

ROBOBEES

A CONVERGENCE OF BODY, BRAIN, AND COLONY



Matt Welsh
Harvard University



HARVARD
School of Engineering
and Applied Sciences

WYSS INSTITUTE

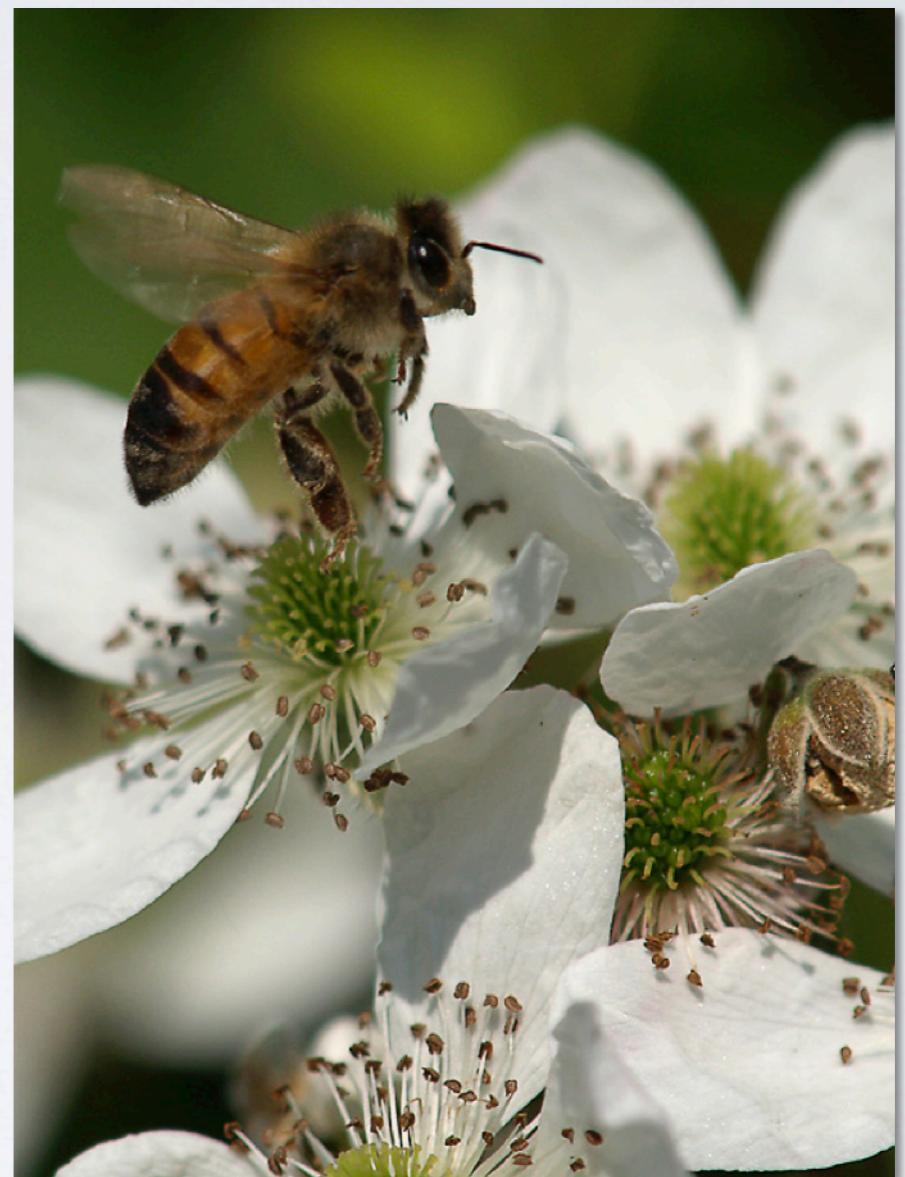




WHAT THE HECK?

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.”



PUT ANOTHER WAY...

PUT ANOTHER WAY...



PUT ANOTHER WAY...



PUT ANOTHER WAY...



PUT ANOTHER WAY...



PUT ANOTHER WAY...

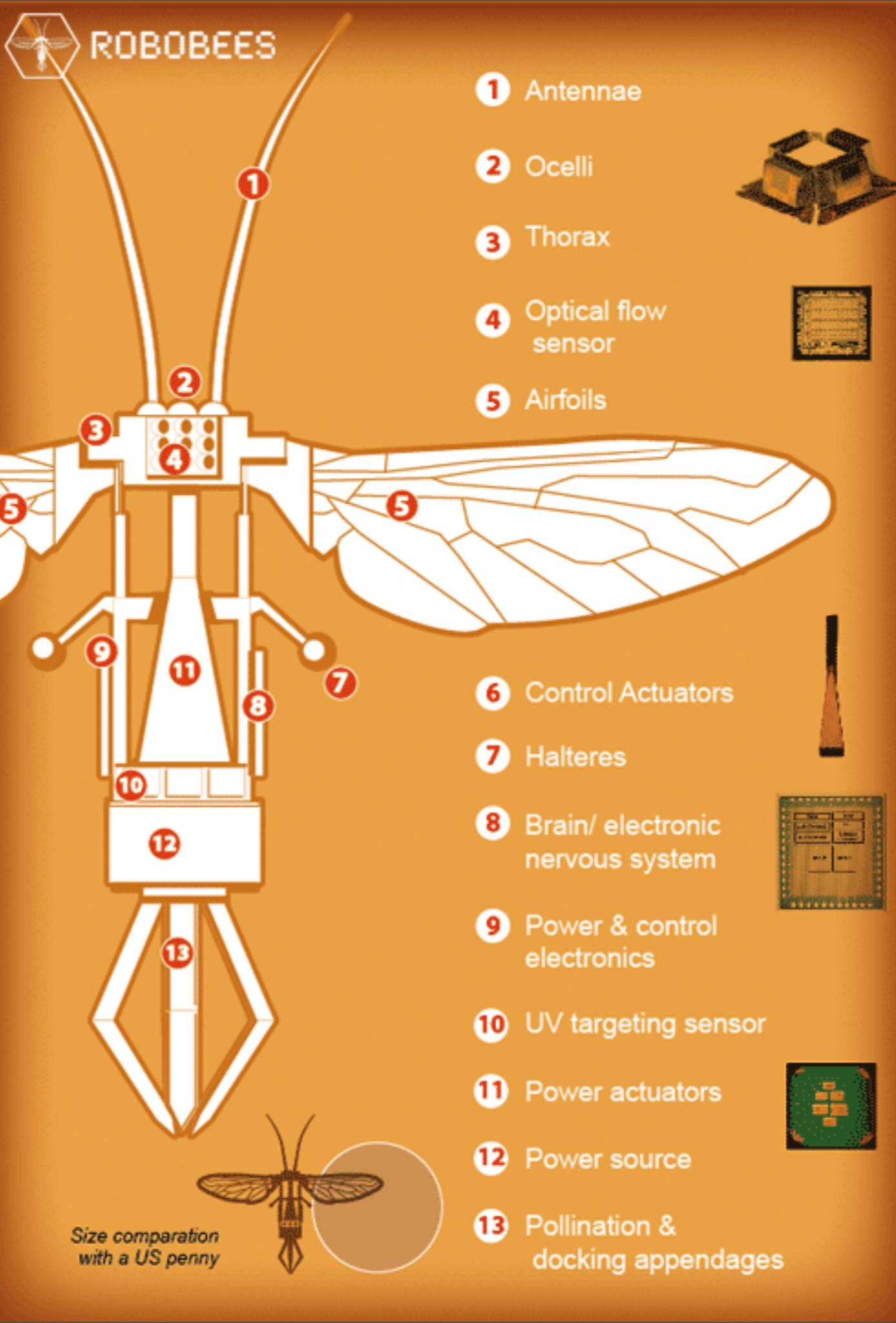


PUT ANOTHER WAY...



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





HARVARD
School of Engineering
and Applied Sciences

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THE TEAM

Northeastern
 Centeye

Gu-Yeon Wei Rob Wood Radhika Nagpal Joe Ayers



Stacey Combes



VLSI

Microrobotics

Distributed
Control

Neurobiology
Biorobotics

Insect biology

David Brooks



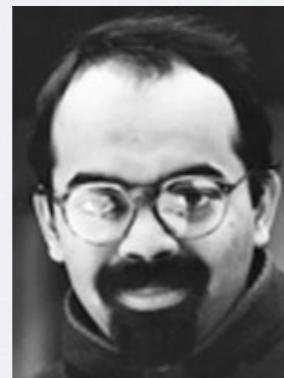
Low-power
architecture

Programming
languages



Greg Morrisett

L. Mahadevan Todd Zickler



Bio-materials



Vision

Geof Barrows



Vision sensors

Some Guy

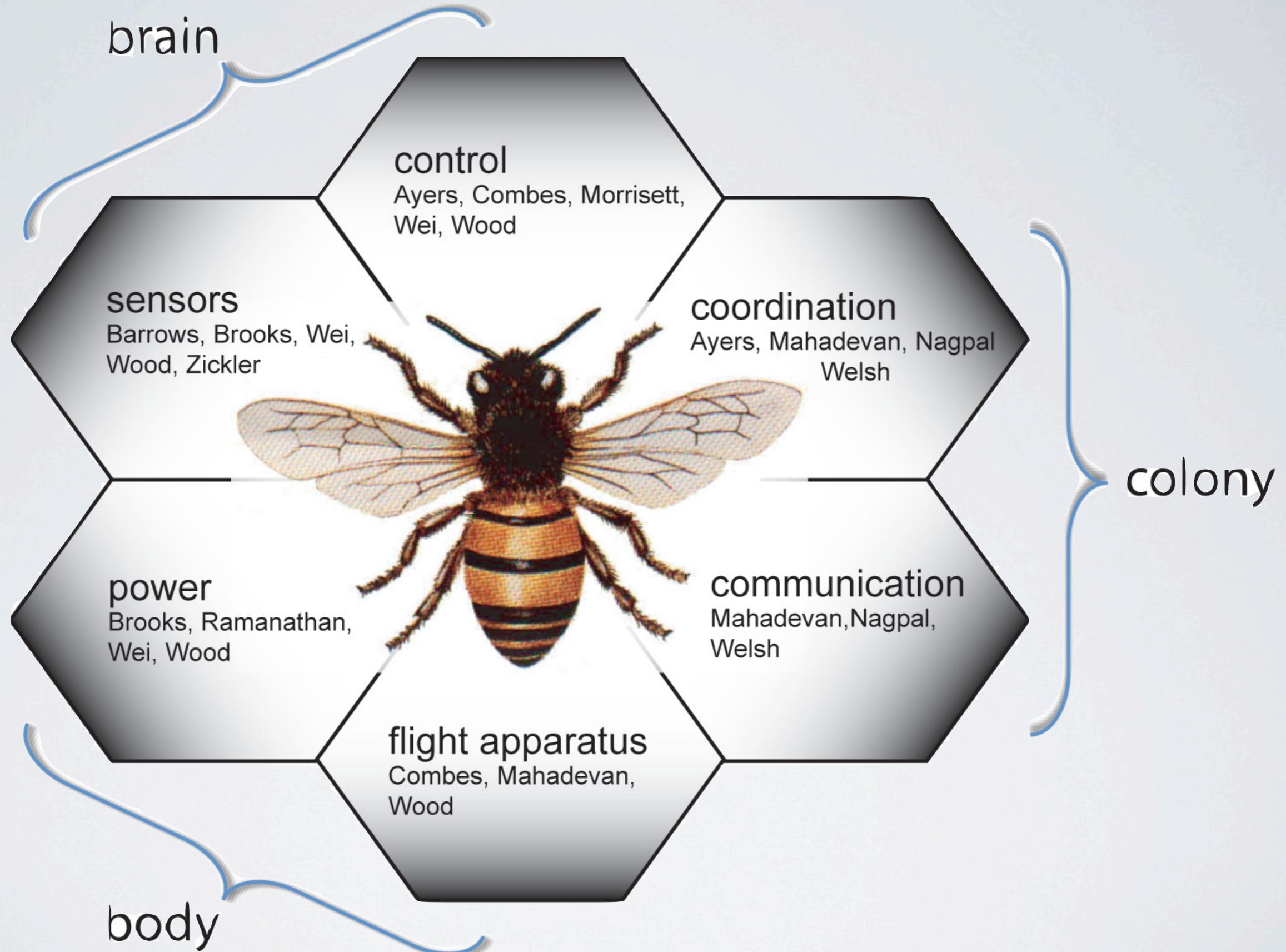


Mascot



Shriram
Ramanathan

Micro fuel cells



MORE THAN JUST POLLLINATION

- 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



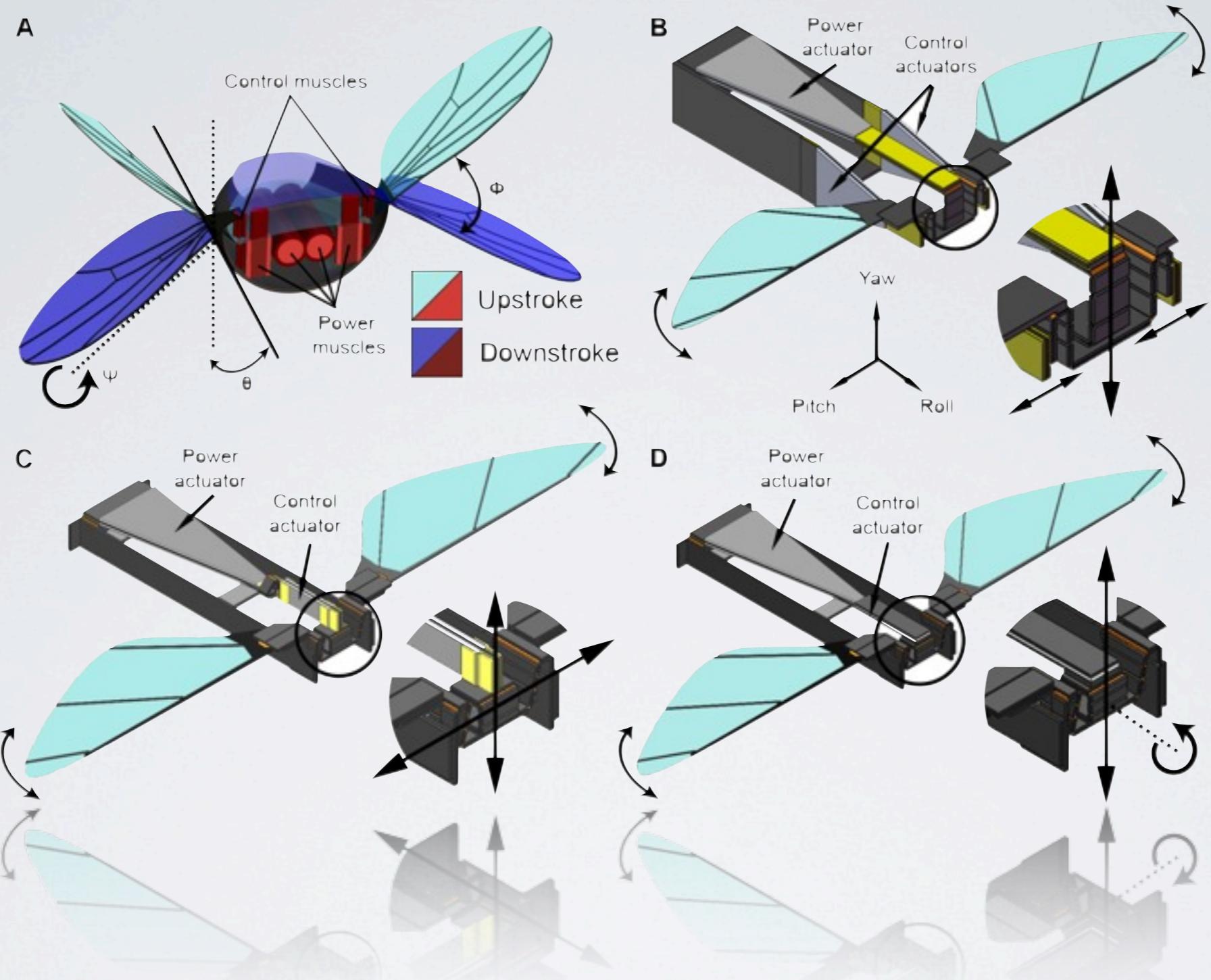
Engineering



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

Chapter One: The Body

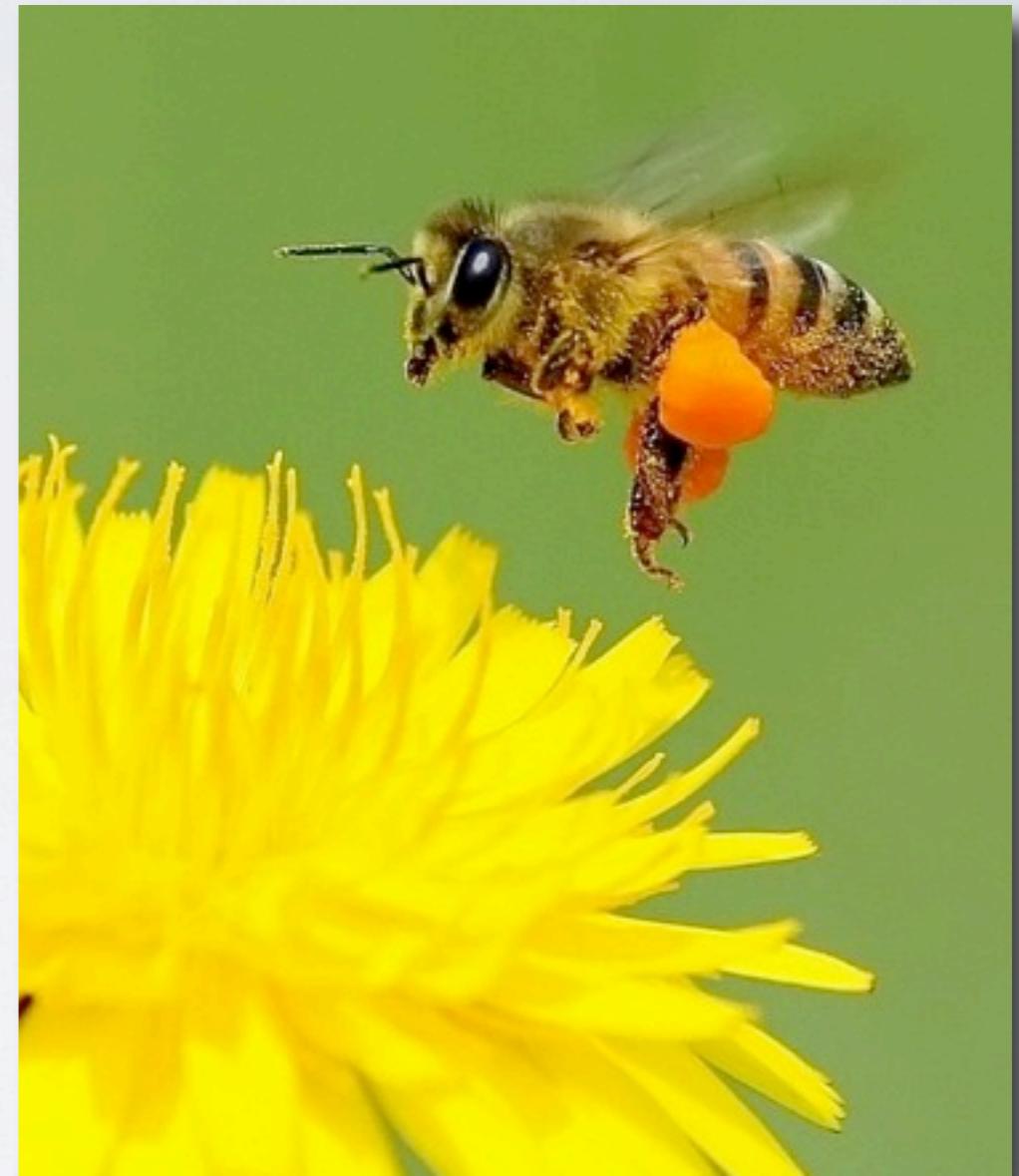




HOW DO THEY FLY?

