# Mobile Robot Systems

## Lecture 1: Introduction to Robotics


Dr. Amanda Prorok

asp45@cam.ac.uk

www.proroklab.org

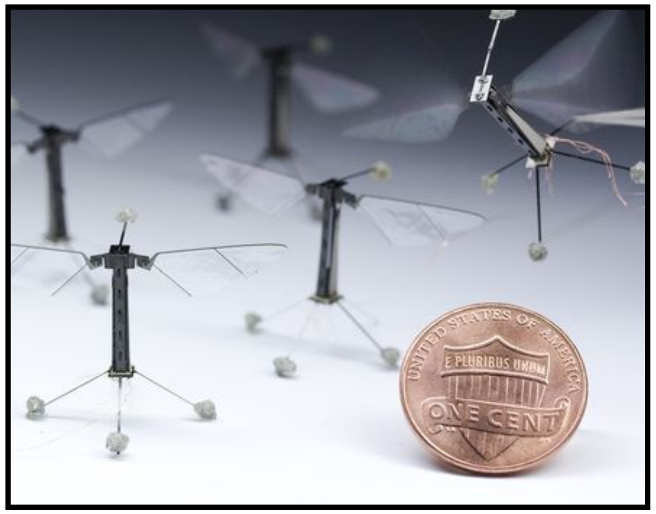
# In this Lecture

- Why study robotics?
- What this course is about.
- Course administration.
- Basics of autonomy + an example
- History of robotics

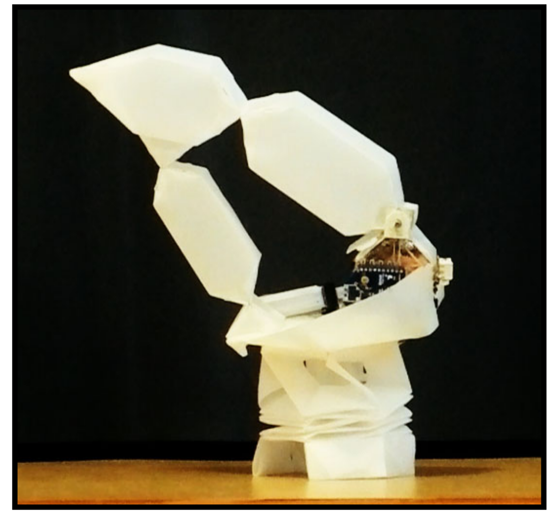
# What is a Robot?

- Etymology of the word ‘robot’
  - Czech playwright Karel Capek, 1921 Play ‘Rossums’s Universal Robots (R.U.R)’
  - Czech words ‘rabota’ + ‘robotnik’ (obligatory work + serf)
- Definition: A **robot** is an autonomous system which exists in the **physical** world, can **sense** its environment, and can **act** on it to achieve some **goals**.
- Definition: An **autonomous** robot acts based upon its own decisions, and is not controlled by a human.

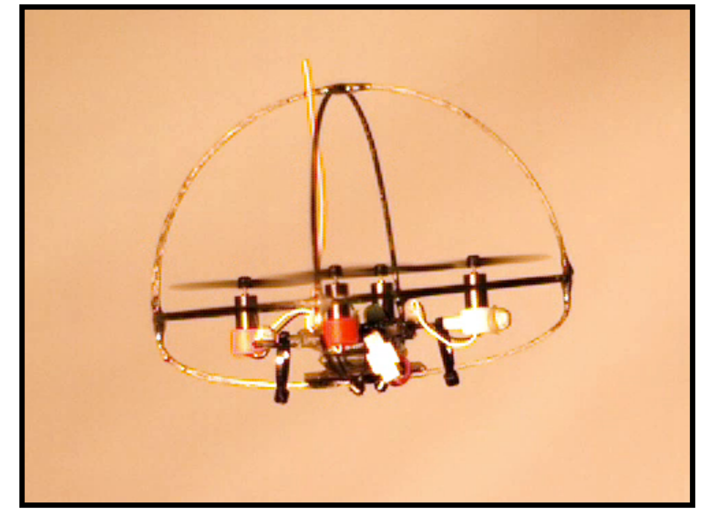
# Autonomous Robots




microrobots
[Wood et al.; Harvard]

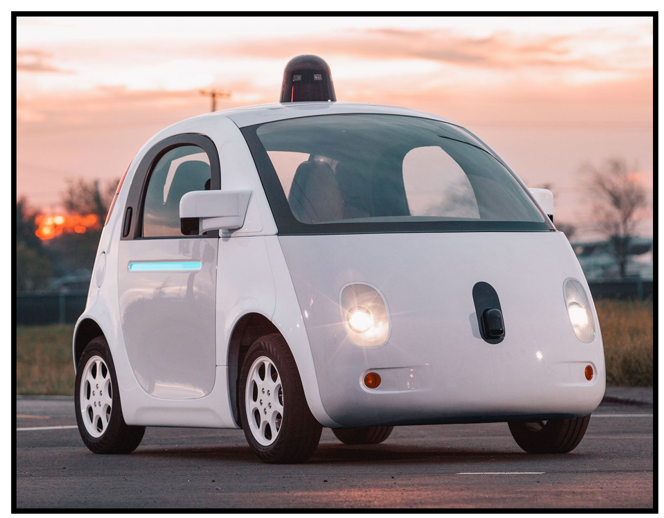


self-foldable / self-actuated
[Sung and Rus; MIT]



lightweight aerial robots
[Kumar et al.; UPenn]

consumer-grade drones
[e.g., DJI]



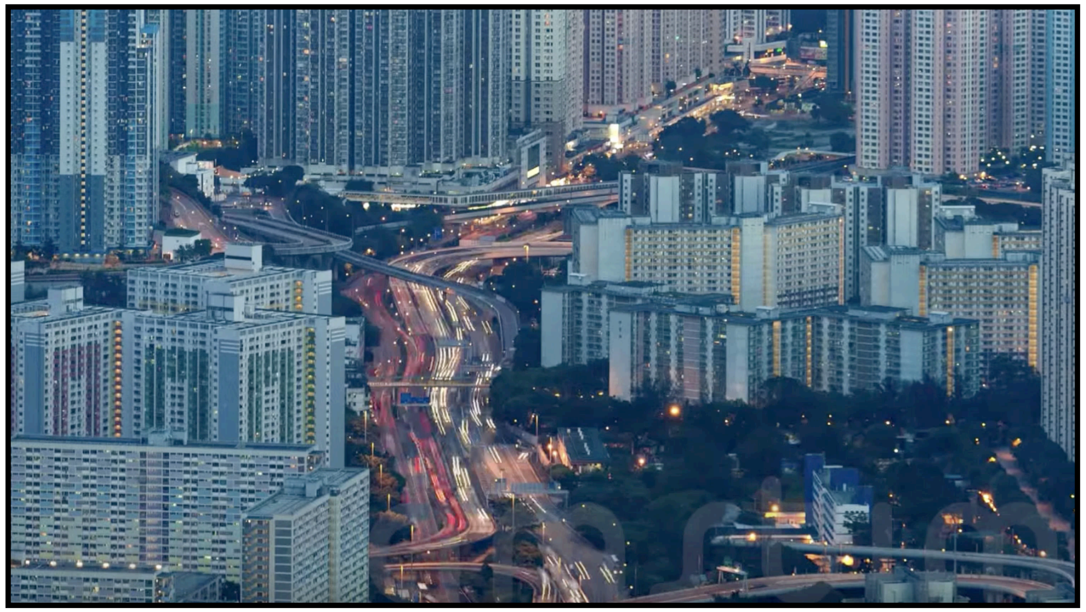
autonomous vehicles
[Google]

educational robots
[Cozmo]

# Why Robots?

- The three D's: **dirty, dull, and dangerous** tasks that no human desires to do, but they have to be done.
- But there is more!
  - **Optimization:** with the introduction of programmable autonomous robots, processes become computable, and can be optimized!
  - Optimization **objectives**:
    - Efficiency
    - Safety
    - Comfort
    - etc…

