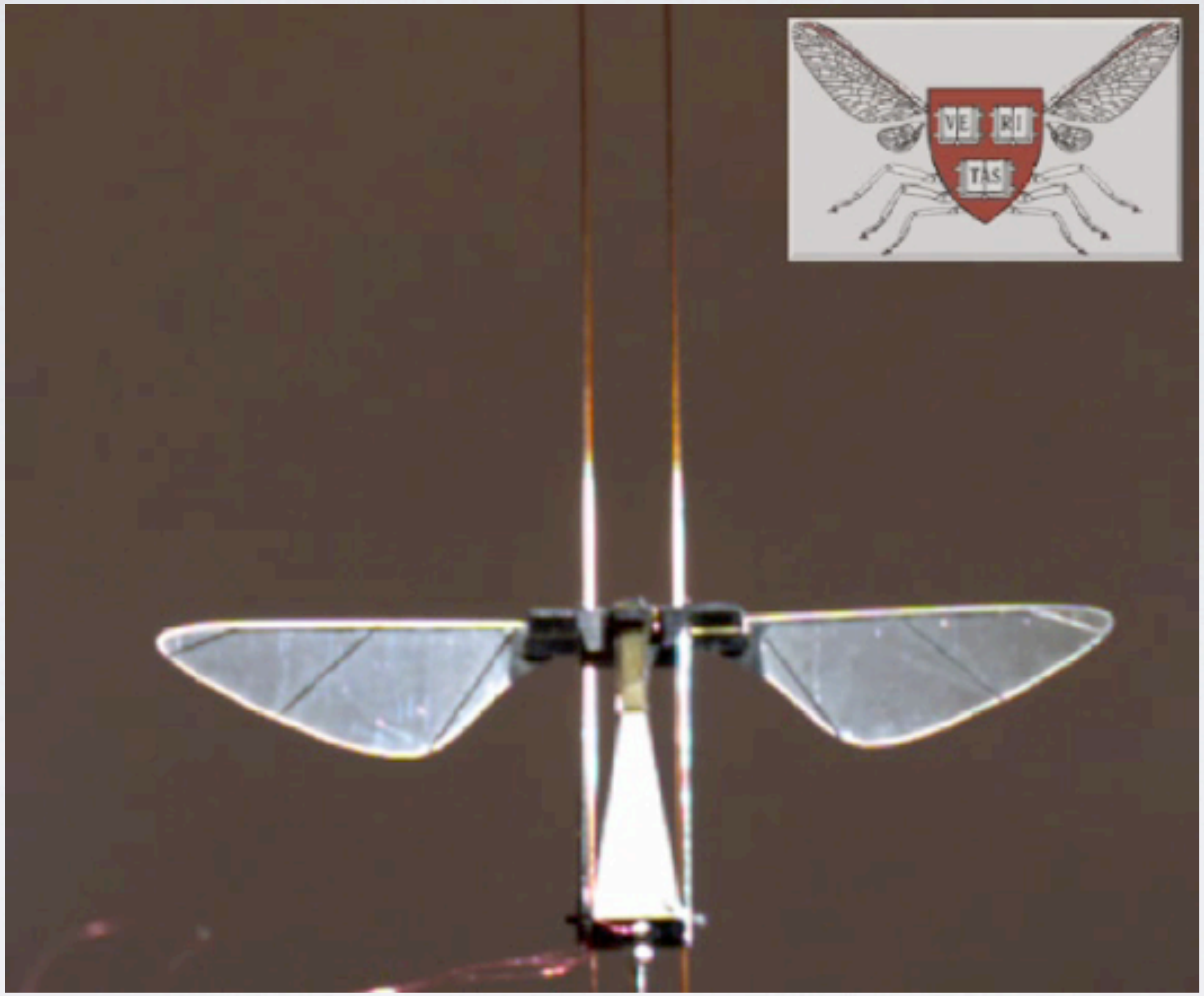
- Video is slow-mo: flapping frequency 110 Hz

FIRST TAKE-OFF



[Wood]

FIRST TAKE-OFF



- On guide wires with 1.2 kV power supply!!

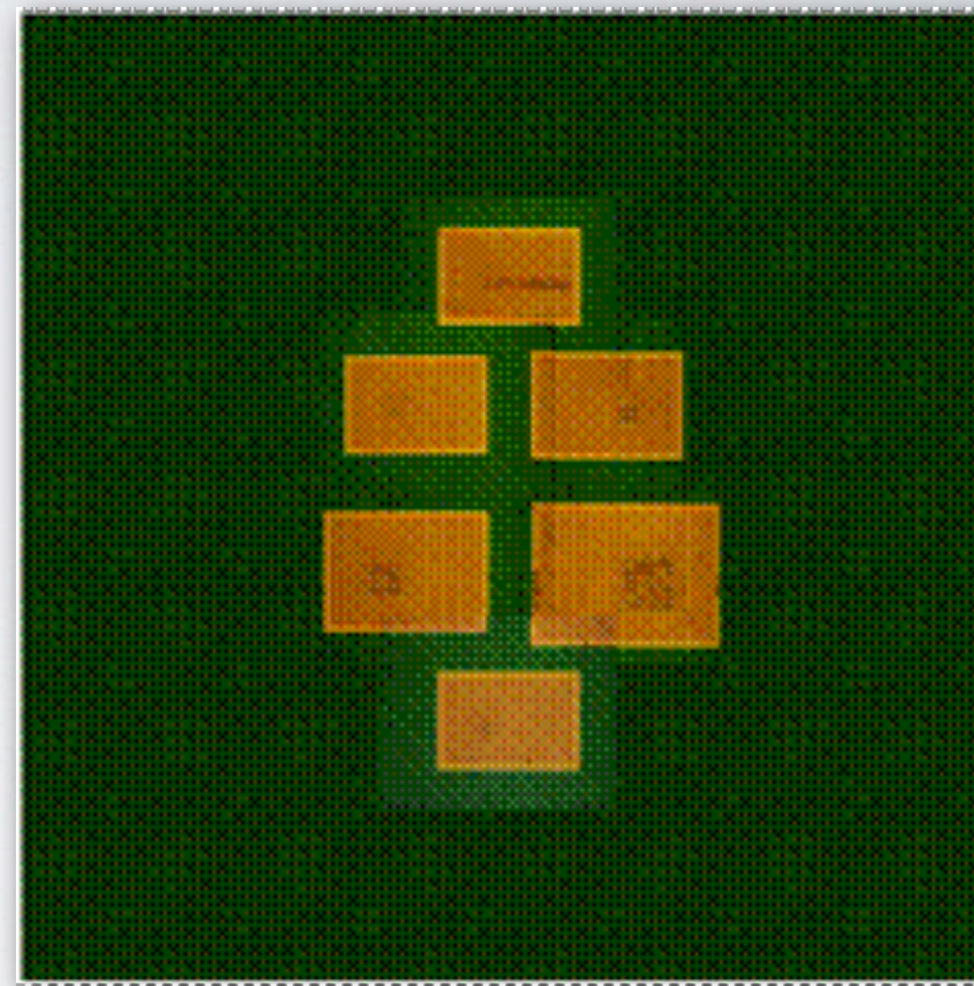
[Wood]

HOW DO THEY GET POWER?

THIN FILM MICRO-FUEL CELLS

Westinghouse SOFC

?

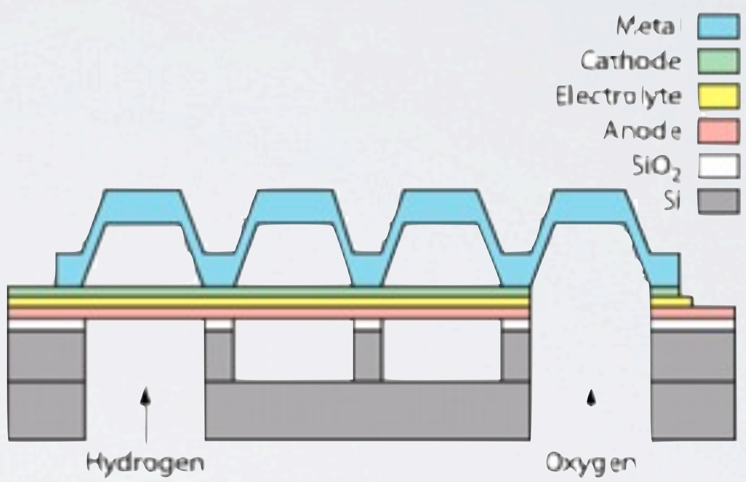


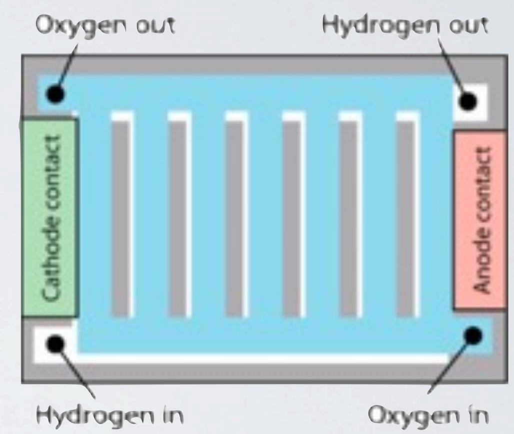
Johnson and Ramanathan, 2007

[Ramanathan]

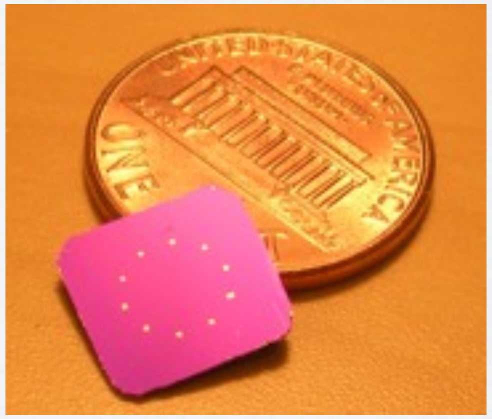
POTENTIAL FOR MICRO FUEL CELLS

- Current limitations:
  Requires hydrogen fuel
  Operate at 200-500 °C
  Power output
  ~100 mW/cm^2

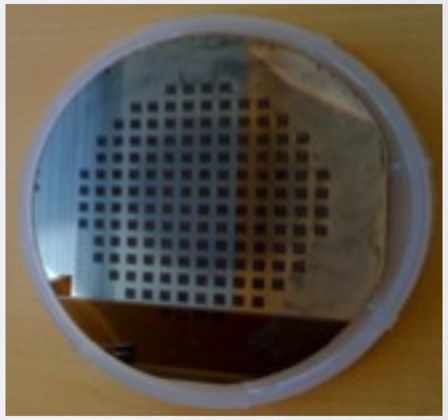




- Future goals:
  Continuous power generation, 1W, breathe air, ambient conditions!



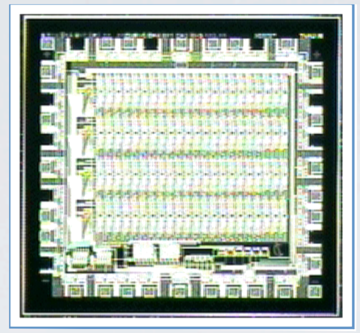
SOFC arrays

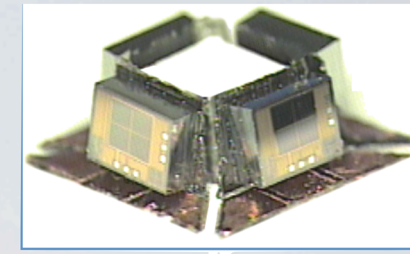


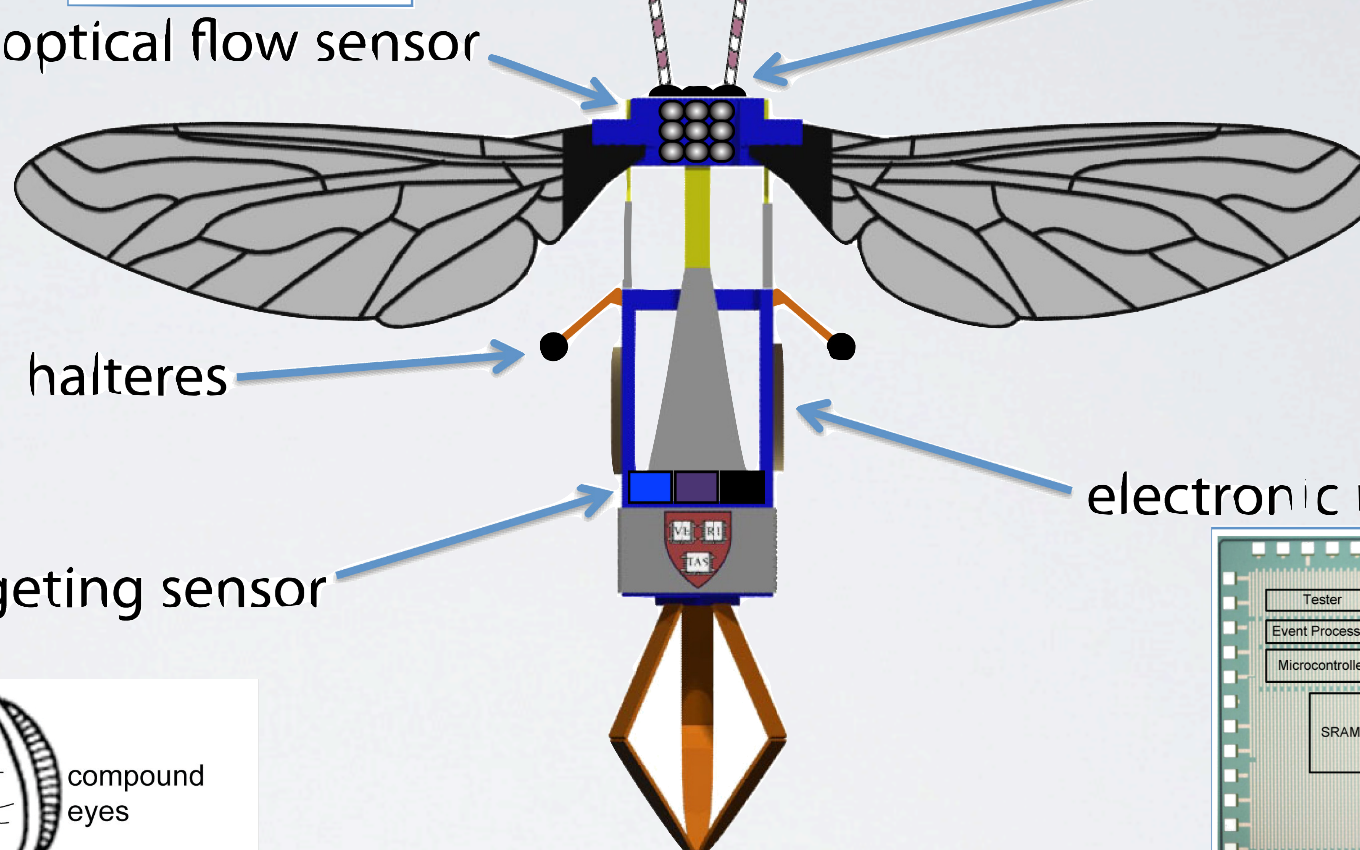
Wafer-scale functional fuel cell arrays

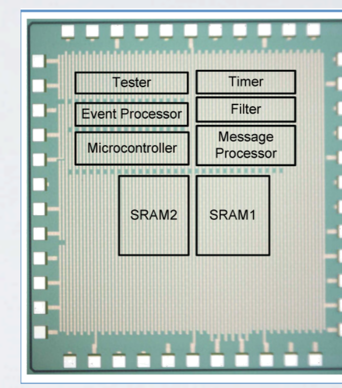
[Ramanathan]