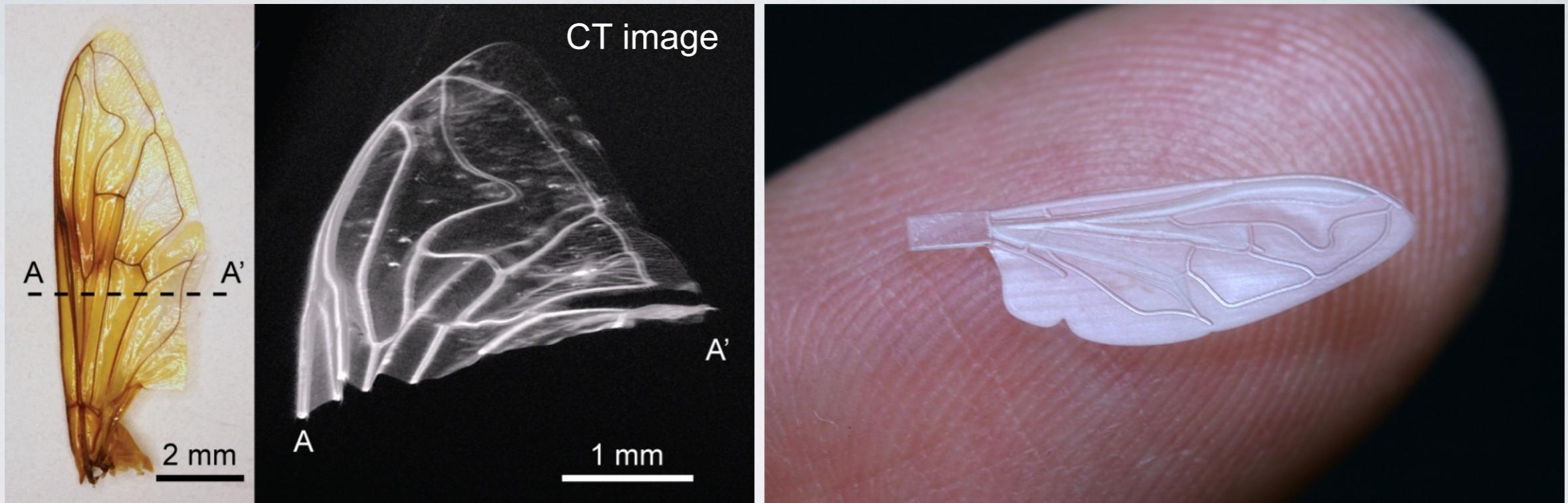
WHY CHOOSE BEES FOR FLIGHT BIOINSPIRATION?

- High payload
 - > able to carry loads \approx 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



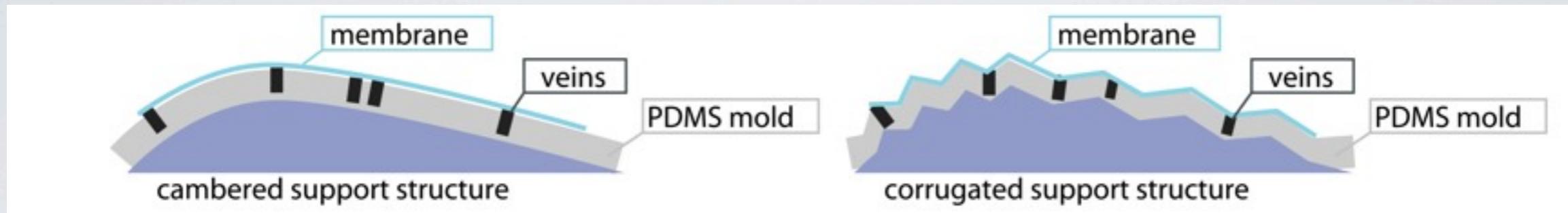
Morphology of natural wing (hover fly)

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]

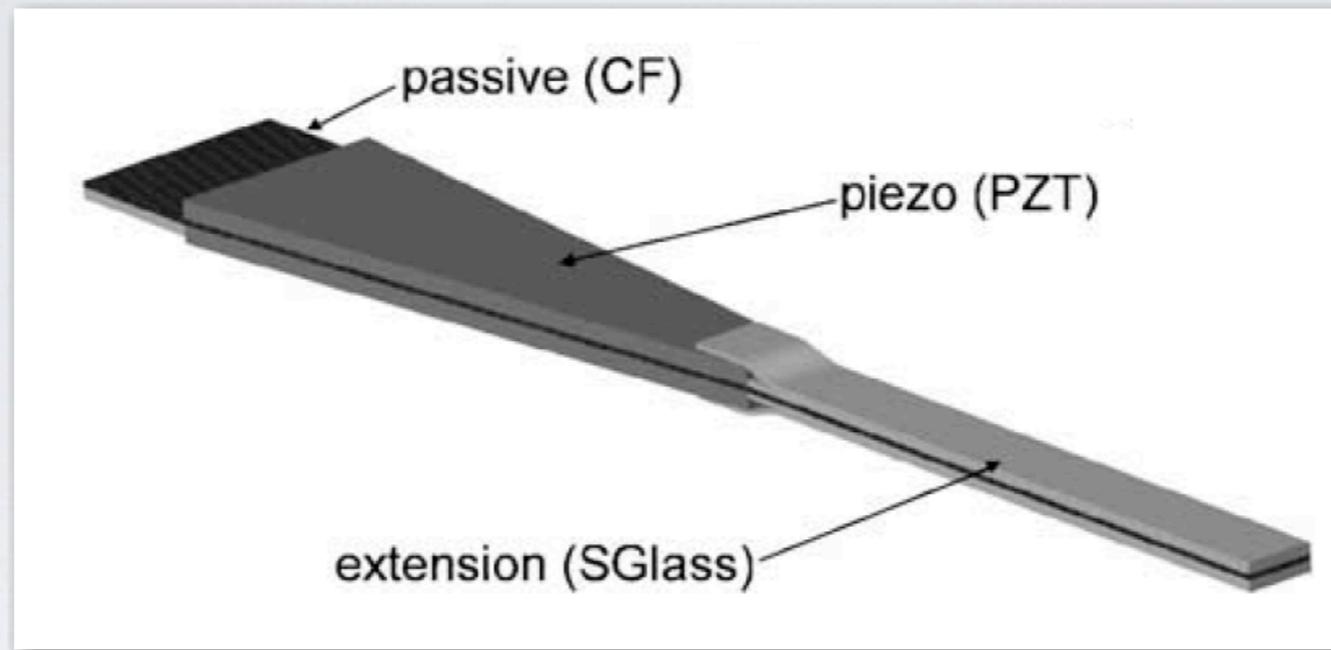
INSECT WING DESIGN: WING CORRUGATION



Fabrication method for cambered and/or corrugated artificial wings

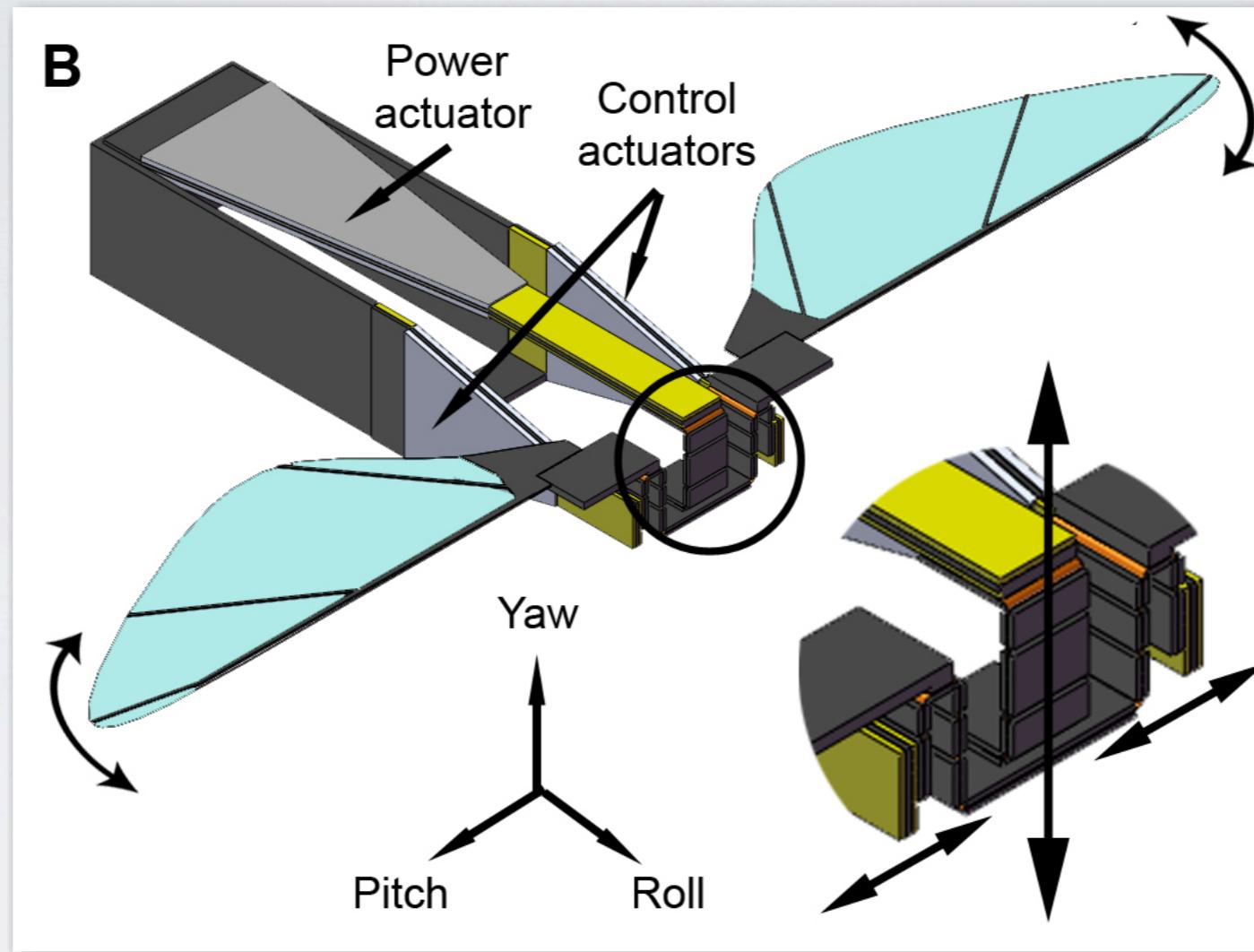
- 3-D profile (e.g., corrugation, camber) affects dynamic behavior of wings
 - > increases bending stiffness while minimizing weight and permitting wing torsion

THE MUSCLE



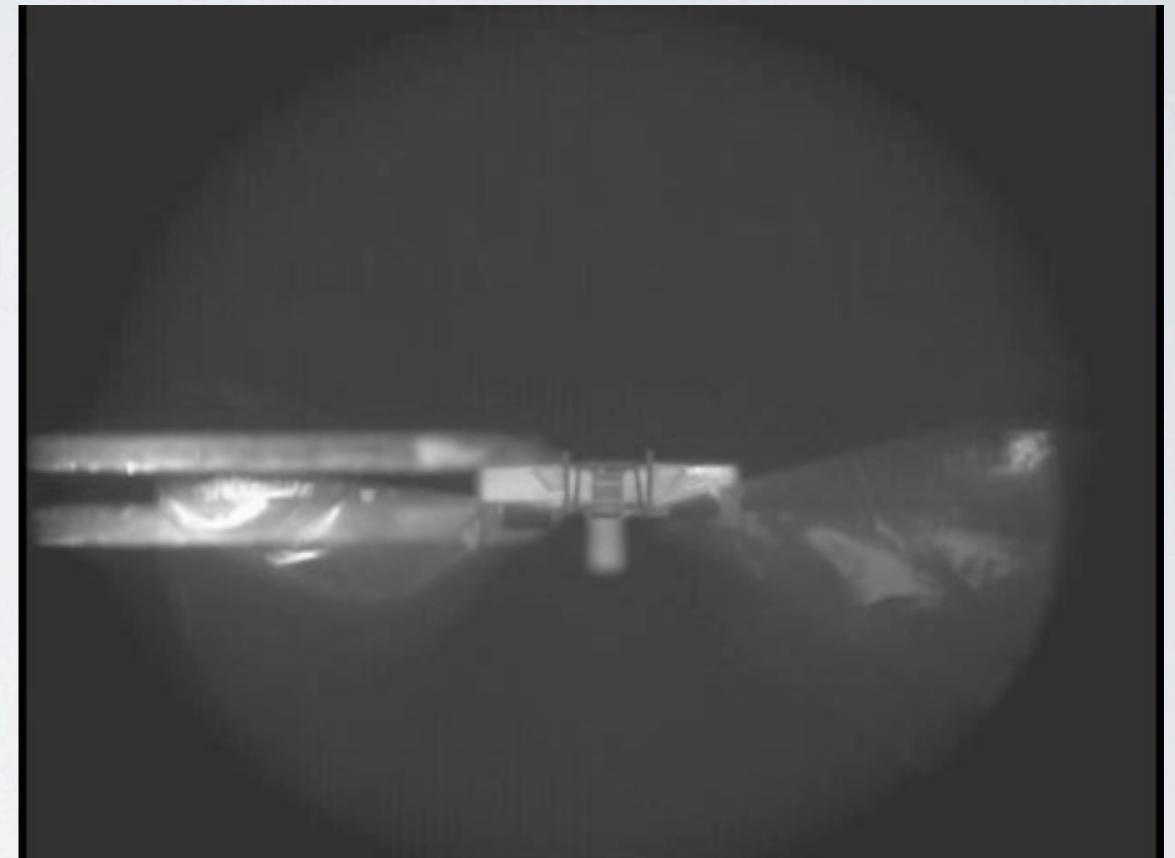
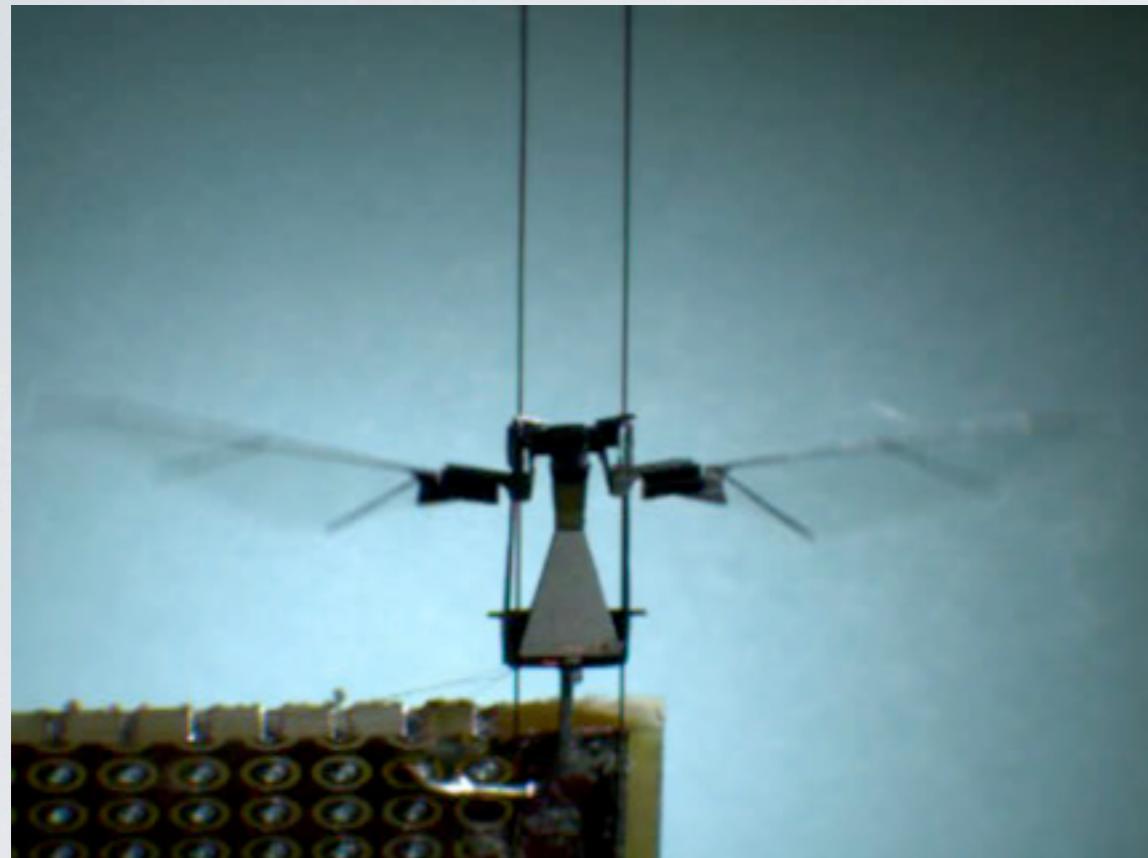
- Piezoelectric actuator
 - 2V produces displacement of ~ 1 micron
 - Needs ~200V for flapping movement of 100 um
 - But a tiny amount of power: tens of mW

CONTROL ACTUATOR



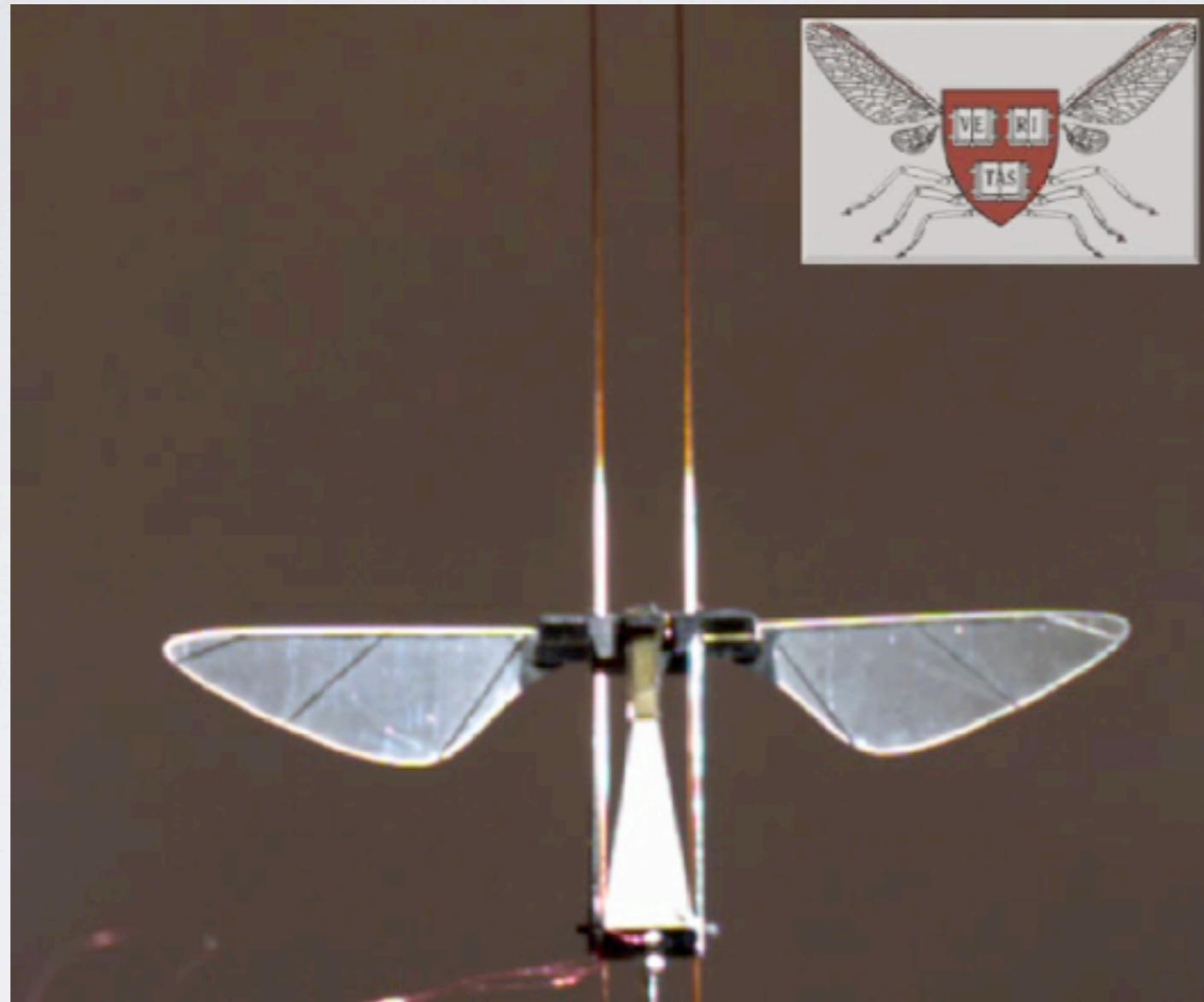
- Thoracic mechanics
 - Separate power and control actuators

