Complex Adaptive Systems & Collective Intelligence

ICTP Universidad de La Habana
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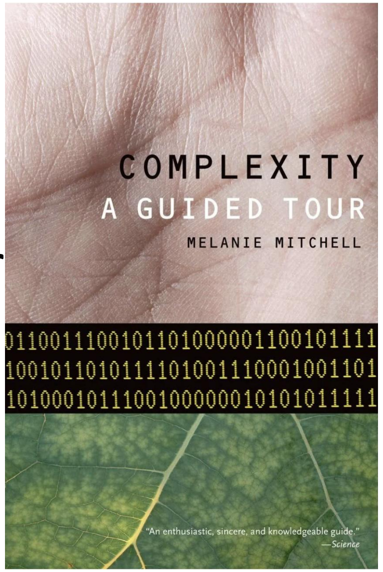
What is a Complex Adaptive System?

Viewpoint 1: Melanie Mitchell, Complexity: A Guided Tour

Complex system: a system in which large networks of components with **no central control** and simple rules of operation give rise to **complex collective behavior, sophisticated information processing, and adaptation** via learning or evolution.

Systems in which organized behavior arises without an internal or external controller or leader are sometimes called self-organizing. Since simple rules produce complex behavior in hard-to-predict ways, the macroscopic behavior of such systems is sometimes called **emergent**.

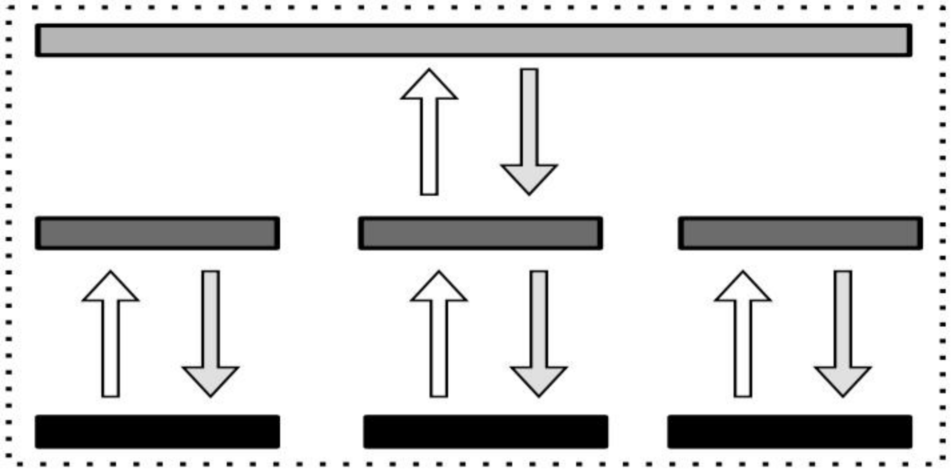
A system that exhibits nontrivial emergent and self-organizing behaviors. The central question of the sciences of complexity is how this emergent self-organized behavior comes about.



What is a Complex Adaptive System?

Viewpoint 2: Brian Arthur, Complexity Economics

Economies are organic and evolutionary… actions and strategies constantly evolve, structures constantly form and re-form …individual behaviors react to the pattern they together create



What is a Complex Adaptive System?

Viewpoint 3: Henri Poincare, 1903 “Science and Method”

Sensitive dependence on initial conditions -> Chaos

It may happen that small differences in the initial conditions produce very great ones in the final phenomena. A small error on the former will produce an enormous error on the latter. Prediction becomes impossible…

What is a Complex Adaptive System?

Viewpoint 3: Charles Darwin, Origin of Species 1859

It is interesting to contemplate a tangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about, and with worms crawling through the damp earth, and to reflect that these elaborately constructed forms, so different from each other, and dependent upon each other in so complex a manner, have all been produced by laws acting around us.

What is a Complex Adaptive System?

Viewpoint 5: Stuart Kauffmann, The Adjacent Possible

The whole biosphere is a vast, linked web of work done to build things so that, stunningly enough, sunlight falls and redwood trees get built and become the homes of things that live in their bark.

The complex web of the biosphere is a linked set of work tasks, constraint construction, and so on. … necessitating a theory of organization that describes what the biosphere is busy doing…Currently we have no theory of it—none at all.

http://edge.org/conversation/the-adjacent-possible

What is a Complex Adaptive System?

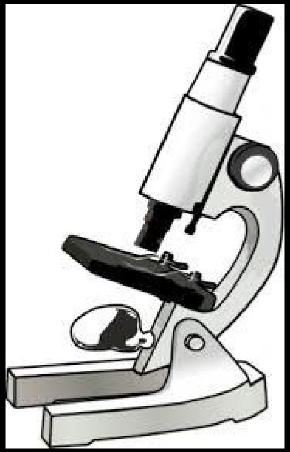
Viewpoint 4: Andreas Wagner, Arrival of the Fittest

- a phenotype like that of a human body is not just a string of DNA. It is a hierarchy of being that descends from the visible organism, its tissues and cells, to the molecular webs formed by metabolic molecules, signaling molecules, and many others, extending down to the level of individual proteins.
- computers are the microscopes of the twenty-first century. They help us understand molecular webs that Darwin did not even know existed. …