# The Future of Mobile Robots



smart infrastructure / mobility-on-demand


connected vehicles / automated highways

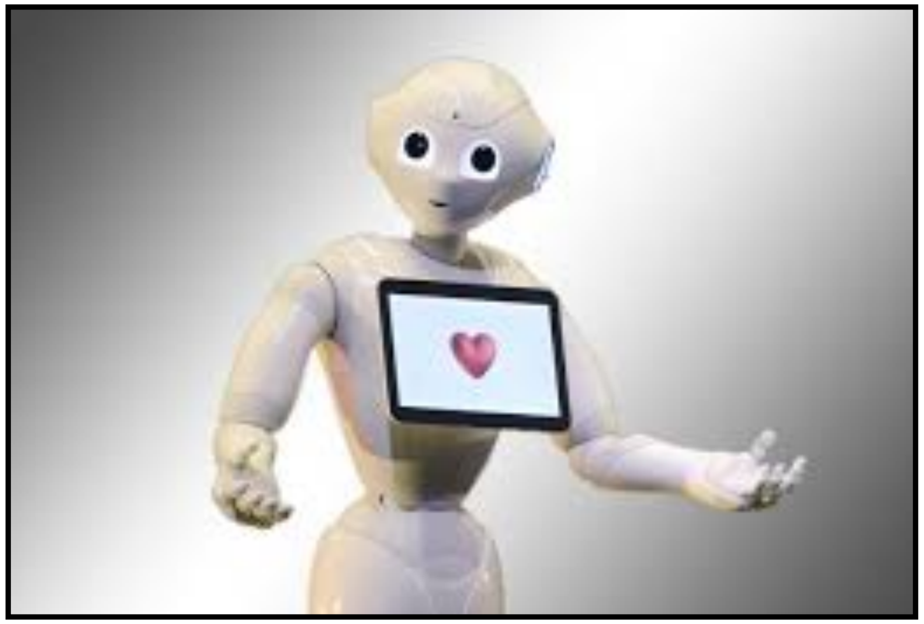
drone swarms / surveillance


truck platoons / long-haul transport

# The Future of Mobile Robots

autonomy on any terrain
[Big Dog; Boston Dynamics]

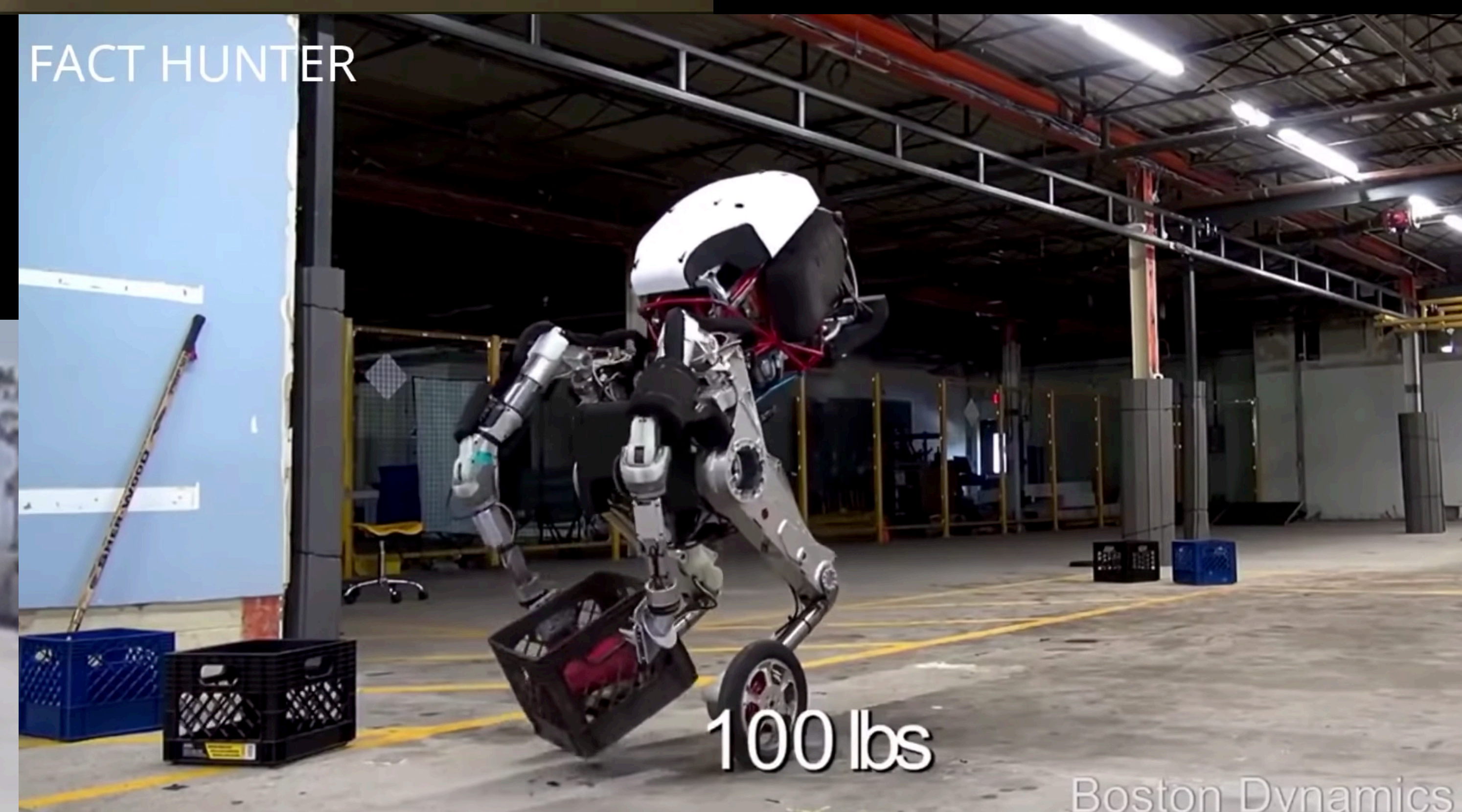
personal robots
[iCub robot]



emotional robots
[Pepper]

What's next?


[Amazon ]




[Boston Dynamics]

[Google]

# Why Study Mobile Robots?

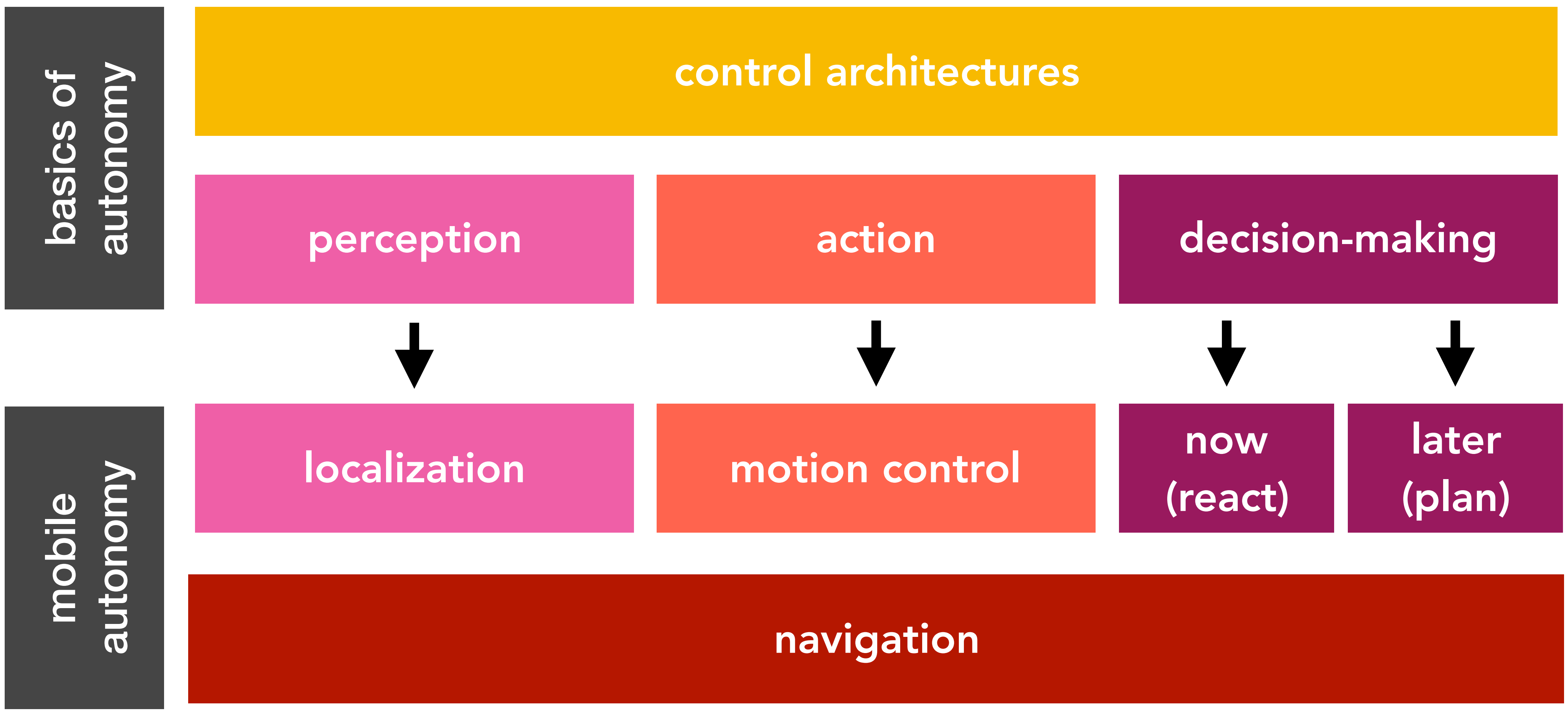
- **Job** prospects in…
  - Transport
    - autonomous driving, taxis, buses
    - self-driving market estimated at over $500 billion
  - Warehouses and logistics
    - E.g.: Amazon have doubled size of robot fleet in recent years
    - Delivery services (e.g., Ocado, Uber Eats)
  - Civilian and humanitarian
    - search and rescue
    - environmental monitoring
    - force multiplication (military)
- Role transformation… From CTOs to **CROs !**