WINGS IN ACTION



- Video is slow-mo: flapping frequency 110 Hz

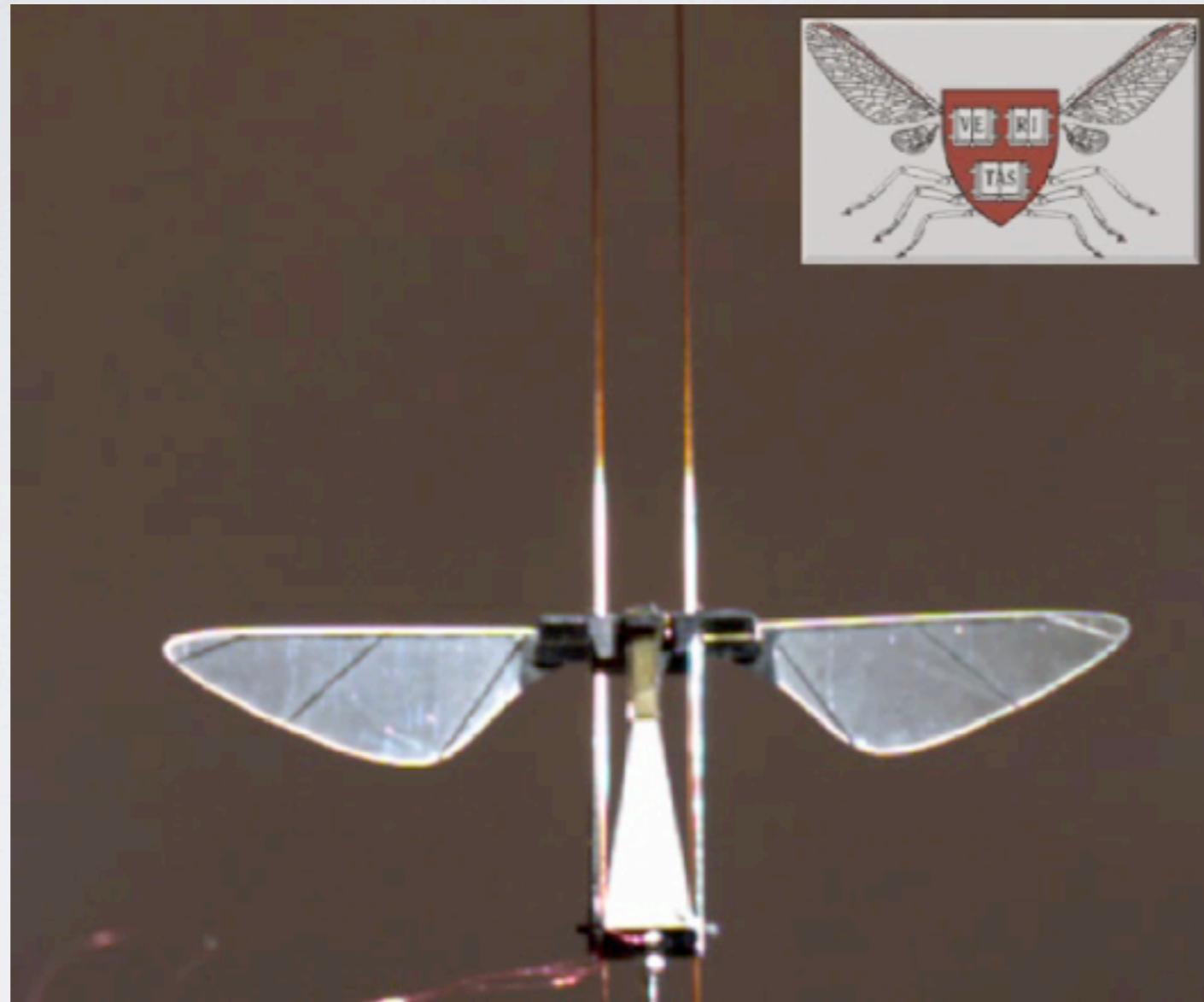
FIRST TAKE-OFF



[Wood]

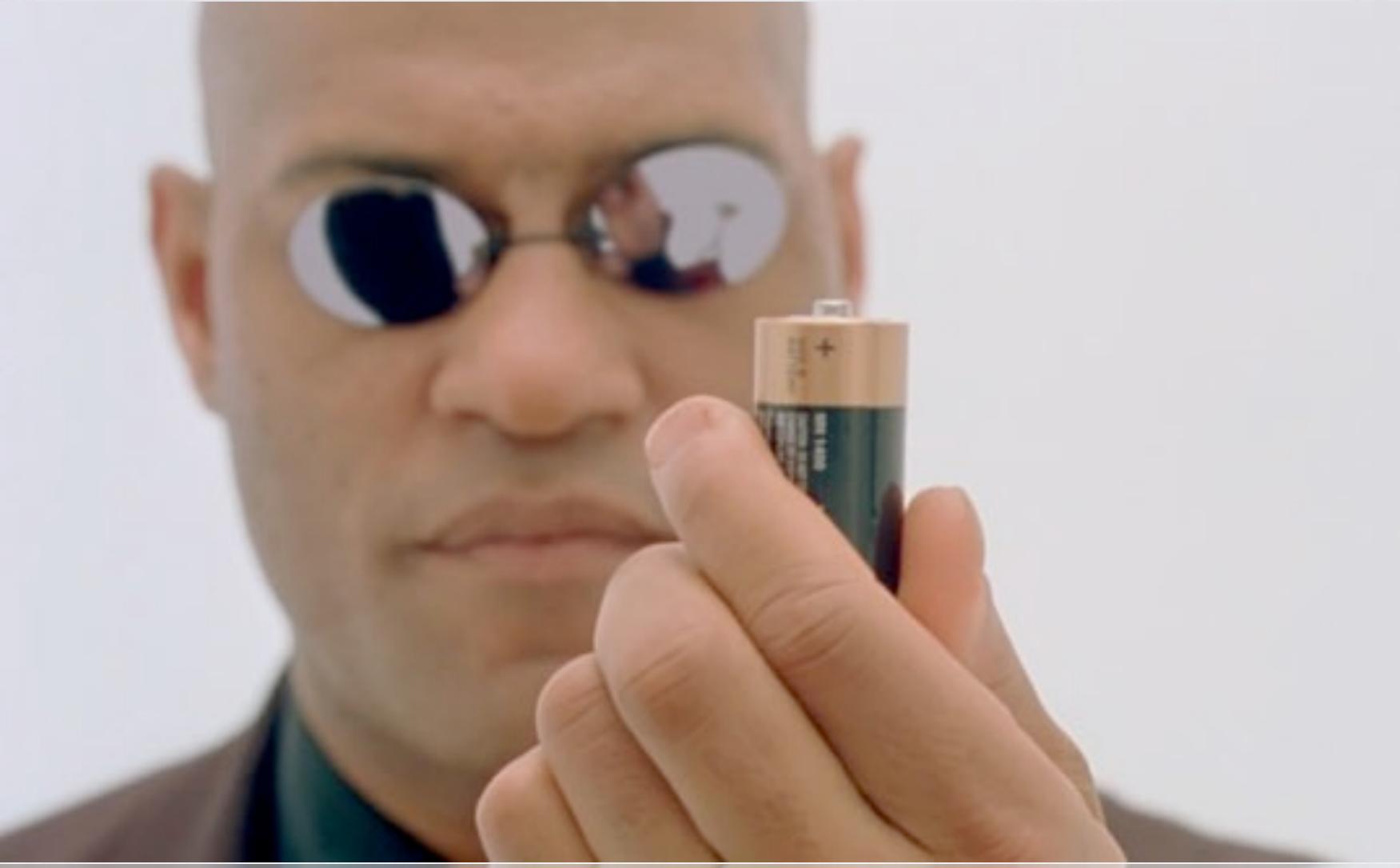
Friday, June 25, 2010

FIRST TAKE-OFF



- On guide wires with 1.2 kV power supply!!

[Wood]

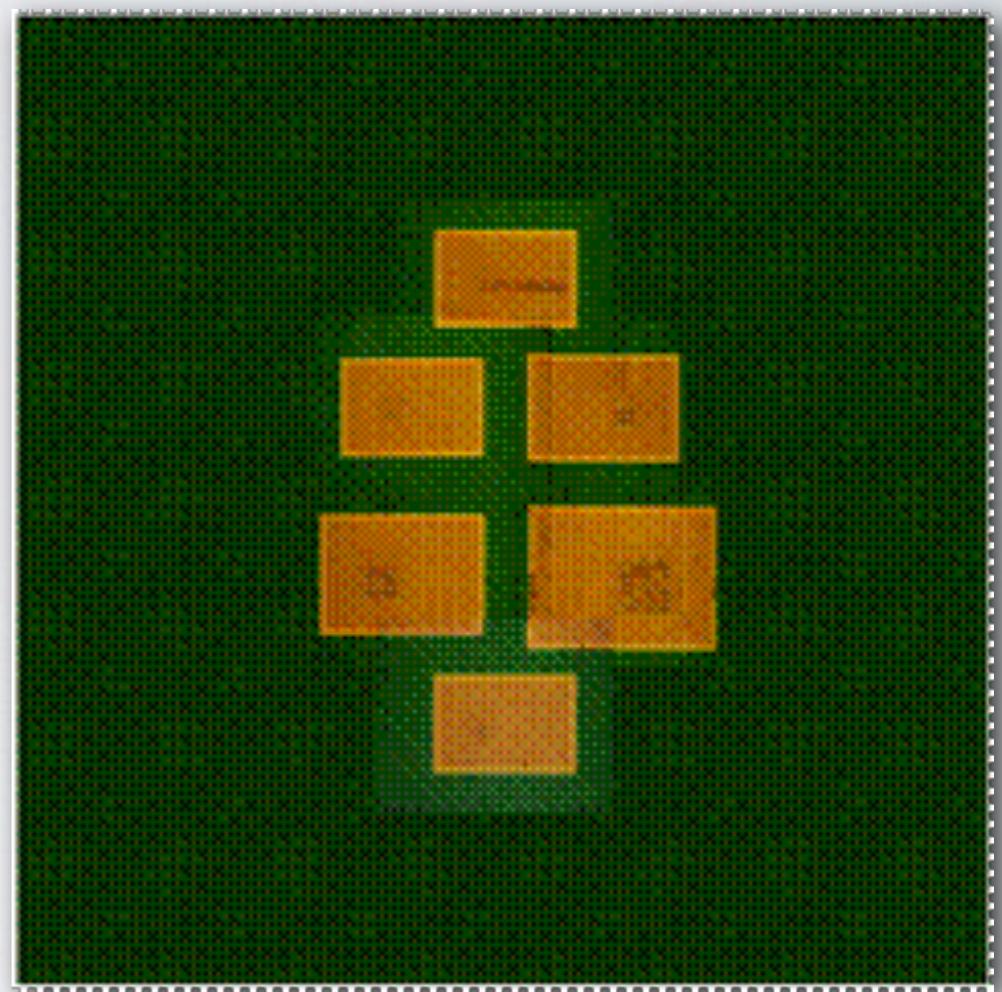
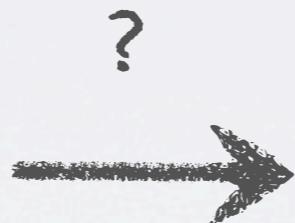


HOW DO THEY GET
POWER?

THIN FILM MICRO-FUEL CELLS



Westinghouse SOFC

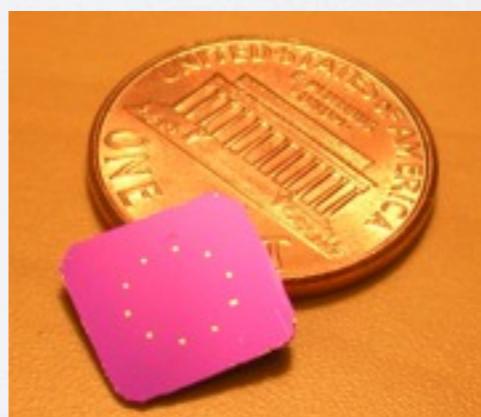
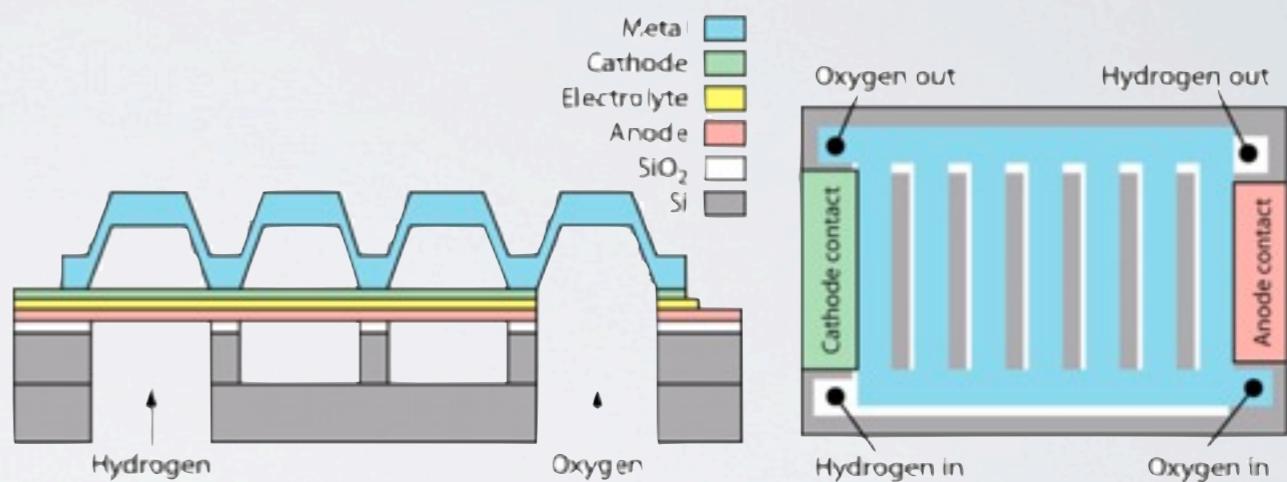


Johnson and Ramanathan, 2007

[Ramanathan]

POTENTIAL FOR MICRO FUEL CELLS

- Current limitations:
 - Requires hydrogen fuel
 - Operate at 200-500 °C
 - Power output
 - ~100 mW/cm²
- Future goals:
 - Continuous power generation, 1W, breathe air, ambient conditions!



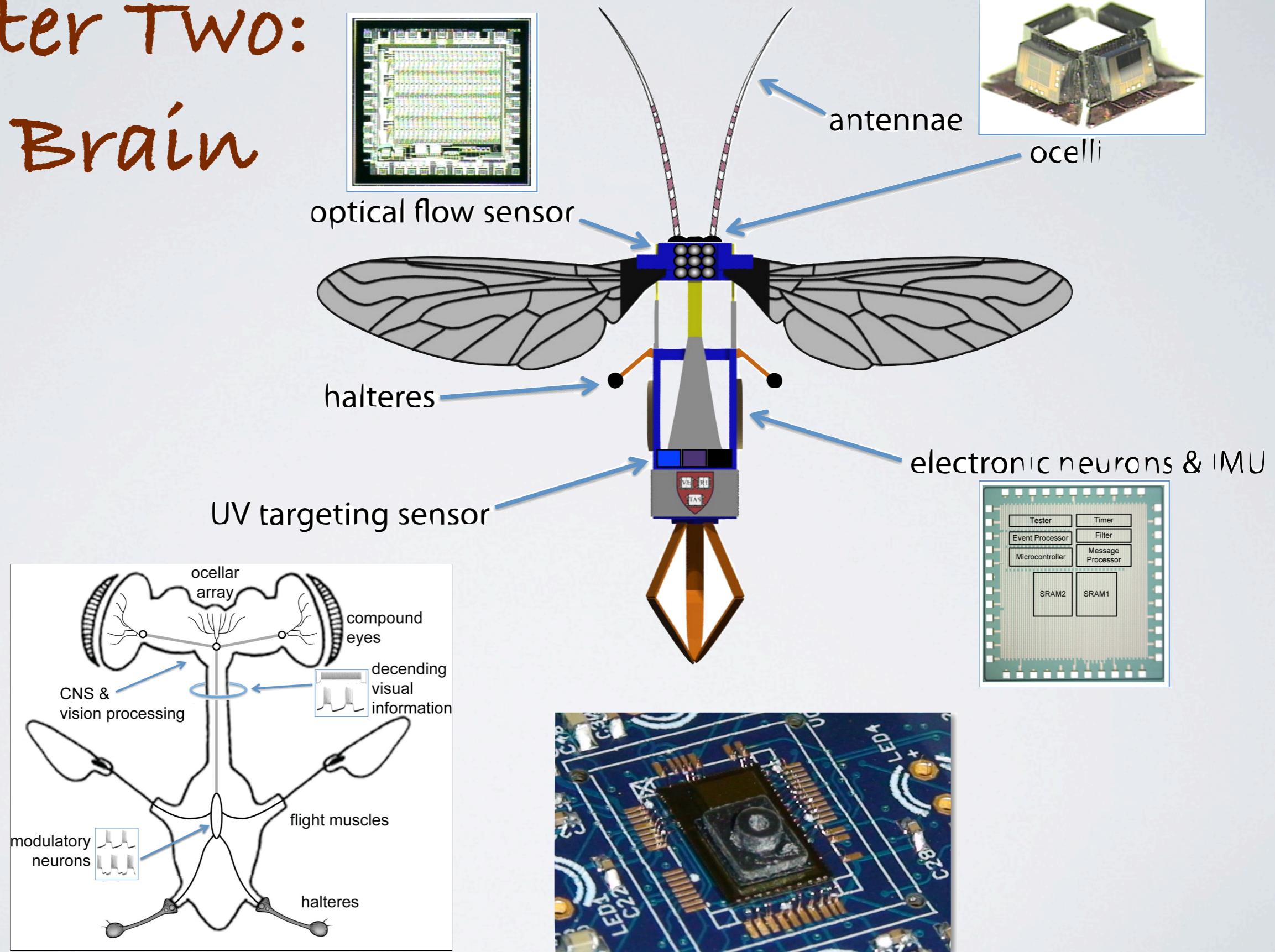
SOFC arrays

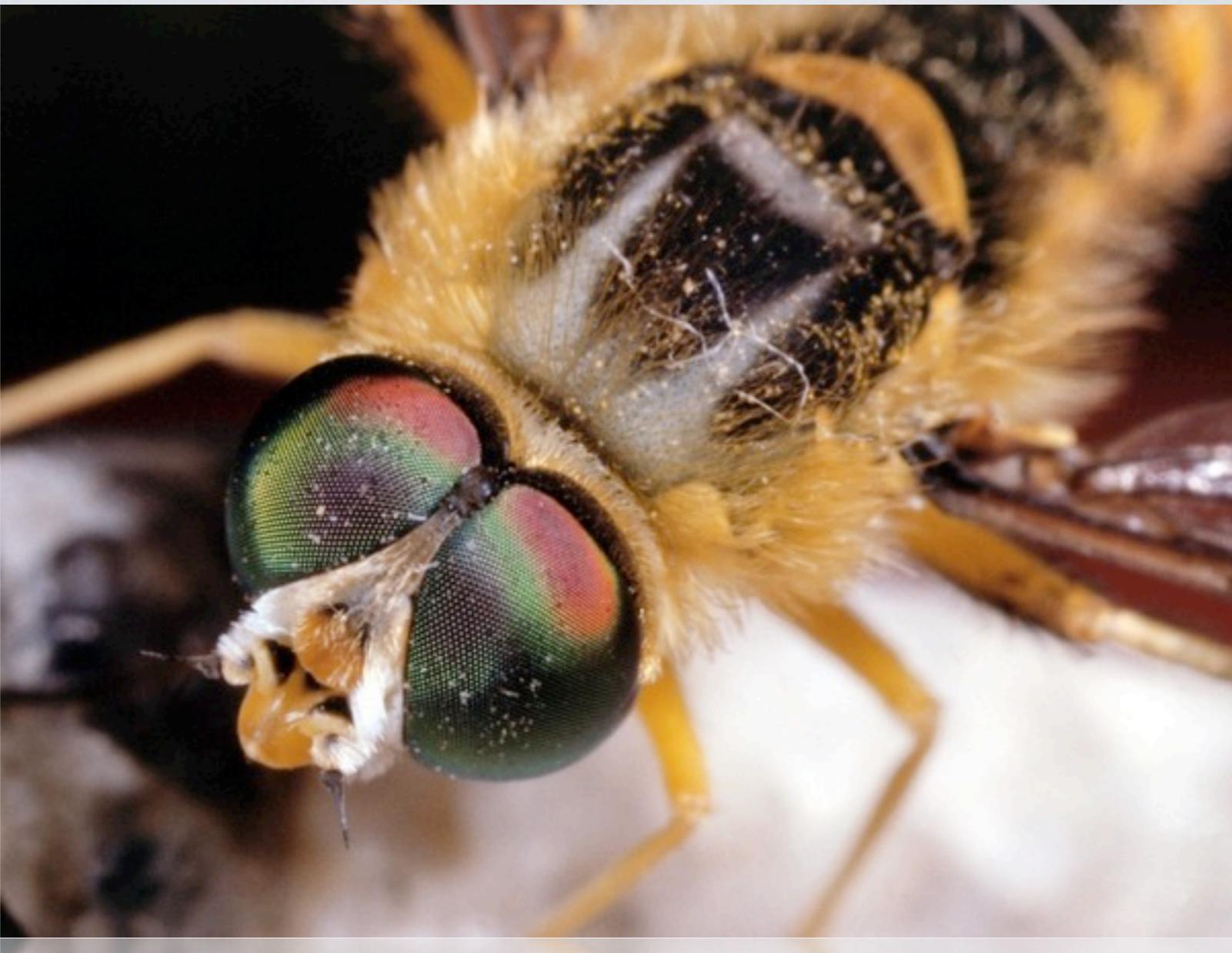


Wafer-scale functional fuel cell arrays

[Ramanathan]