Traditional Science

Reductionism: zoom in

Learn more & more about less & less

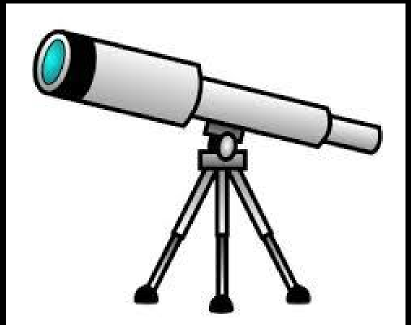


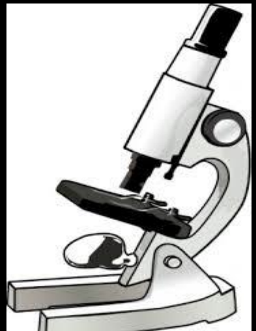
Complexity Science

Look across scales: zoom in & zoom out

Use multiple perspectives

Understand how structure emerges
from interactions within & across levels





Complex Adaptive Systems

Interactions
Systems composed of interacting components

Emergence
Structure emerges from interactions among components and between components and their environment

Scale
Systems are nested and structure emerges at different scales

Evolution
Systems are dynamic and adapt to internal and external conditions

What are examples of CAS?

Team up with 2-3 people

List some CAS and explain why they are CAS.

Describe:

- Interactions
- Emergence
- Relevant scales & nested reactions
- Evolution/adaptation

New Mexico is the birthplace of the interdisciplinary study of Complex Adaptive Systems

And UNM Computer Science is a great place to do a PhD to study CAS!

Bio-inspiration

“In native ways of knowing, human peoples are known as the younger brothers of creation, we say that humans have the least experience of how to live, and thus the most to learn. We must look to our teachers among the other creatures for guidance. They teach us by example. They’ve been on the earth far longer than we have, and have had time to figure things out.

… We need to learn to listen.”

From Braiding Sweetgrass, Robin Wall Kimmerer

What can computer scientists learn from collective animal behavior?

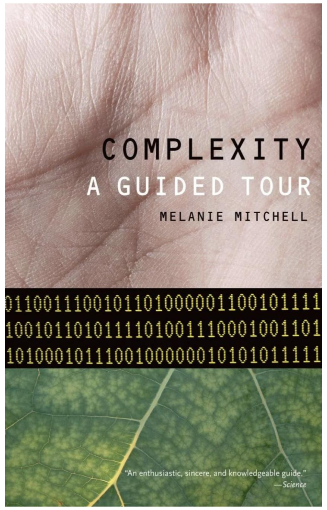
- Everything!

- Evolution →
  - Genetic algorithms →
    - Genetic programming →
      - Evolving neural networks in generative AI

- Ant foraging behaviors ->
  - Swarm robotics -->
  - General models of collective search →
    - Back to biology to understand collective search in immunology
  - General models of cooperation →
    - To understand cooperation (or lack of it) in human societies

Analogies, Ants & Ant Analogies

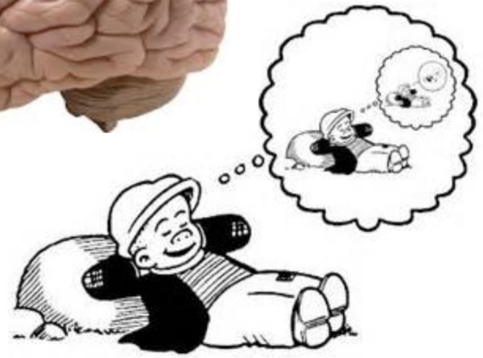
"Thinking and consciousness emerge from the brain via the decentralized interactions of large numbers of simple neurons, analogous to the emergent behavior of systems such as cells, ant colonies and the immune system."



Collective Animal Behavior as a model for how mind emerges from brain

Douglass Hofstadter *Gödel, Escher Bach & I am a Strange Loop*

“I Am My Brain’s Most Complex Symbol”