# Why Study Mobile Robots?

- Learn foundational **methods**…
  - Perception
  - Planning
  - Motion control
  - Automation
  - Coordination

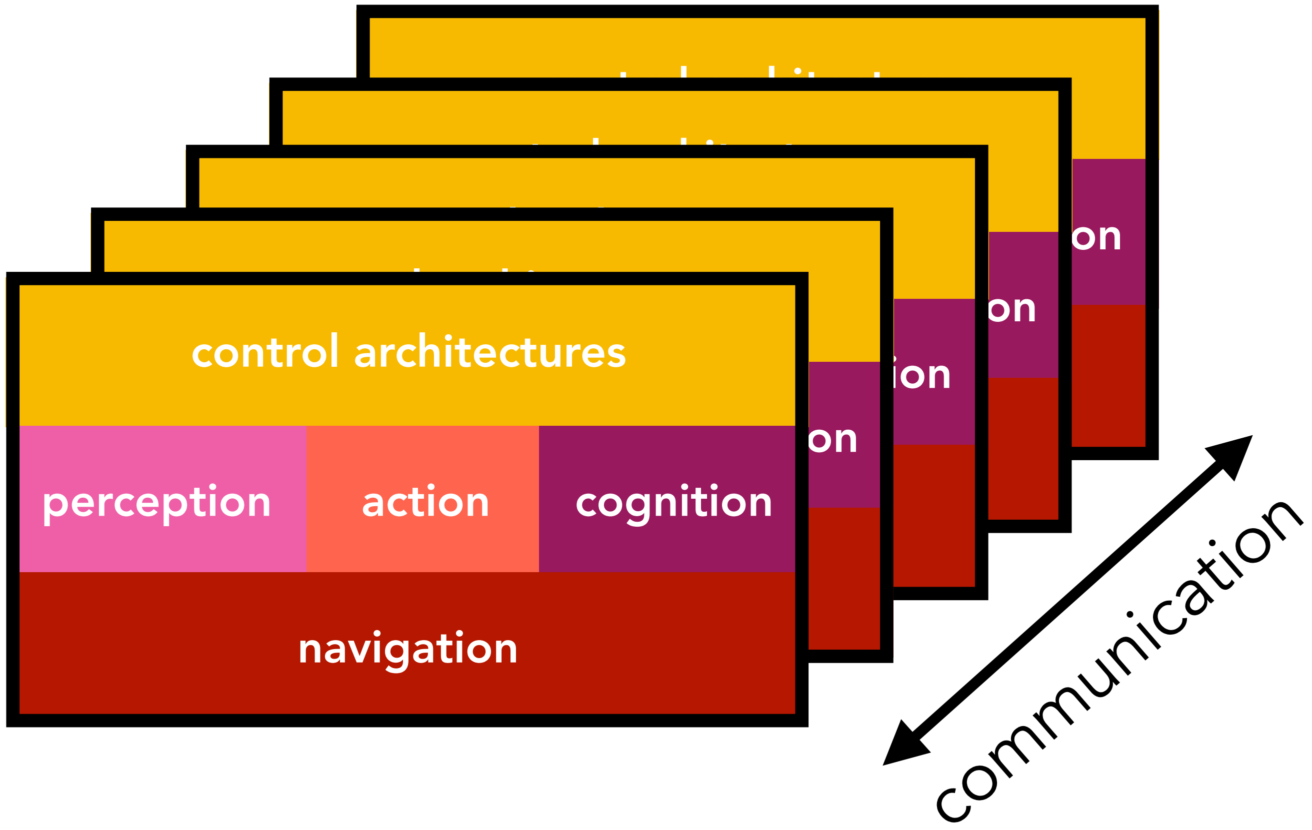
# What This Course is About

- Design of this course + focus on **autonomous mobile robots**



# What This Course is About

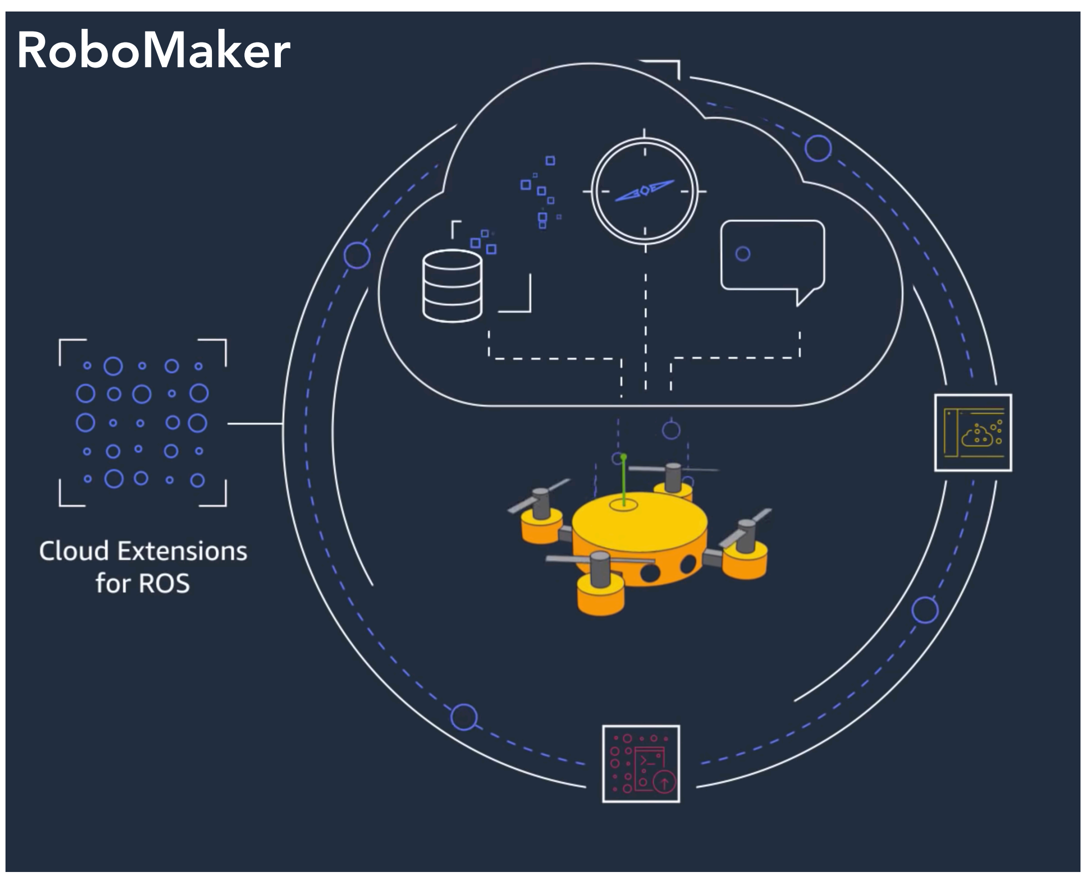
- Design of this course + focus on **autonomous mobile robots**
- **Multiple** mobile robots → multi-robot systems
- Higher-order goals
- Coordination facilitated through communication

