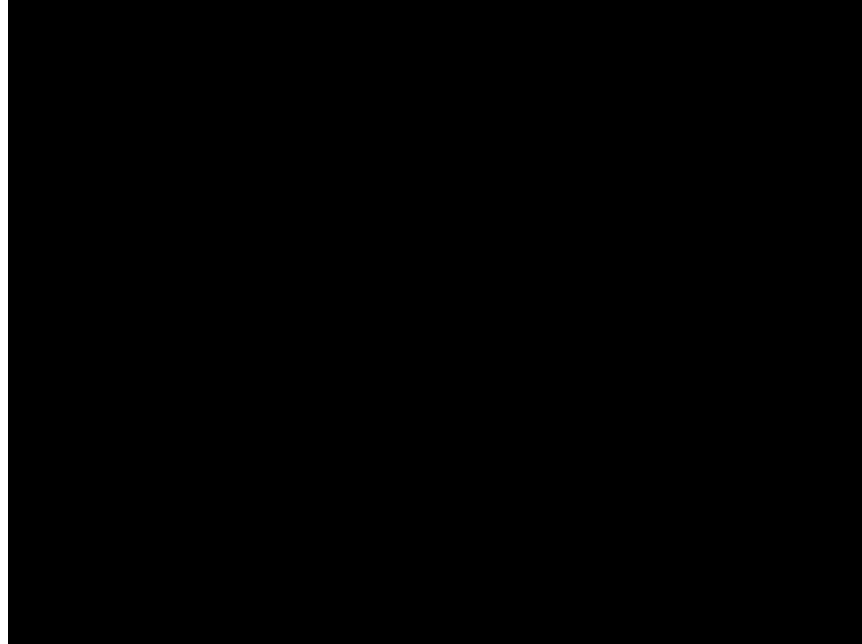


NASA's Tensegrity Robot: The future of evolutionary robotics?

<https://www.youtube.com/watch?v=wR0AllwEgSE>

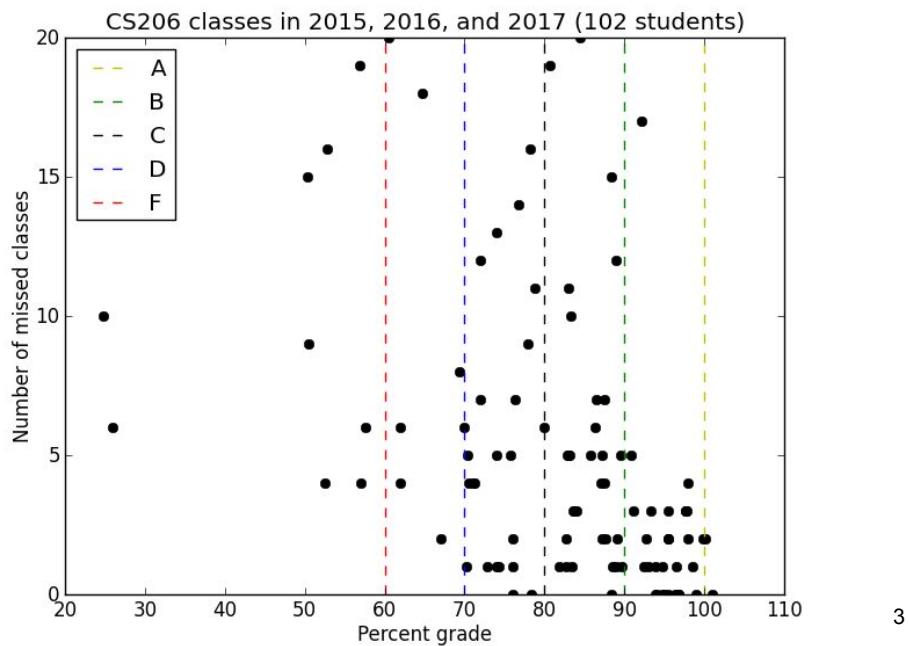


1

The syllabus is available from BlackBoard.

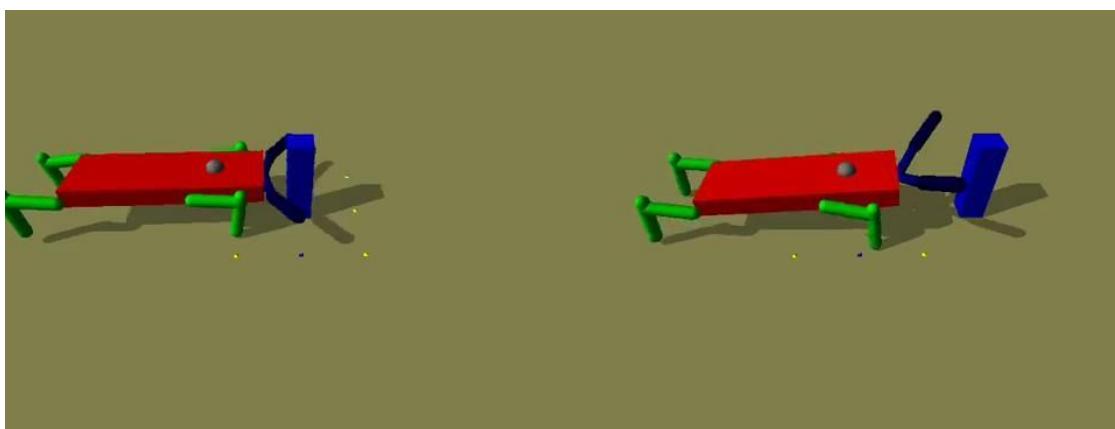
2

Here's why you should come to class.



Anatomy of an evolutionary robotics experiment:

1. Create a **task environment**.
2. Create the **robot**.
3. Create the robot's brain, or **Artificial Neural Network (ANN)**.
4. Use an **evolutionary algorithm** to optimize the ANN so that the robot performs the desired task in its environment.



Who I am:

1993 – 1997: Undergraduate in Computer Science from McMaster University, Hamilton, Canada

1997 – 1998: Software Engineer,
Computing Devices Canada, Calgary, Canada

1998 – 1999: MSc in Evolutionary and Adaptive Systems from Sussex University, Brighton, England

1999 – 2003: PhD in Mathematical and Physical Sciences from University of Zurich, Switzerland

2003 – 2006: Postdoctoral work at Cornell University, Ithaca, NY

Present: Associate Professor, UVM

5

What I expect from you:

- Feedback
- Common sense
- Regular, not necessarily perfect attendance
- Hard work
- Memorization of key concepts (job interviews are closed-book)
- Creativity
- Self - learning
- A positive attitude when working with me, the TA, or fellow students.

6

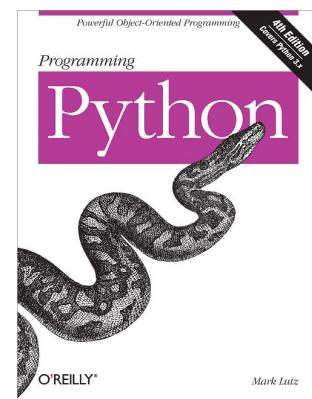
What you cannot expect from me:

- Help with buggy code
(eg. “Why is my program crashing?”)
- Help with learning a programming language, installing software, etc.

7

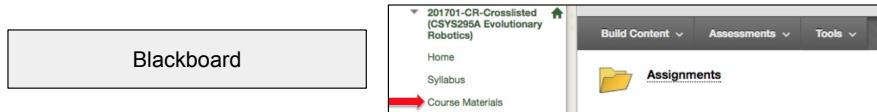
What you can expect from me:

- Help with specific programming questions...
(eg. “Why do I need to deallocate memory?”)
- ... but only after you’ve consulted online resources
and your peers.
(Google “Python tutorial”)
www.codecademy.com
- Help with conceptual issues
 (“Can you go over the genetic algorithm again?”)
- Clarification about the assignments / project
- An emphasis on concepts, rather than specific tools,
because tools change, but concepts change more slowly.