Emulating biological search strategies in robot swarms

Melanie E. Moses

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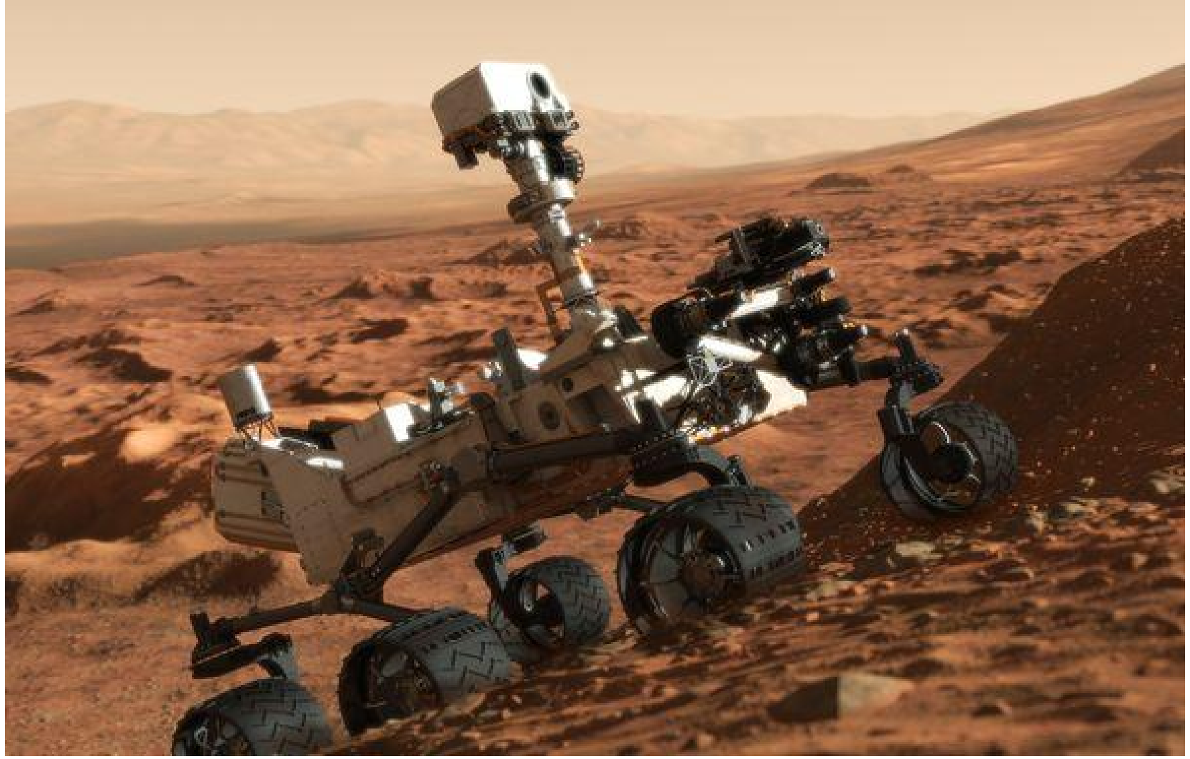
University of New Mexico

External Faculty, Santa Fe Institute

Robot Swarms: fast, scalable & robust search in physical environments



Opportunity required 11 years to travel 26 miles

12 autonomous Swarmies searched 26 miles each day

NASA Swarmathon

Can we automate discovery of effective search strategies using simple robots?

- Unstructured environments
- Unknown target locations
- Unreliable hardware
- Unreliable communication
- No central control

How should we search in the physical world?

- Environmental structure is variable and often unpredictable
- Resource distributions vary
  - Density
  - Area
  - Patchiness in space
  - Persistence in time
- Search objectives vary: fast vs. complete search
- Physical transport takes time

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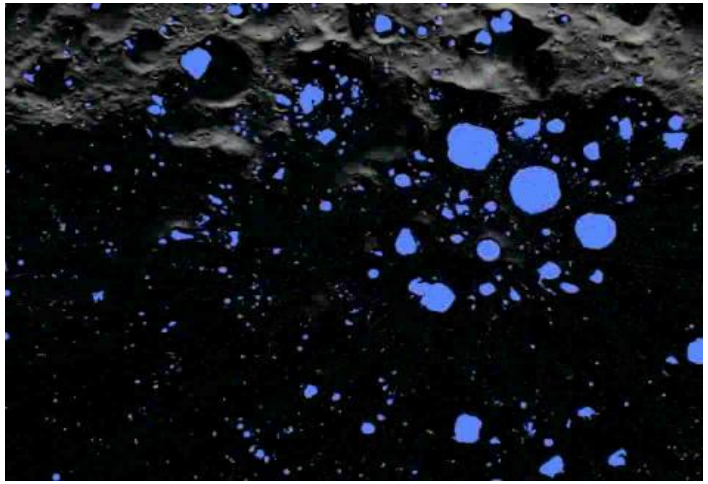

Ice patches on the moon

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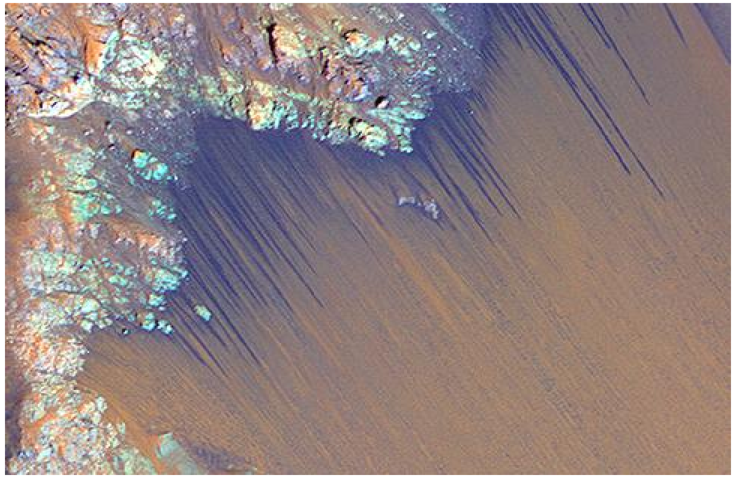