Chapter Two: The Brain

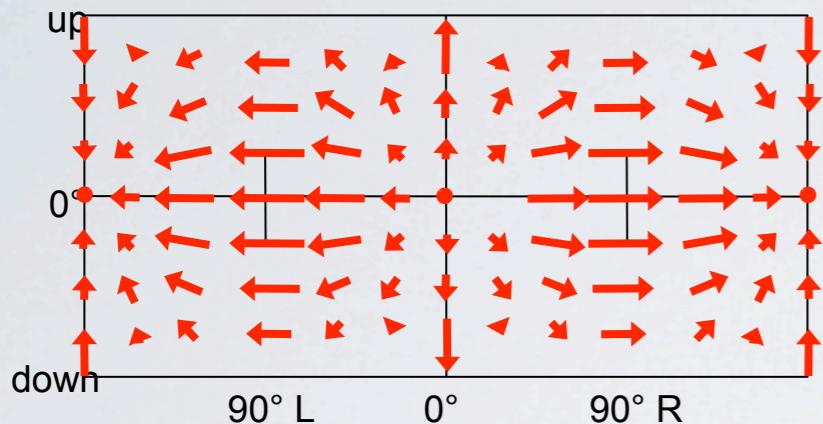




HOW DO THEY SEE
THE WORLD?

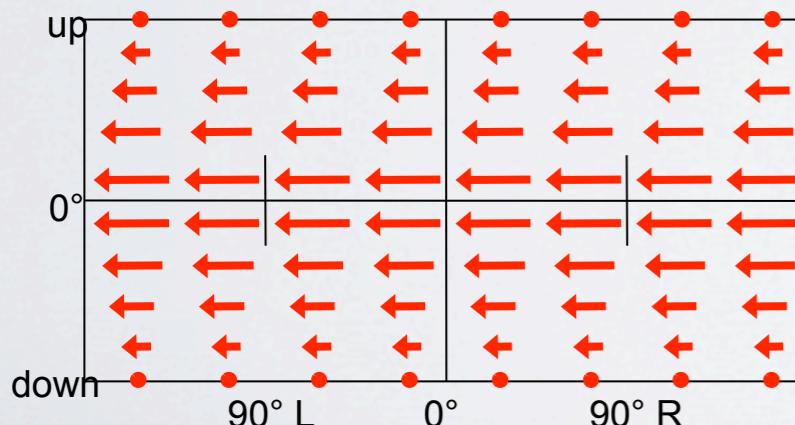
OPTICAL FLOW SENSING

Move Forward



Optical flow can directly sense velocity-related information

Yaw Right

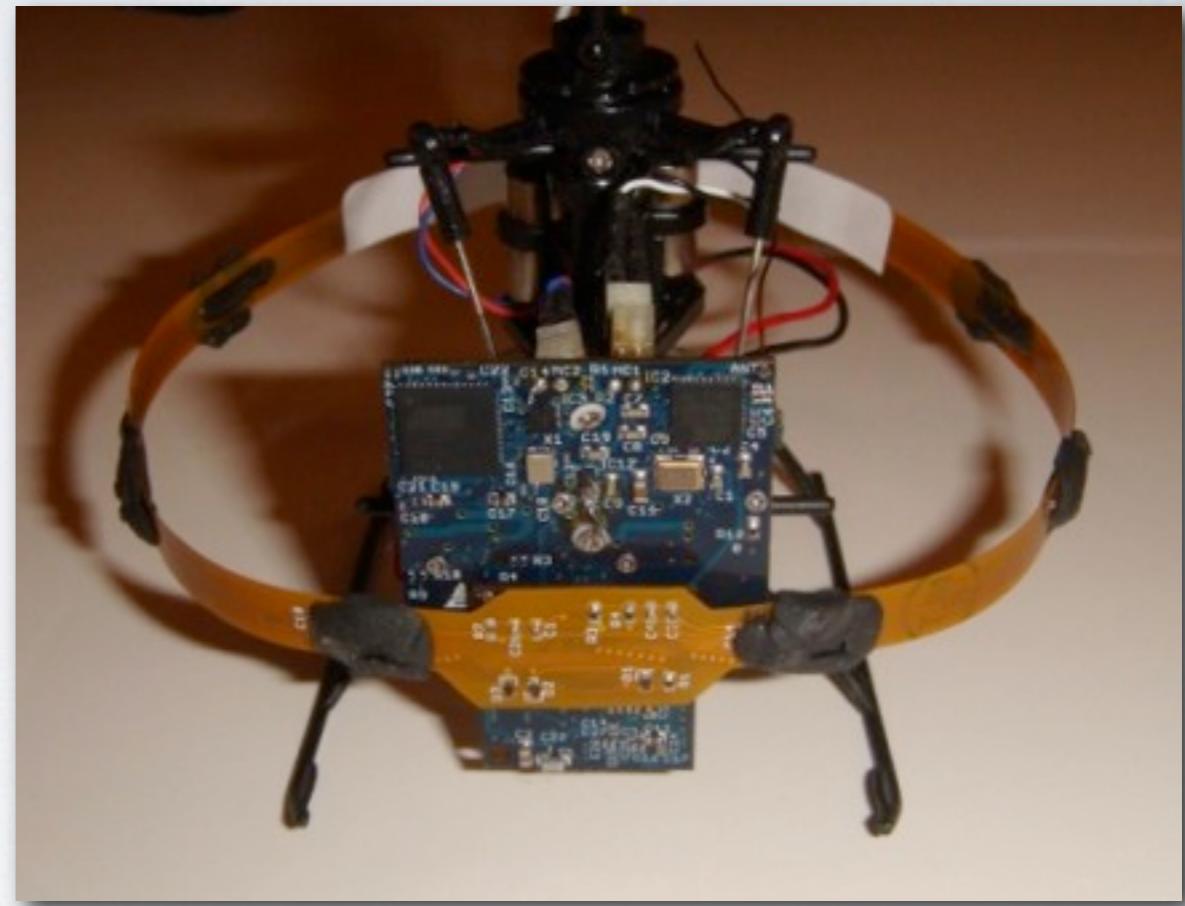
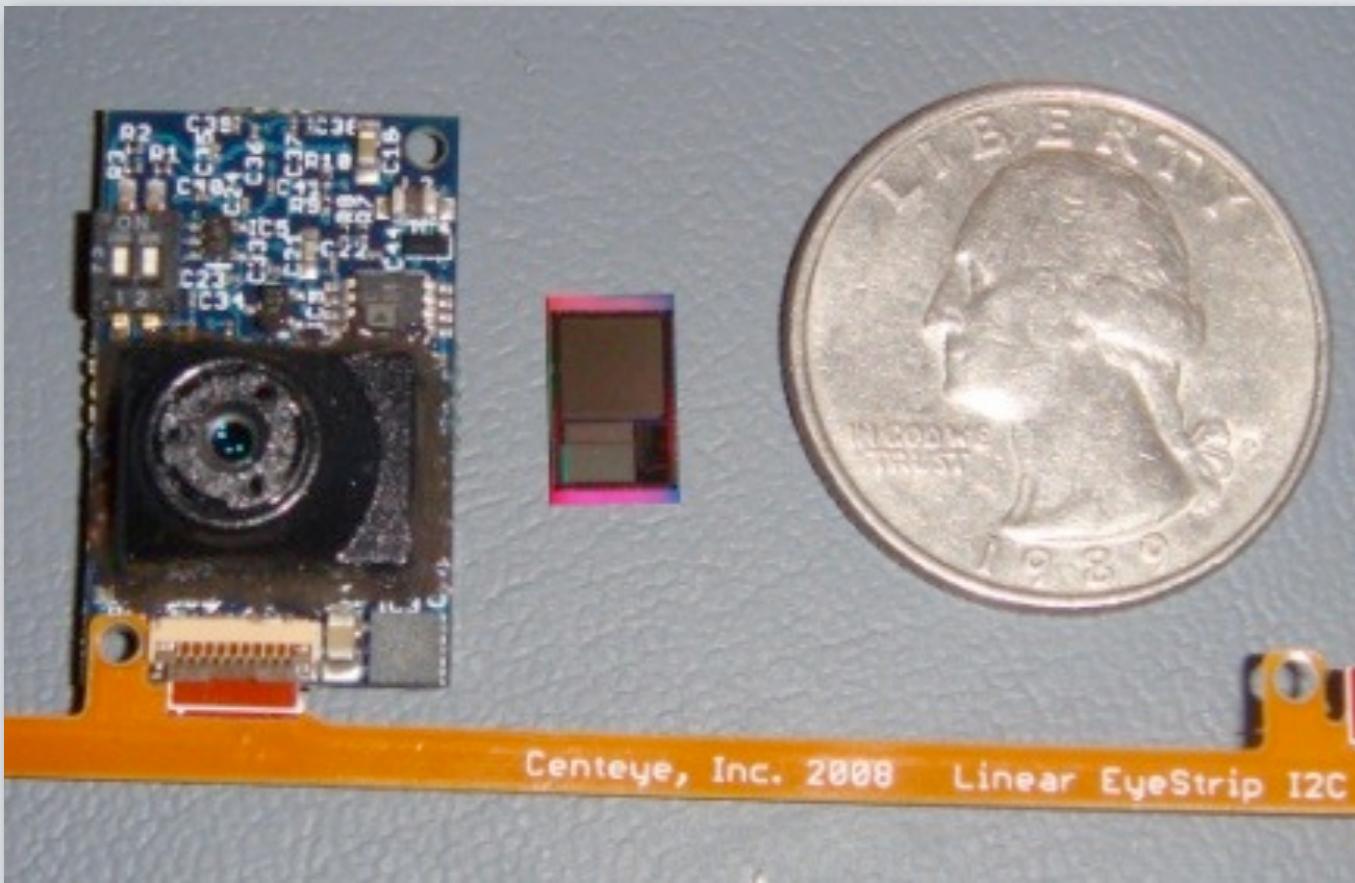


Optical flow can provide gyro-type information



<http://www.youtube.com/watch?v=ckVQrwYljAs>

OPTICAL FLOW SENSORS

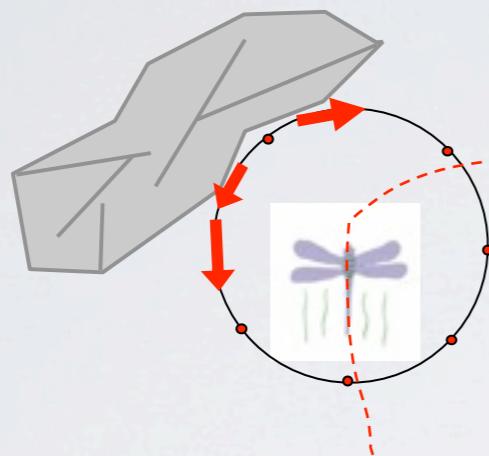


- Cheap, simple CCD array: 64x64 pixels, greyscale
- Don't need high-res cameras!

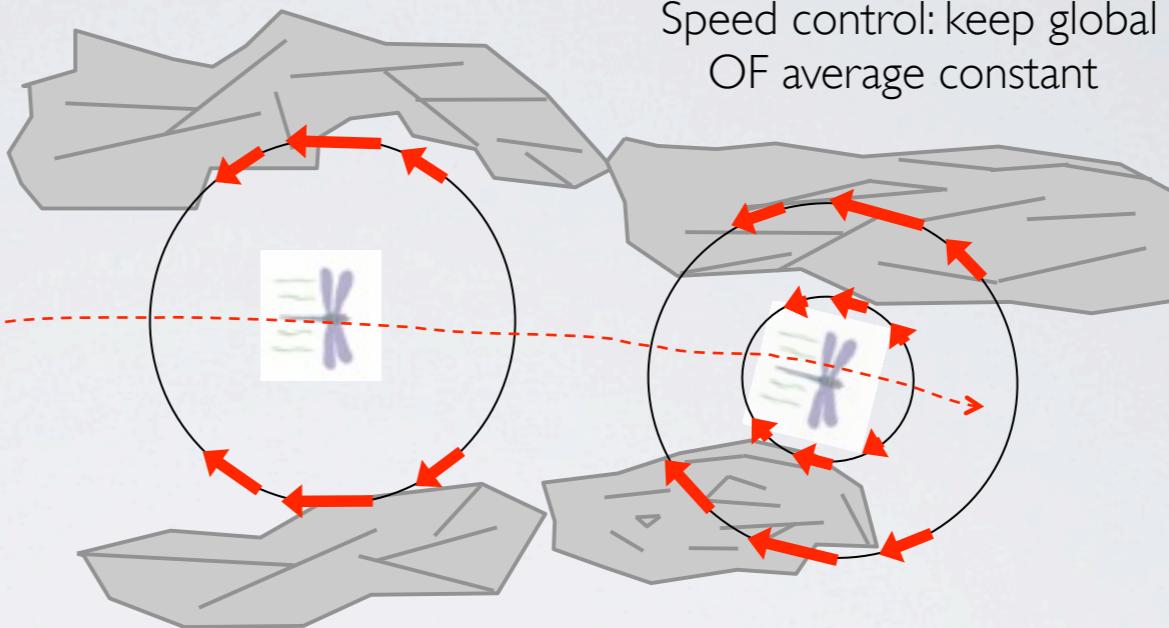
[Centeye]

USING OPTICAL FLOW

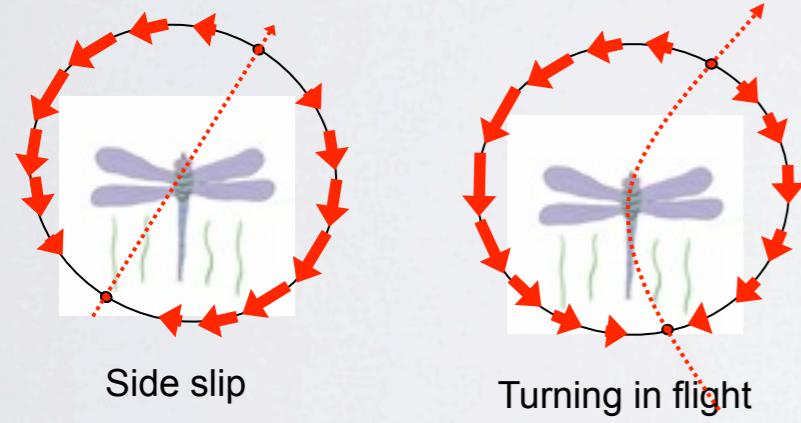
Collision avoidance:
Saccade away from regions
with high OF