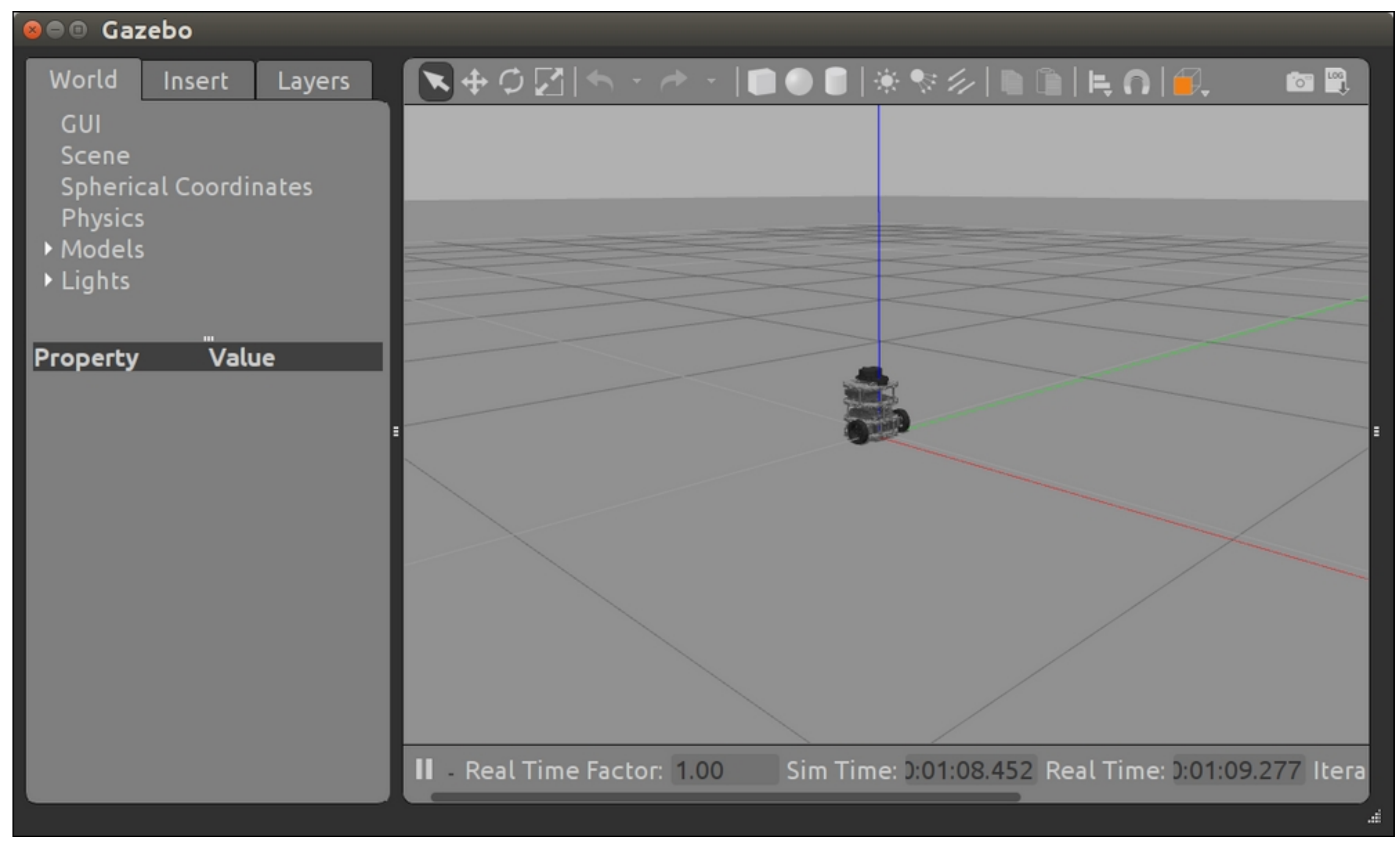


# What This Course is About

- Hands-on, learning by doing
- Our reference platform: the Turtlebot III Burger
- Our simulation platform: Gazebo
- Code: ROS library and Python
- Advanced platform: Amazon AWS RoboMaker

ROS.org



# Resources

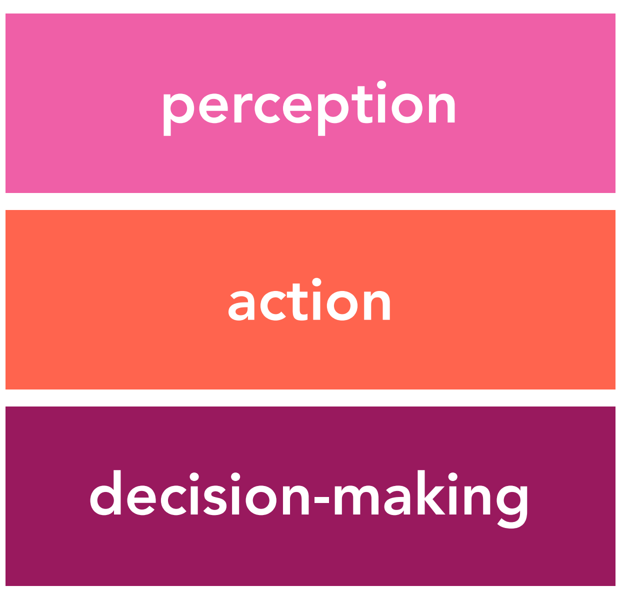
- Your setup options (see tutorial in Assignment 0, posted on Moodle):
  - **Local** installation (Ubuntu, ROS, Gazebo)
  - Amazon AWS **RoboMaker** (Cloud IDE and simulation)
    - Launched Dec. 2018. We are the *first class worldwide* to use this!
    - Your feedback is desired!
  - Recommended: try both setups.
- Robot **hardware**: needed for Assignment 2 (and option for mini-projects)
- **Moodle**:
  - 1 main page (assignment hand-outs, announcements, slides, help forum)
  - Part III / MPhils have separate page for uploading assignments.
- **Teaching Assistants** (lab demonstrators):
  - Alex (ar968), Mickey (mmwhitzer@seas.upenn.edu ), Nikhil (nc528), Qingbiao (ql295)

# Course Schedule

- Lectures: Tuesdays and Thursdays, 11:00; detailed syllabus on Moodle
- 4 Assisted Lab Sessions : Tuesdays, 14:00-16:00; Intel Lab
  - Lab 1: Jan 22  (release Assignment 1)
  - Lab 2: Jan 29
  - Lab 3: Feb 5  (release Assignment 2)
  - Lab 4: Feb 12
- Assignment 0: setup your tools and complete warm-up exercises
- Assignment 1: due date: Feb 1, 2019
- Assignment 2: due date: Feb 15, 2019
- Mini-projects (topics to be released early Feb.):
  - Report, Part II (**in pairs**): March 12, 2019;
  - Report, Part III/MPhil (**individual**): April 25, 2019
  - Presentations: Thursday March 14, 14:00-17:00

# Basics of Autonomy

- Challenges:
  - How to model and perceive the world?
  - How to process information and execute actions?
  - How to reason and plan in the face of uncertainty?




The field of robotics provides:

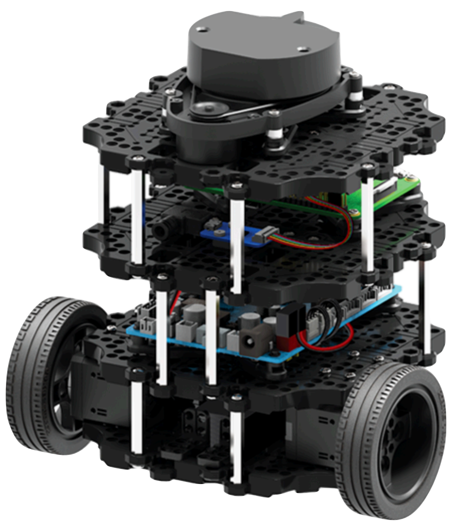
- Methods that implement each of these 3 modules
- Methods (architectures) that combine the 3 modules