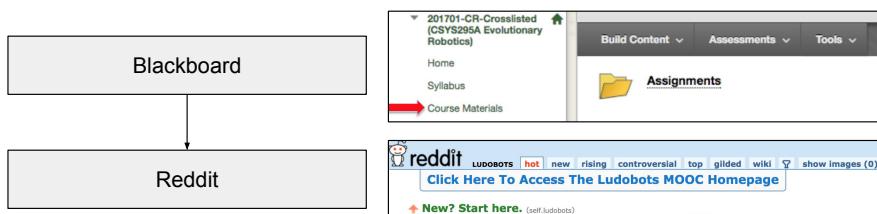
8

Weeks 1 to 10: Complete 10 cumulative programming assignments:



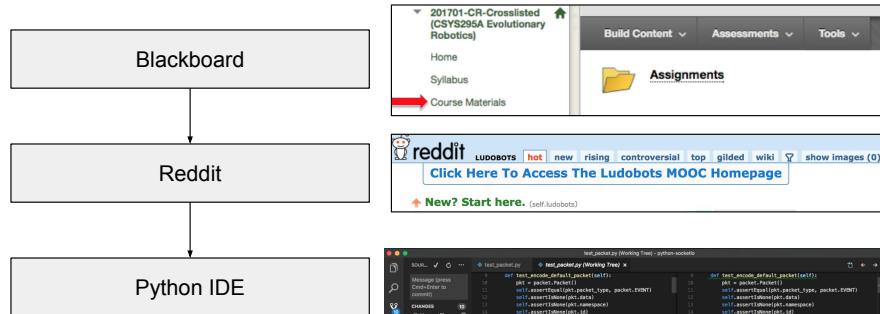
9

Weeks 1 to 10: Complete 10 cumulative programming assignments:



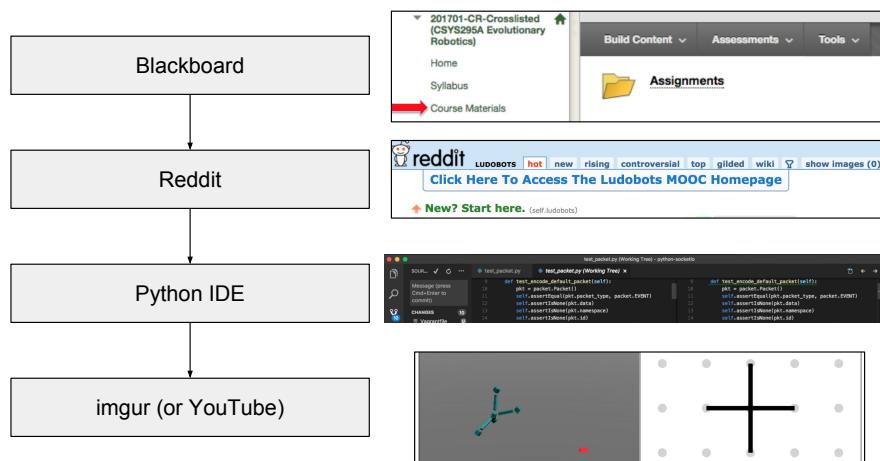
10

Weeks 1 to 10: Complete 10 cumulative programming assignments:



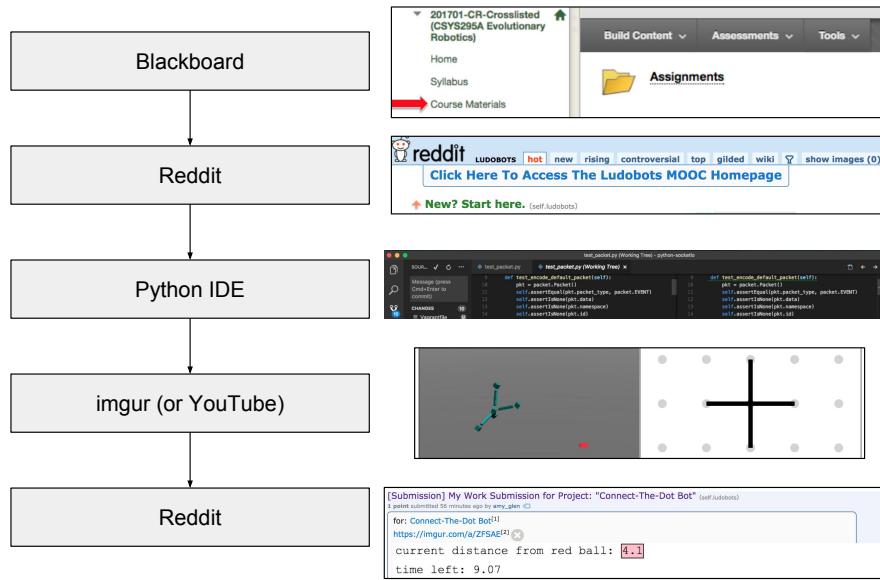
11

Weeks 1 to 10: Complete 10 cumulative programming assignments:



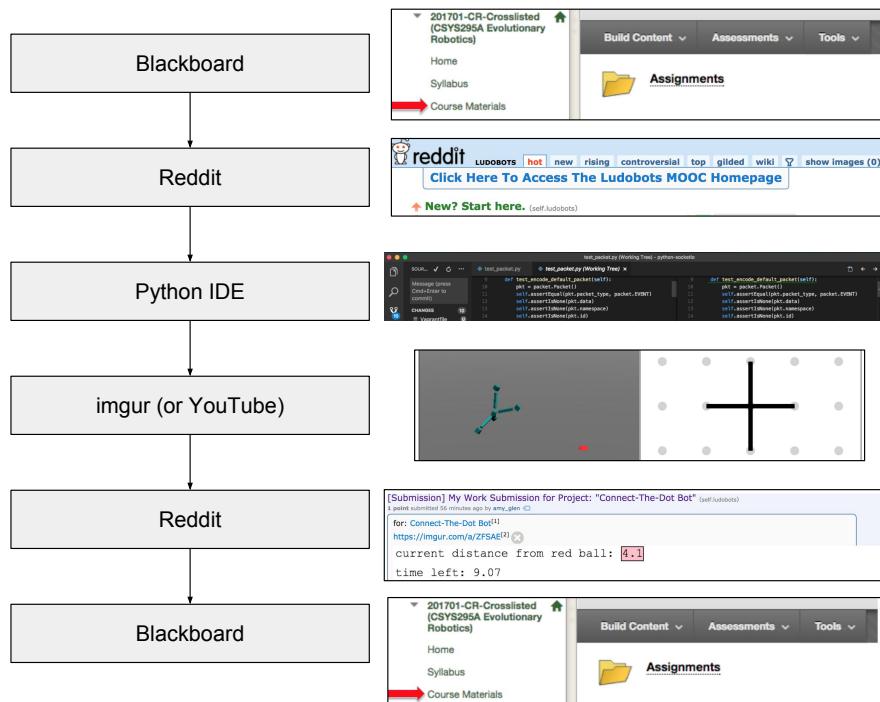
12

Weeks 1 to 10: Complete 10 cumulative programming assignments:



13

Weeks 1 to 10: Complete 10 cumulative programming assignments:



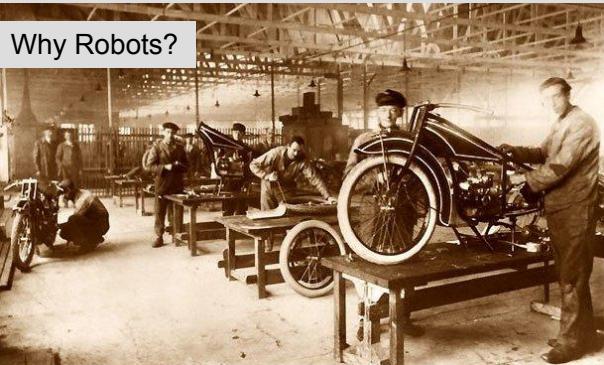
14

Weeks 11 to 14: Use the system to conduct an evolutionary robotics experiment.

1. Given the same optimizer, neural network and eight hours of behavior optimization on the same computer, does a quadrupedal robot evolve to walk further or not as far as a hexapedal robot, or is there no significant difference?
2. Create five fitness functions that not only select for locomotion on the quadrupedal robot, but each also selects for a particular gait: walking, trotting, canter, galloping and pronking.
3. Create a fitness function that rewards NNs for locomotion, but penalizes them for requiring a lot of energy to realize the gait. This is difficult, as there are two solutions that are not desirable: evolution finds fast but inefficient gaits, or ‘gaits’ in which the robot does not move, and therefore does not consume energy.
4. Equip the robot with a simulated laser range finder, which tells the robot about objects in its environment. Evolve a robot that walks toward round objects, but walks away from rectangular objects.

15

Why Robots?



16

Why Robots?

It is one of the few ‘open frontiers’ in science:

There is no guiding theory about intelligence

Guiding theory in biology: evolution

Guiding theory in physics: Newtonian and quantum mechanics

Guiding theory in chemistry: ...

...

There are several Nobel Prizes waiting to be won in this field.

It is one of the most interdisciplinary areas of study:

Evolutionary biology

Neuroscience

Cognitive science

Psychology

Biomechanics

Physics

Computer Science

Mechanical engineering, electrical engineering, bio-engineering

Chemistry

Mathematics

Philosophy (of mind)

17



Why Robots Outside?