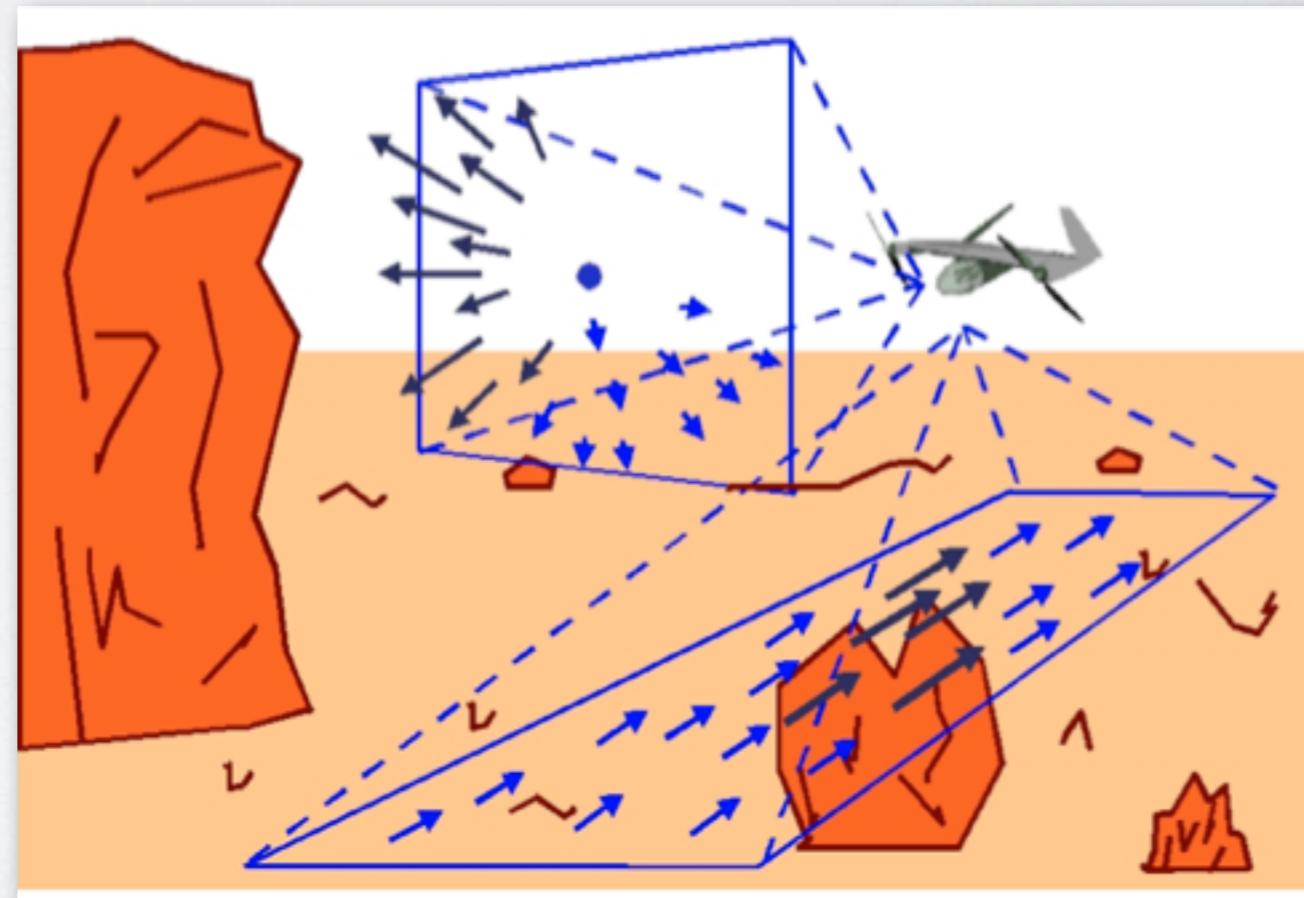
Centering: equalize lateral OFs

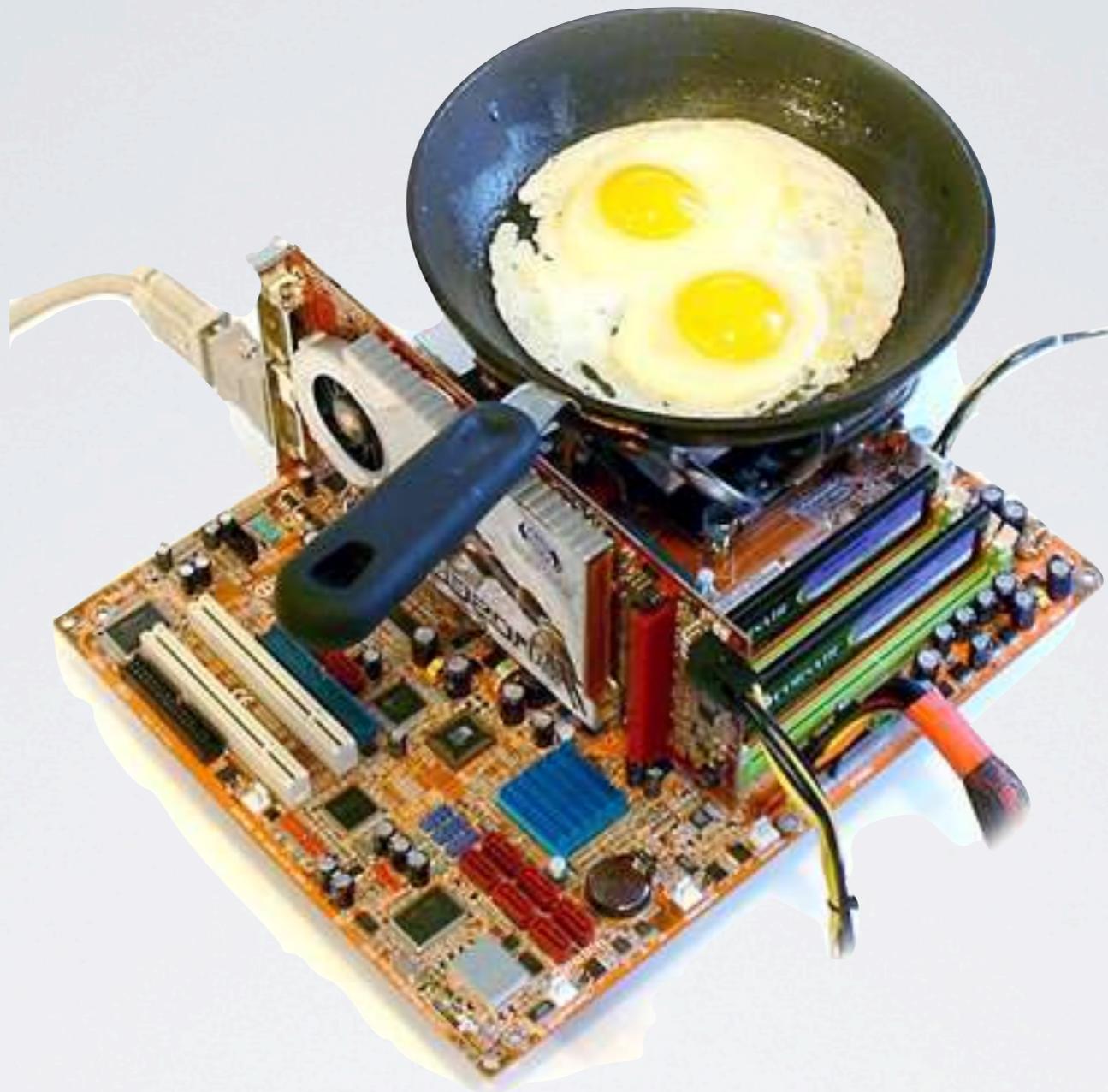


Speed control: keep global
OF average constant



[Centeye]

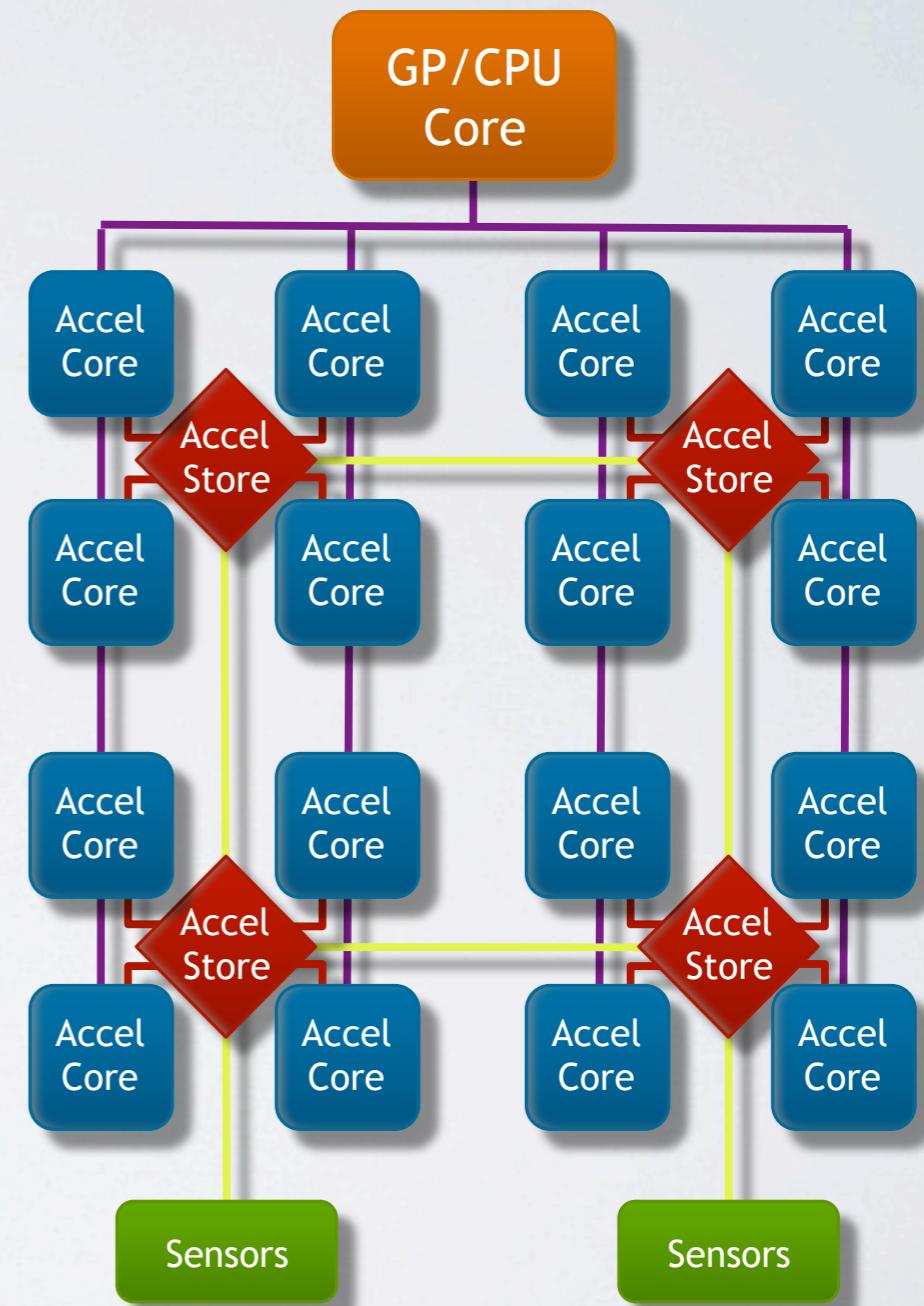




HOW DO THEY COMPUTER?

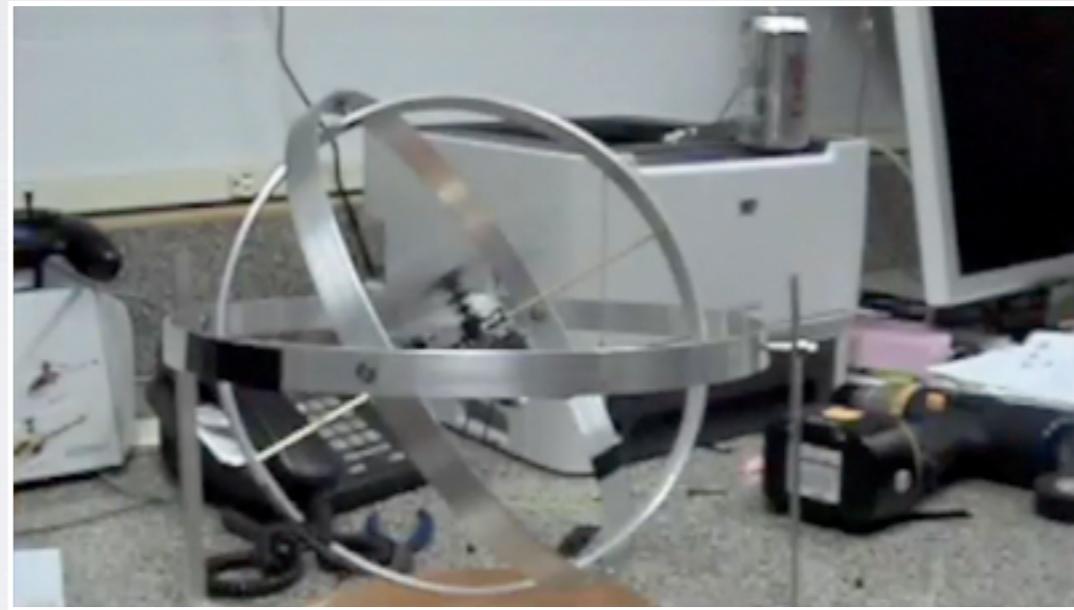
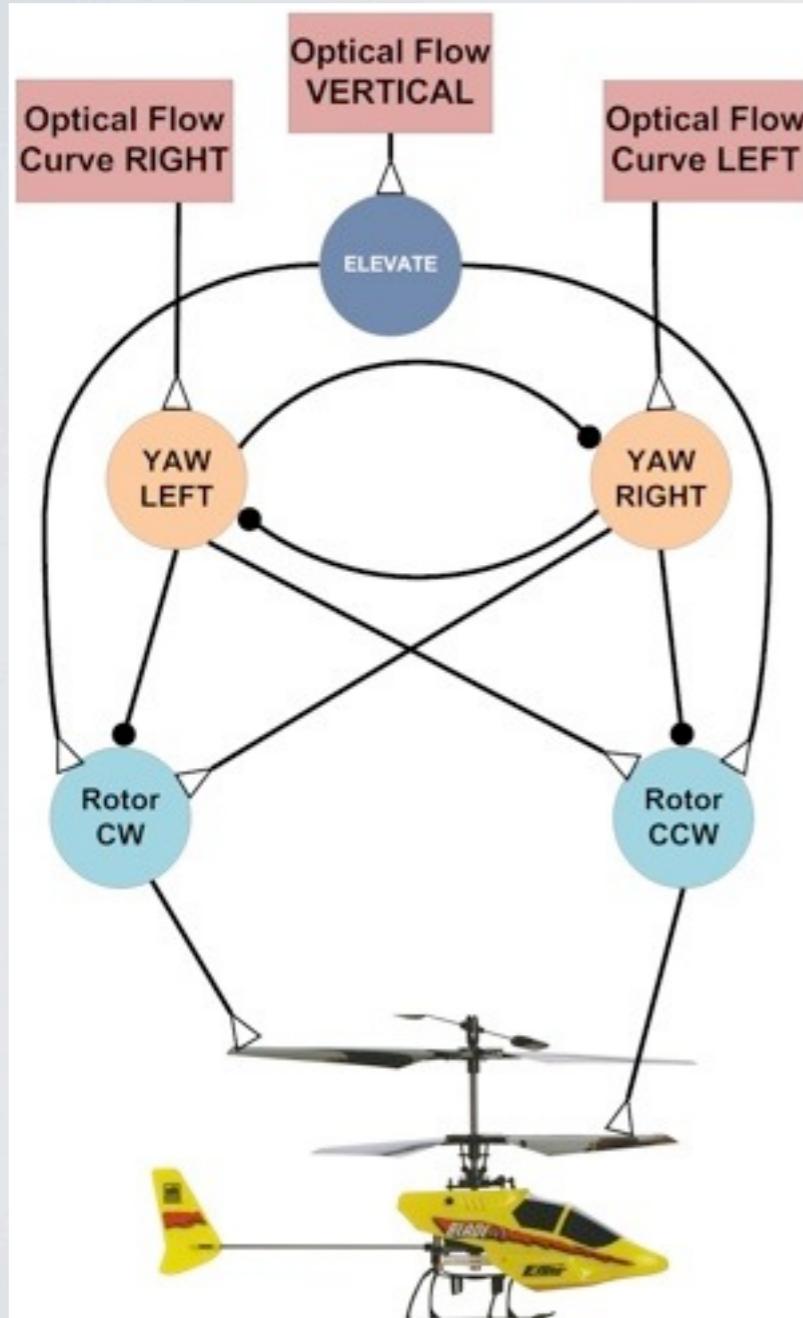
BRAIN ARCHITECTURE