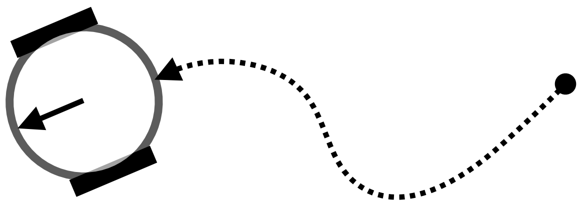
# Intro to Perception

***Where am I? What am I doing?***

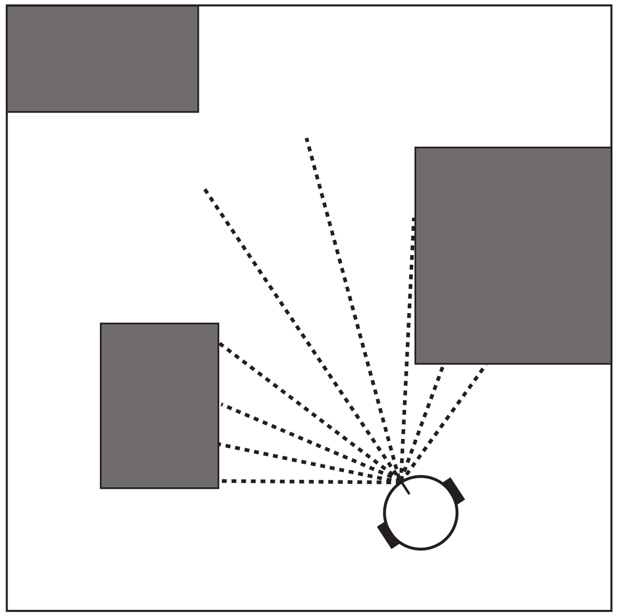
**perception**

**Example** (localization):
Turtlebot uses 1 proprioceptive sensor and 1 exteroceptive sensor to infers its pose.





odometry-based



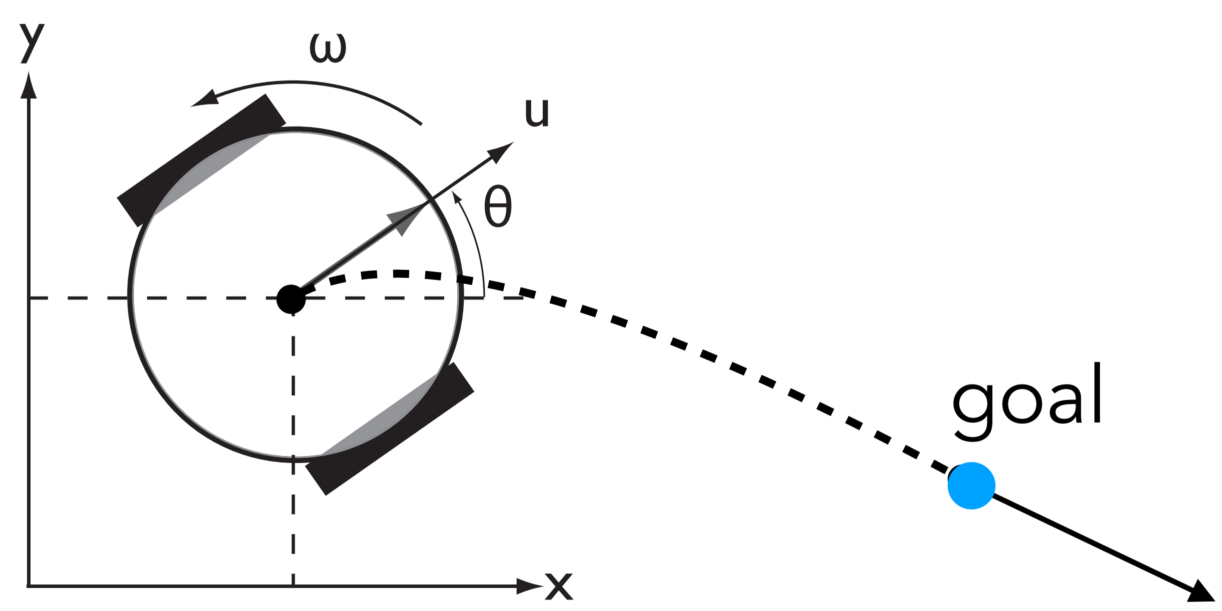
map-based

# Intro to Action

***What force should my motors exert?***

action

**Example** (motion control for a wheeled robot):
Compute rotational and forwards velocities (or acceleration).

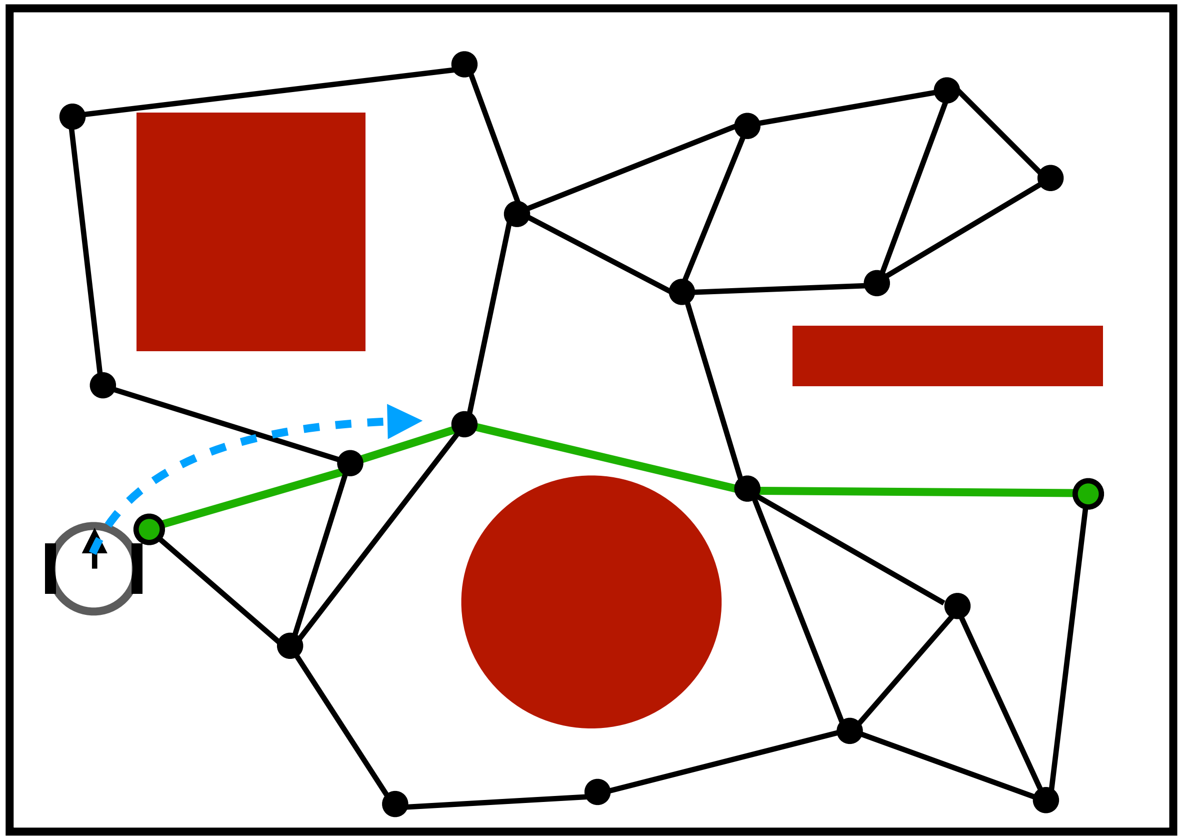


# Intro to Decision-Making

***What is my plan to achieve my goal?***

**decision-making**

**Example** (deliberative planning):
Compute a path that does not collide with obstacles and that respects the robot's motion constraints.