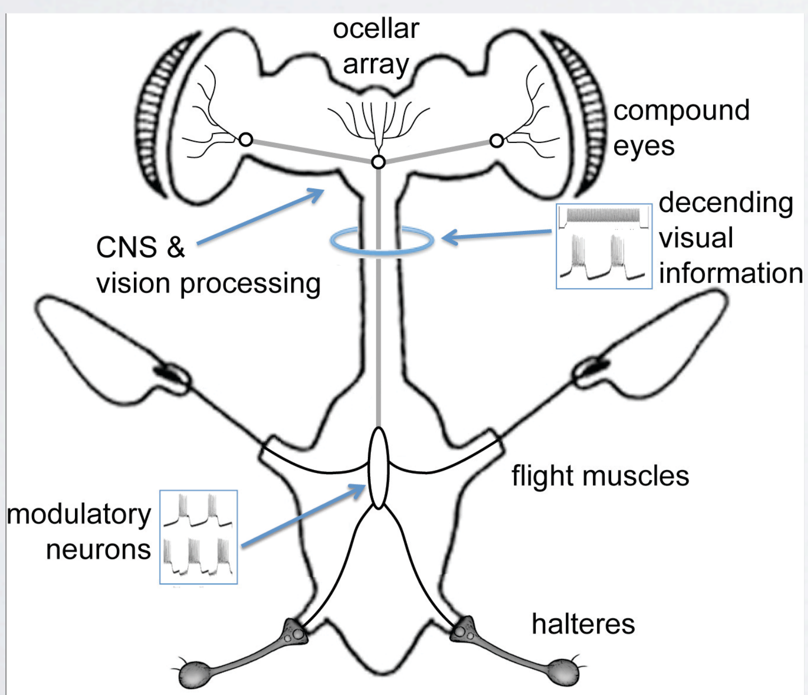
Chapter Two: The Brain







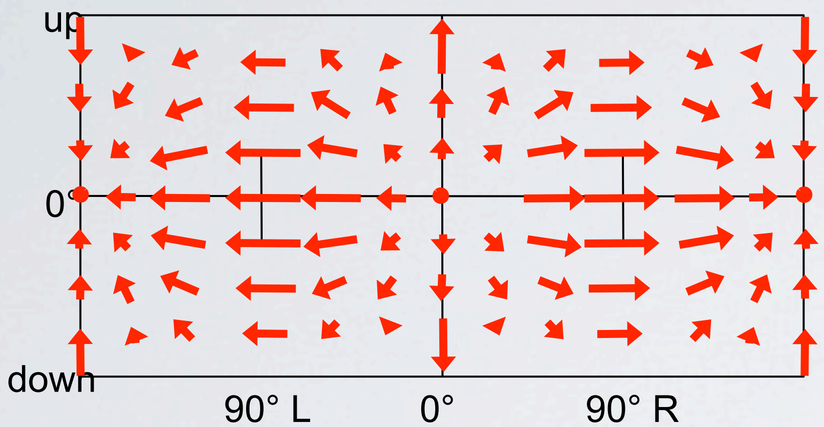




HOW DO THEY SEE THE WORLD?

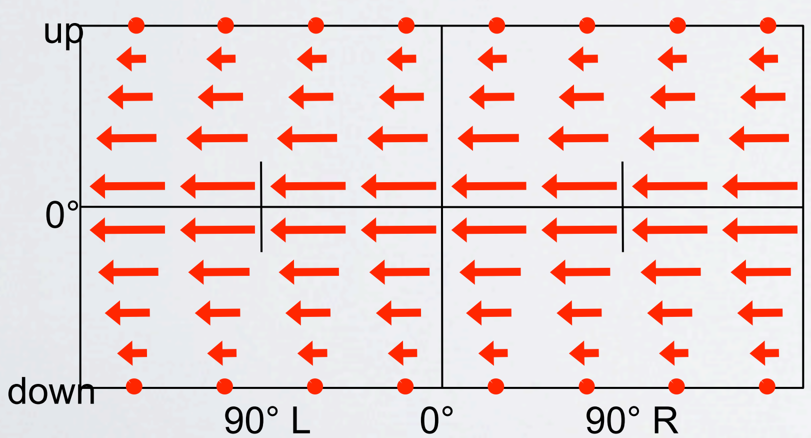
OPTICAL FLOW SENSING

Move Forward



Optical flow can directly sense velocity-related information

Yaw Right

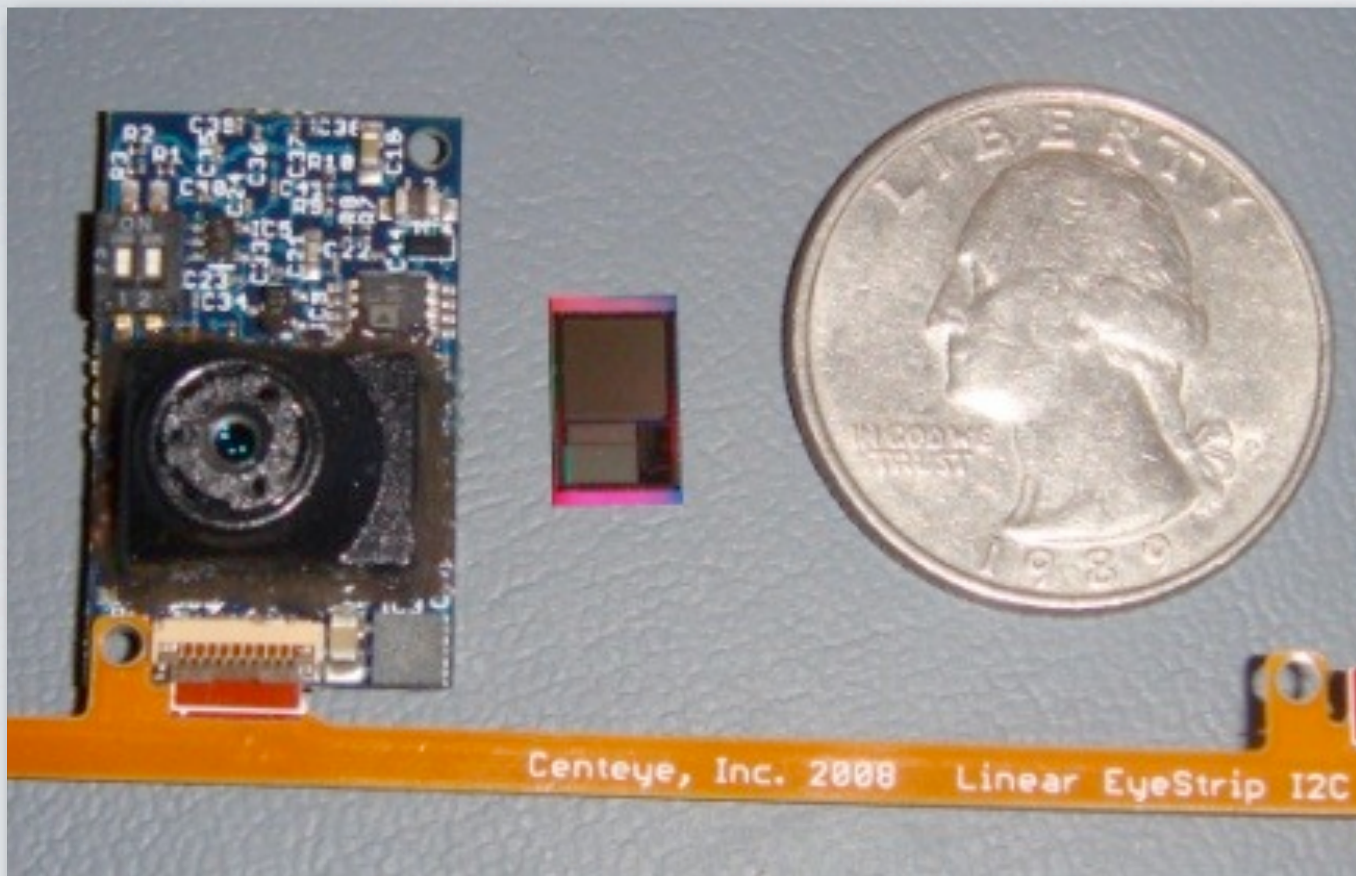


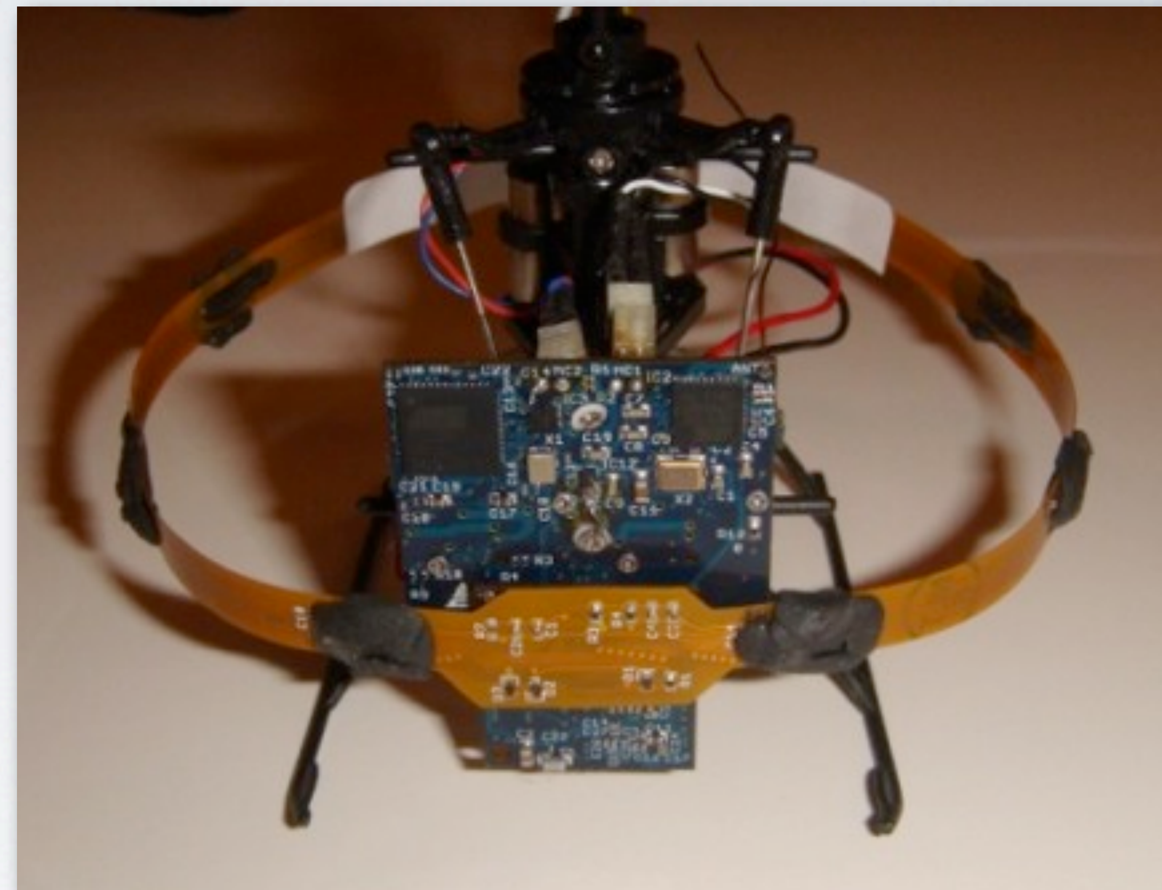
Optical flow can provide gyro-type information

http://www.youtube.com/watch?v=ckVQrwYIjAs

[Centeye]

OPTICAL FLOW SENSORS

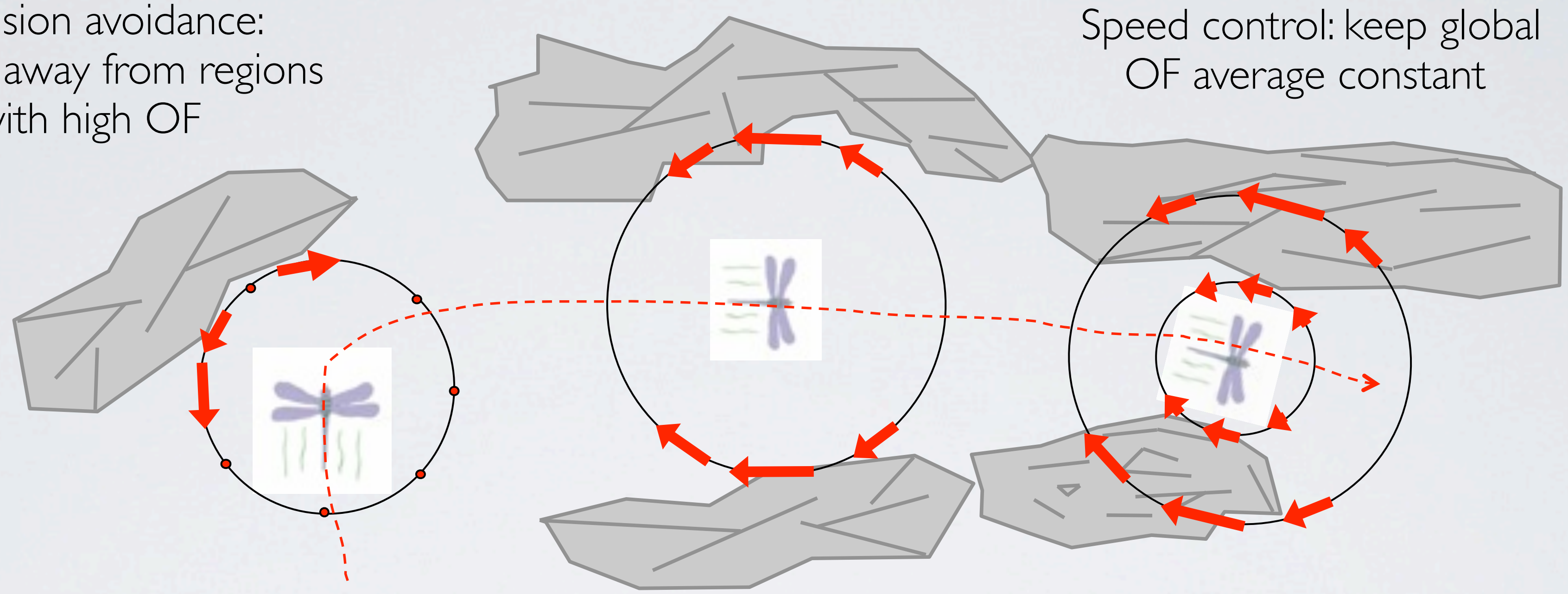


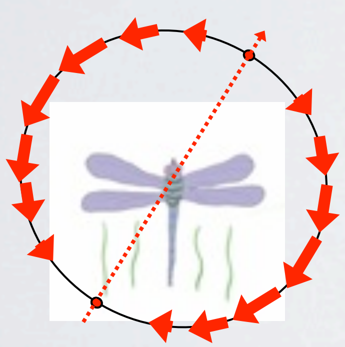


- Cheap, simple CCD array: 64x64 pixels, greyscale
- Don't need high-res cameras!