- 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



COORDINATION



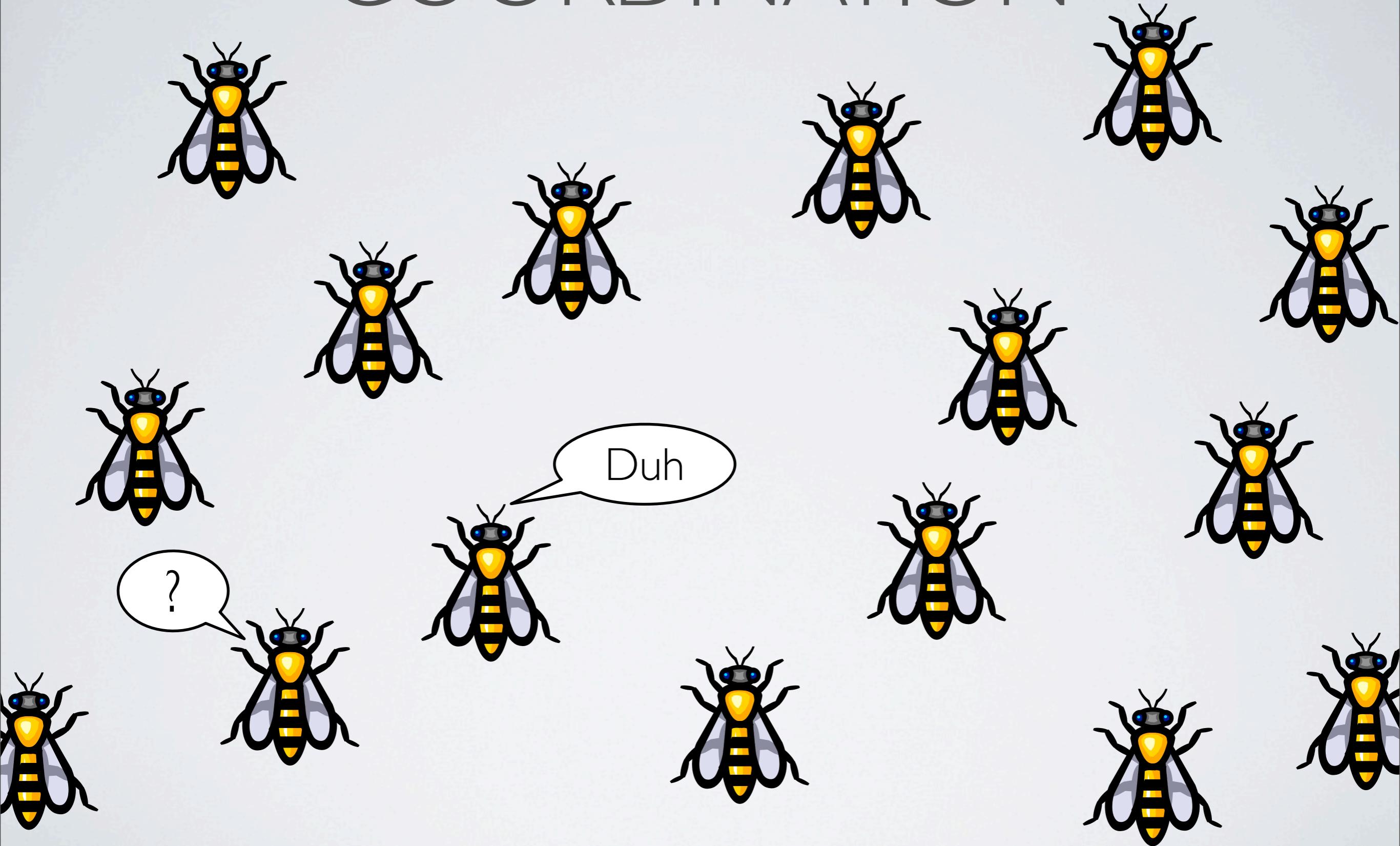
COORDINATION



COORDINATION



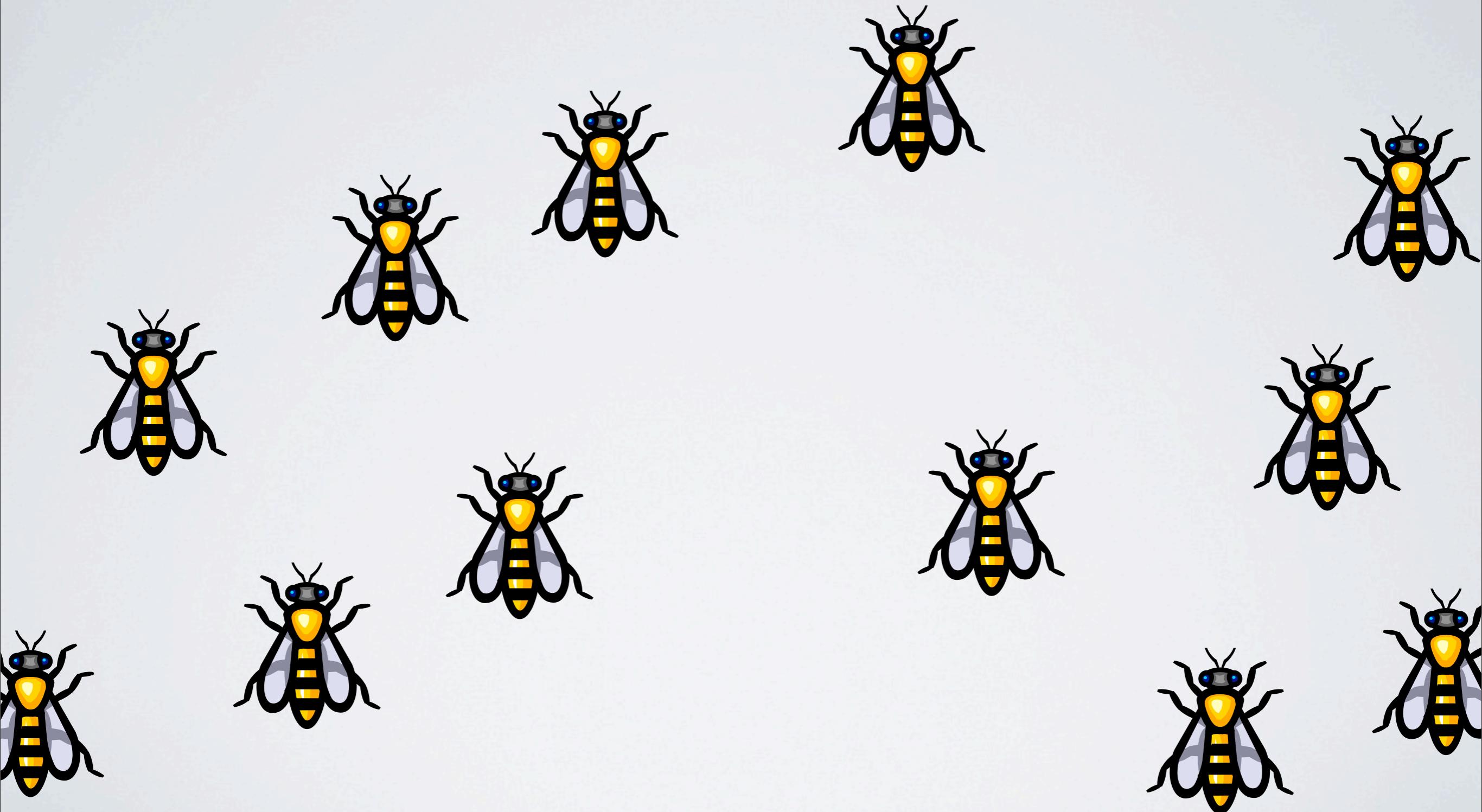
COORDINATION



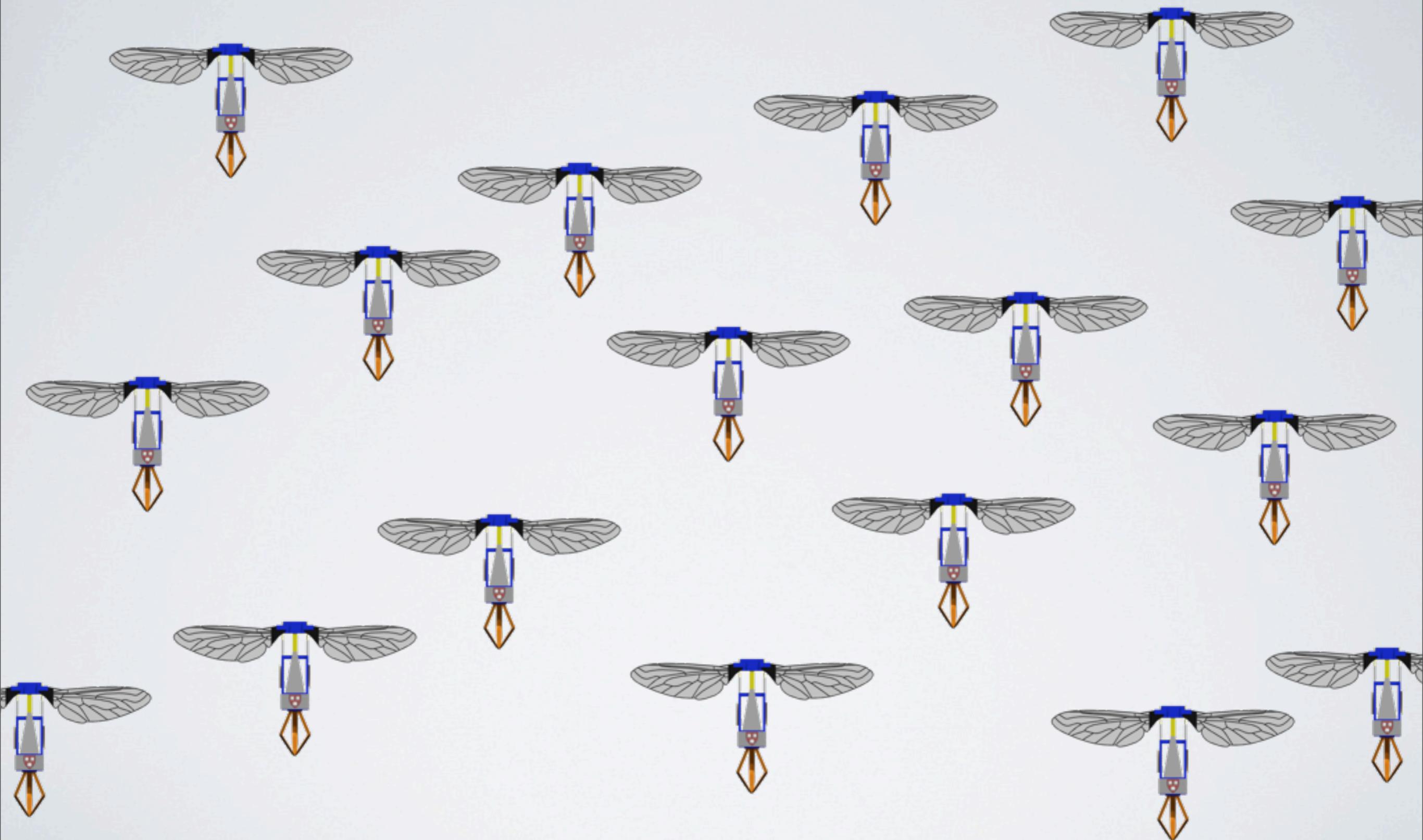
COORDINATION



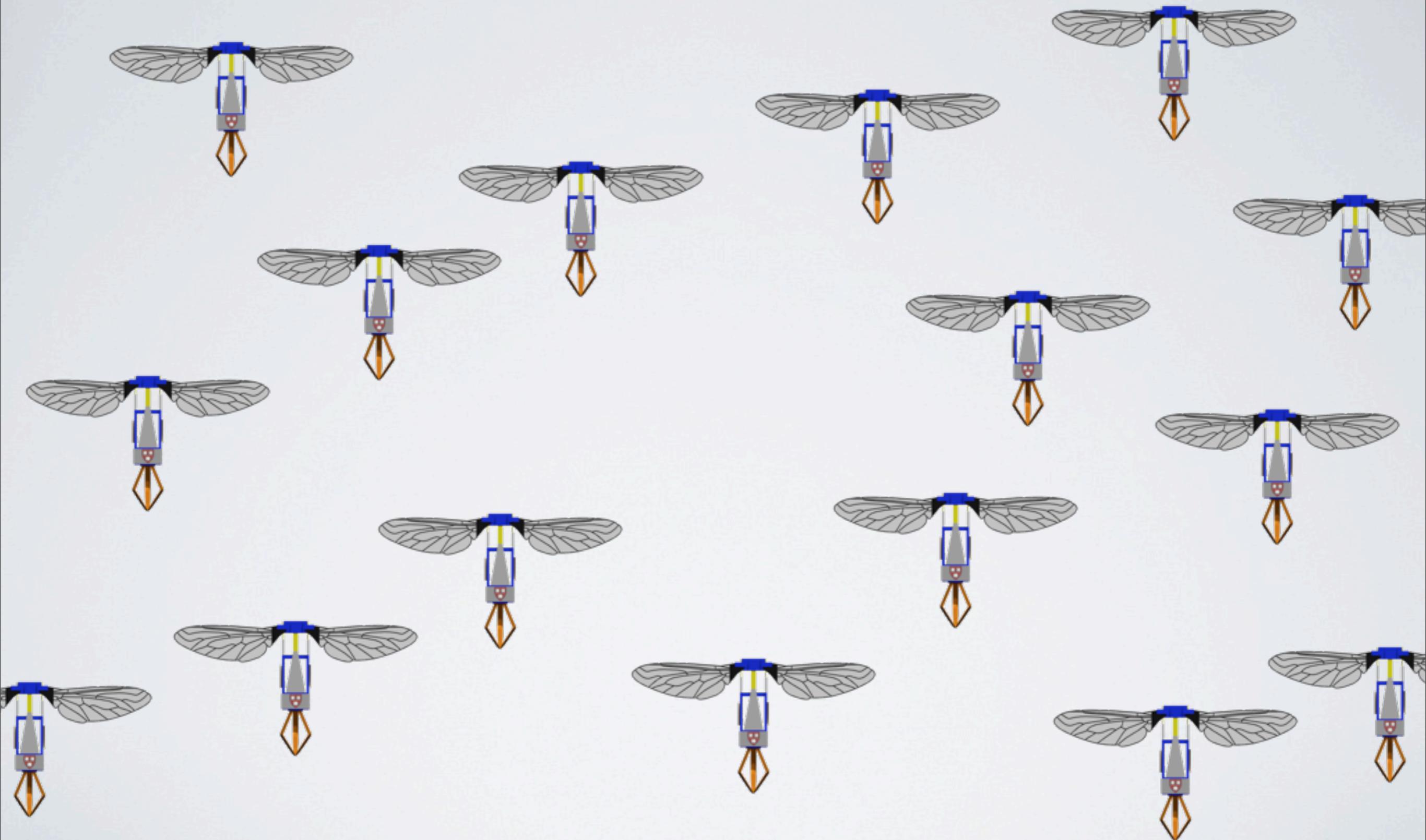
COORDINATION



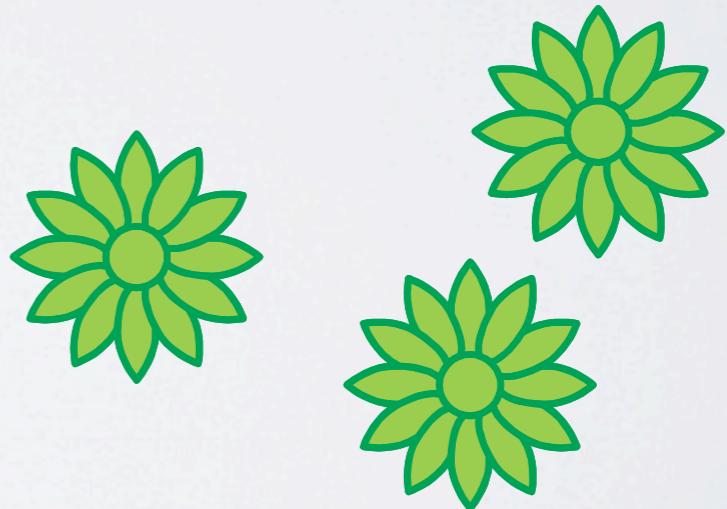
COORDINATION



COORDINATION



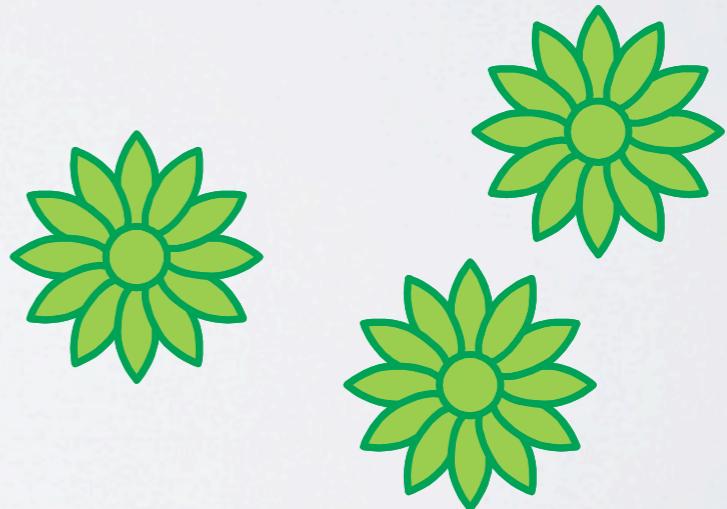
SEARCH ALGORITHMS



- What's “optimal?”
- How to adapt to changing conditions?

[Nagpal]

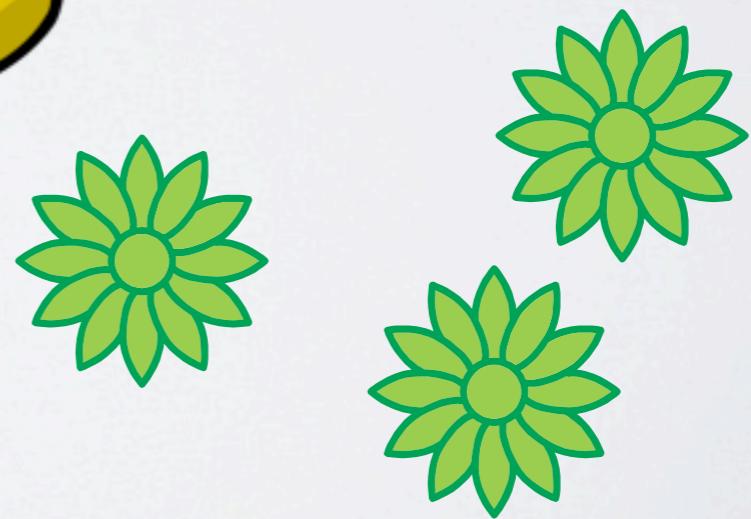
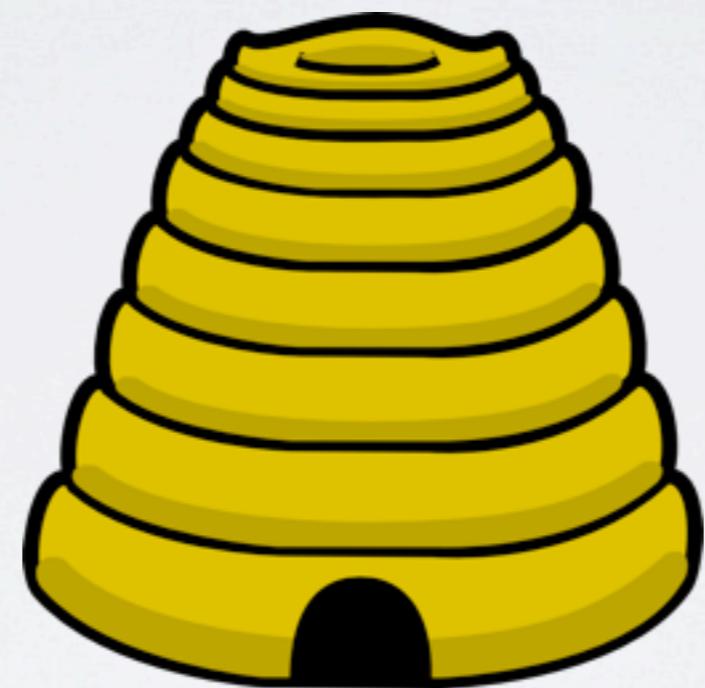
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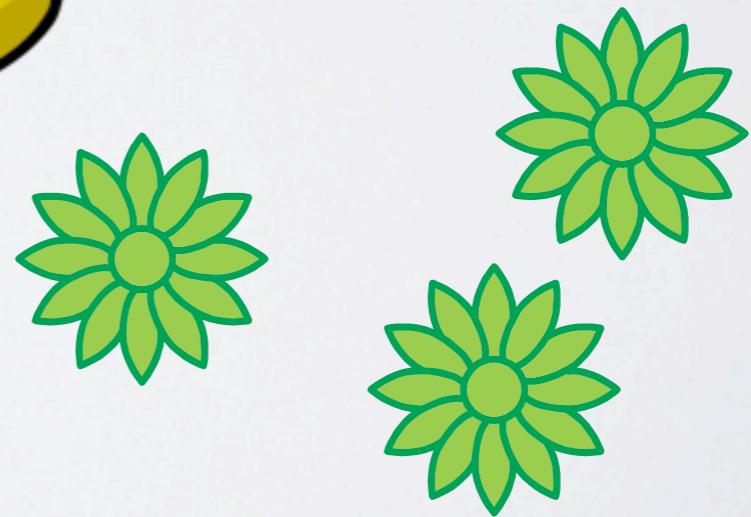
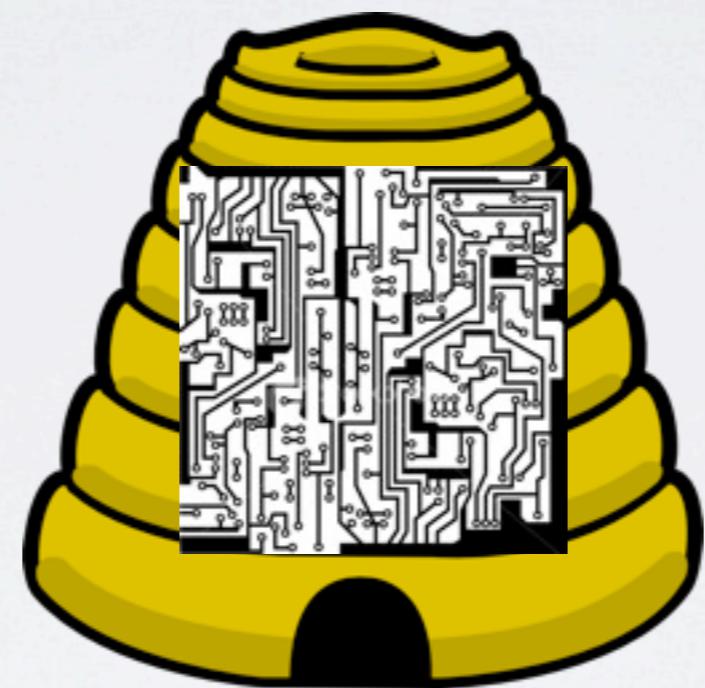
[Nagpal]

THE HIVE



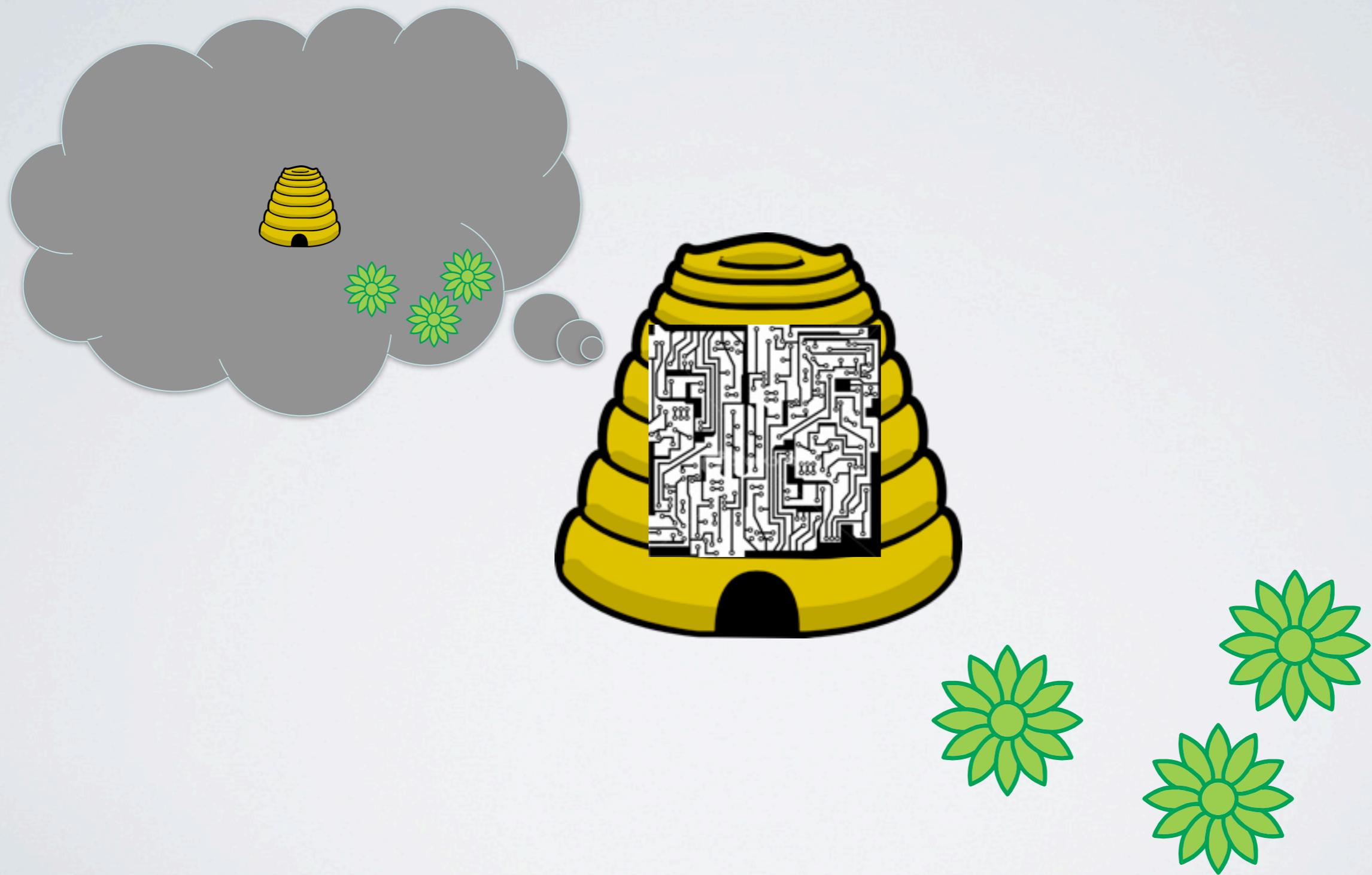
[Nagpal]