deliberative planning

# Intro to Multi-Robot Coordination

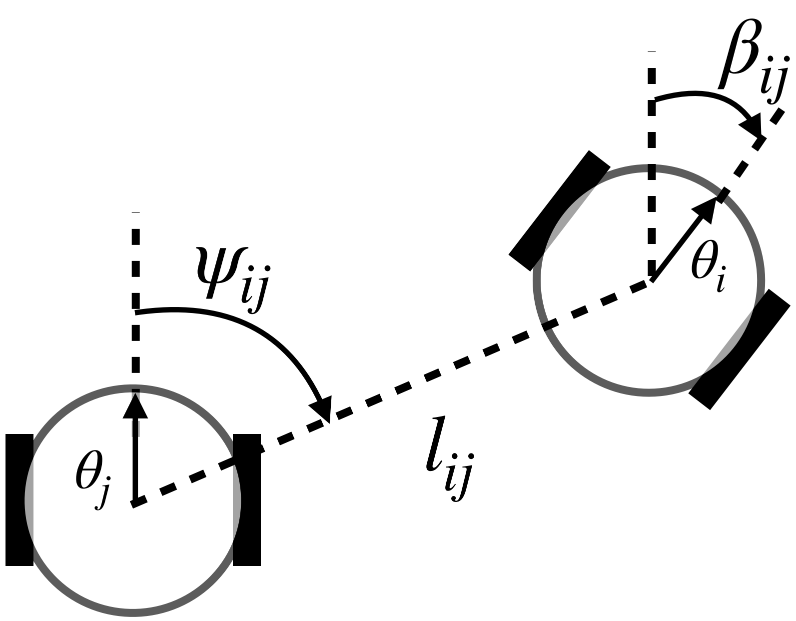
perception

action

decision-making

***What are our best actions / decisions as a team?***

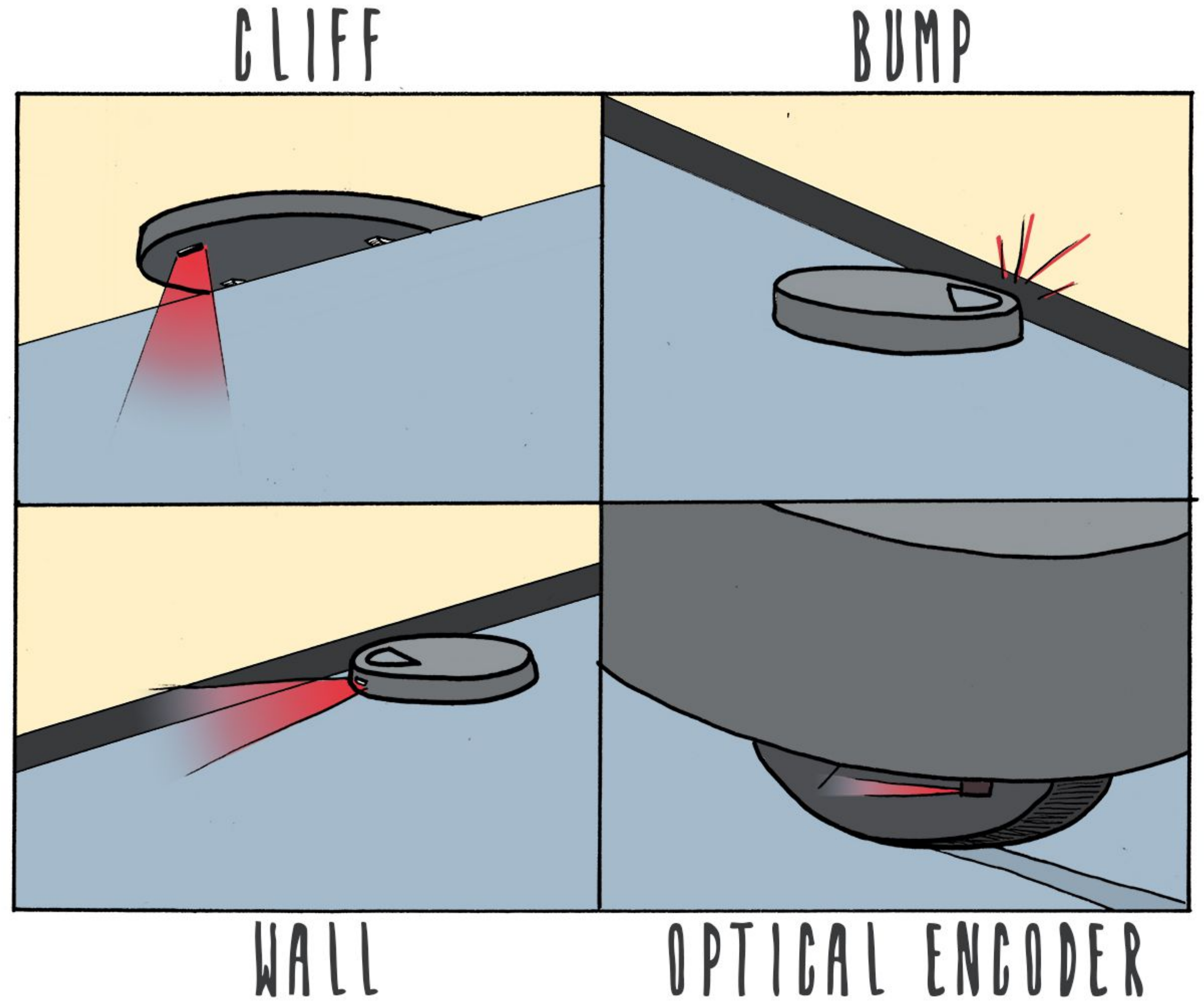
**Example** (collective movement):
Compute controls for leader and follower robots such that the formation is maintained during motion.




leader-follower control

# An Extremely Simple Robot

- Roomba (an early version)
- Roomba's sensors:
  - cliff sensors
  - bump sensors
  - wall sensors
  - optical encoder




- With these simple sensors, the robot can already infer a few things about the world around it!

* image source: www.cnet.com

# An Extremely Simple Robot

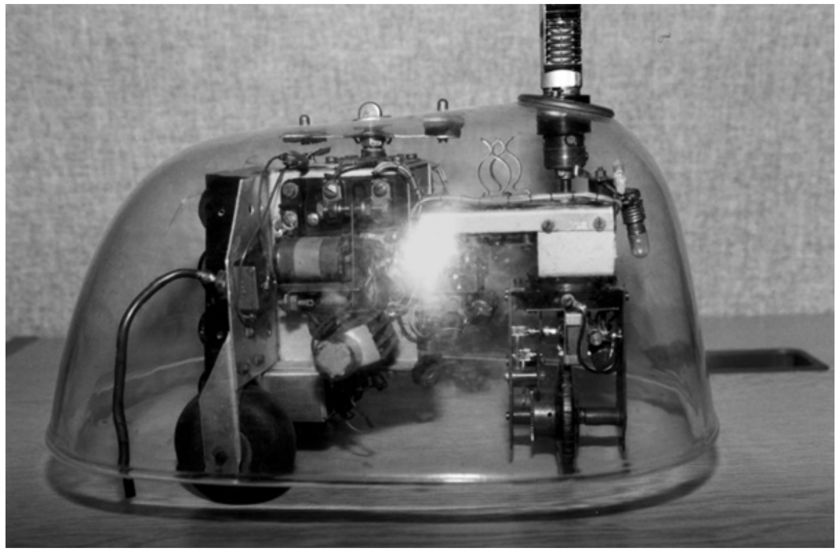
- Behaviors (from patent filing in 2002):
  - Wall-following: if robot bumps into something
  - Straight: after certain distance, turn random angle, or, after bumped into something
  - Later versions: spiral if on a dirty spot, or until robot bumps into something

# A Brief History of Robotics

- Robotics emerged from the influences of:
  - **Control Theory**: the mathematics of controlling machines. Fundamental principles that govern all mechanical systems. Early **1900s**: new maths (differential equations) to formalize control systems. In robotics, most important aspect of control theory is feedback control.
  - **Cybernetics**: the integration of sensing, action, and the environment. Pioneered in **1940s** by Norbert Wiener who applied control theory to biological systems. Study of communication and control processes in biological and artificial systems.
  - **Artificial Intelligence**: the mechanisms for planning and reasoning; emerged in the **1950s**

# The First Robot

- William Grey Walter (1910 - 1977): neurophysiologist; interested in building biomimetic machines



- ***Tortoise*** robot:
  - tricycle-like design (one motor per wheel)
  - one photocell; one bump sensor
  - rechargeable battery
  - analog circuit and vacuum tubes connecting sensors with wheels
- Behaviors:
  - find light / head towards light / back away from light
  - turn and push to avoid obstacles
  - recharge battery
- Control: reactive, with prioritized reflexes
- First example of 'artificial life'; Tortoises now shown in museums around the world

https://www.youtube.com/watch?v=lLULRlmXkKo

# Braitenberg

- Book: Vehicles, 1984
- ***Gedanken experiment***:
  - Create simple robots (vehicles) to produce seemingly complex behaviors
- Major source of inspiration for early roboticists
- Behavior: also reactive robots (like the Tortoise)
  - more on this in Lecture 2!