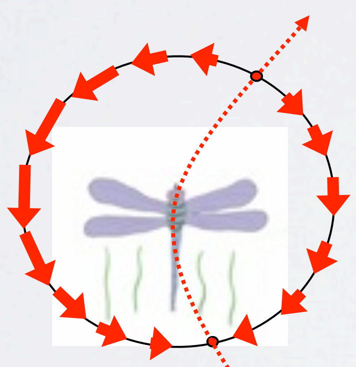
[Centeye]

USING OPTICAL FLOW

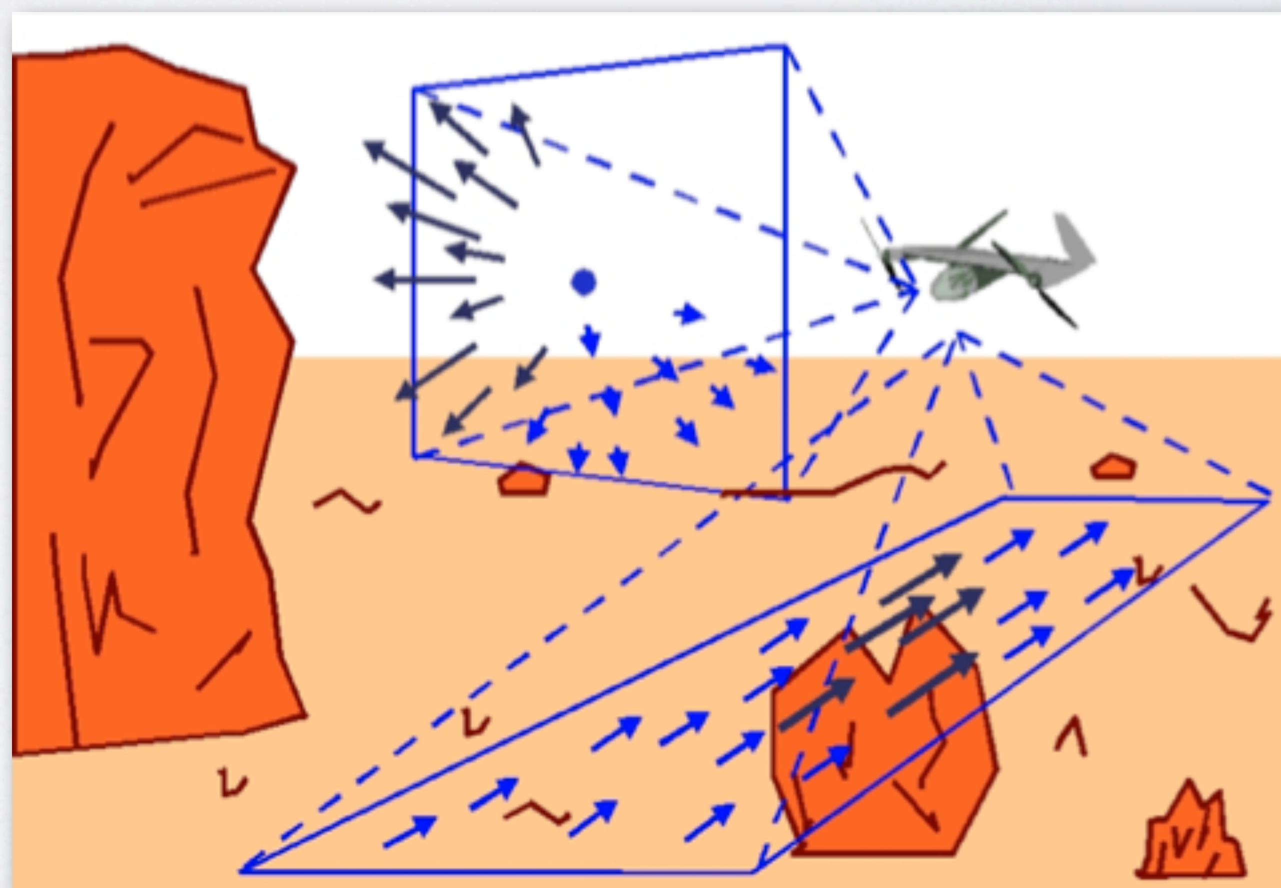




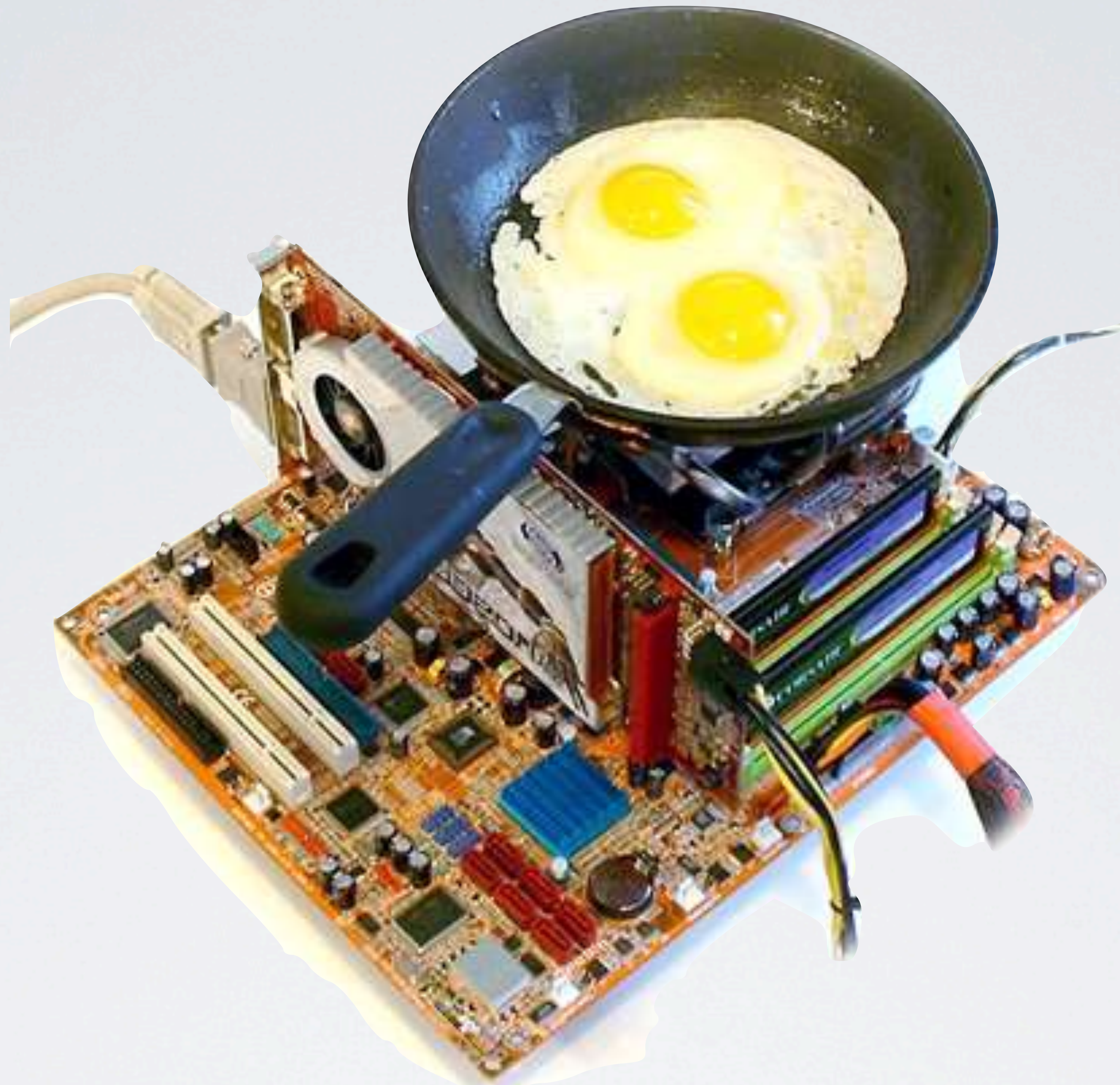
Side slip



Turning in flight



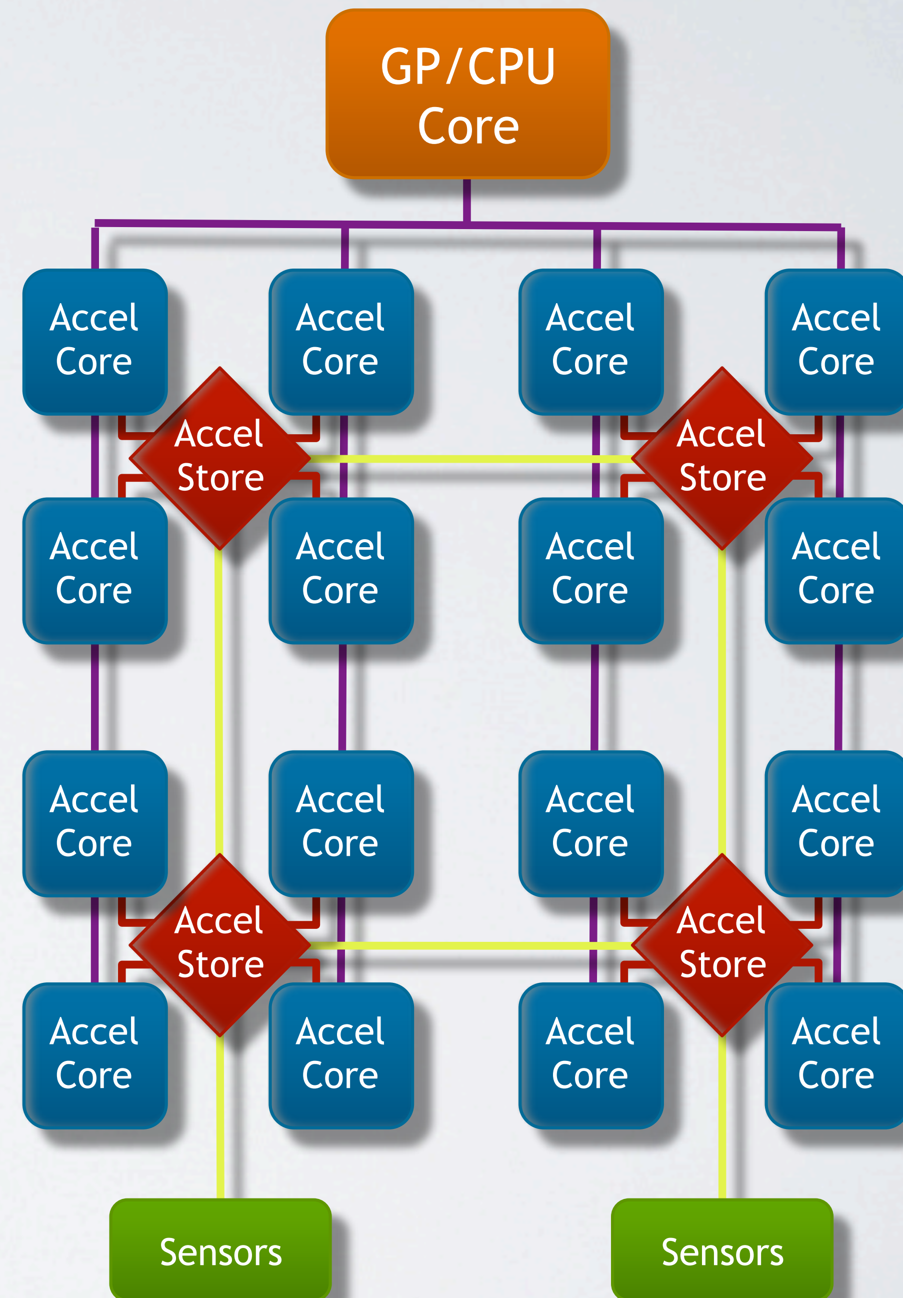
[Centeye]



HOW DO THEY COMPUTE?