THE HIVE



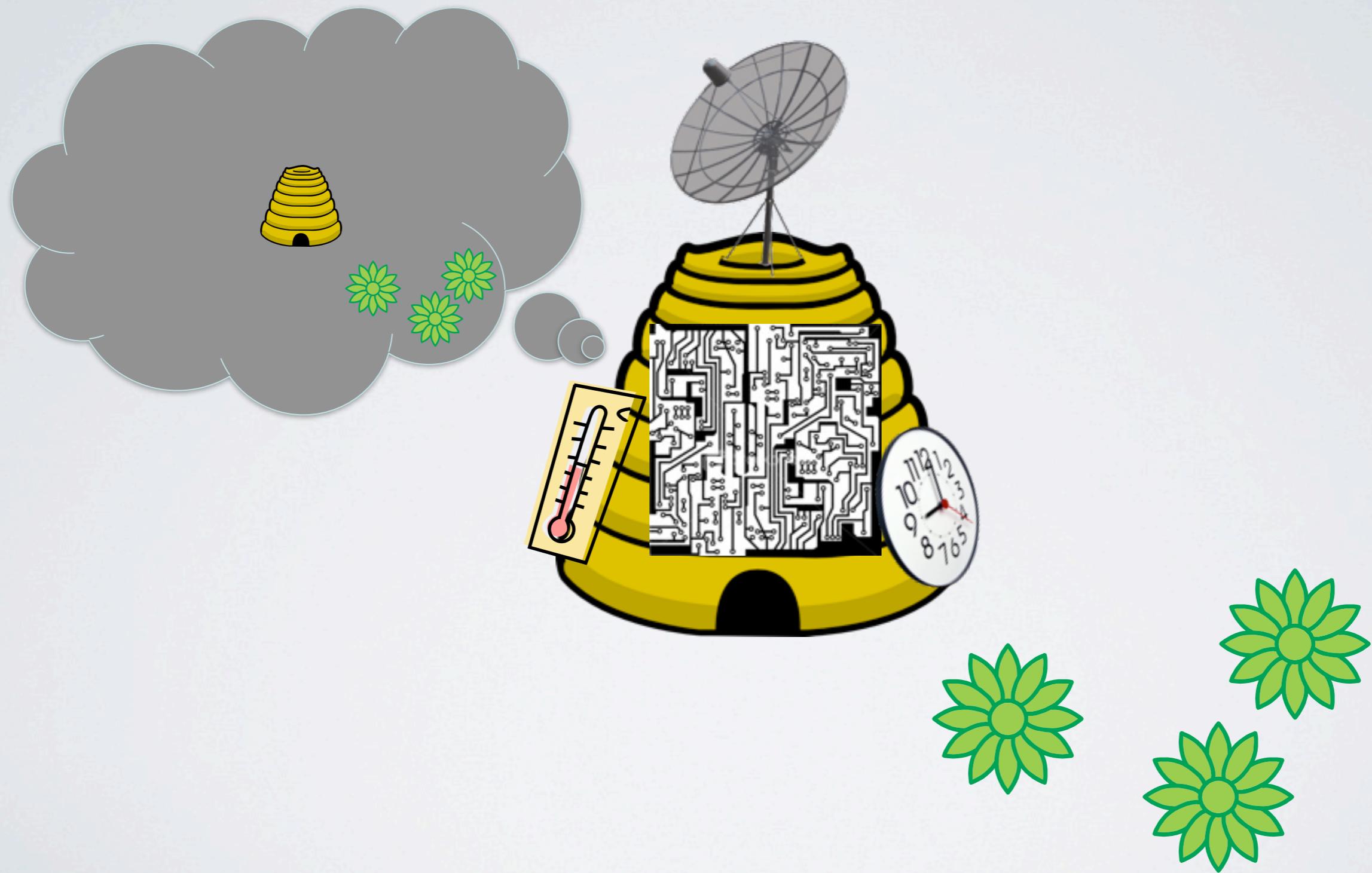
[Nagpal]

THE HIVE



[Nagpal]

THE HIVE



[Nagpal]



HOW DO WE PROGRAM
THEM?

THE OLD WAY...

[Welsh, Morrisett]

Matt Welsh - Harvard University

41

THE OLD WAY...

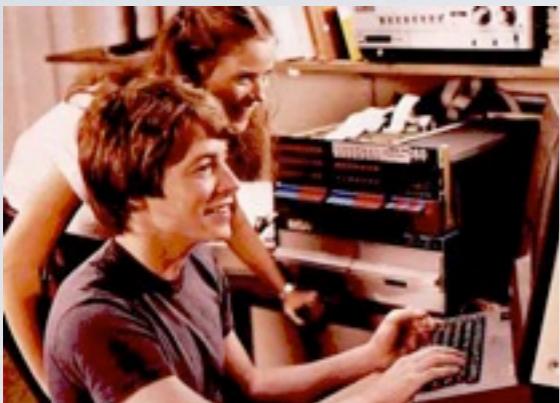


[Welsh, Morrisett]

Matt Welsh - Harvard University

41

THE OLD WAY...



→ c code

[Welsh, Morrisett]

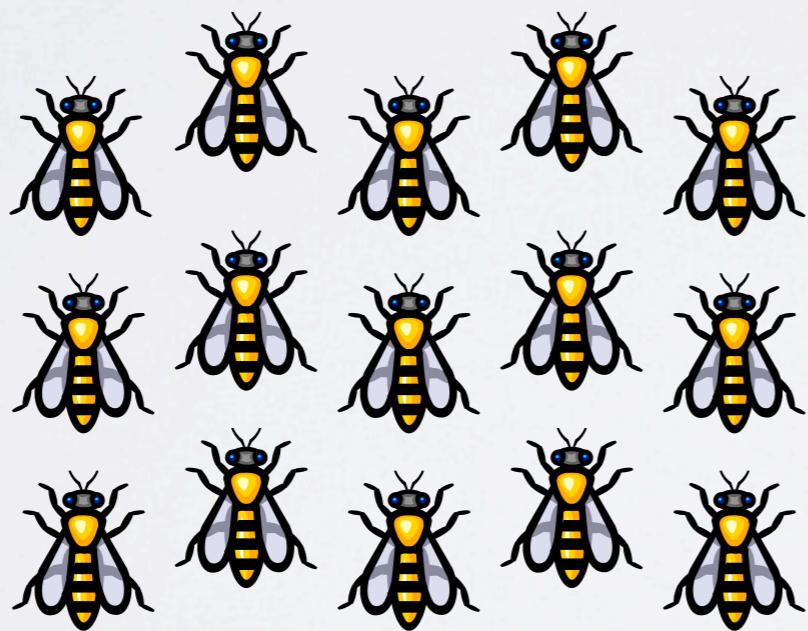
Matt Welsh - Harvard University

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THE OLD WAY...



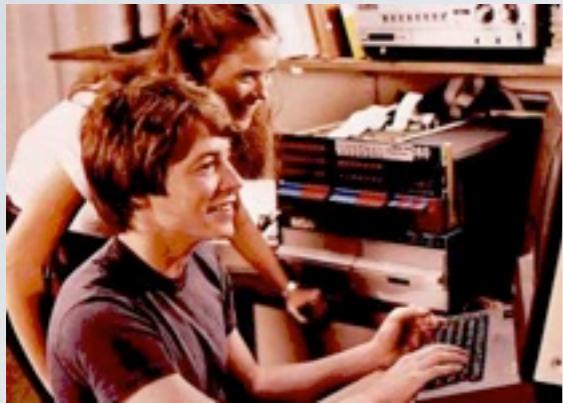
→ c code



Box o' bees

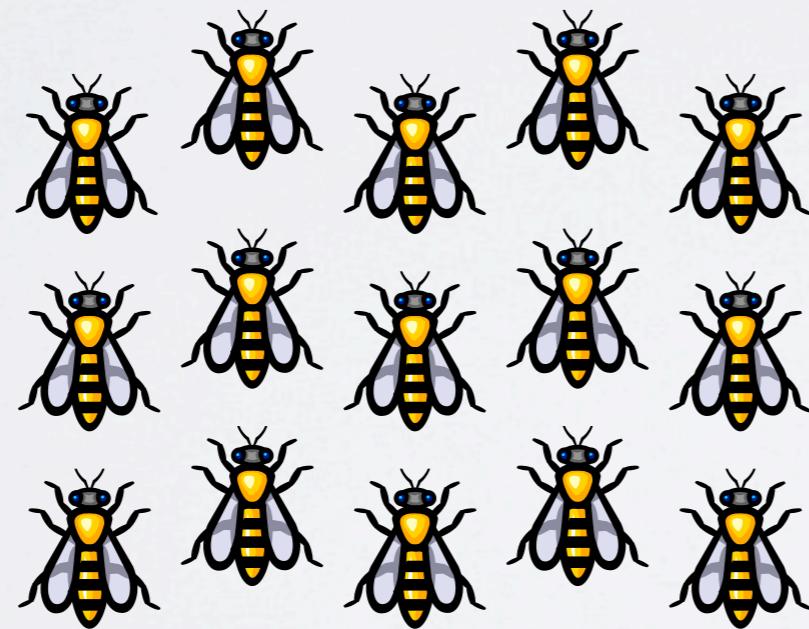
[Welsh, Morrisett]

THE OLD WAY...



→ c code

No doubt full of bugs



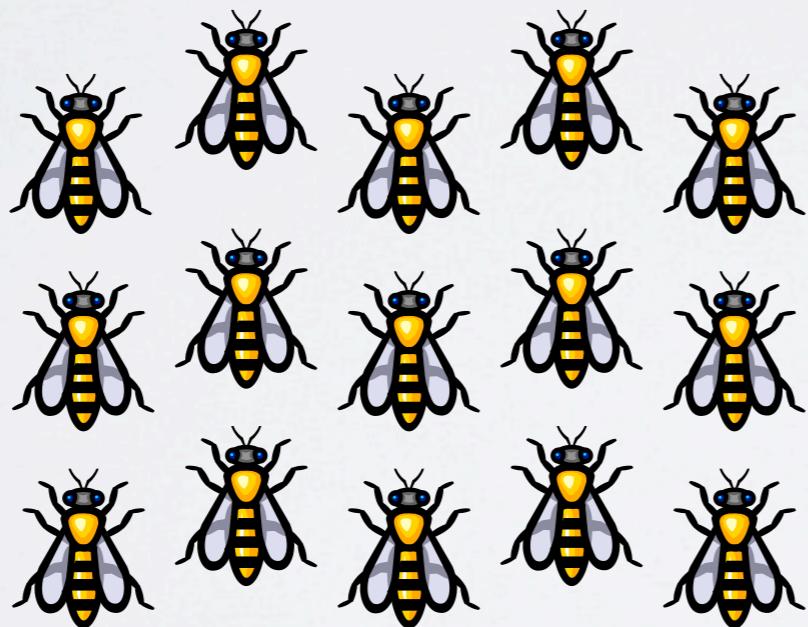
Box o' bees

[Welsh, Morrisett]

THE OLD WAY...



→ c code



Box o' bees

No doubt full of bugs



Havoc and mayhem

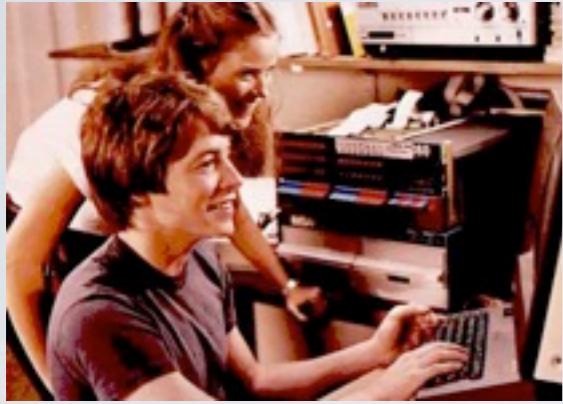
[Welsh, Morrisett]

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...

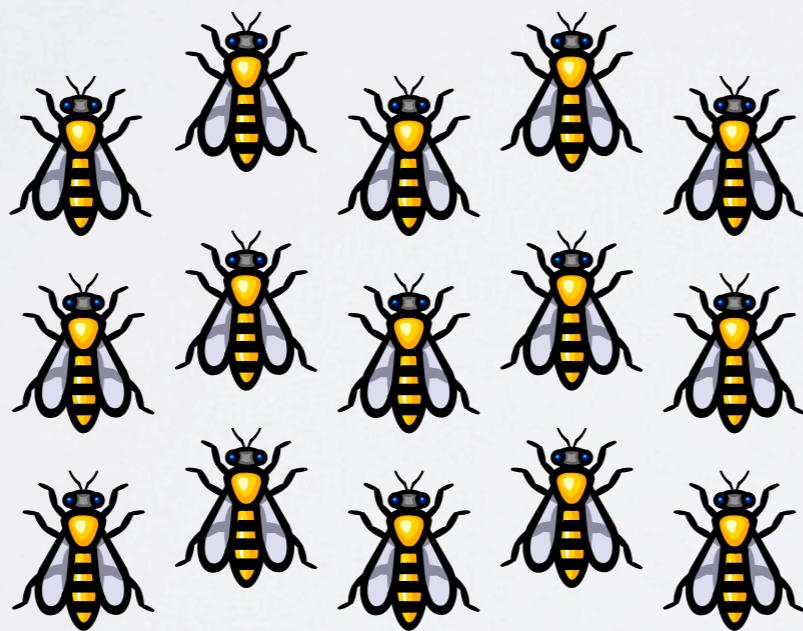


Macroprogram

THE NEW WAY...

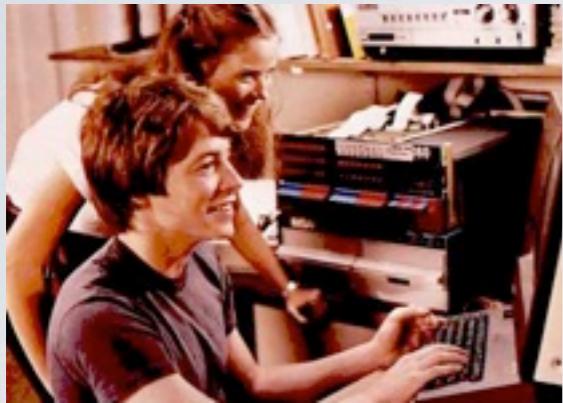


→ Macroprogram

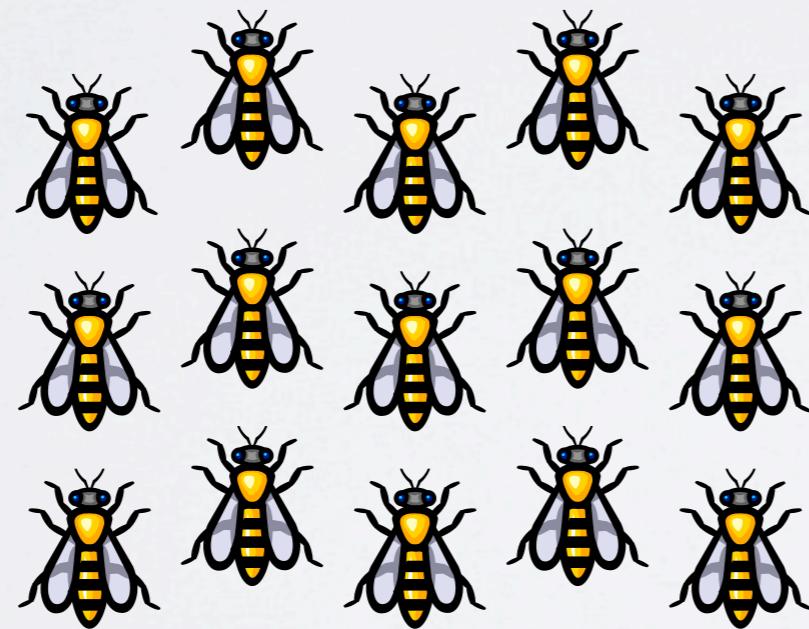


Box o' bees

THE NEW WAY...



Macroprogram



Box o' bees



Beautiful
swarm behavior

THE NEW WAY...



Macroprogram



Box o' bees

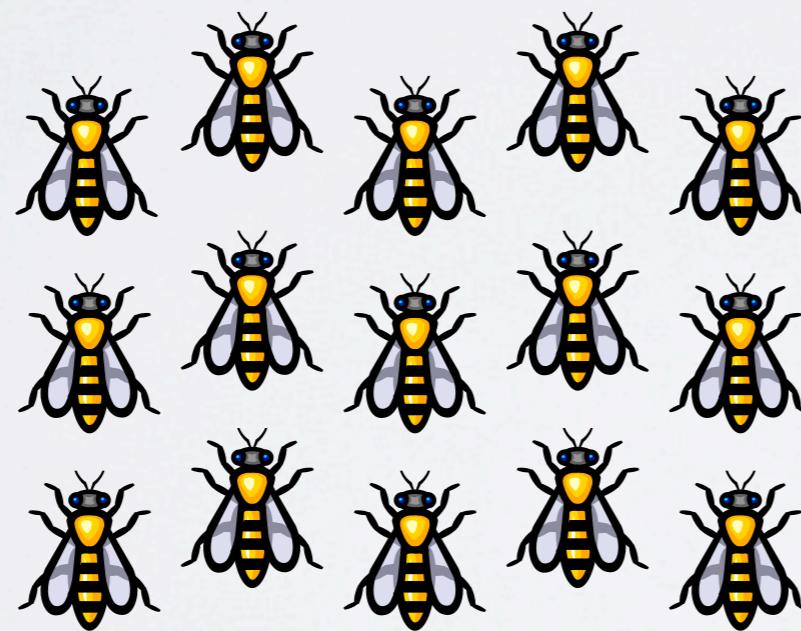


Beautiful
swarm behavior

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!