Large-scale outdoor infrastructure:

Wind farms,
Solar farms,
Wave farms,
Tide farms,

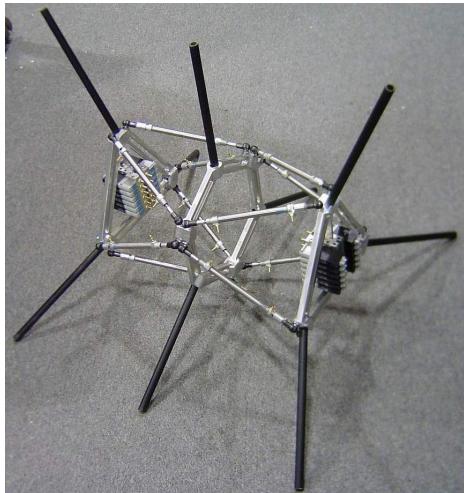
...

18

Why Evolutionary Robotics?

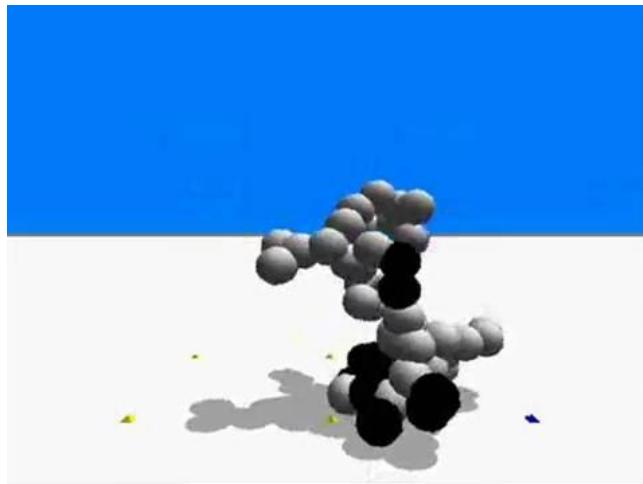
1. Creating a controller for a robot is non-intuitive:
requires automation

	t1	t2	t3	t4	t5	t6	t7	t8	...
m1	+1	+1	+1	+1	+1	-1	+1	-1	...
m2	-1	+1	+1	+1	-1	+1	+1	+1	...
m3	+1	+1	+1	-1	+1	+1	-1	+1	...
m4	+1	-1	+1	+1	-1	+1	+1	-1	...
...									



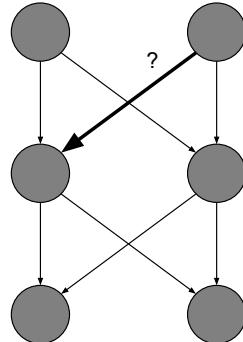
Why Evolutionary Robotics?

1. Creating a controller for a robot is non-intuitive: requires automation
2. Learning algorithms only optimize controllers;
evolution can optimize the whole robot.



Why Evolutionary Robotics?

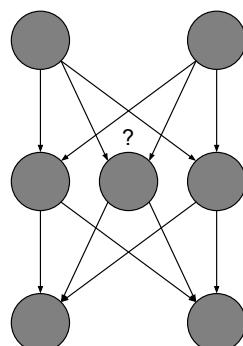
1. Creating a controller for a robot is non-intuitive: requires automation
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21

Why Evolutionary Robotics?

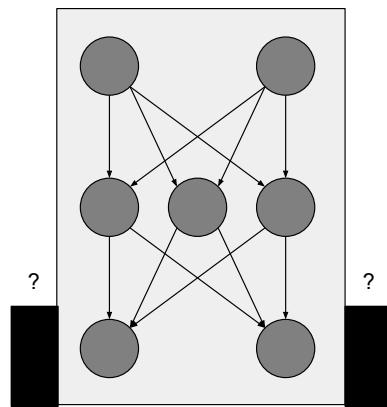
1. Creating a controller for a robot is non-intuitive: requires automation
2. Learning algorithms only optimize controllers;
evolution can optimize the whole robot.



22

Why Evolutionary Robotics?

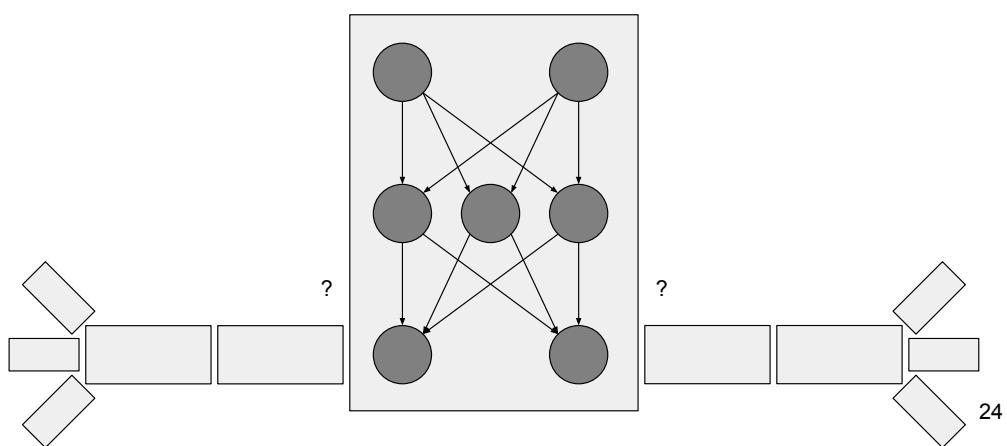
1. Creating a controller for a robot is non-intuitive: requires automation
2. Learning algorithms only optimize controllers;
evolution can optimize the whole robot.



23

Why Evolutionary Robotics?

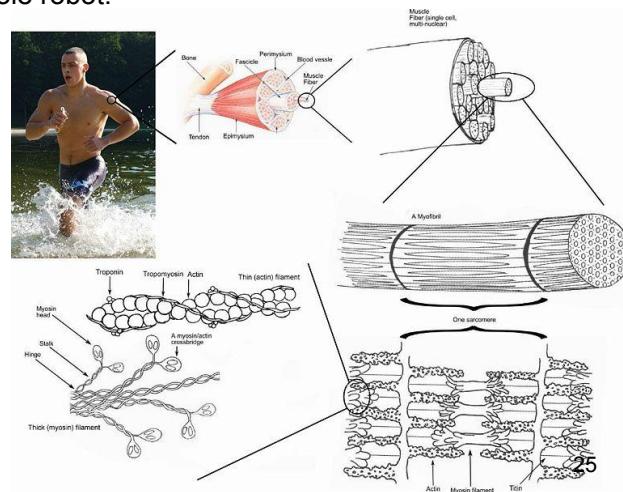
1. Creating a controller for a robot is non-intuitive: requires automation
2. Learning algorithms only optimize controllers;
evolution can optimize the whole robot.



24

Why Evolutionary Robotics?

1. Creating a controller for a robot is non-intuitive: requires automation
2. Learning algorithms only optimize controllers; evolution can optimize the whole robot.
3. Biological evolution produced adaptive agents of unparalleled complexity ***with no supervision***.

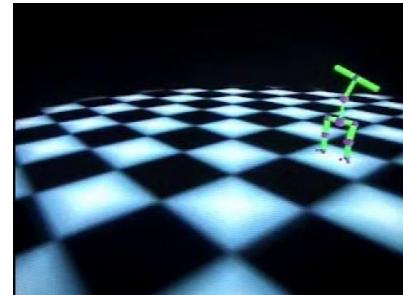


Why Evolutionary Robotics?