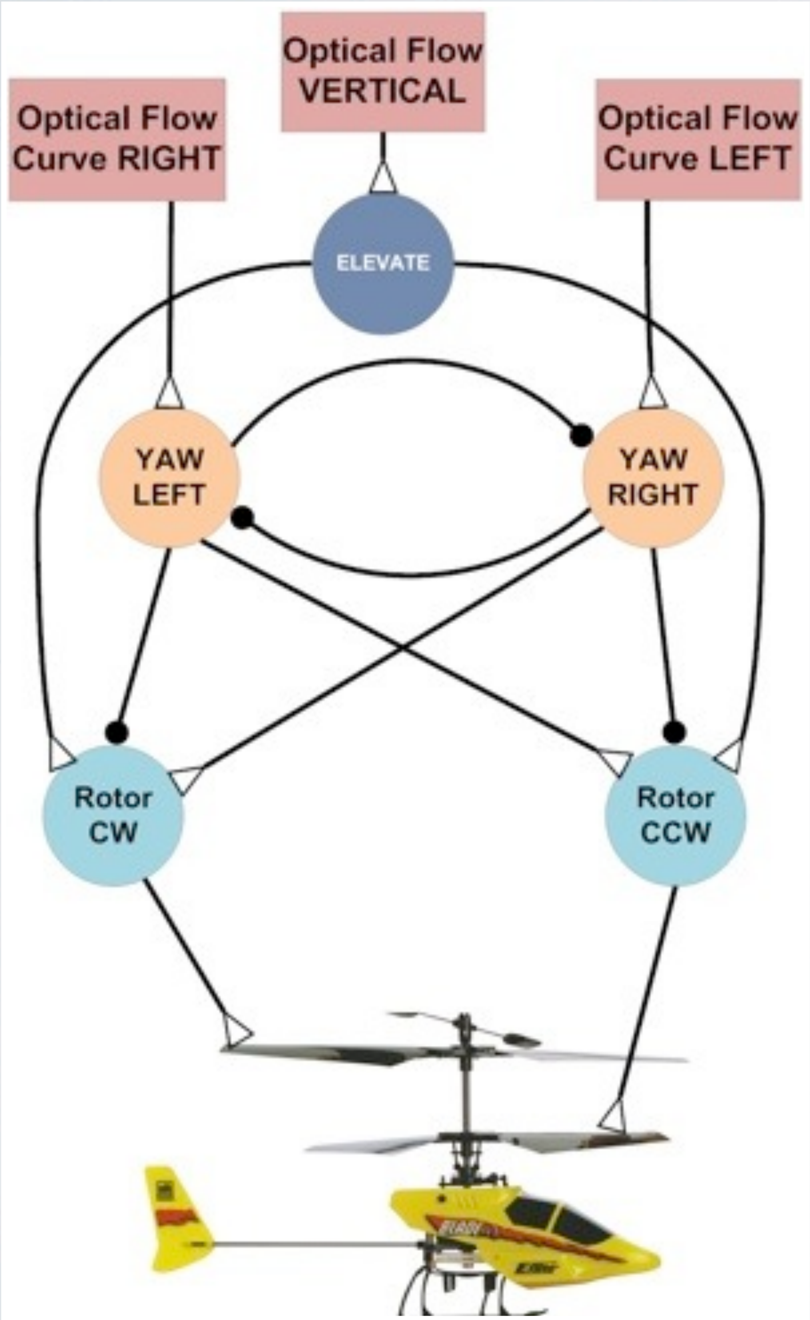
BRAIN ARCHITECTURE

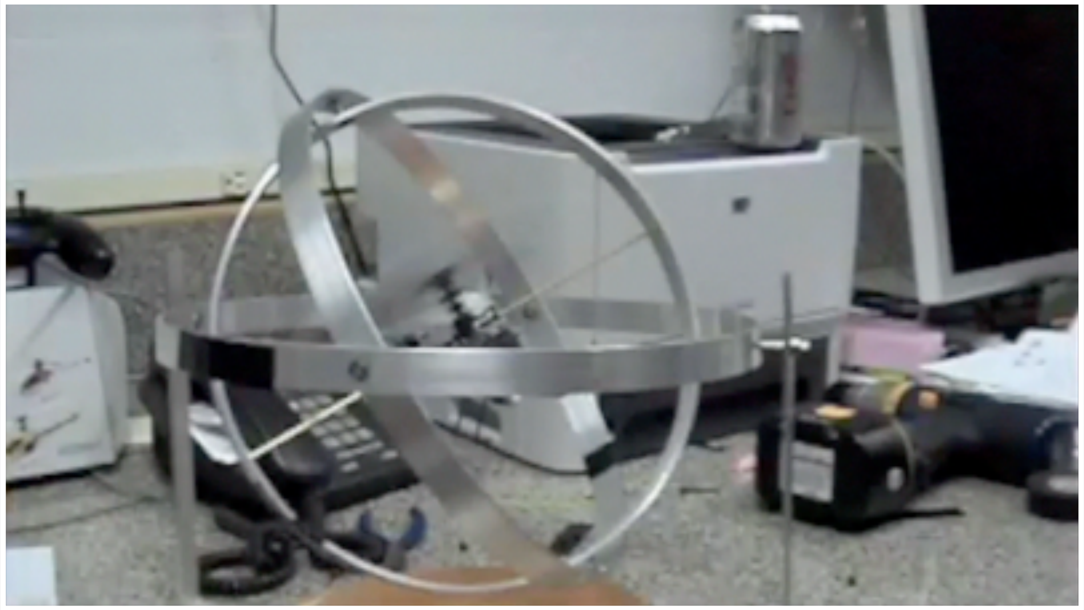
- Accelerator-based processor design
- Ultra low power: microwatts
- General-purpose CPU core
- Accelerators for specialized tasks (navigation, vision, control)



[Brooks & Wei]

ARTIFICIAL NEURAL CONTROL





[Ayers]

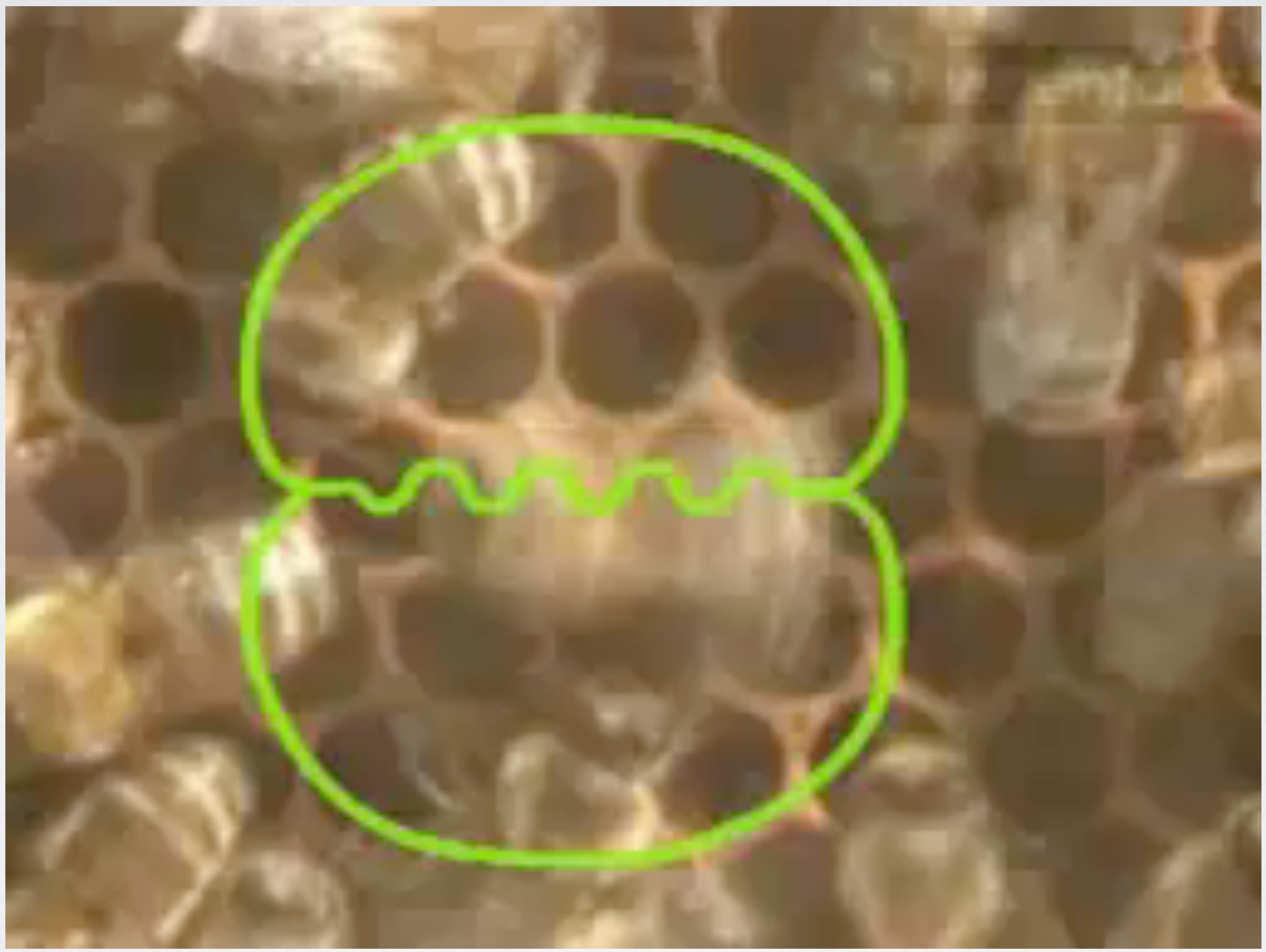
- Optical flow provides information on surroundings

- Discrete-time mapped (DTM) neurons, coded into microcontroller, controls rotors

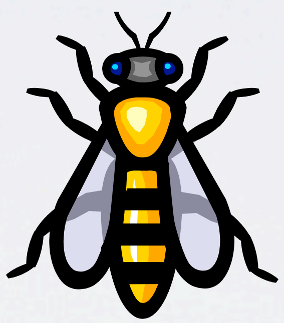
Chapter Three: The Colony

HOW DO THEY WORK TOGETHER?

WAGGLE DANCE



COORDINATION



COORDINATION

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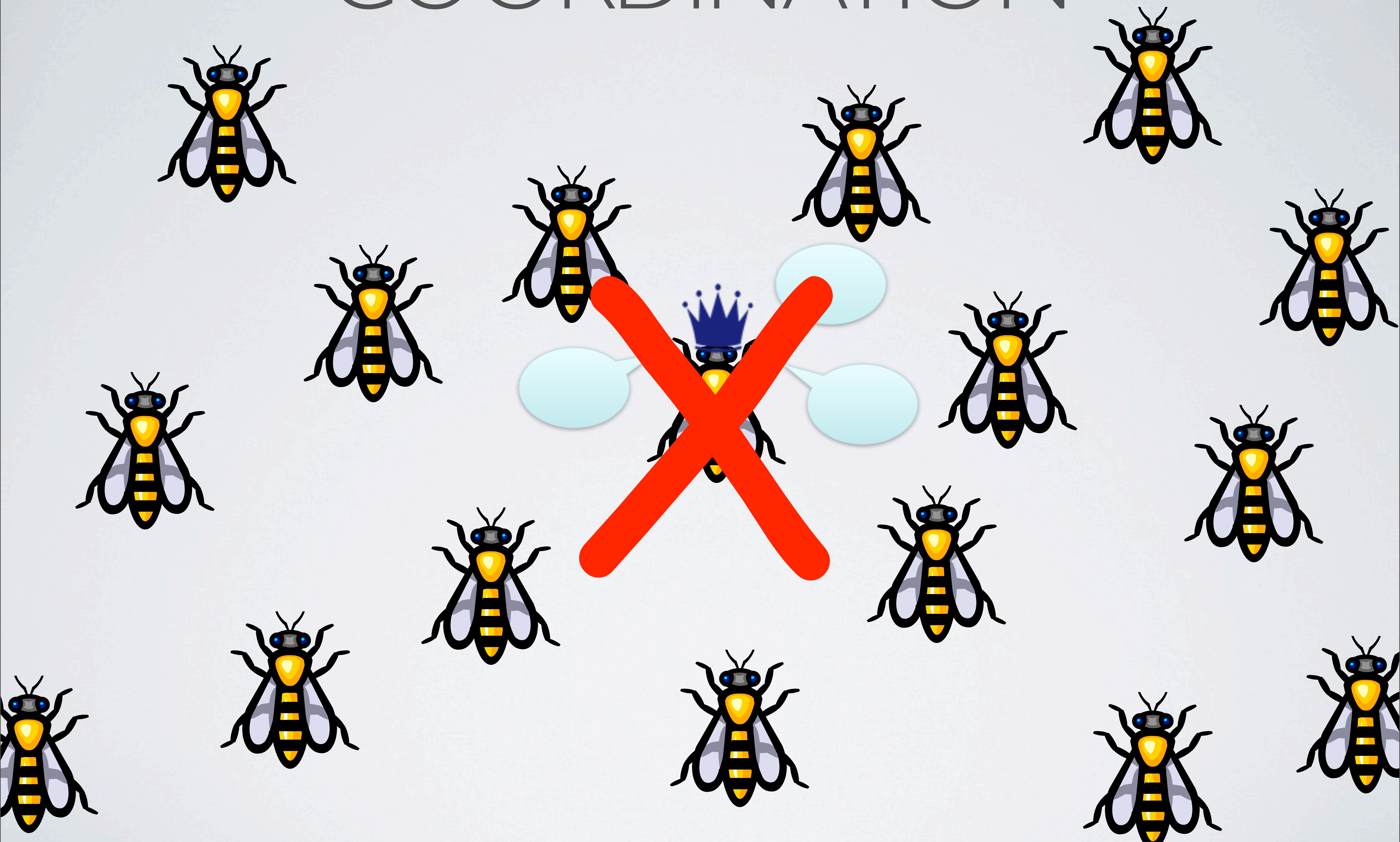

COORDINATION

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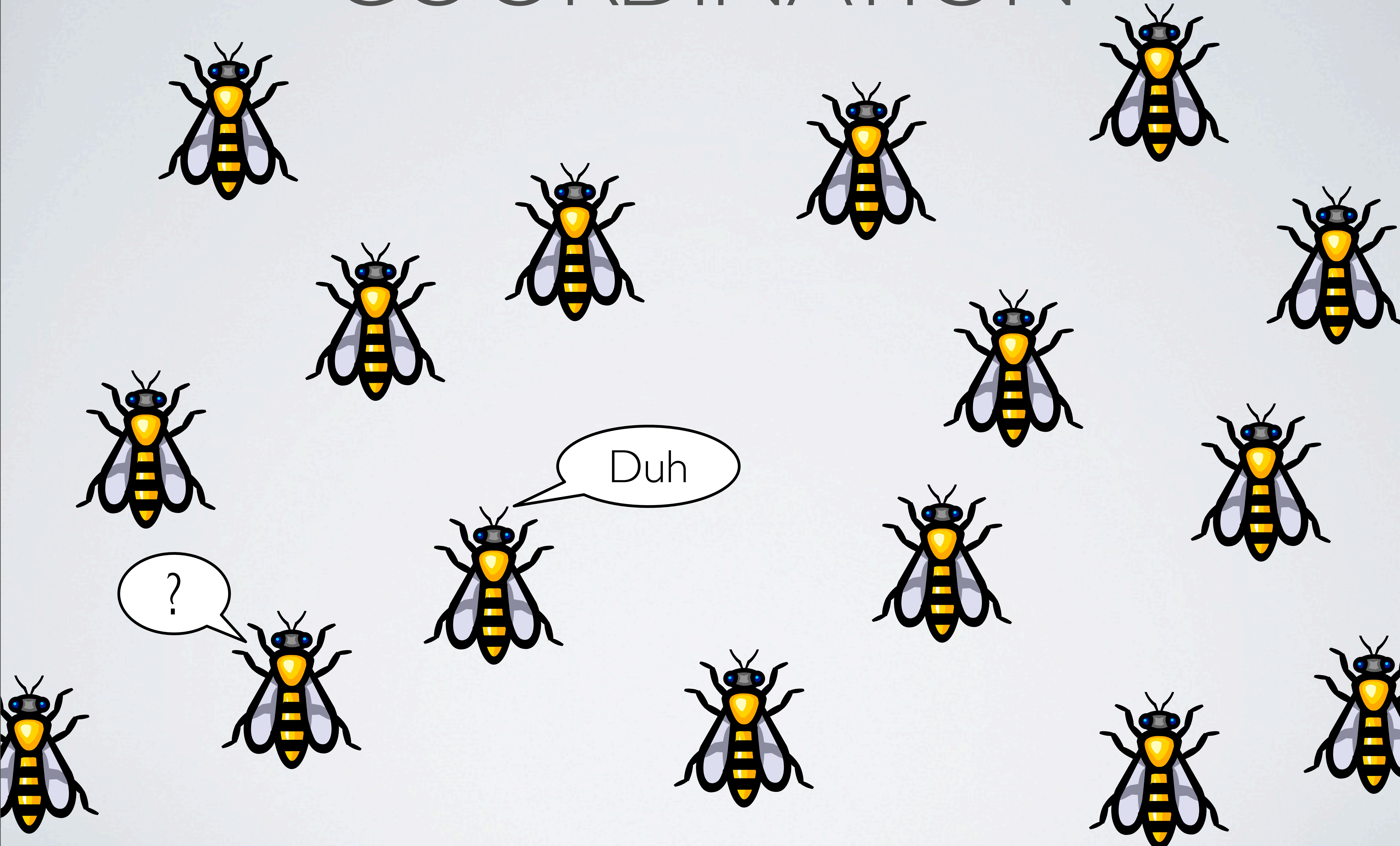