Ephemeral water on Mars

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Search and rescue

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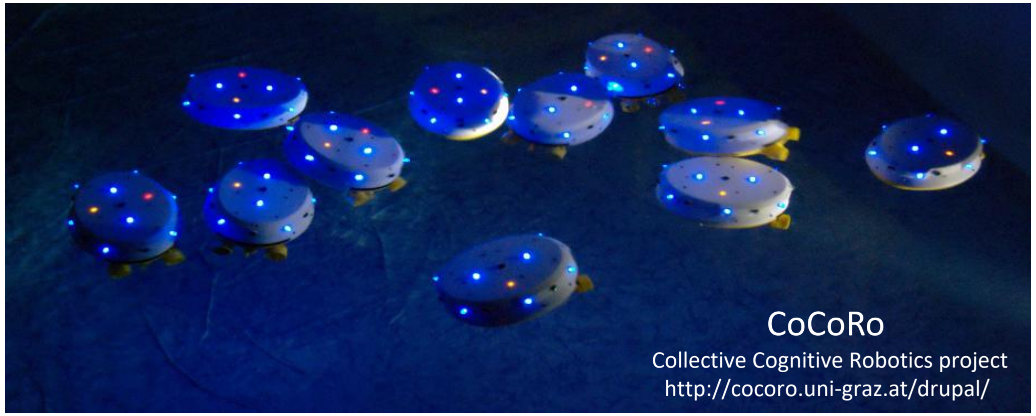
Hazardous waste cleanup

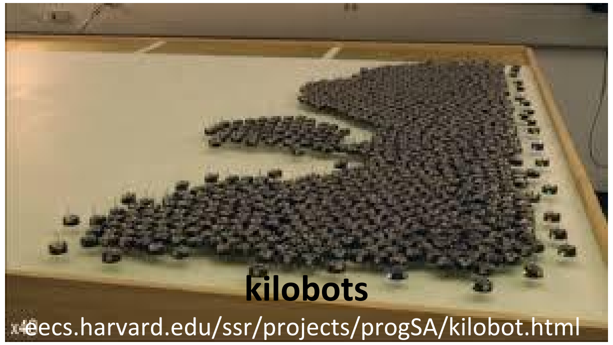
- Part 1: Understand distributed search in biology
- Part 2: Mimic biological search strategies in robots

Swarm Robotics

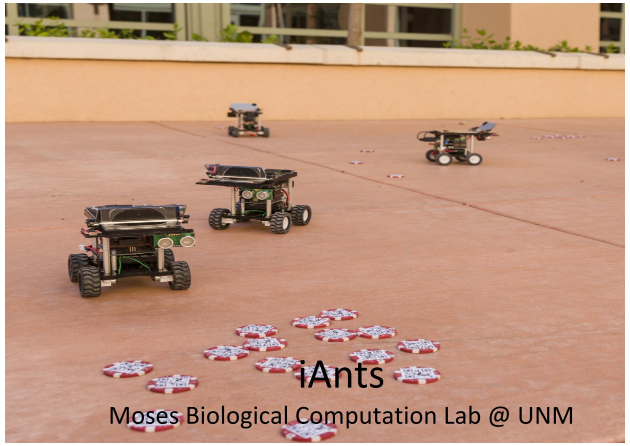


CoCoRo
Collective Cognitive Robotics project
http://cocoro.uni-graz.at/drupal/

GRASP Lab
gizmag.com/grasp-nano-quadrotor-robots-swarm/21302/



kilobots
eecs.harvard.edu/ssr/projects/progSA/kilobot.html



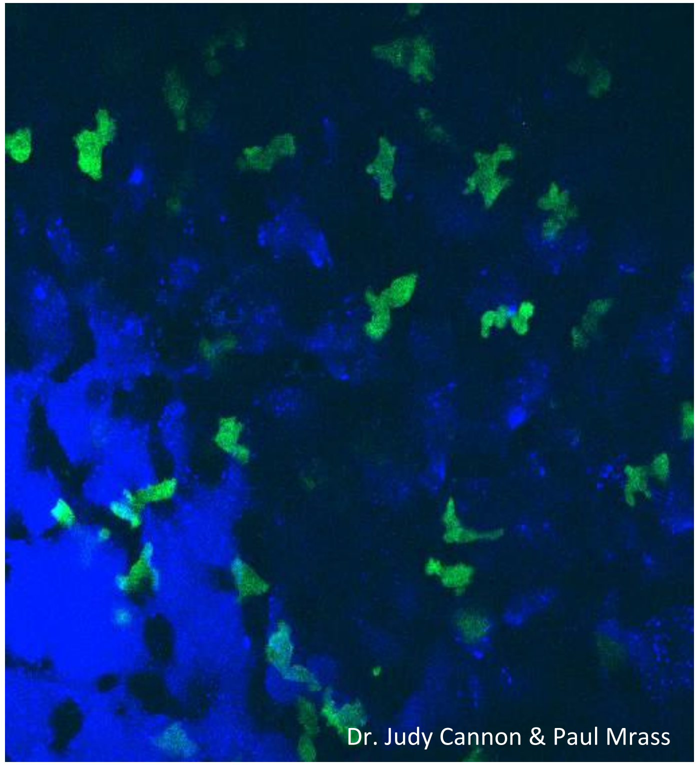
iAnts
Moses Biological Computation Lab @ UNM