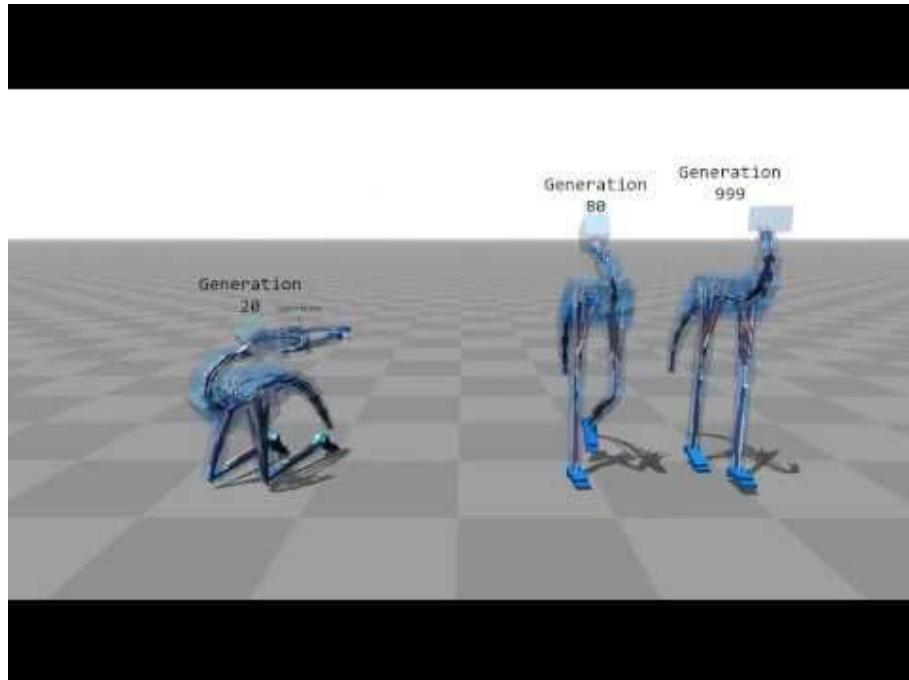
1. Creating a controller for a robot is non-intuitive: requires automation
2. Learning algorithms only optimize controllers; evolution can optimize the whole robot.
3. Biological evolution produced adaptive agents of unparalleled complexity ***with no supervision***.
4. Most learning algorithms require detailed supervision:

	t1	t2	t3	t4	t5	t6	t7	t8	...
m1	+1	+1	+1	+1	+1	-1	+1	-1	...
m2	-1	+1	+1	+1	-1	+1	+1	+1	...
m3	+1	+1	+1	-1	+1	+1	-1	+1	...
m4	+1	-1	+1	+1	-1	+1	+1	-1	...

... Should have been '+1'

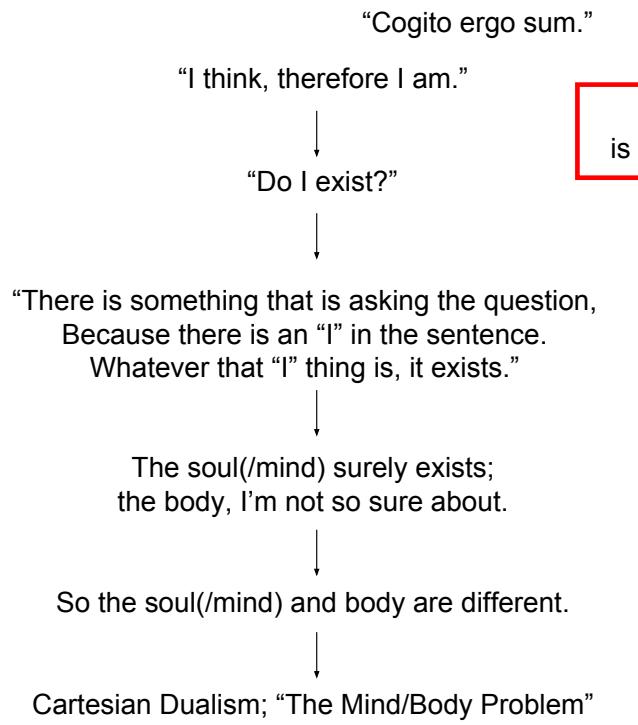


Why Evolutionary Robotics?



27

“Cogito ergo sum.”

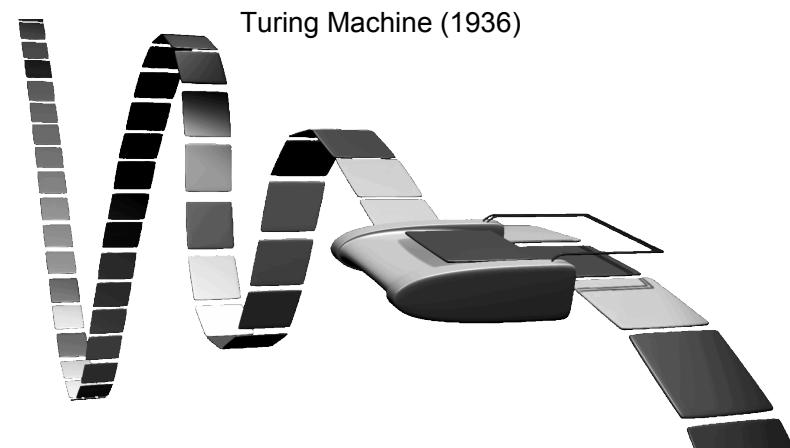


Information in red boxes
is not on the uploaded slides.



We tend to think input first, then information processing, then output.

The very definition of a computer relies on this notion of input first, then processing, then output.



Q: Give a brief definition of a Turing machine.

A:

The Dartmouth Summer Research Conference on Artificial Intelligence (1956)
[Origin of the word “**artificial intelligence**”]

Proposal: “We propose that a 2 month, 10 man study of artificial intelligence be carried out during the summer of 1956 at Dartmouth College in Hanover, New Hampshire. The study is to proceed on the basis of the conjecture that

every aspect of learning or any other feature of intelligence can in principle be so precisely described that a machine can be made to (reproduce?) → simulate it.

An attempt will be made to find how to make machines use language, form abstractions and concepts, solve kinds of problems now reserved for humans, and

improve themselves.

We think that a significant advance can be made in one or more of these problems if a carefully selected group of scientists work on it together for a summer.”

4

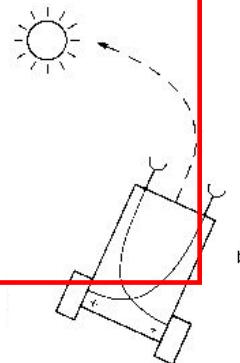
The Dartmouth Summer Research Conference on Artificial Intelligence (1956)
[Origin of the word “**artificial intelligence**”]

Attendees: John McCarthy
Marvin Minsky
Nathaniel Rochester
Claude Shannon
Ray Solomonoff
Oliver Selfridge
Trenchard More
Arthur Samuel
Herbert Simon, and
Allen Newell

5

Goals of Artificial Intelligence:
(p. 17, *How The Body...*)

- (1) – E.g., how do simple animals translate the detection of light into phototaxis (moving toward light sources)?
- (2) –
- (3) –



6

An example of classical Artificial Intelligence: ELIZA

```

File Edit Options Buffers Tools Help
I am the psychotherapist. Please, describe your problems.
Each time you are finished talking, type RET twice.
I have a terrible headache.
Maybe you should consult a doctor of medicine, I am a psychotherapist.
Okay, I'll do that then.
Can you elaborate on that?
What are you talking about? No I cannot elaborate. See you later.
Why do you say that?
Now you're just talking nonsense!
What makes you believe now I am just talking nonsense?
You are not making any sense.
Perhaps your plans have something to do with this.
"doctor"

```

Created by Joseph Weizenbaum between 1964 to 1966



Internet chatbots

Sample ELIZA Rule: User: "I [verb] [proper noun]" →
ELIZA: "Why do you [verb] [proper noun]?"

Q: Other candidate rules?

7

Turing Machine: Abstract description of a minimal computer.

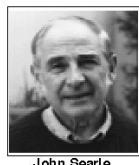
If a computer can make a human think it is intelligent, it is intelligent.



8

3. John Searle, 1980a, 1980b, 1990b
The Chinese Room argument. Imagine that a man who does not speak Chinese sits in a room and is passed Chinese symbols through a slot in the door. To him, the symbols are just so many squiggles and squoogles. But he reads an English-language rule book that tells him how to manipulate the symbols and which ones to send back out. To the Chinese speakers outside, whoever (or whatever) is in the room is carrying on an intelligent conversation. But the man in the Chinese Room does not understand Chinese; he is merely manipulating symbols according to a rule book. He is instantiating a formal program, with success the first few times, maybe. But nevertheless, he does not understand Chinese. This shows that instantiation of a formal program is not enough to produce semantic understanding or intentionality.

Note: For more on "Turing tests," see Map 2. For more on formal programs and instantiation, see the "Is the brain a computer?" arguments on Map 1, the "Can functional states generate consciousness?" arguments on Map 6, and sidebar, "Formal Systems: An Overview," on Map 7.



John Searle



Take a
squiggle-squiggle
sign from basket
number 1 and put
it next to a
squiggle-squiggle
sign from basket
number 2

in • ten • tion • al • it • y: The property (in reference to a mental state) of being directed at a state of affairs in the world. For example, the belief that Sally is in front of me is directed at a person, Sally, in the world. Intentionality is sometimes taken to be synonymous with representation, understanding, consciousness, meaning, and semantics. Although there are important and subtle distinctions in the definitions of "intentionality," "understanding," "semantics," and "meaning," in this debate they are sometimes used synonymously.