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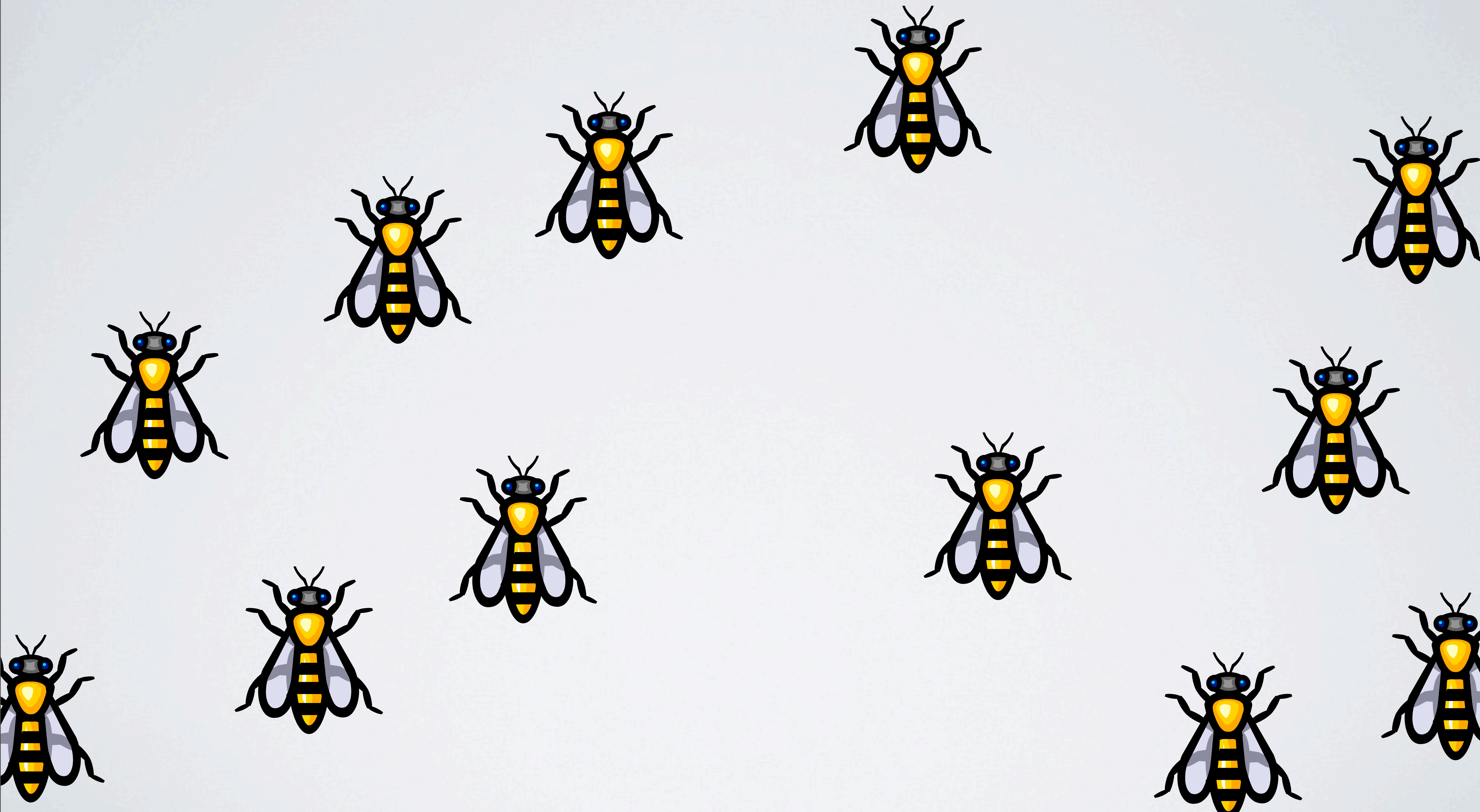

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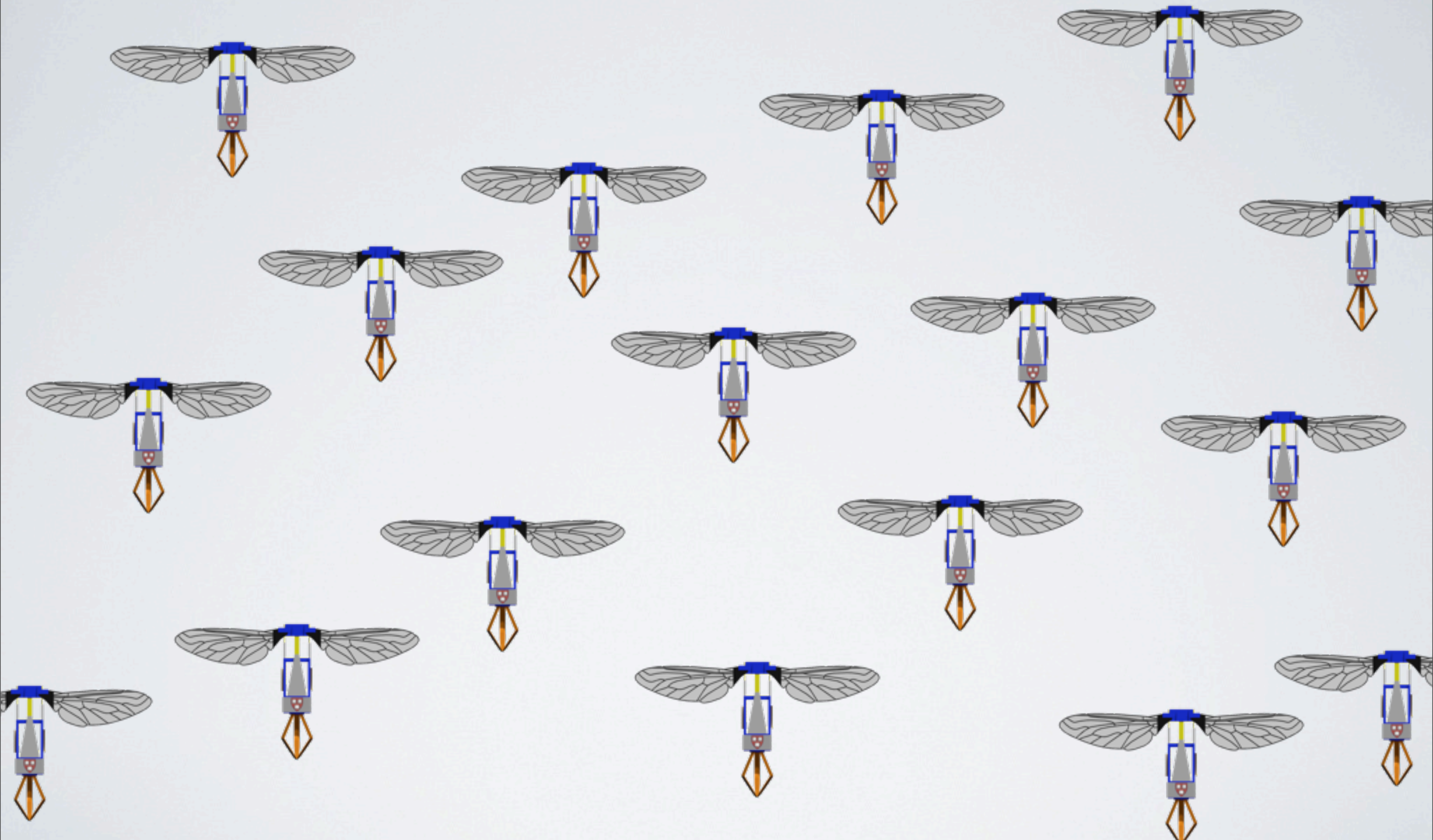
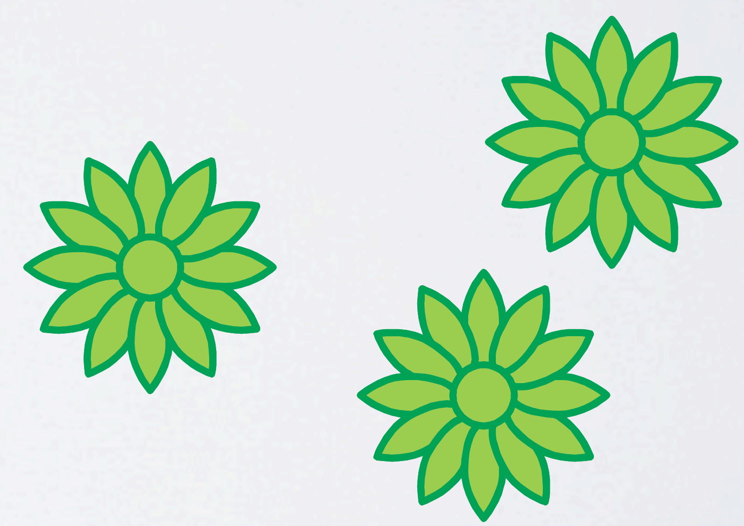


COORDINATION

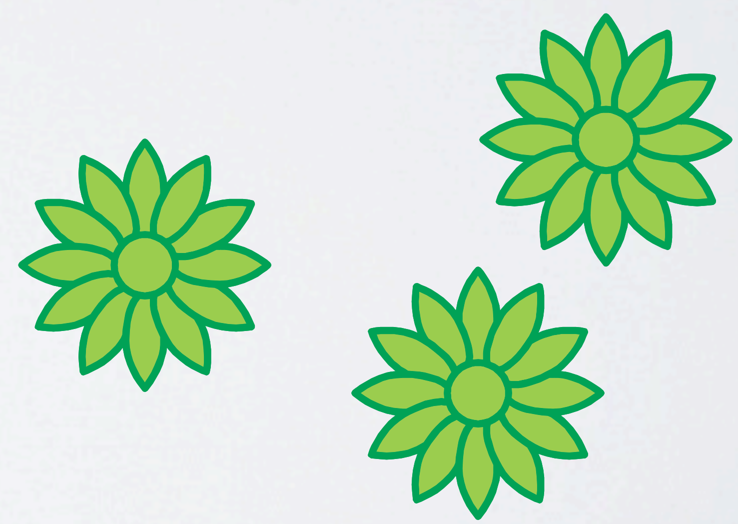
SEARCH ALGORITHMS



- What's "optimal?"
- How to adapt to changing conditions?

[Nagpal]

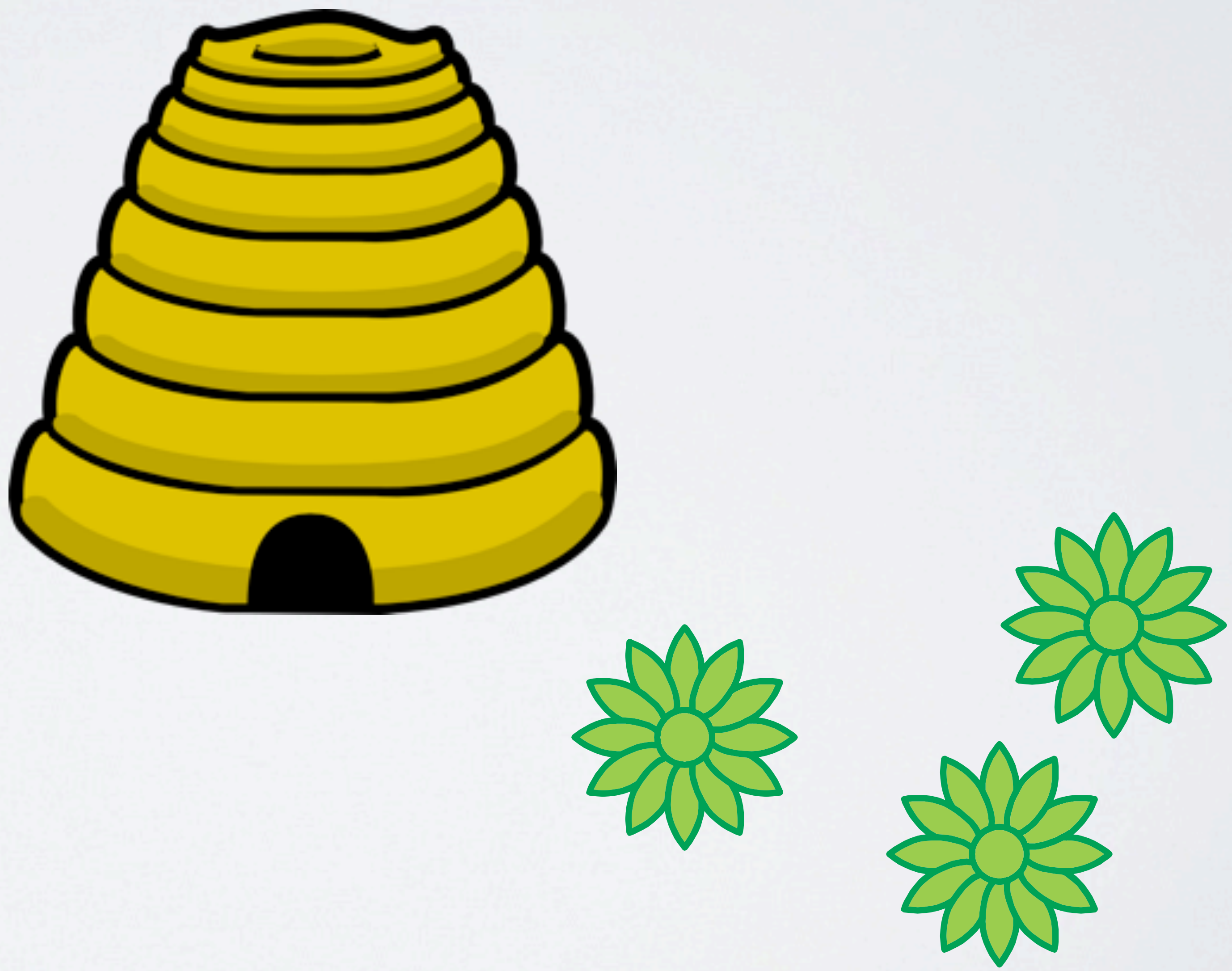
SEARCH ALGORITHMS



- What's "optimal?"
- How to adapt to changing conditions?