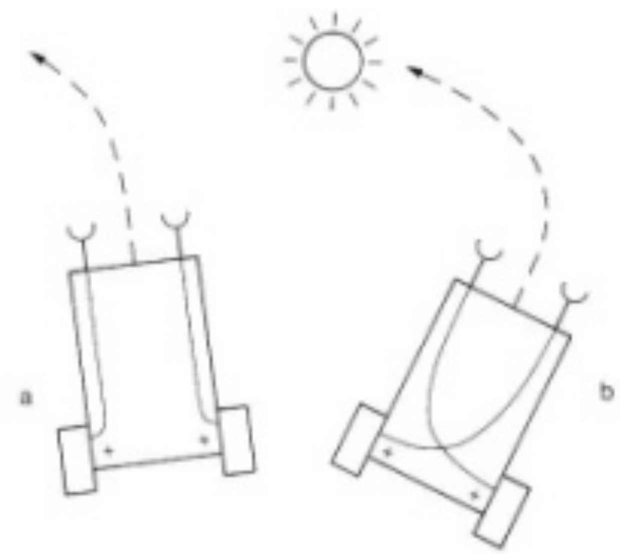


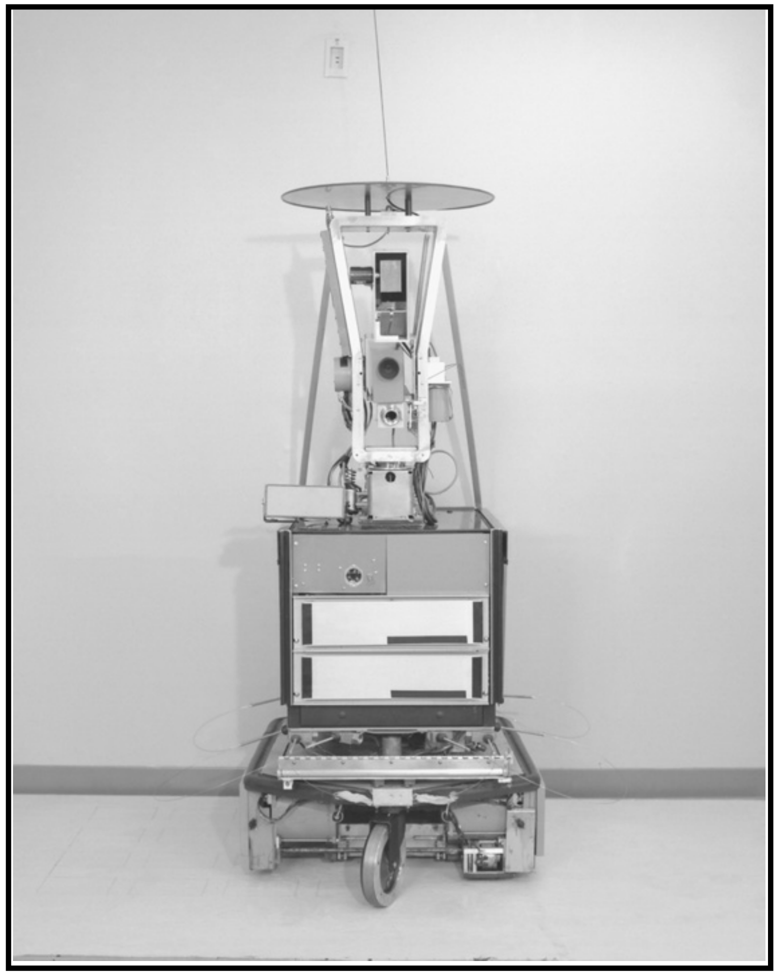

*image: Braitenberg

# Artificial Intelligence

- Origin: in 1956 at a workshop at Dartmouth University, USA
- ***Dartmouth Summer Research Project on Artificial Intelligence***
- Some of the researchers present: Marvin Minsky, John McCarthy, Allan Newell, Herbert Simon, Claude Shannon, John Nash, etc…
- Outcome of meeting - what we need for AI is:
  - Internal models of the world
  - Search through possible solutions
  - Planning and reasoning to solve problems
  - Symbolic representation of information
  - Hierarchical system organization
  - Sequential program execution

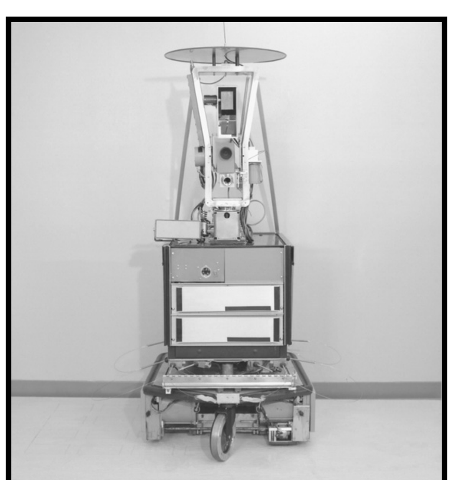
# Shakey

- Built in the 1960s at Stanford Research Institute (SRI)
- Shakey robot:
  - Camera and contact sensors
  - Application of AI techniques to vision algorithms
  - Lived in a simple black and white world
  - The robot shook when trying to execute its navigation plans!
- Reasoning:
  - Planning with STRIPS
  - Programmed in LISP



# A Paradigm Shift

- Robots developed based on classical AI techniques in 1970s and 1980s thought **too hard** and **too slowly**.
- 1980s robotics enters a new phase:
  - reactive control
  - hybrid control
  - behavior-based-control
- In stark contrast to purely deliberative control!
- Creation of faster, more robust, intelligent machines!



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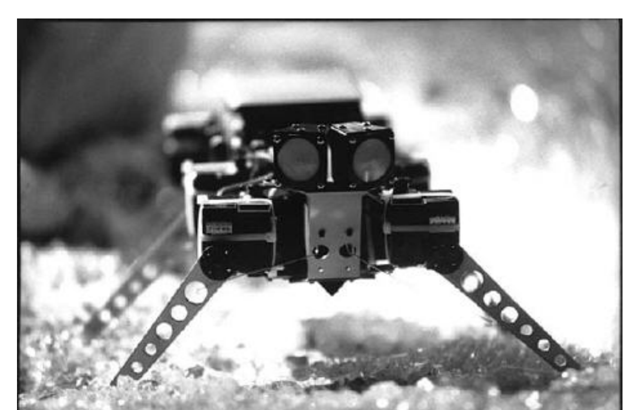
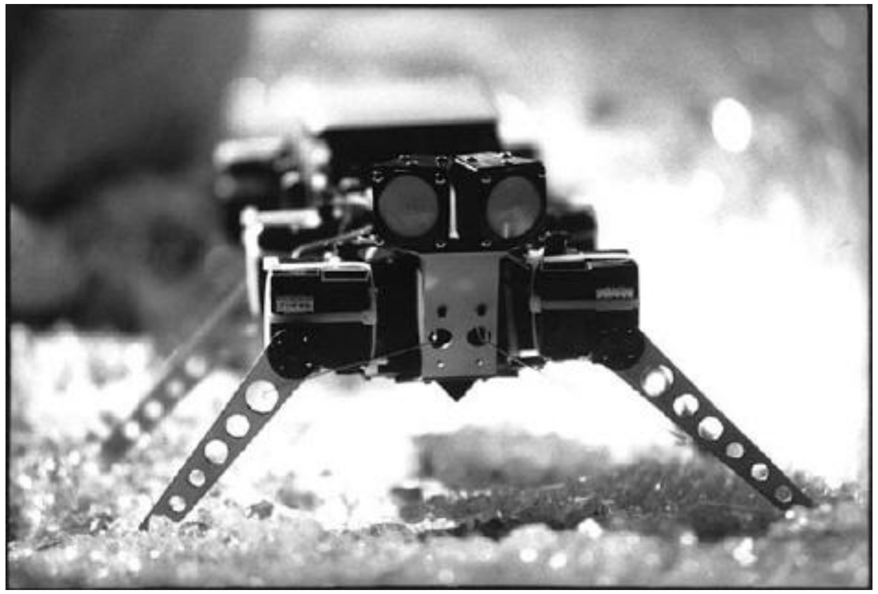


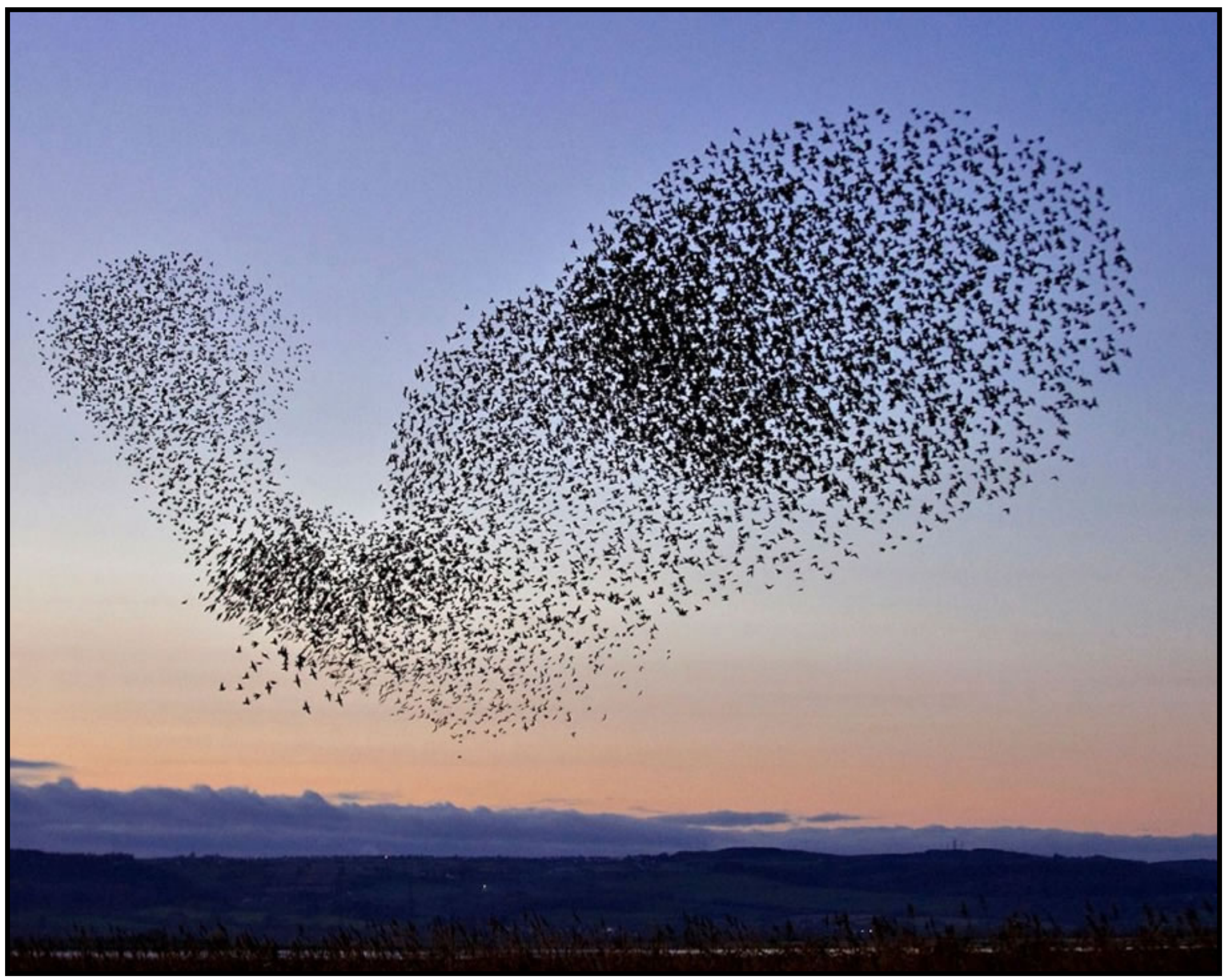
# Behavior-Based Robots

- A new wave in AI in the 80s-90s!
  - Spearheaded by **Rodney Brooks** (MIT) and later Ronald Arkin (Georgia Tech)
  - Stepping away from complex AI, deliberative planning (e.g., a chess-playing computer) to the **basics** of intelligence.
  - How? By realizing that organisms in nature follow simple sets of **reactive rules**… Giving rise to: **reactive behaviors**



# Behavior-Based Robots

- Behavior-based architectures had a huge impact on collective intelligence and swarm robotics.