Swarmanoid
iridia.ulb.ac.be/~mdorigo/

Distributed Search in Biology
Robust, Flexible & Scalable

Cooperative search behaviors emerge from local interactions among agents & their environment

Ants in the desert



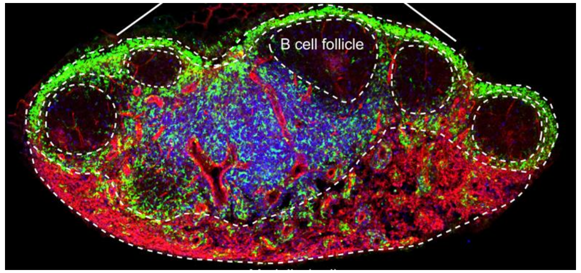
T cells in the lung

Ant Colonies: Flexibility Across Environments

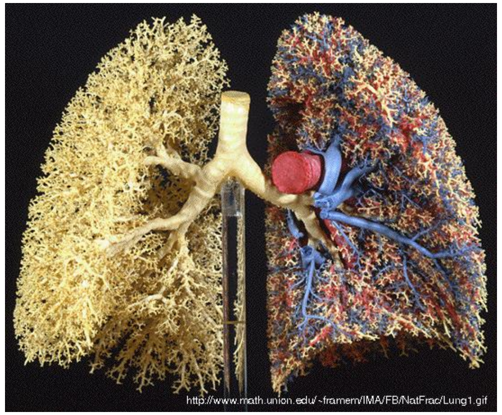
14,000 ant species in diverse habitats across earth's ecosystems

Scalability to Millions of Ants

Immune Systems: Flexibility Across Environments



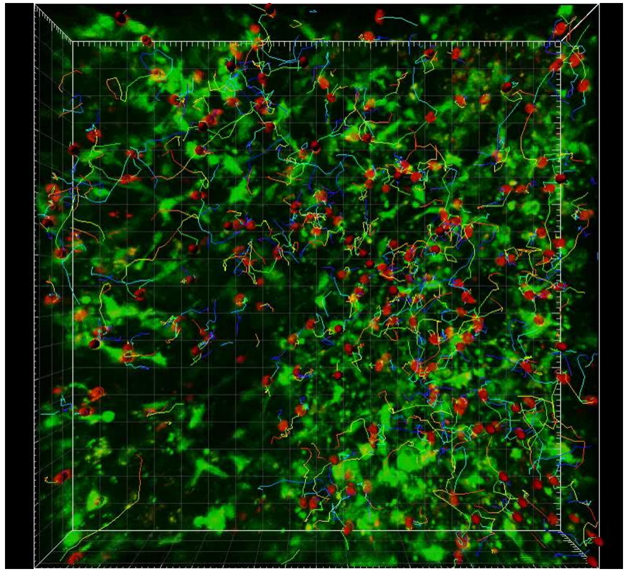
lymph node

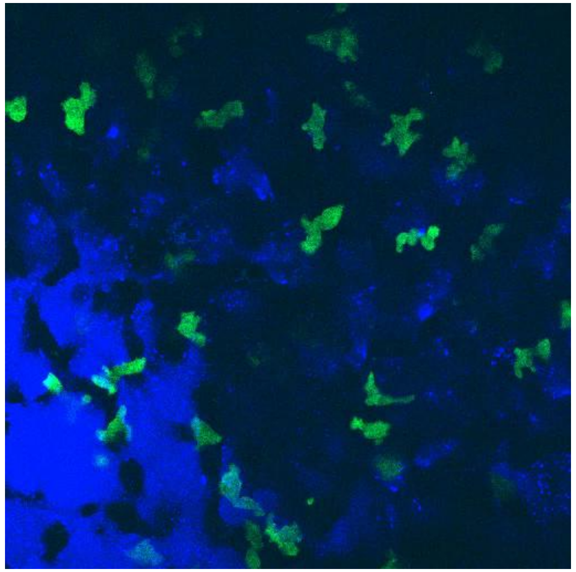


T cells search for pathogens in multiple organs

Each organ is a different environment

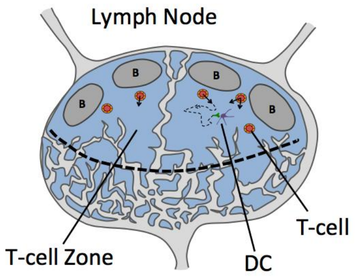
Different movement & communication in different organs