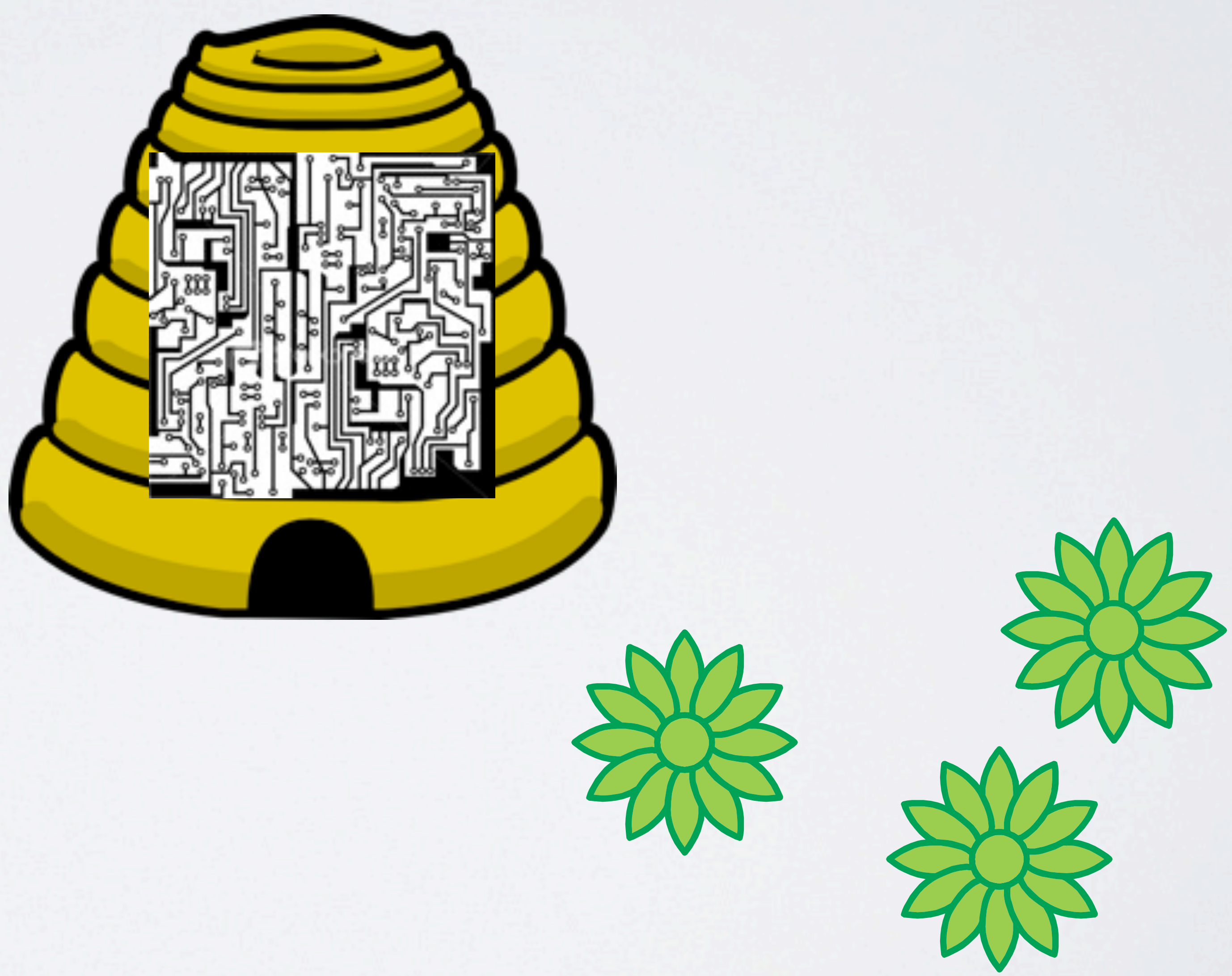
[Nagpal]

THE HIVE



[Nagpal]

THE HIVE



[Nagpal]

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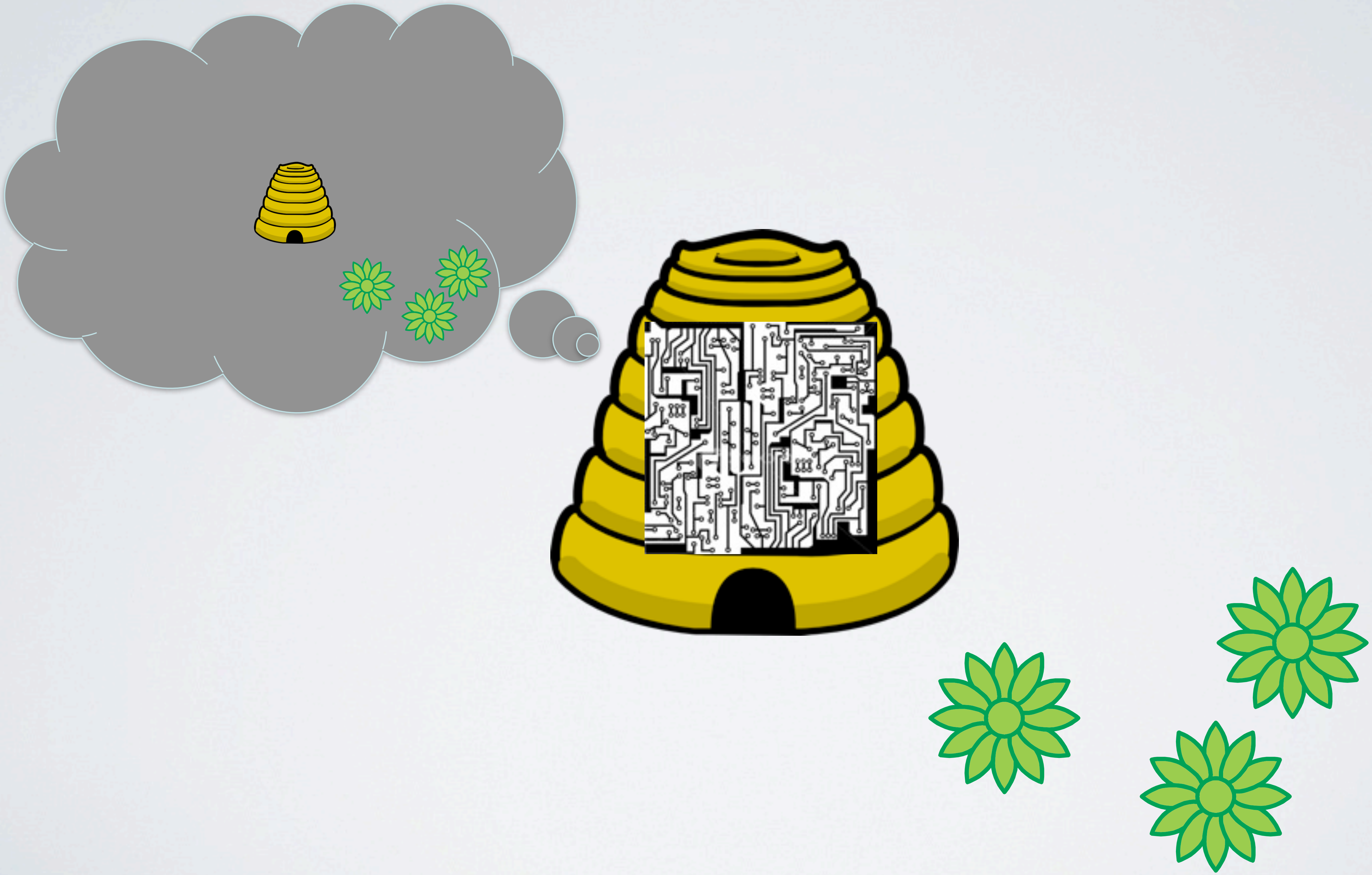
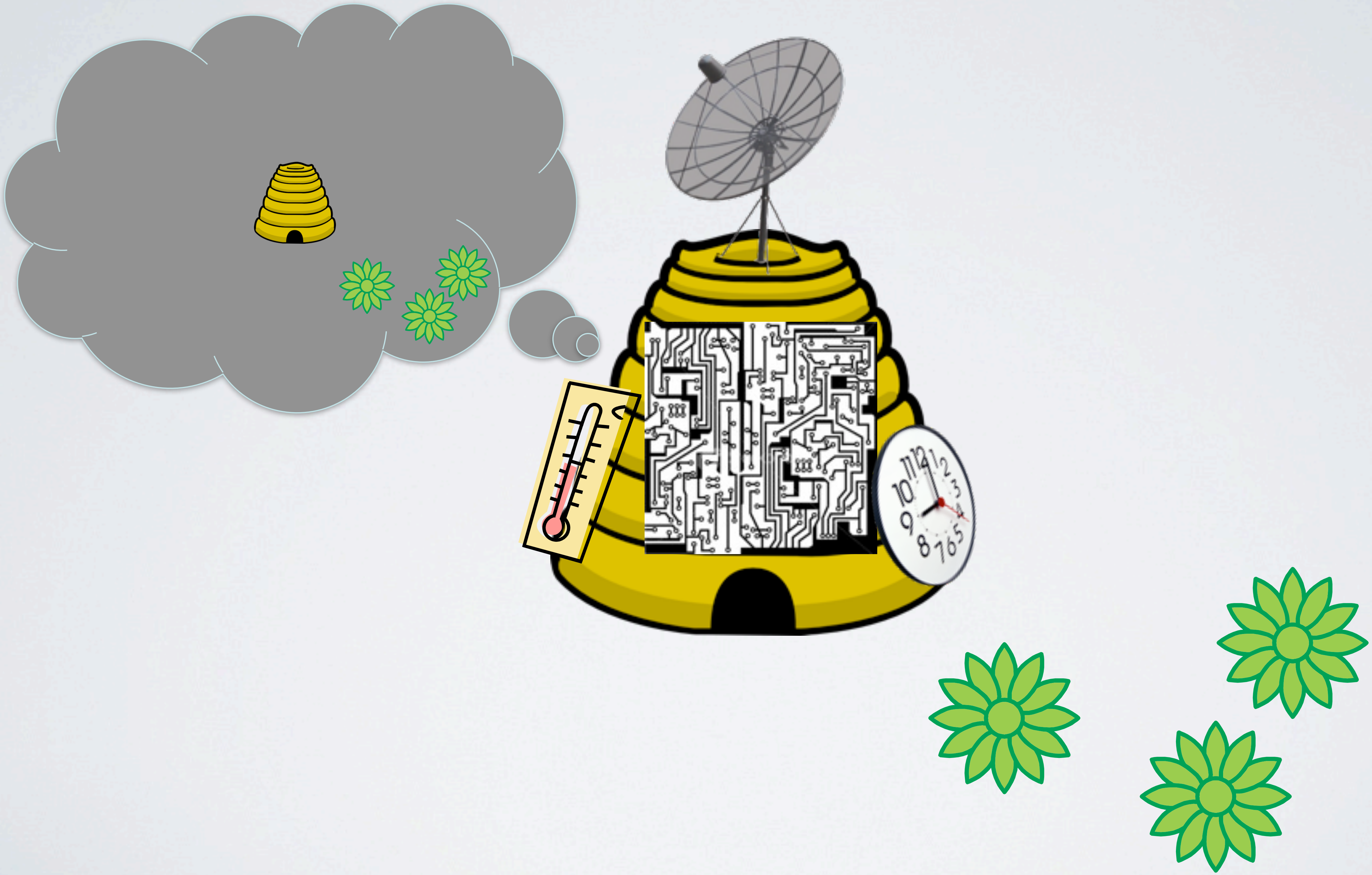


[Nagpal]

THE HIVE



[Nagpal]

HOW DO WE PROGRAM THEM?

THE OLD WAY...

[Welsh, Morrisett]

THE OLD WAY...

[Welsh, Morrisett]

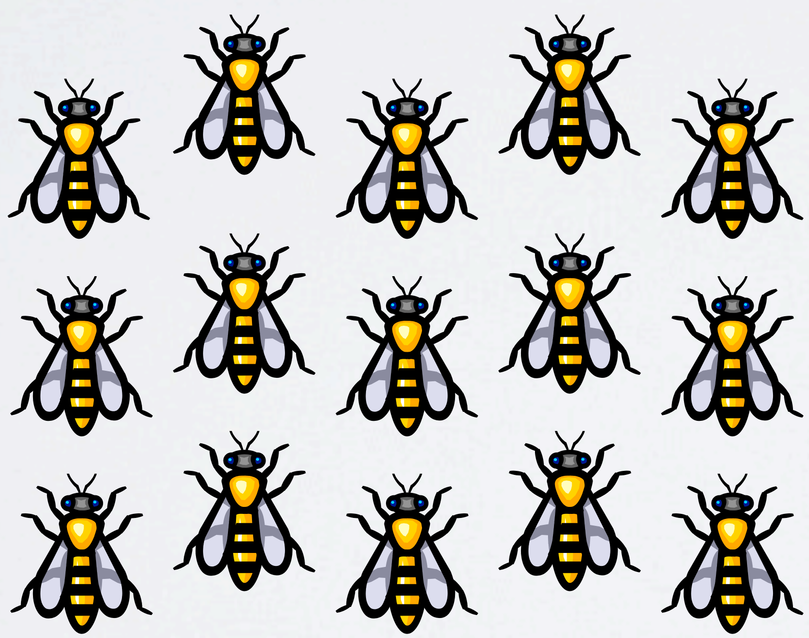
THE OLD WAY...

→ C code

[Welsh, Morrisett]

THE OLD WAY...

C code



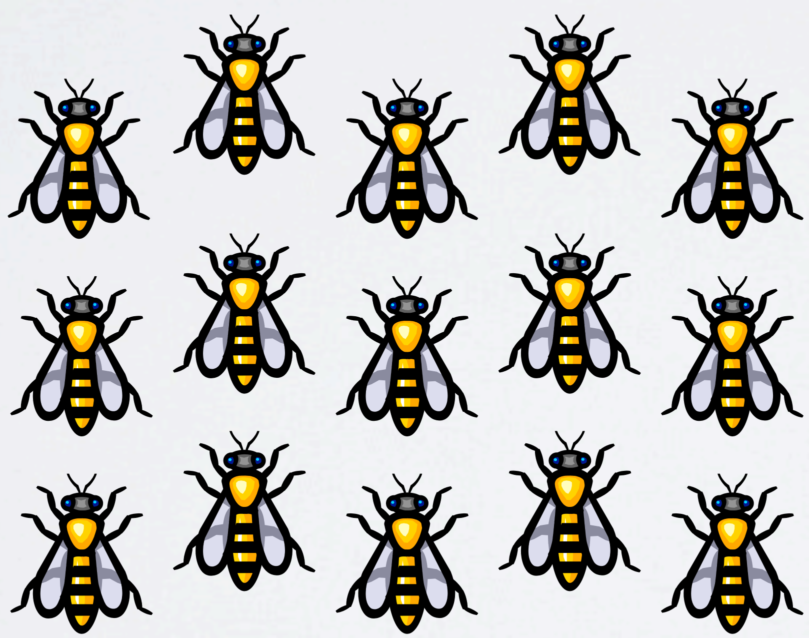
Box o' bees

[Welsh, Morrisett]

THE OLD WAY...

C code

No doubt full of bugs



Box o' bees

[Welsh, Morrisett]

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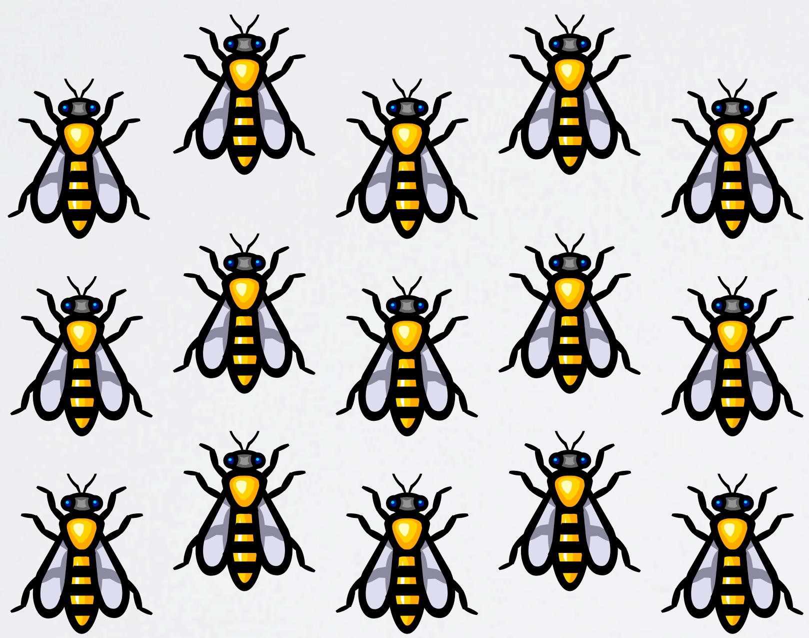


Box o' bees

Havoc and mayhem

[Welsh, Morrisett]

THE OLD WAY...

- Too low level -- program at the individual bee level
- Difficult to reason about global behavior
- Difficult to reason about failure, resource limitations, or environmental changes

THE NEW WAY...