9

Valentino Braitenberg, *Vehicles*

Source Material: [http://www.bcp.psych.ualberta.ca/~mike/
Pearl_Street/Margin/Vehicles/index.html](http://www.bcp.psych.ualberta.ca/~mike/Pearl_Street/Margin/Vehicles/index.html)

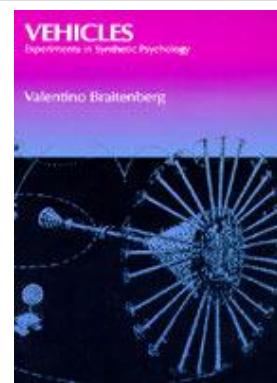
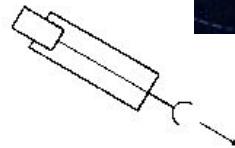
Introduces a series of (hypothetical) simple robots that seem, to the outside observer, to exhibit complex behavior.

The complex behavior does not come from a complex brain, but from a simple agent *interacting* with a rich environment.

Vehicle 1: Getting around

A single sensor is attached to a single motor.
Propulsion of the motor is proportional to the signal detected by the sensor.

The vehicle will always move in a straight line, slowing down in the cold, speeding up in the warm.



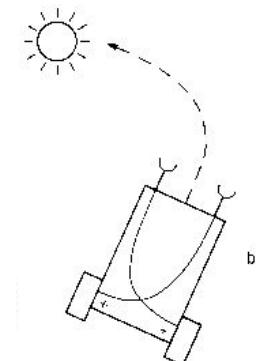
Braitenberg: "Imagine, now, what you would think if you saw such a vehicle swimming around in a pond. It is restless, you would say, and does not like warm water. But it is quite stupid, since it is not able to turn back to the nice cold spot it overshot in its restlessness. Anyway, you would say, it is ALIVE, since you have never seen a particle of dead matter move around quite like that."

10

Valentino Braitenberg, *Vehicles*

Vehicle series 2: Fear and aggression

Each vehicle has two sensors and two motors.
Still a directly proportionate relationship between the signal strength and force of the motor.



The Aggressor

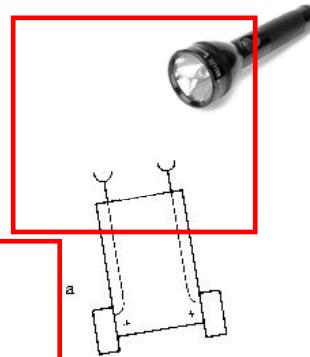
Left sensor is attached to the right motor;
right sensor is attached to the left motor;
Will charge the light if it's dead-ahead;
Will charge the light if it's off to the side;
Will eventually hit it, as long as the light stays in the vicinity.

11

Valentino Braitenberg, *Vehicles*

Vehicle series 2: Fear and aggression

Each vehicle has two sensors and two motors.
Still a directly proportionate relationship between
the signal strength and force of the motor.



The

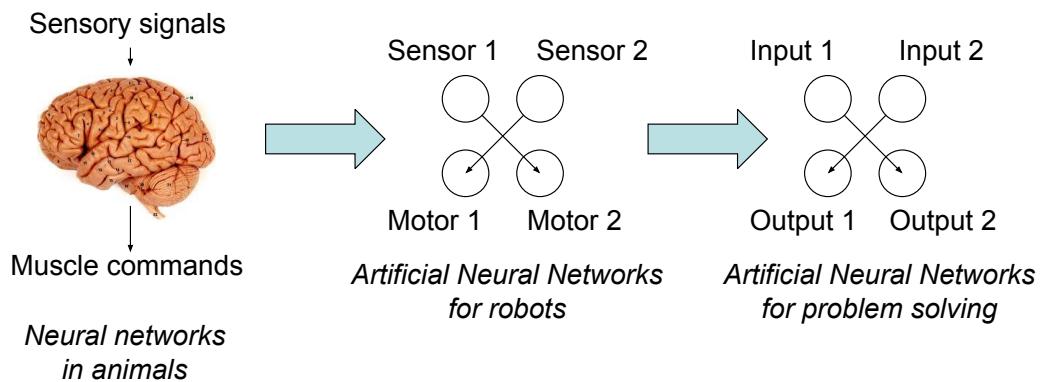
Left sensor is attached to the **left** motor;
right sensor is attached to the **right** motor...

Q: How will this vehicle behave?

12

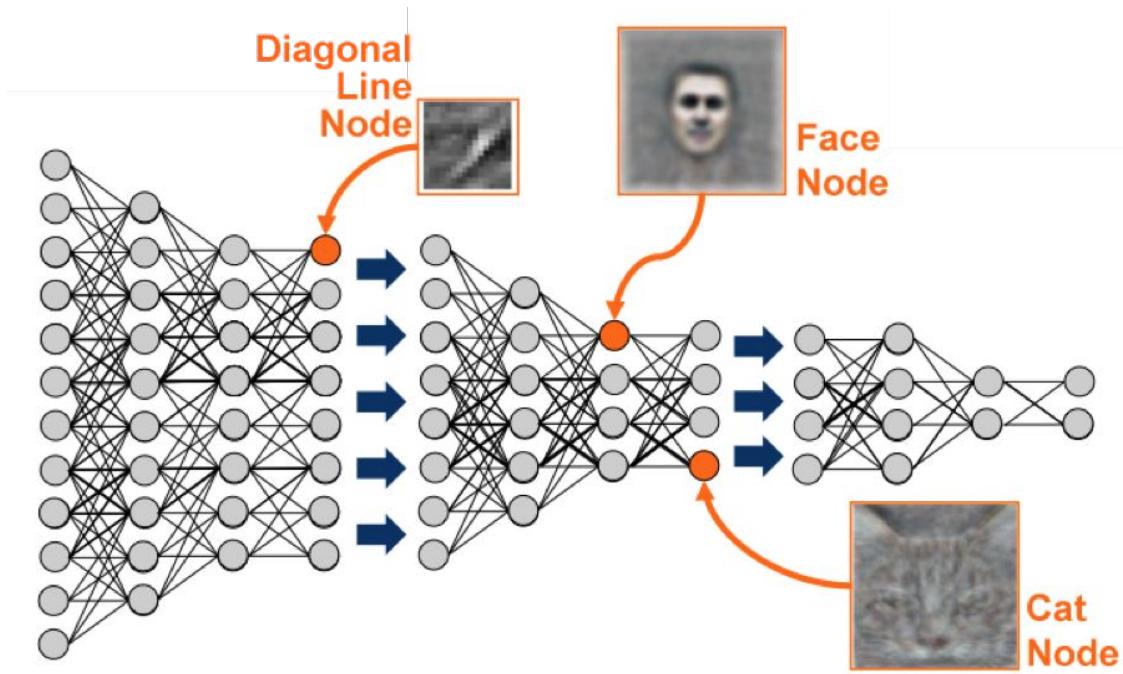
Connectionism (1980s): Networks, rather than IF/ELSE statements

Sample ELIZA Rule: **IF** User: "I [verb] [proper noun]",
THEN: ELIZA: "Why do you [verb] [proper noun]?"



13

"Deep" Learning (now): Networks with lots of layers



14

The popularity of AI research waxes and wanes.

AI has suffered two "winters" so far: one in the 1970s, and another in the 1990s:

en.wikipedia.org/wiki/AI_winter

We are currently enjoying an AI "High Summer".

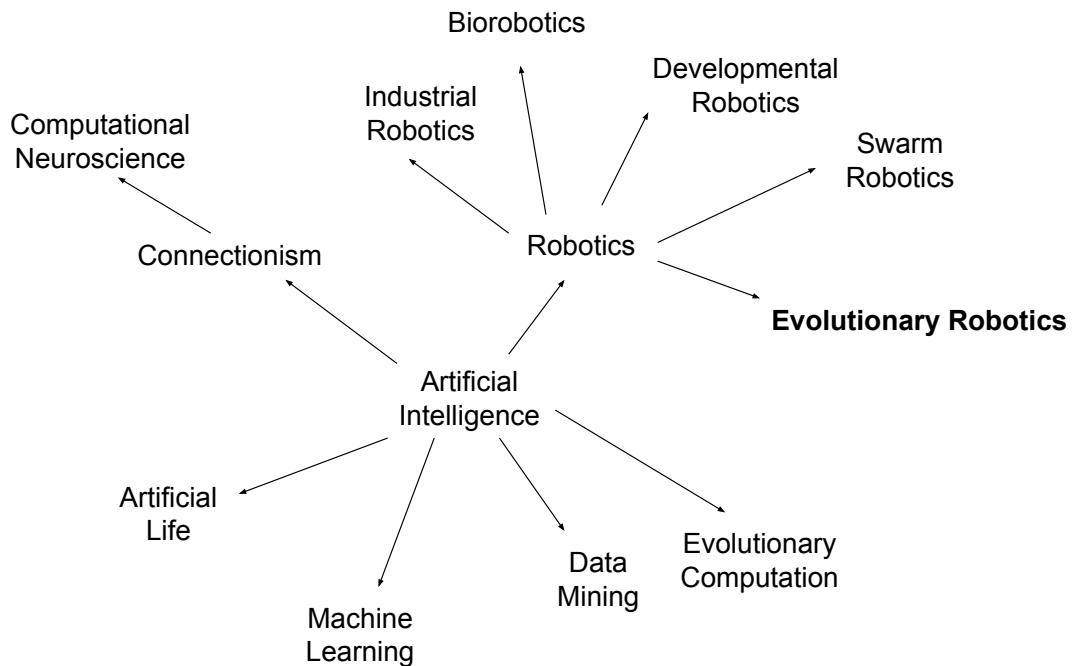
...is a third "winter" on the way?