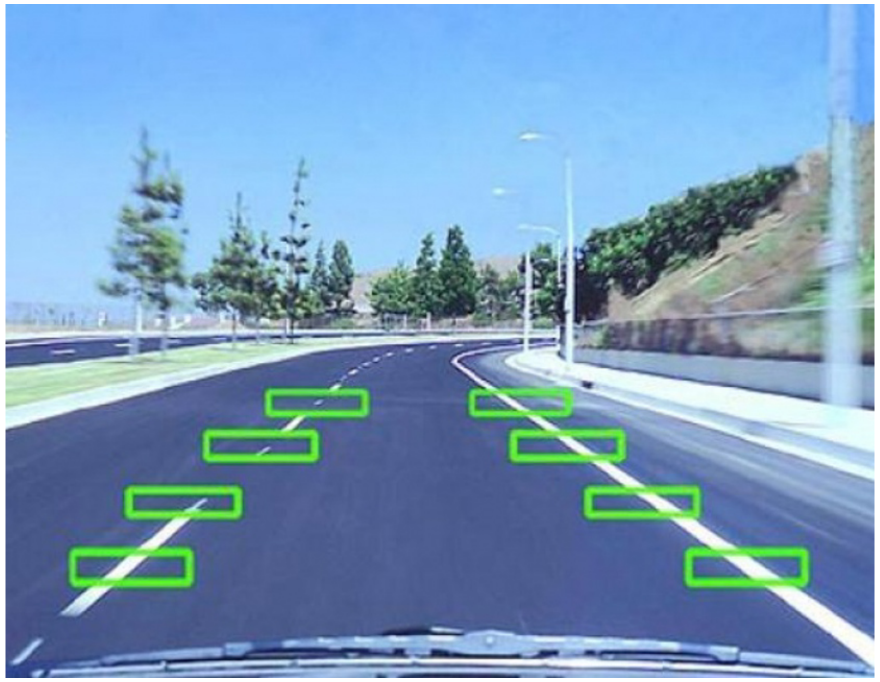
starlings

drones

# Reactive Control Architectures

- Many useful behaviors today still take inspiration from reactive and behavior-based control paradigms.

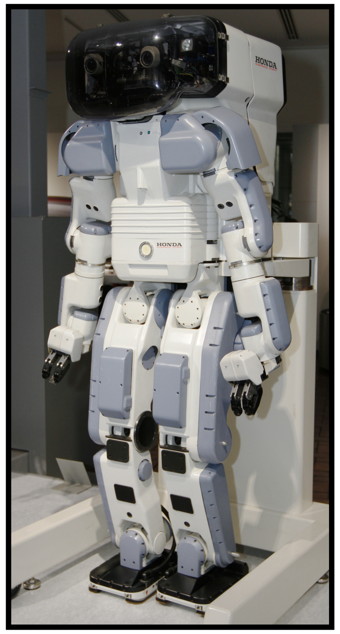
wall-following



centering

obstacle avoidance

# 1990s to Today - A Few Highlights





1996: P2, Honda

2002: First Roomba vacuum cleaner

2004: DARPA Grand Challenge

2005: self-replication (Cornell)

2011: agressive control for UAVs (UPenn)

2012: Amazon buys Kiva

2014: swarm robotics (Harvard)

*2015 and onwards: trend away from first principles-based approaches to data-driven approaches (black box control)*

# Further Reading

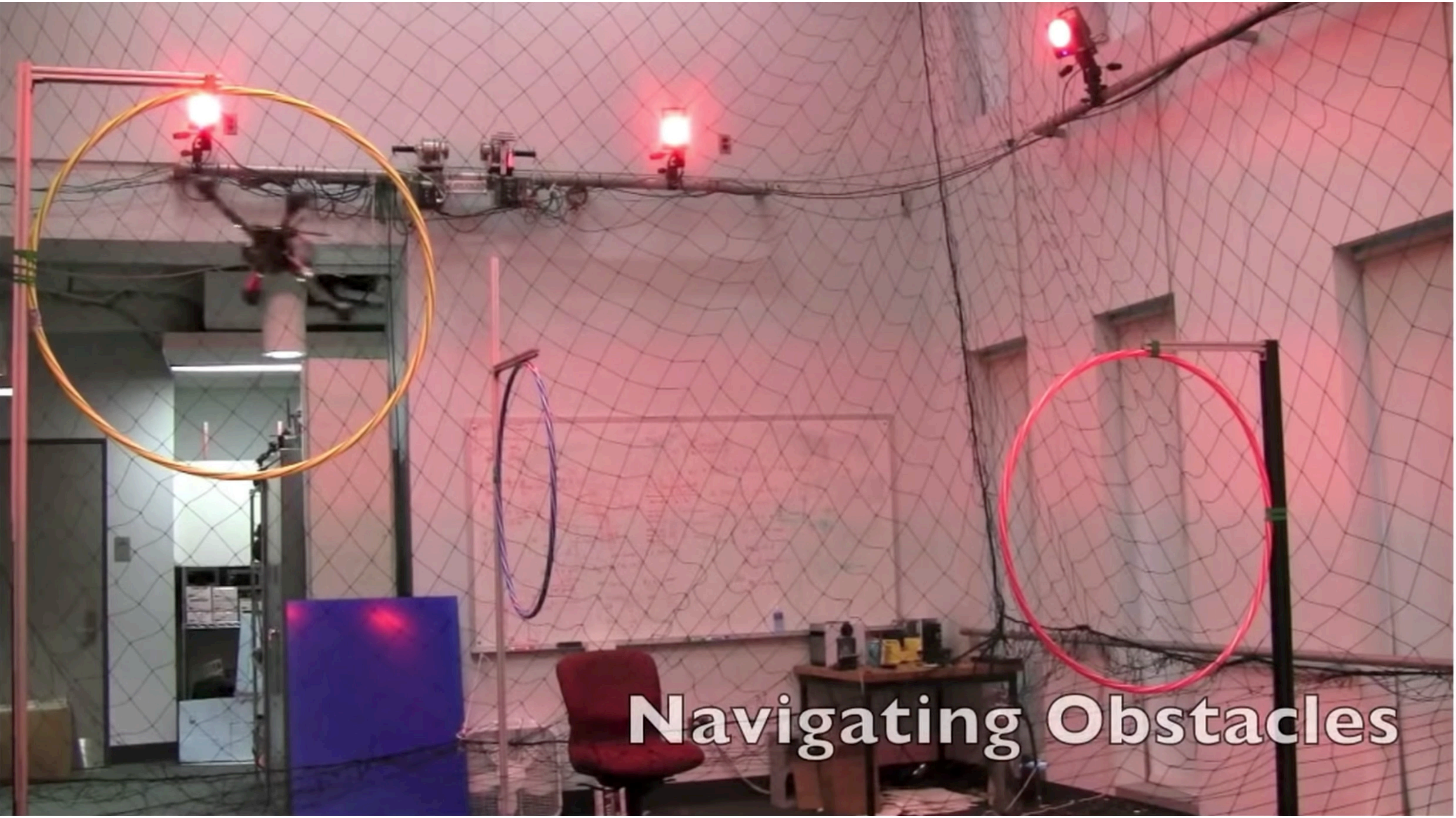
More historical articles:

- “Cybernetics or Control and Communication in the Animal and the Machine” by Norbert Wiener (1948) and Introduction to Cybernetics by W. R. Ashby (1956).
- Scientific American articles about Grey Walter robotics ideas “An imitation of life”, in 1950 (182(5): 42-45), and “A machine that learns”, in 1951 (185(2): 60-63).
- Hans Moravec wrote two books: “Mind Children” and “Robot: Mere Machine to Transcendent Mind”. Both books make predictions about the future of robotics and AI.

Books that cover fundamental concepts:

- Elements of Robotics, F Mondada et al., 2018
- Autonomous Mobile Robots, R Siegwart et al., 2004

# Advances in Motion Control




[Kumar, Mellinger; UPenn]