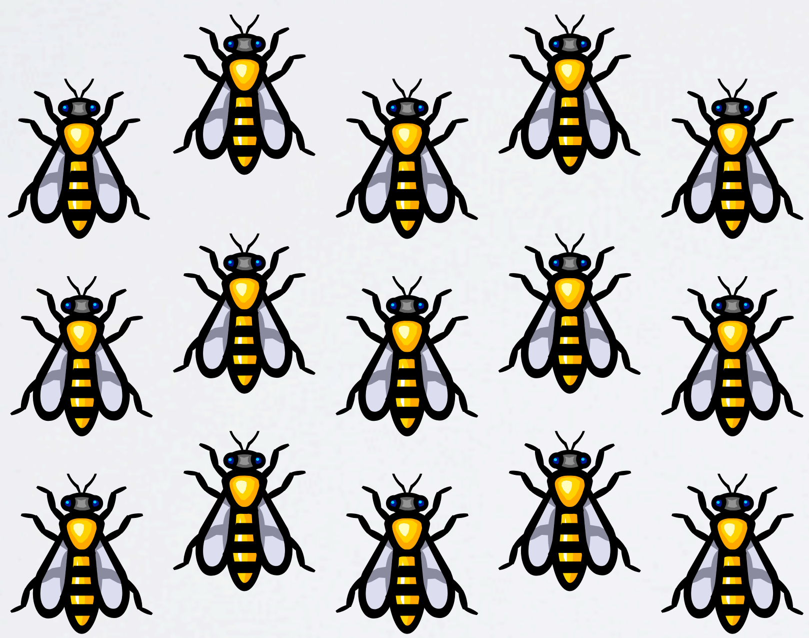
THE NEW WAY...

THE NEW WAY...

→ Macroprogram

THE NEW WAY...

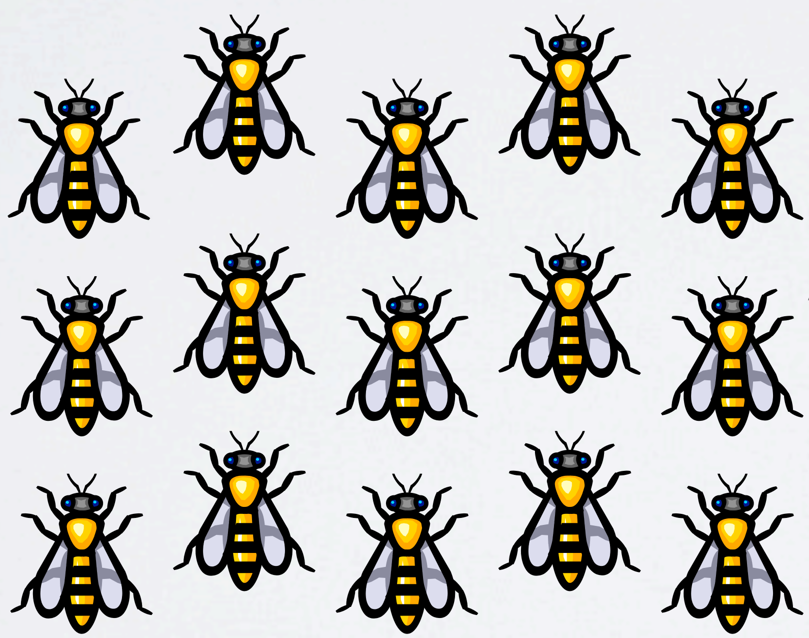
Macroprogram



Box o' bees

THE NEW WAY...

Macroprogram

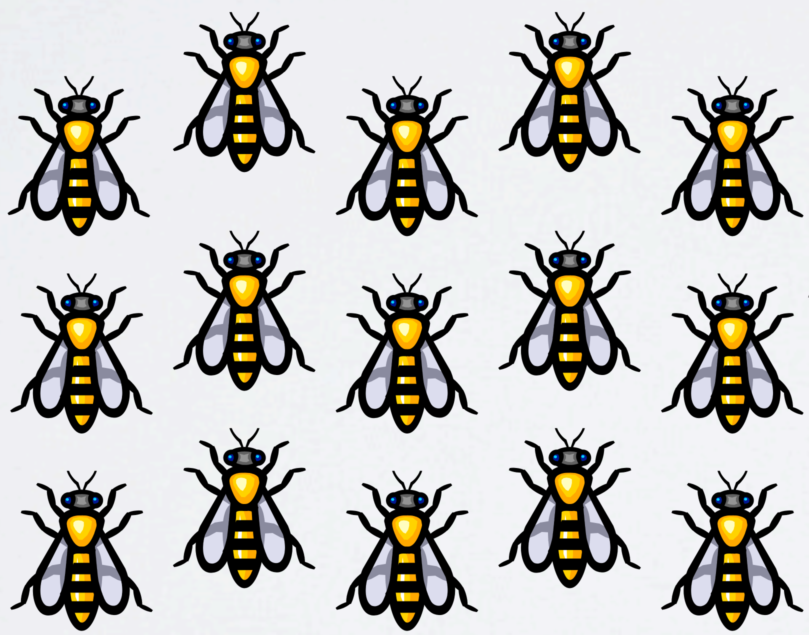


Box o' bees

Beautiful swarm behavior

THE NEW WAY...

Macroprogram

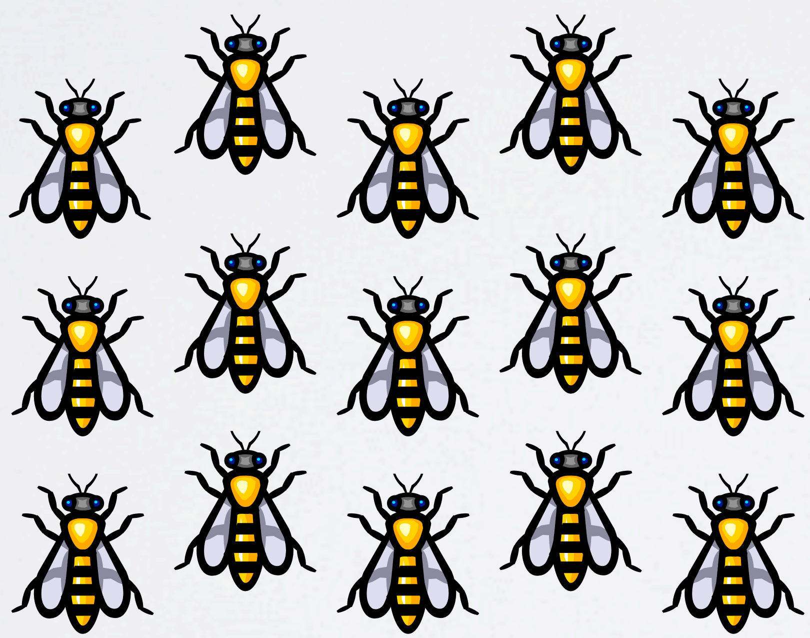


Box o' bees

Beautiful swarm behavior

THE NEW WAY...

Macroprogram



Box o' bees

Beautiful swarm behavior

MACROPROGRAMMING

- Program the swarm, not the bee
- Automatically compile swarm program to bee programs
- Compiler generates code to handle communication, failure detection, task assignment, and resource management
- Needs a powerful runtime environment to support collective behavior -- Karma Distributed OS

WHAT'S THE RIGHT PROGRAMMING MODEL?

- Declarative specification:
  "pollinate crop", "make beard"

- Constraint solving:
  pollinate (@Hive, time) :– timestamp(@Source,Time) ,
  detect(@Source, flower), landOn(@Source, true)

- Spatial/temporal:
  (where (no-flower) (disperse) (brownian))

- SQL query:
  "SELECT pollen FROM flowers"

HOW DO WE TEST OUR IDEAS?

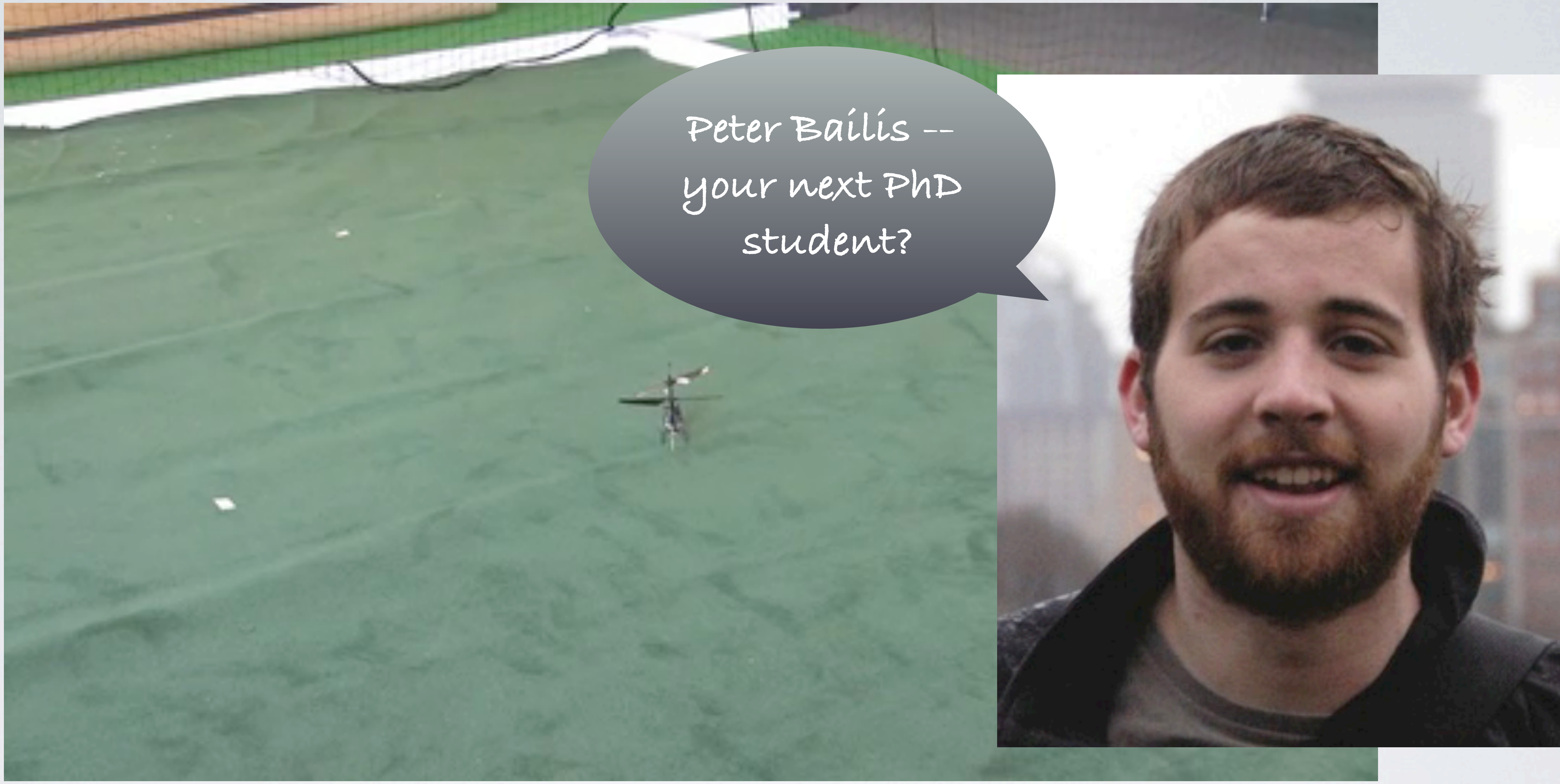
MICRO-HELICOPTERS!

- eFlite MCX, around $100
- Custom control board with AVR32 microcontroller, 802.15.4 radio, optical flow sensor interface

HELICOPTER TESTBED

- Plan: 50 helicopters under wireless control
- Remotely accessible via the Web

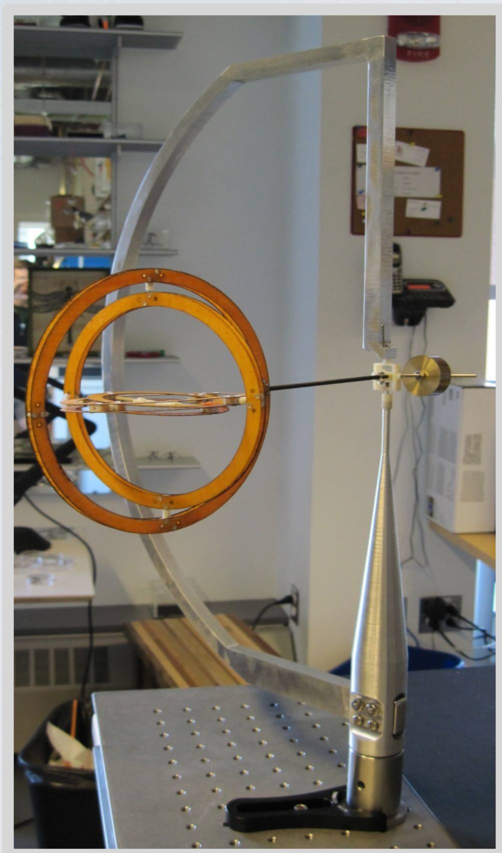
HELICOPTER TESTBED

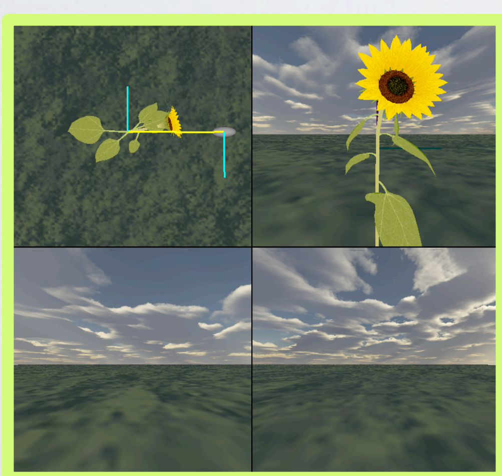


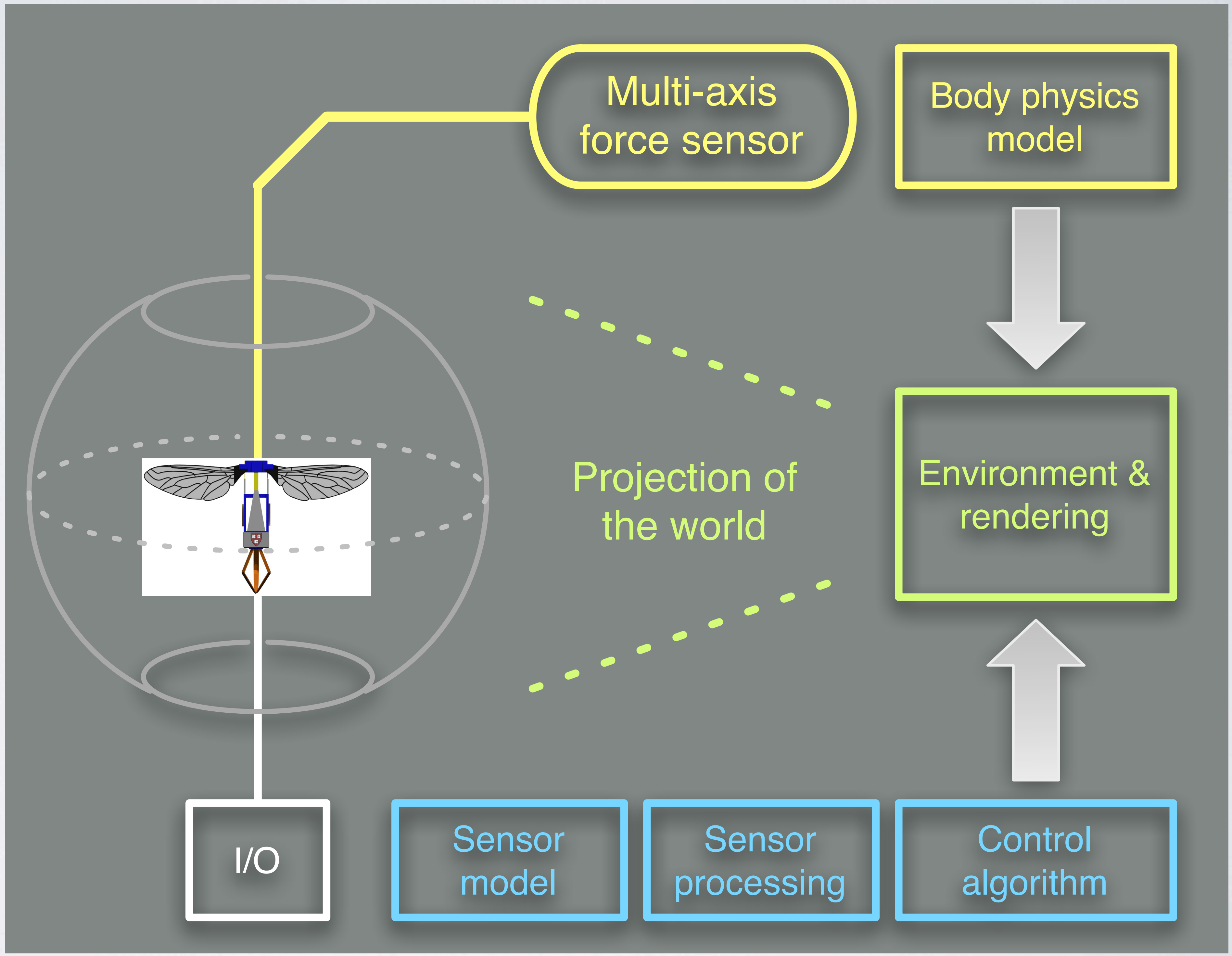
- Plan: 50 helicopters under wireless control