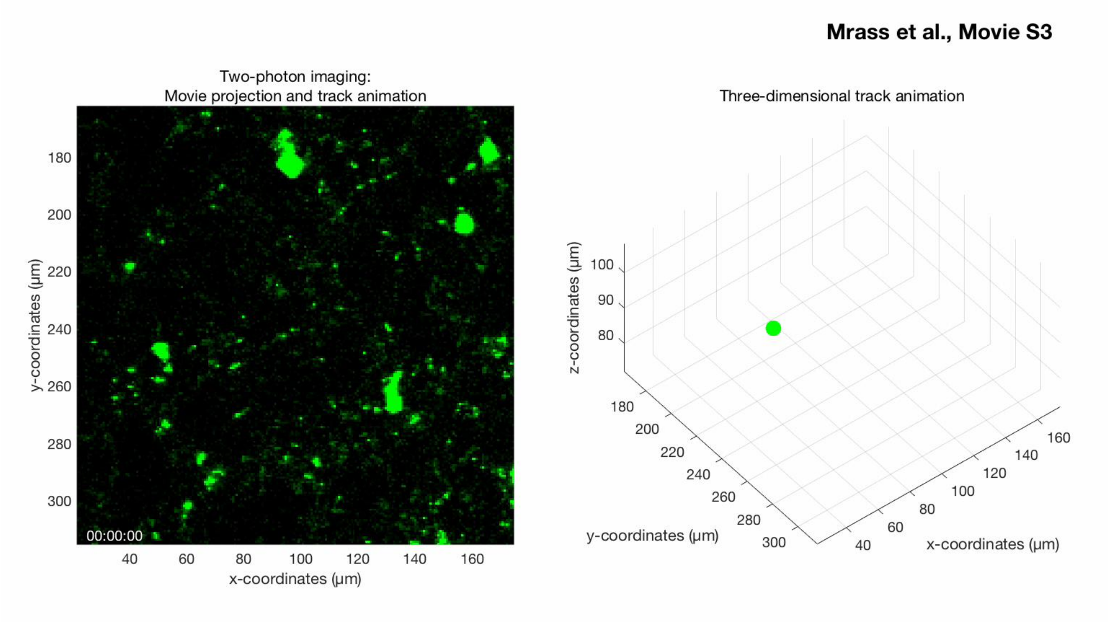


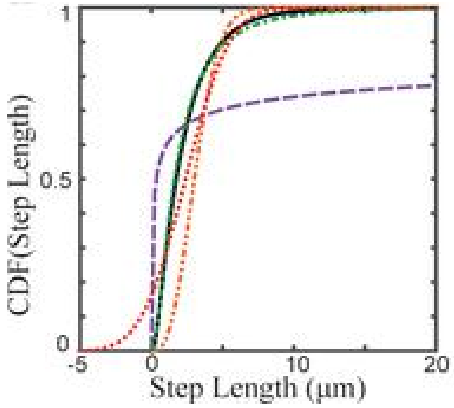
[Moses et al Frontiers 2019]

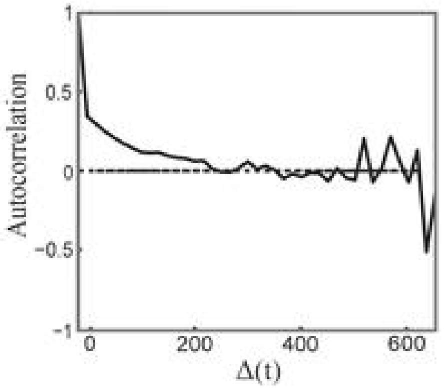
Measuring T cell movement in the Lung & Lymph Node