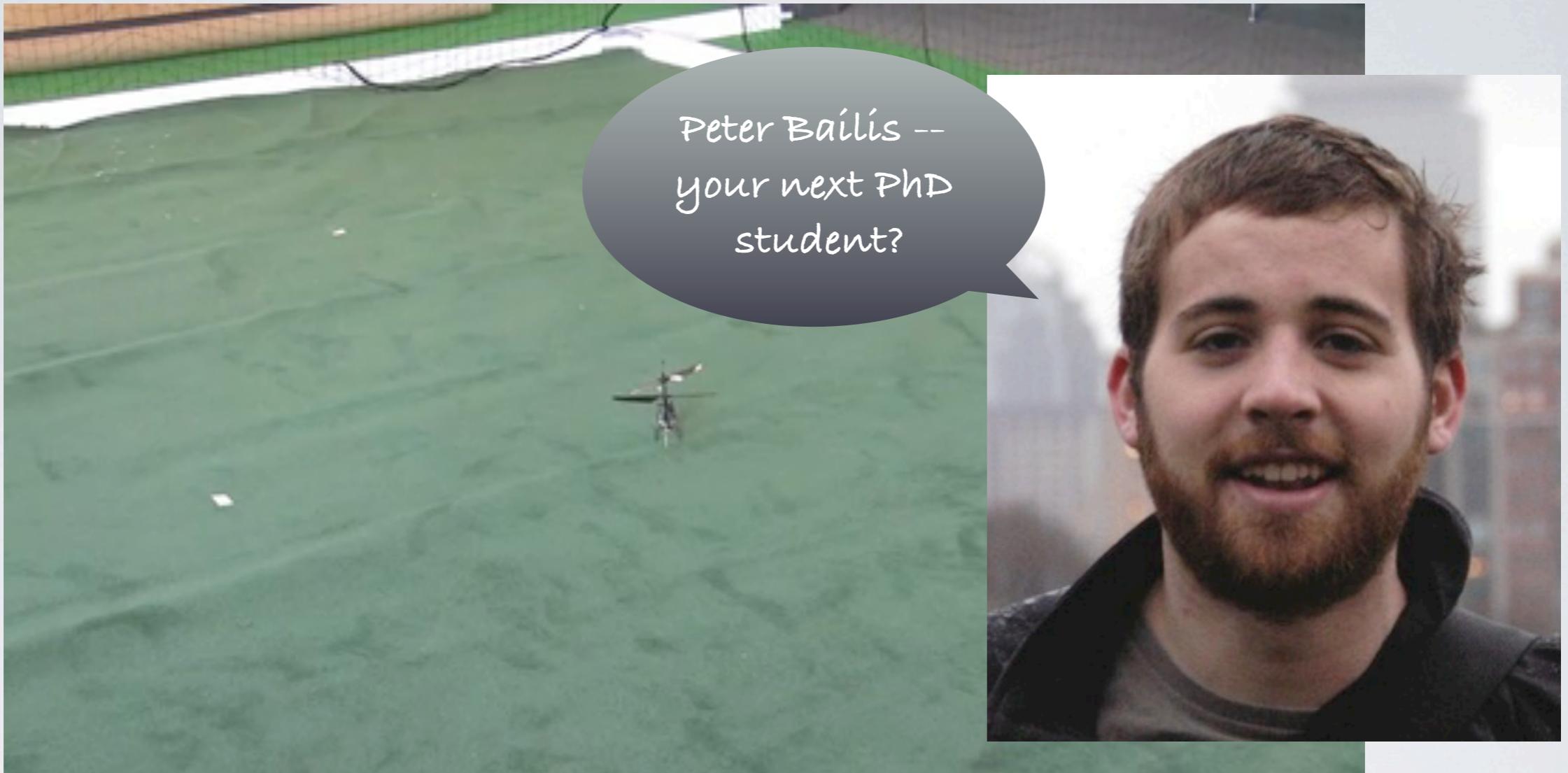
- eFlite MCX, around \$100
- Custom control board with AVR32 microcontroller,
802.15.4 radio, optical flow sensor interface

HELICOPTER TESTBED



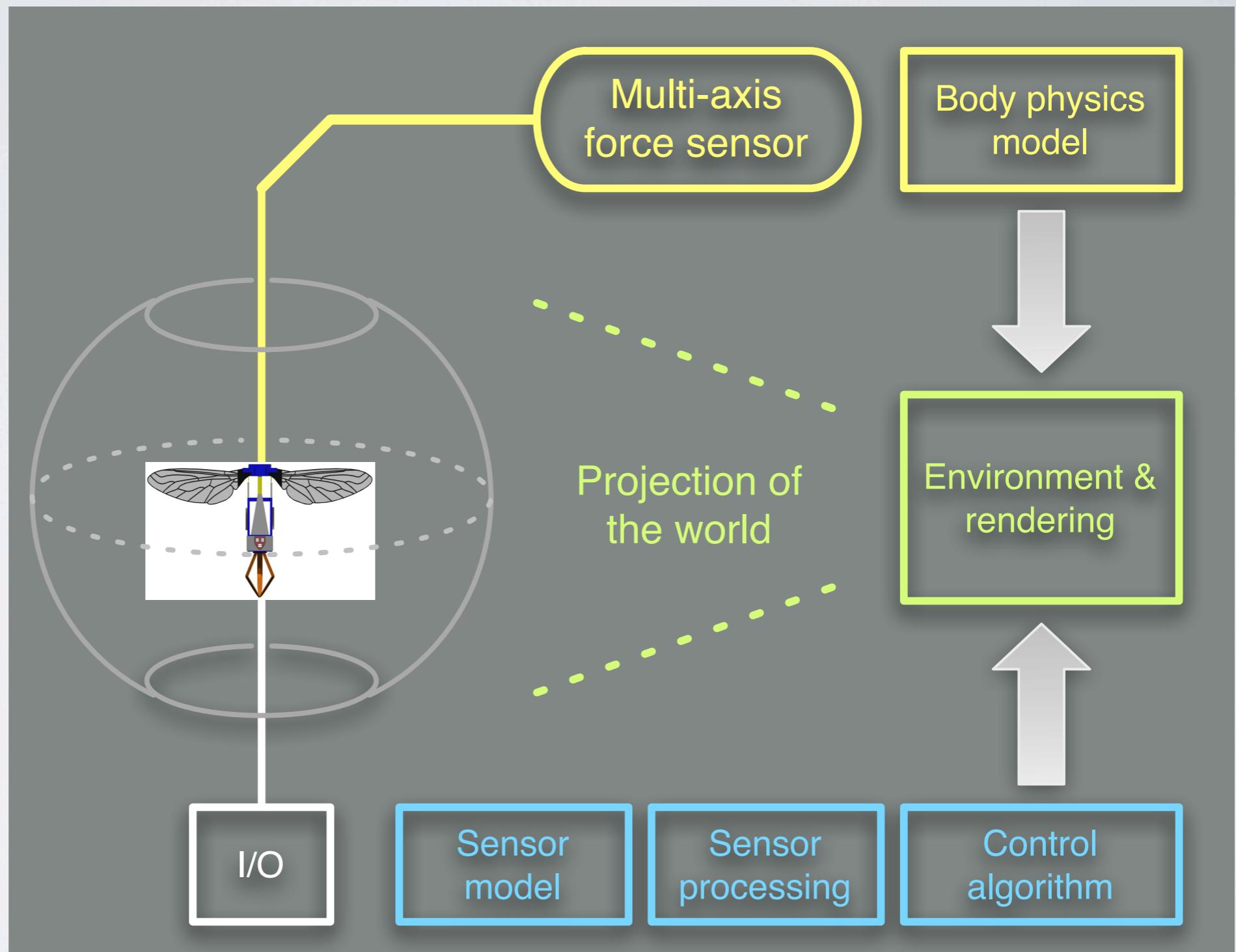
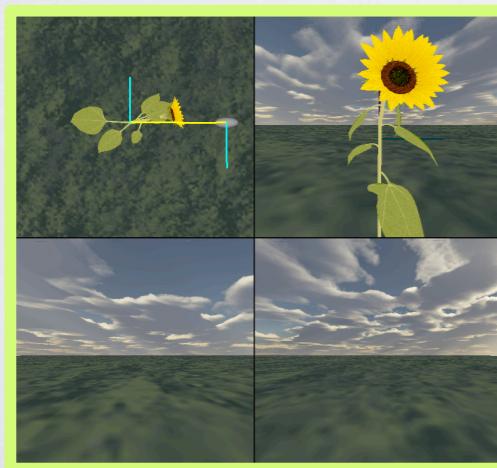
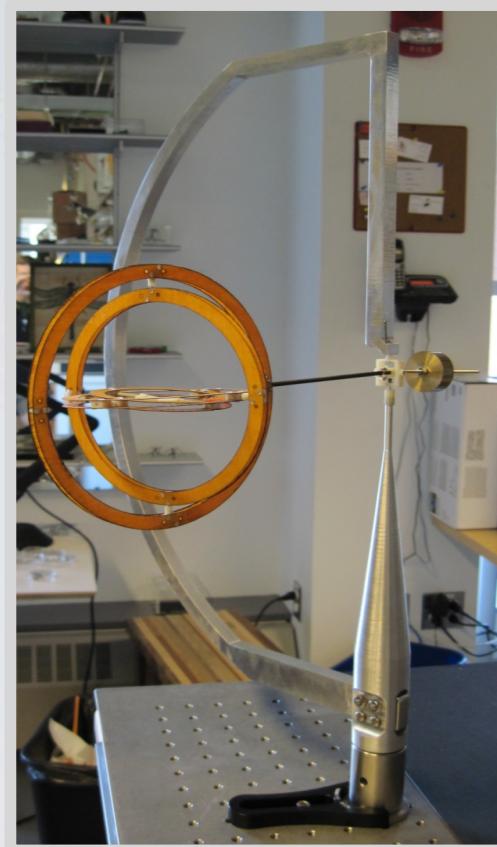
- Plan: 50 helicopters under wireless control
- Remotely accessible via the Web

HELICOPTER TESTBED



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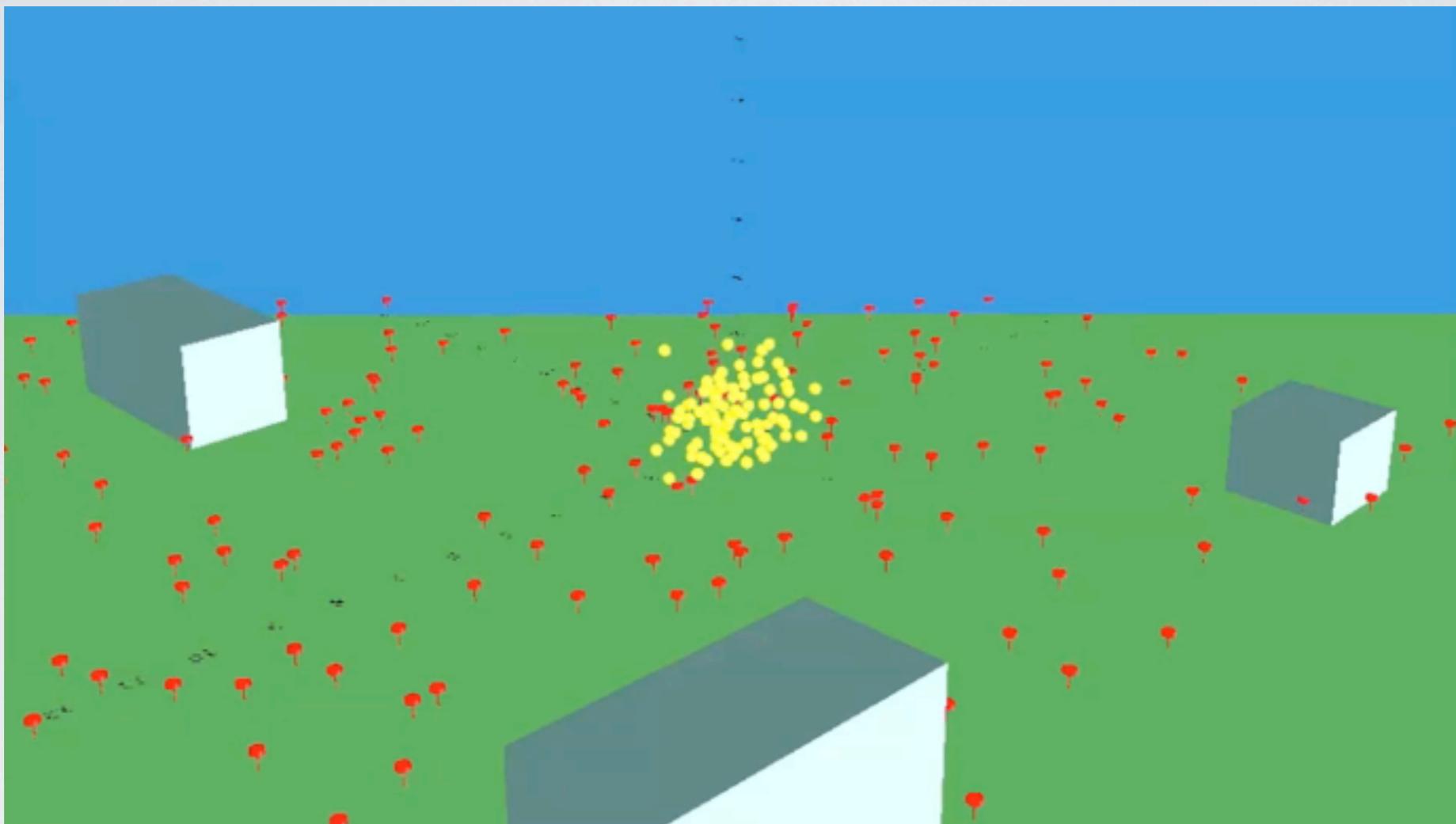
THE ROBOBEE “MATRIX”



[Brooks, Wei, Wood & Zickler]

Friday, June 25, 2010

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?

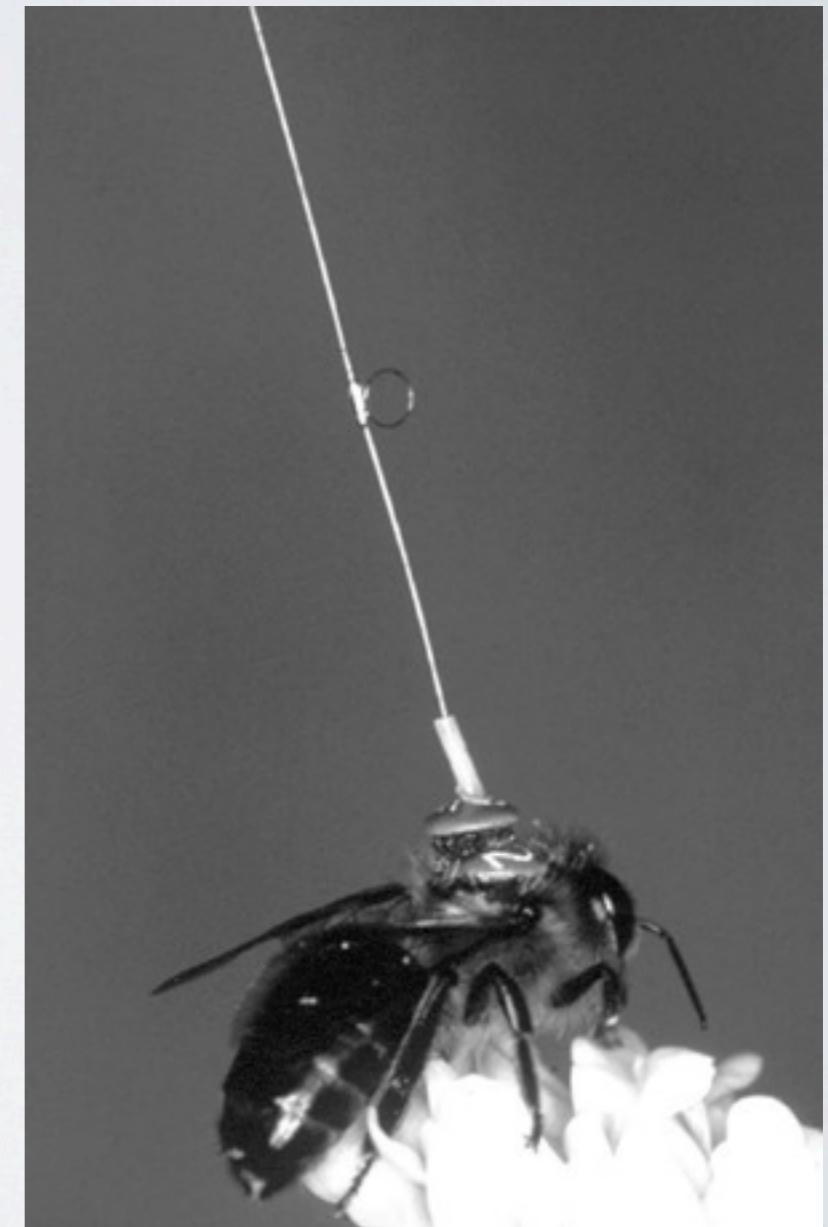
IN THE LAB: MOTION CAMERA SYSTEM

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



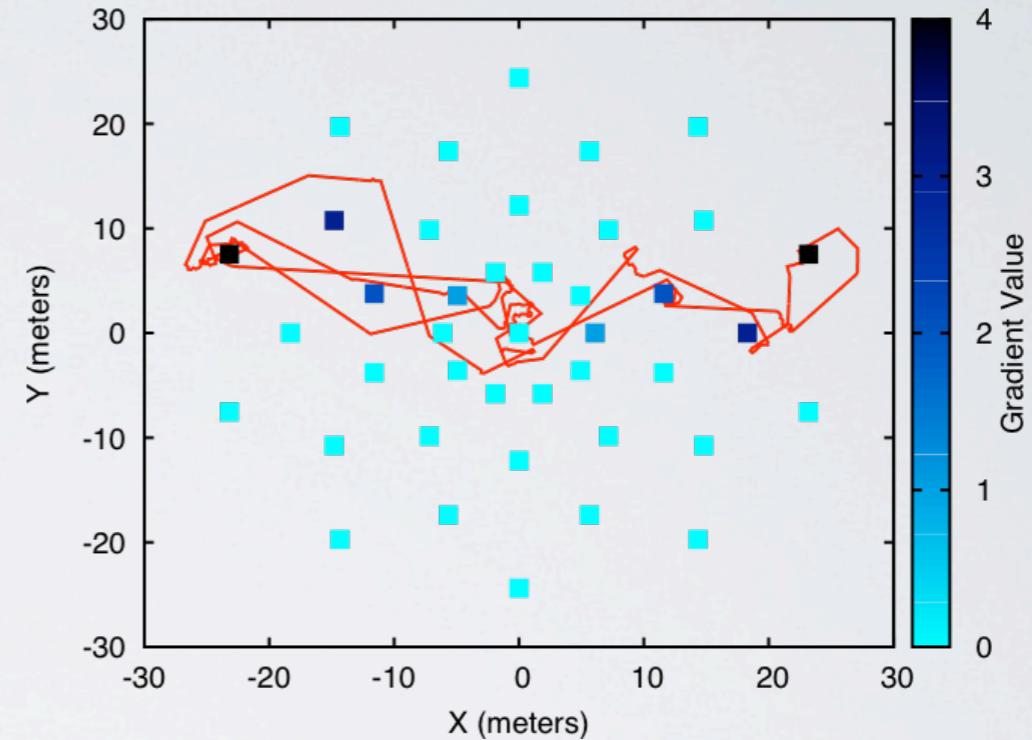
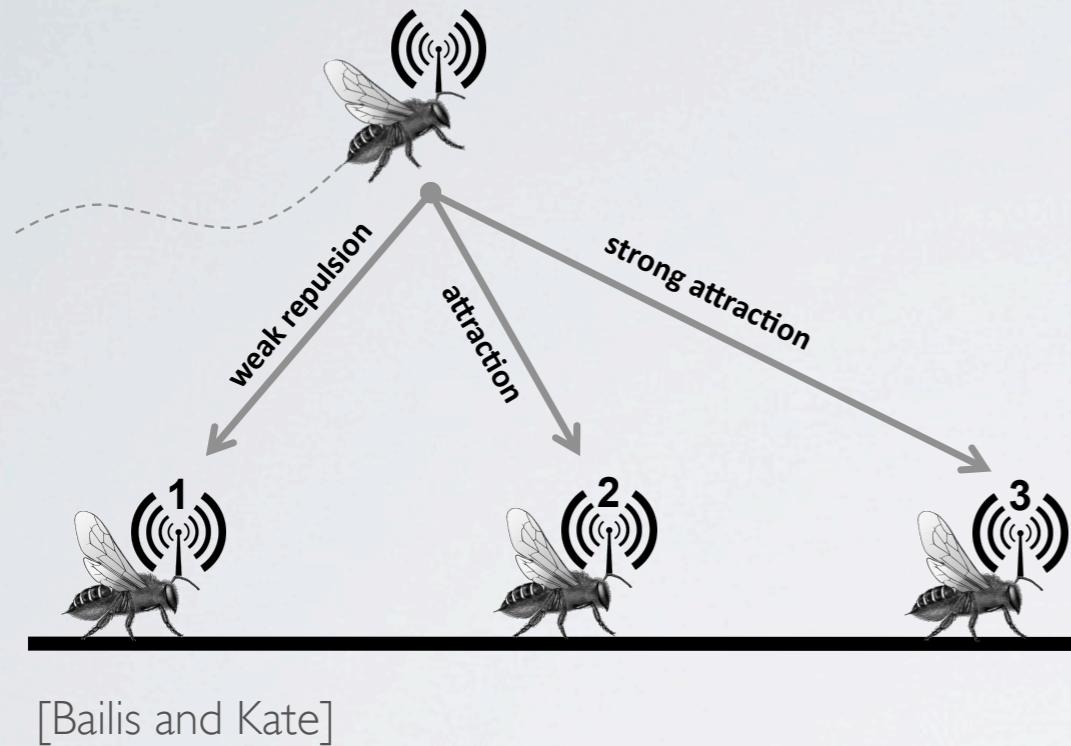
IN THE FIELD: HARMONIC RADAR

- 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



- 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!



<http://robobees.seas.harvard.edu>
mdw@eecs.harvard.edu

Special thanks to the National Science Foundation