Hans Moravec:

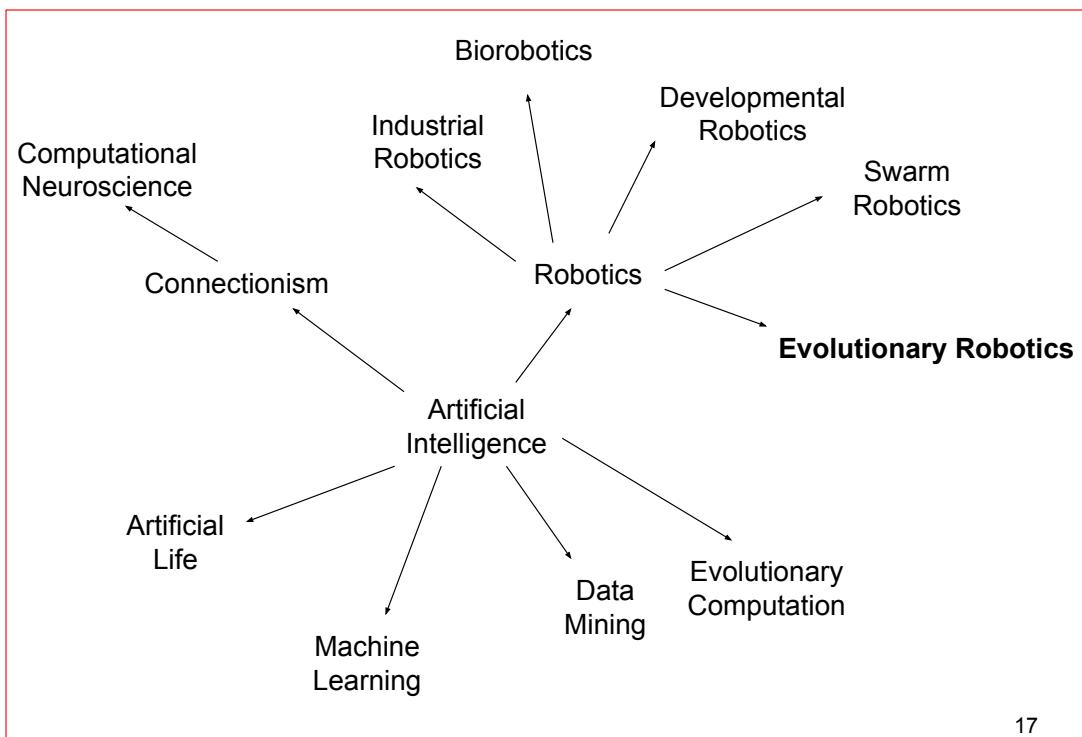
"Many researchers were caught up in a web of increasing exaggeration. Their initial promises to DARPA had been much too optimistic. Of course, what they delivered stopped considerably short of that. But they felt they couldn't in their next proposal promise less than in the first one, so they promised more."

- p. 115, Crevier, Daniel (1993),
AI: The Tumultuous Search for Artificial Intelligence,
 New York, NY: BasicBooks, ISBN 0-465-02997-3

15



16



17

Cognitive ability:

Challenge: How to recognize objects in a scene; where are the object's boundaries?
This problem is known as 'image segmentation' in the field of computer vision.

It is one of the most difficult problems in computer science.



1

Cognitive ability: Pattern recognition

Challenge: How to recognize objects in a scene; where are the object's boundaries?
This problem is known as 'image segmentation' in the field of computer vision.

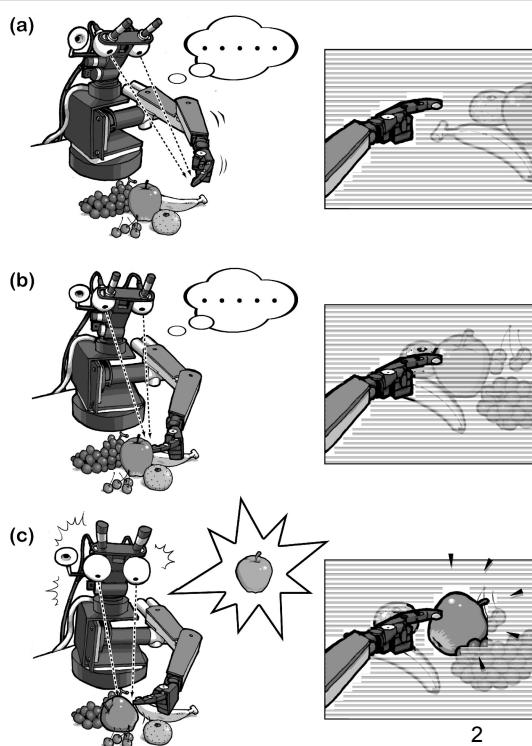
Solution:

Cog: **interacts** with the scene,
rather than passively observing it.

Q: What else can Cog infer about the
objects it interacts with?

Early integration of vision and manipulation.

G Metta, P Fitzpatrick
Adaptive Behavior, 2003



2

Cognitive ability:



Kasparov vs. Deep Blue:

Won its first game against world champion:
Won its first match against world champion:

Q: How does Deep Blue work?

3

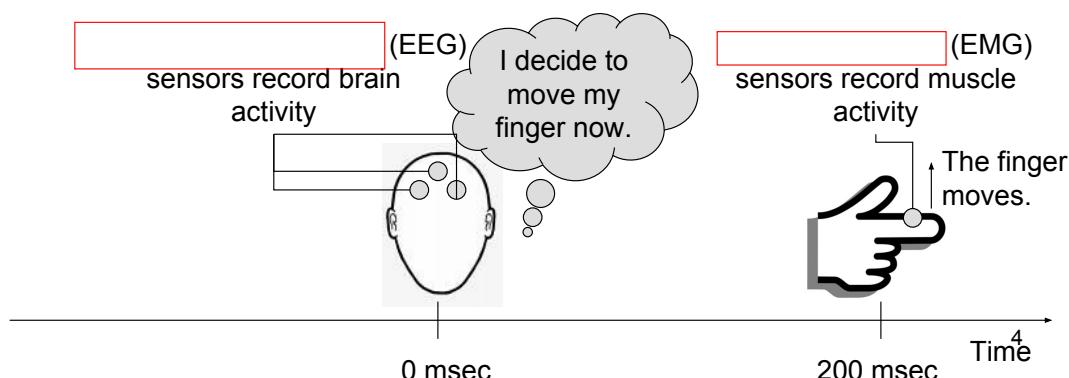
Cognitive ability:

Example: Another aspect of human cognition: free will.

Most people believe that they have free will:

"I decide in my mind that I want to do something, and then I do it."

Libet, B., Gleason, C. A., Write, E. W., and Pearl, D. K. (1983). Time of conscious intention to act in relation to onset of cerebral activity (readiness-potential): The unconscious initiation of a freely voluntary act. *Brain*, **106**: 623-642.



Warning: Thinking about thinking is misleading; introspection is dangerous

Example: Another aspect of human cognition: free will.

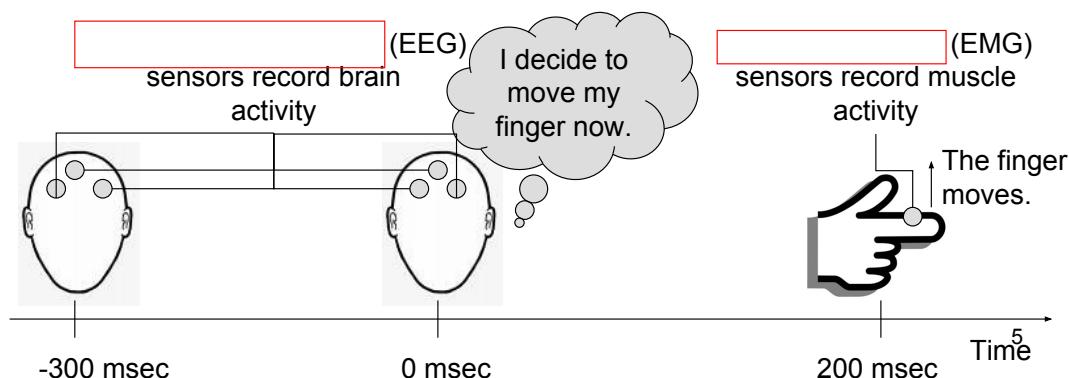
Most people believe that they have free will:

"I decide in my mind that I want to do something, and then I do it."