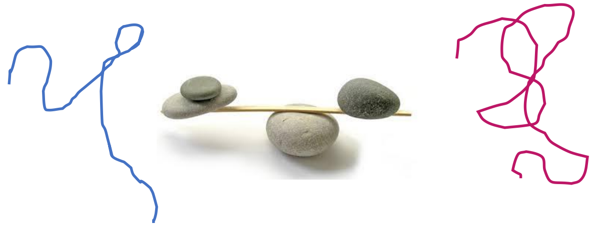


Cannon Lab, UNM HSC









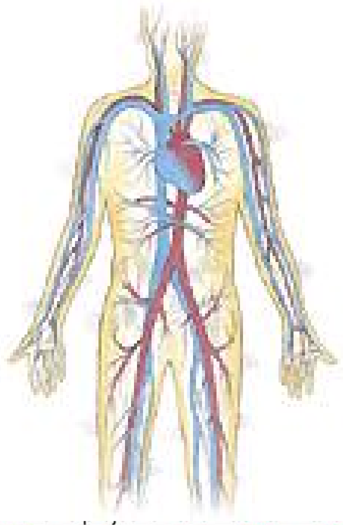
Extensive Search

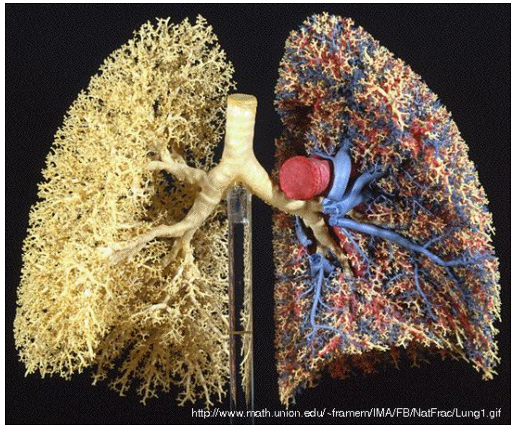
Thorough Search

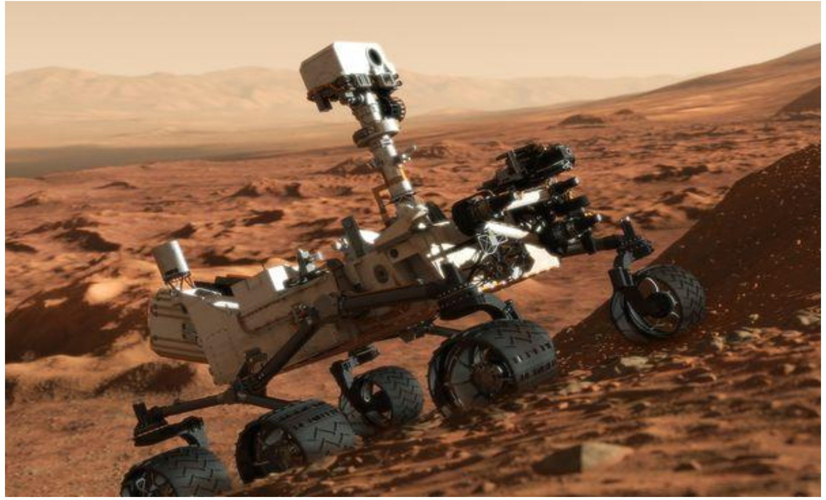
Lognormal Step Length Distribution with Correlation over 5 mins

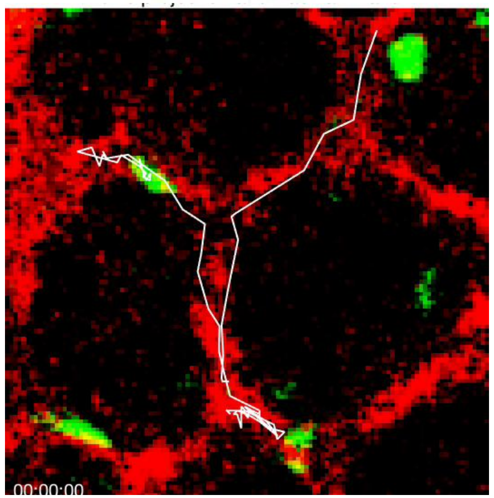
[Mrass et al Nature Comm 2018]
[Fricke et al PLoS Comp Bio 2016]