- Remotely accessible via the Web

THE ROBOBEE "MATRIX"

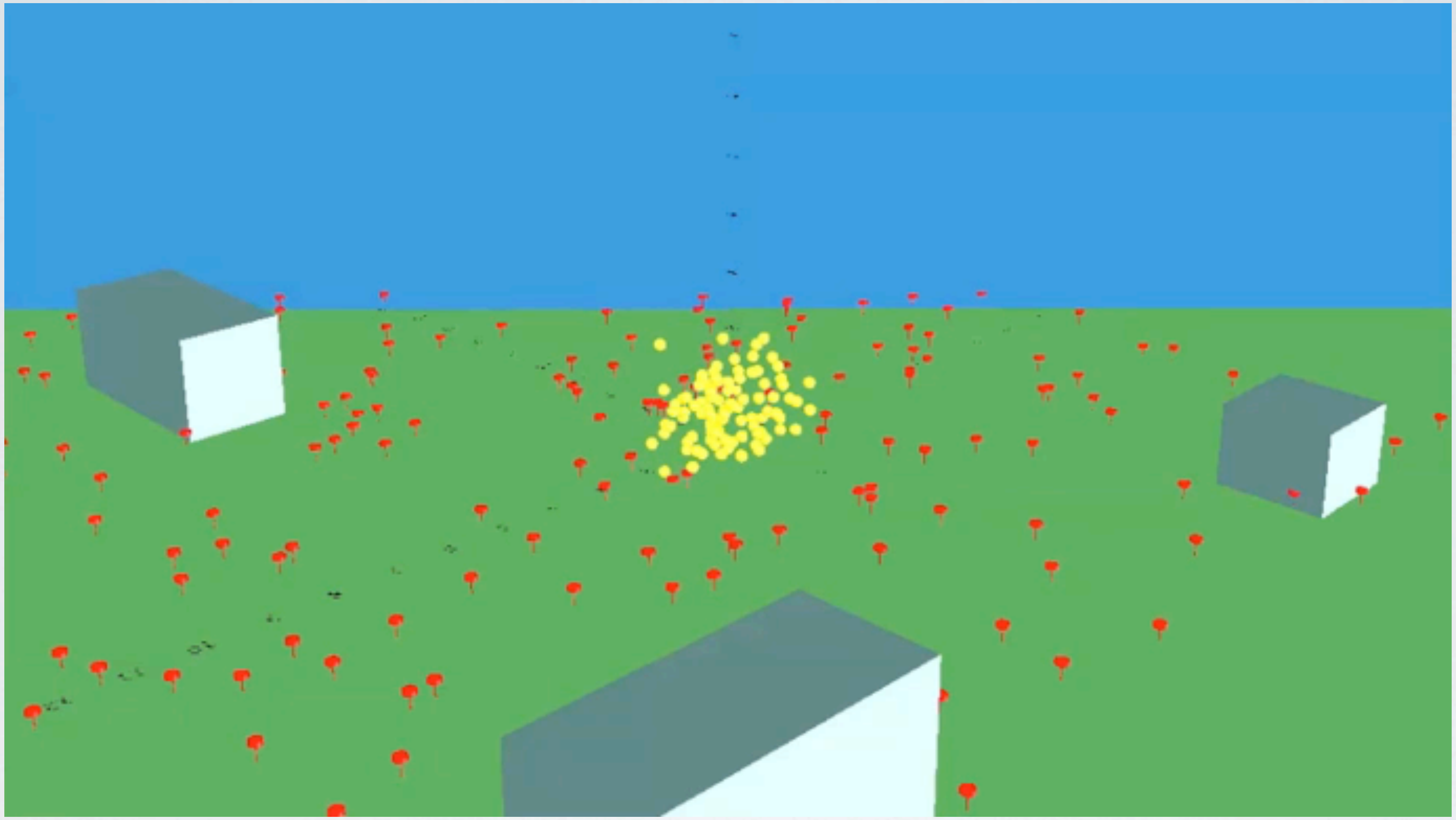






[Brooks, Wei, Wood & Zickler]

SIMBEEOTIC SIMULATION



[Diana Cai and Bryan Kate]

- Highly-scalable, physics-driven simulator
- Can simulate 1000's of RoboBees in real time

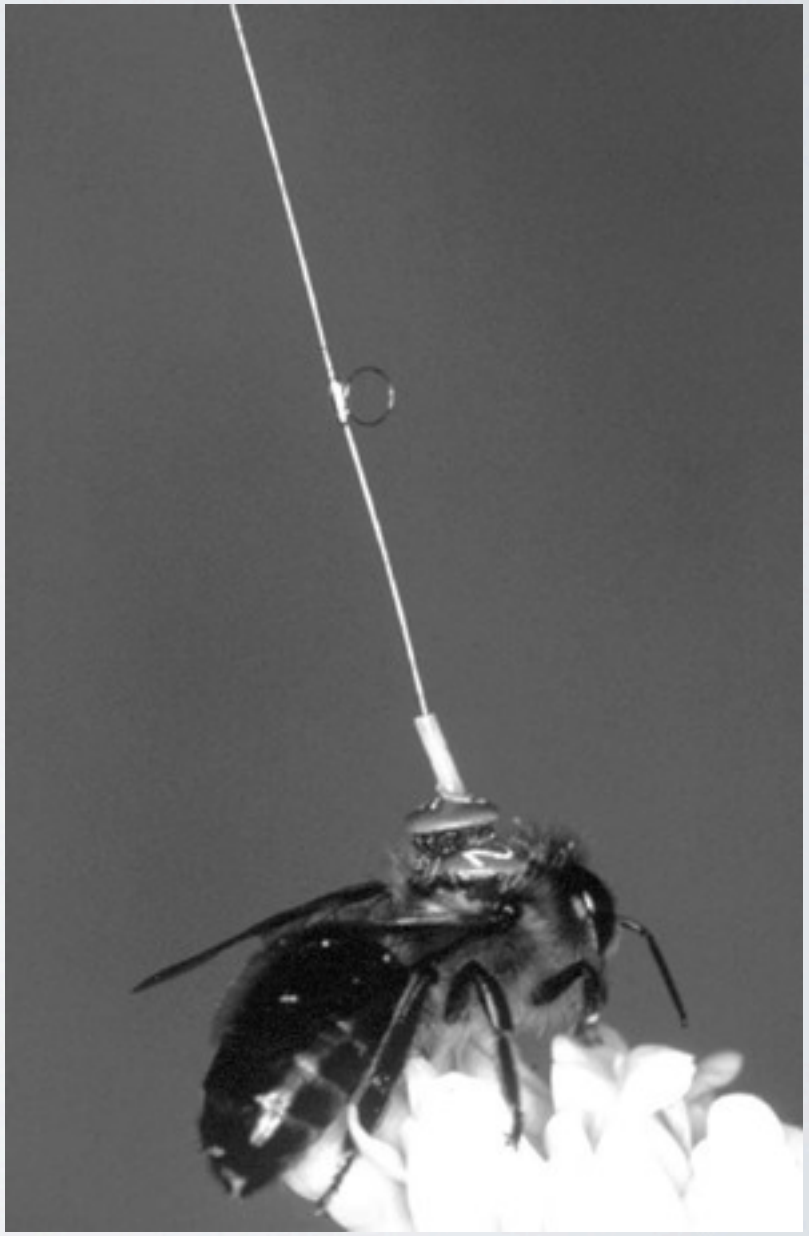
HOW DO WE KNOW WHERE THEY ARE?

IN THE LAB: MOTION CAMERA SYSTEM

- Real-time 3D motion capture system based on IR cameras and reflective markers
- Millimeter level accuracy
- Expensive: $100k+

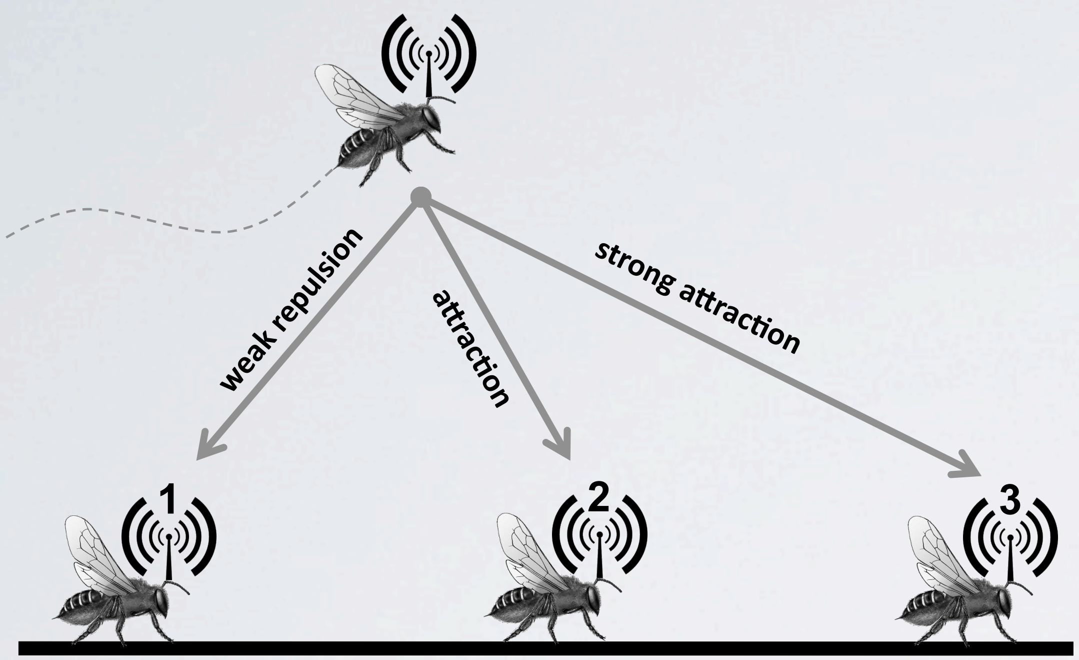
IN THE FIELD: HARMONIC RADAR

- Widely used for insect foraging studies
- Small (3 mg) transponder on bee
- Unclear what the accuracy is like!

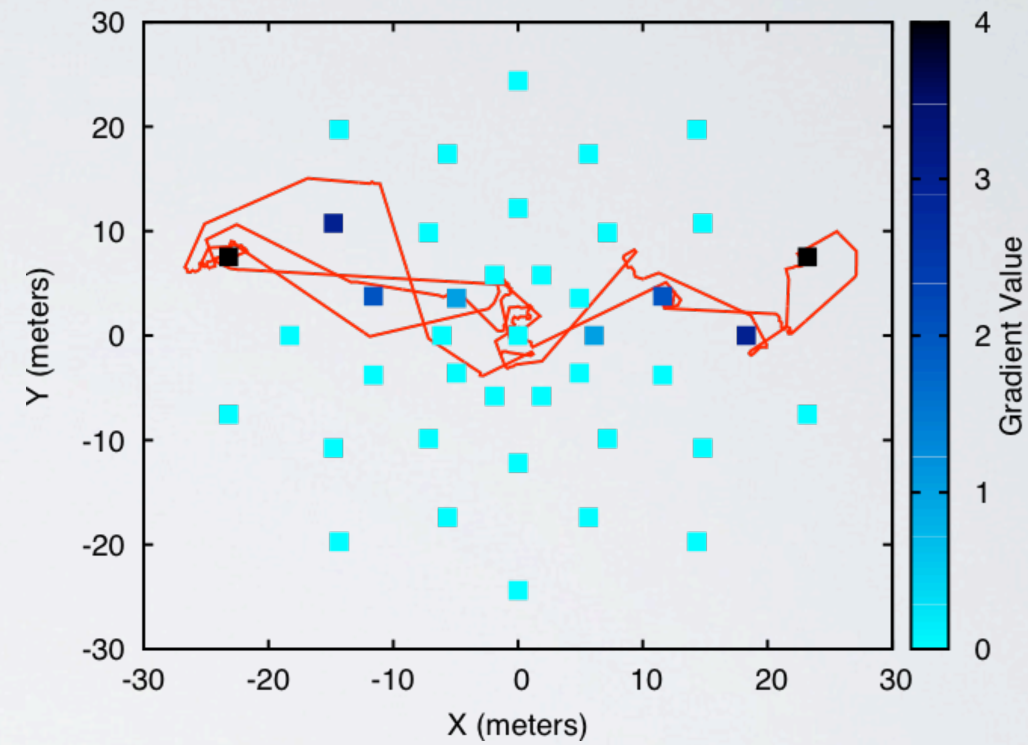



[Riley and Smith 2002]

RF ASSISTED NAVIGATION



[Bailis and Kate]



- Bees on ground act as guiding beacons
- Can attract or repel bees in-flight to coerce paths
- Powerful gradient-based spatial control

HOW TO GET $10 MILLION FROM THE NSF

- Hallway chat between Gu-Yeon Wei and Rob Wood (PIs)
- Turned into a short white paper, team recruited
- All-hands brainstorming meeting - sketch an outline
- Division of labor - blocks of text and figures
- Integration
- Circulate for feedback

BACKLASH

Sean Hannity "Waste 102" - March 12, 2010

Thanks!

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