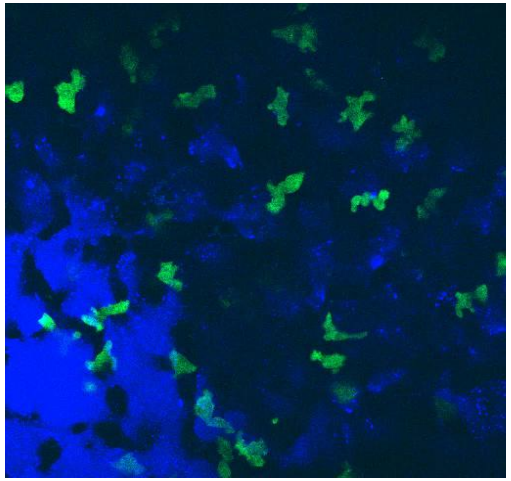
Scalability to Trillions of Cells







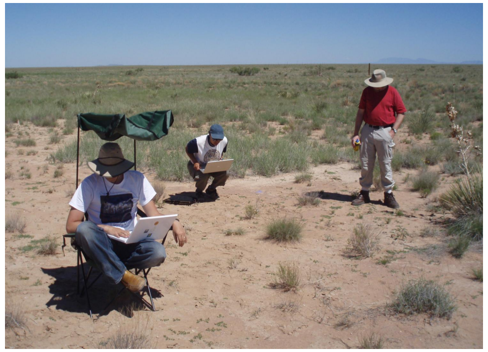


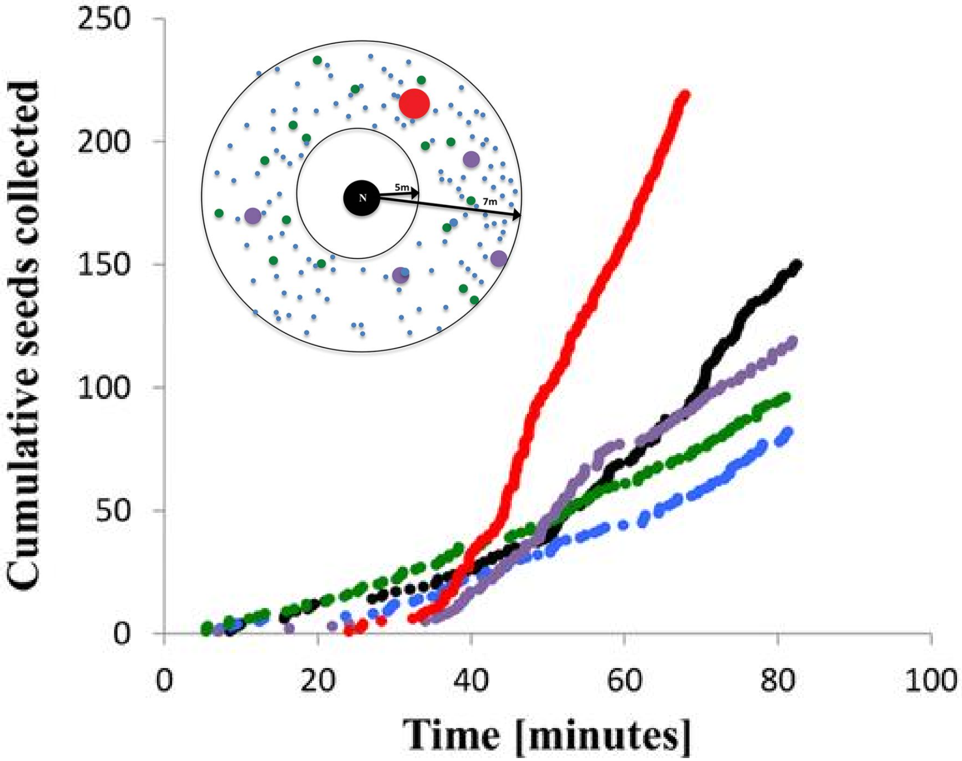


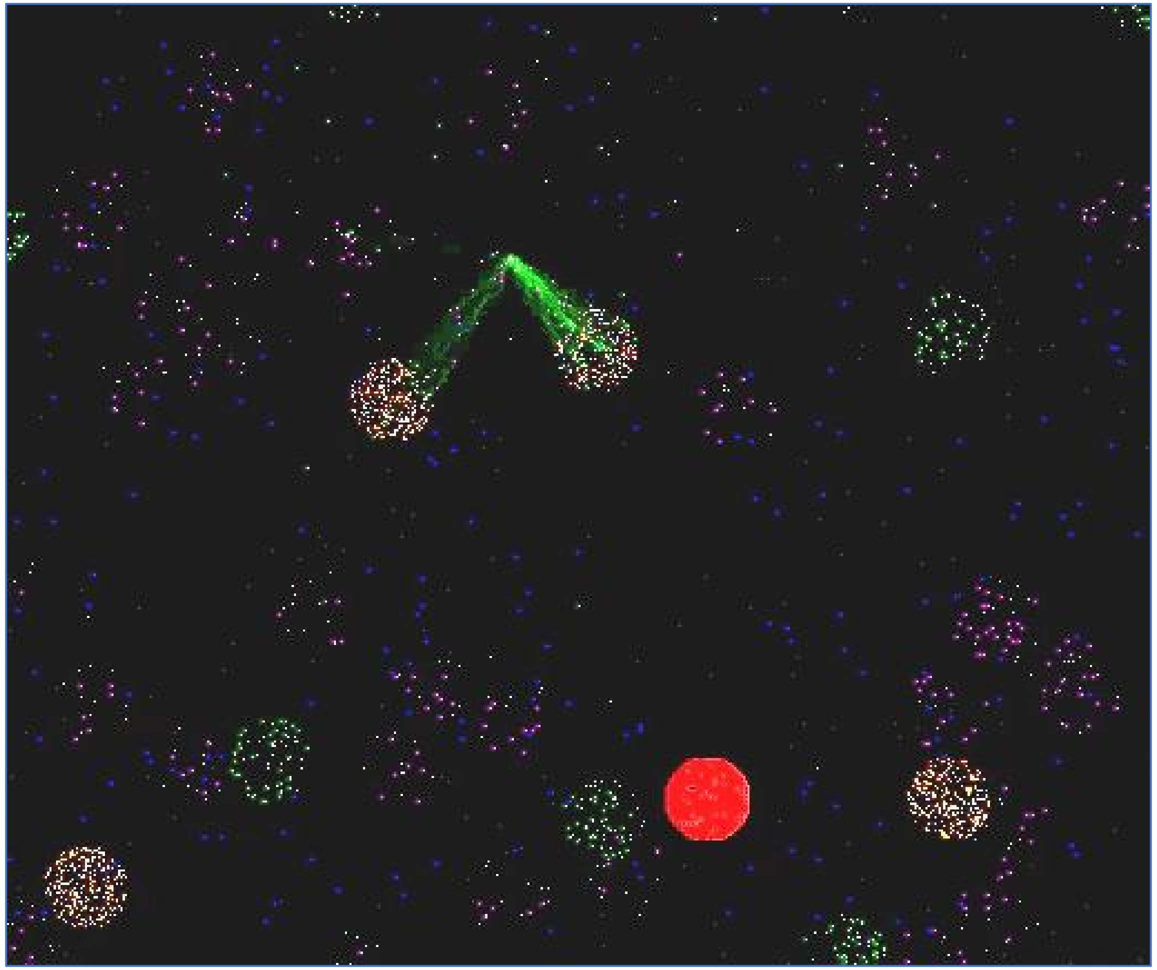
Equivalent to an army of Mars rovers patrolling 100 billion km multiple times each day!

Mrass et al, Nature Communications, 2018

How do desert seed harvesters search?







[Flanagan 2011, 2013; Letendre 2013]