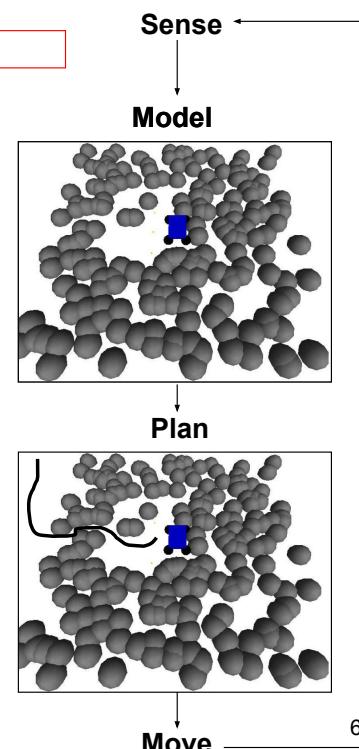
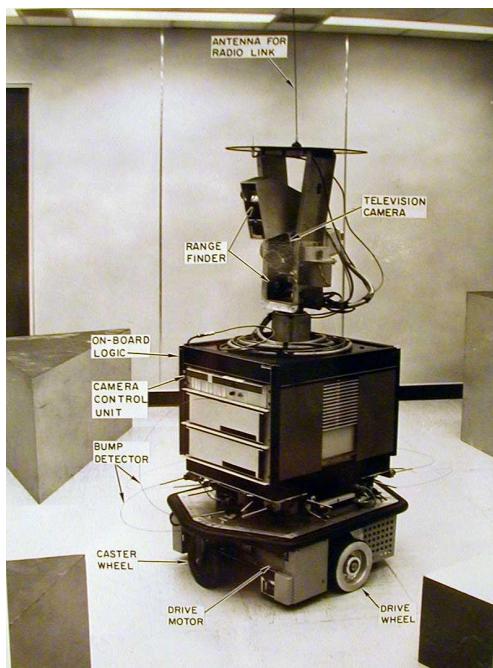
→ Thinking about free will seems to imply that free will exists ... but does it?

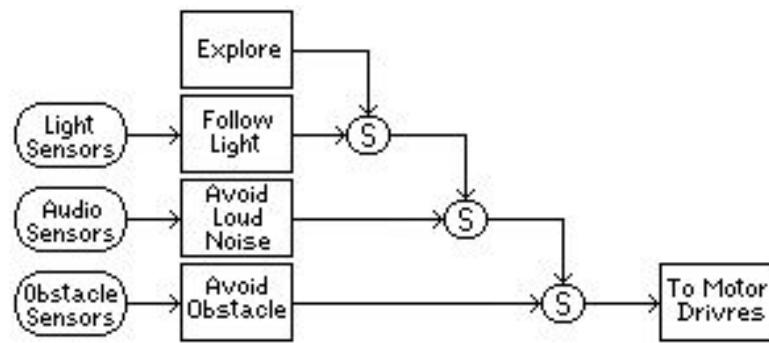
Observation: Brain activity associated with the finger movement begins 300 msec before the subject experiences the conscious will to move the finger.

Conclusion: If free will is unconscious, and our consciousness has no control over it, then it can't be "free" will.



Embodied Planning





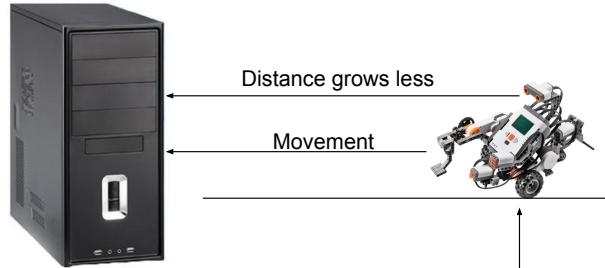
1. Behaviors are arranged in parallel, not serial.
2. One behavior is always in control at any one time.
3. When stimuli are not present, higher levels *subsume* control of the robot.

7

(This does not count as a body→)

Why not?

A body is a tool for affecting
the world,
and for being affected by it.



Embodied cognition: the way you process information is affected by the fact that you have a body.

Example: If you have a body that can move, and you can see,
then moving will cause *immediate feedback*.

Non-embodied technologies (such as computers) must wait for feedback from another computer (via packets) or a person (via an input device).

8

(**Embodied cognition:** the way you process information is affected by the fact that you have a body.)

Situated cognition: the way you process information is affected by the fact that you are physically situated in the world.

Example: Embedded devices

Changes in sensor readings are often the result of physical processes:

1. they occur in real-time,
2. they are not under the control of the device or agent,
3. and they do not wait for a signal from the device to change.

Specific example: A wireless sensor senses changes in light levels; light levels change regardless of whether the device records the data or not.

A computer: Data within computer memory does not change, unless it is explicitly changed by the computer itself.

9

Embodied and Situated cognition

(**Embodied cognition:** the way you process information is affected by the fact that you have a body.)

Situated cognition: the way you process information is affected by the fact that you are physically situated in the world.

A **complete agent** is an agent that is both situated and embodied.

Complete agents have three important properties that distinguish them from other kinds of agents:

1. They are subject to the laws of physics (by being in the world).
Q: Examples?

2. They generate sensory stimulation (through behavior).
Q: Examples?

3. They affect the environment (through behavior).
Q: Examples?

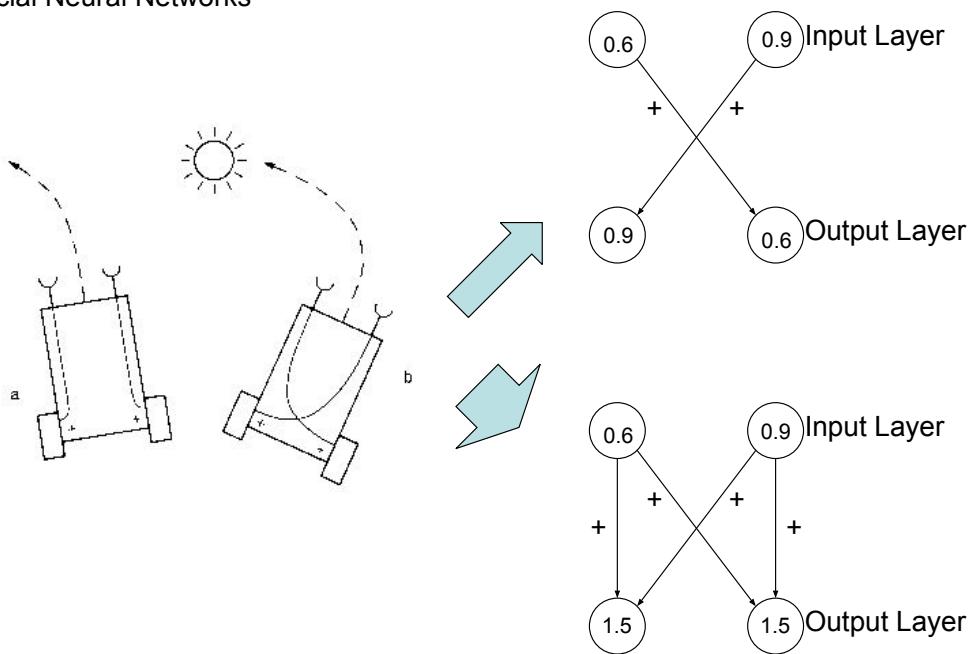
10

Classification of technologies:

	Disembodied	Embodied
Not situated		
Situated		

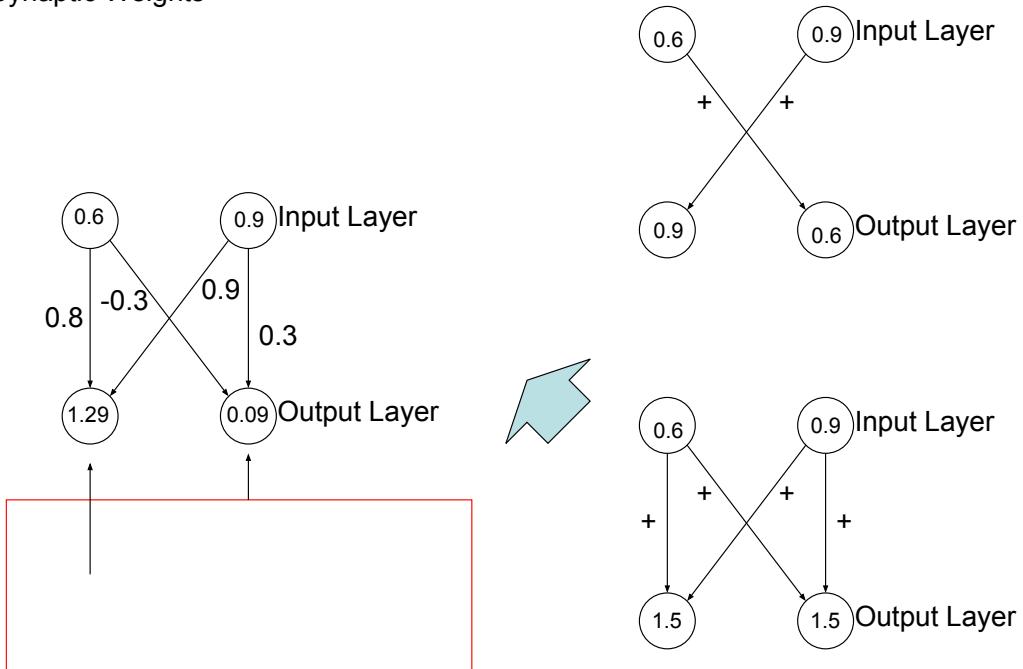
11

Artificial Neural Networks



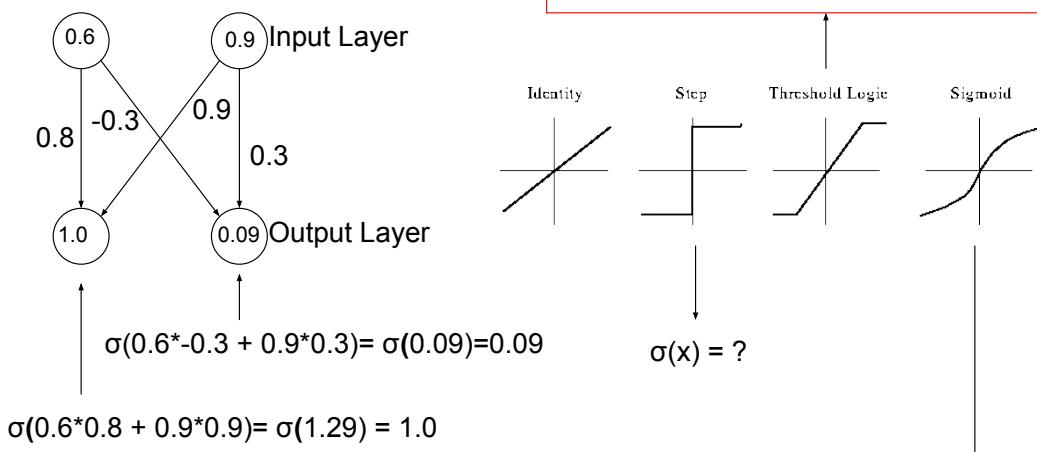
1

Synaptic Weights



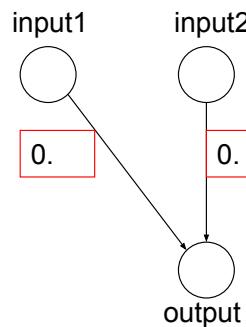
2

Activation functions: keeping neuron values within limits



3

Neural networks as functions



$$\sigma(x) = \begin{cases} 1 & : x > \boxed{} \\ 0 & : x \leq \boxed{} \end{cases}$$

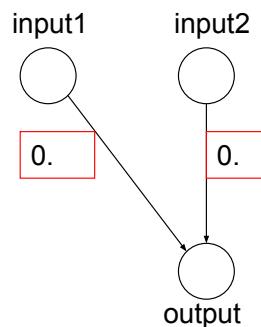
Truth Table:

input1	input2	output
0	0	0
0	1	0
1	0	0
1	1	1

$$\begin{aligned} \sigma(0^* + 0^*) &= \sigma(\quad) = 0 \\ \sigma(0^* + 1^*) &= \sigma(\quad) = 0 \\ \sigma(1^* + 0^*) &= \sigma(\quad) = 0 \\ \sigma(1^* + 1^*) &= \sigma(\quad) = 1 \end{aligned}$$

4

Neural networks as functions



$$\sigma(x) = \begin{cases} 1 & : x > \boxed{} \\ 0 & : x \leq \boxed{} \end{cases}$$

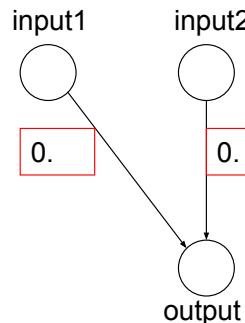
Truth Table: or

input1	input2	output
0	0	0
0	1	1
1	0	1
1	1	1

$$\begin{aligned} \sigma(0^* + 0^*) &= \sigma(\quad) = 0 \\ \sigma(0^* + 1^*) &= \sigma(\quad) = 1 \\ \sigma(1^* + 0^*) &= \sigma(\quad) = 1 \\ \sigma(1^* + 1^*) &= \sigma(\quad) = 1 \end{aligned}$$

5

Neural networks as functions



$$\sigma(x) = \begin{cases} 1 & : x > \boxed{} \\ 0 & : x \leq \boxed{} \end{cases}$$

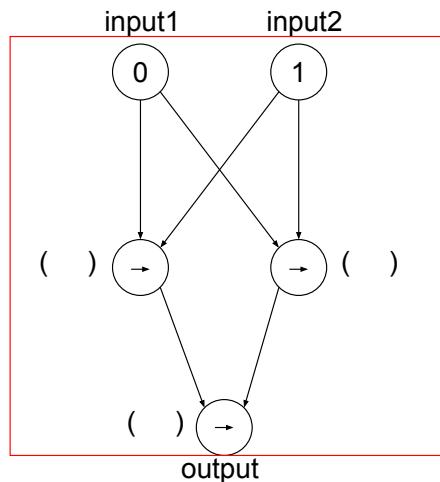
Truth Table: xor

input1	input2	output
0	0	0
0	1	1
1	0	1
1	1	0

$\sigma(0^* + 0^*) = \sigma(\quad) = 0$
$\sigma(0^* + 1^*) = \sigma(\quad) = 1$
$\sigma(1^* + 0^*) = \sigma(\quad) = 1$
$\sigma(1^* + 1^*) = \sigma(\quad) = 0$

6

Hidden neurons allow for nonlinear transformations



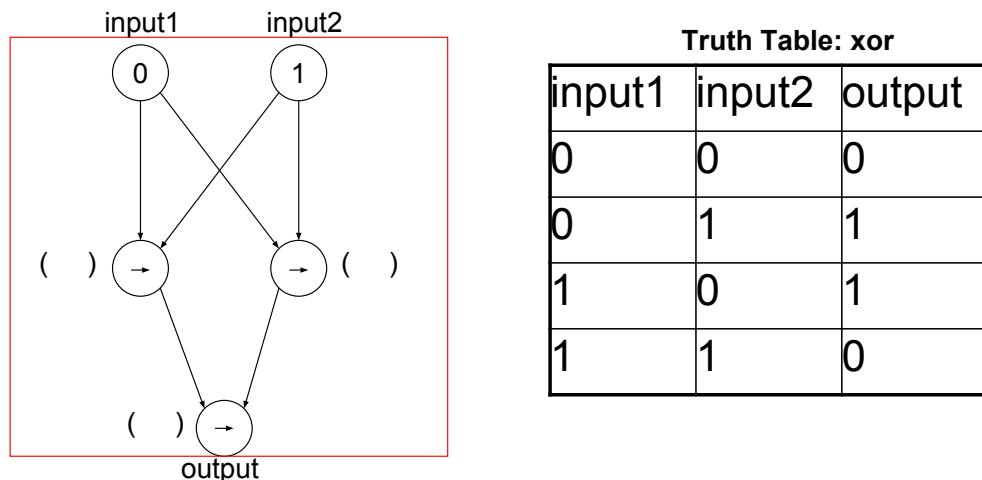
$$\sigma(x) = \begin{cases} 1 & : x > (\quad) \\ 0 & : x \leq (\quad) \end{cases}$$

Truth Table: xor

input1	input2	output
0	0	0
0	1	1
1	0	1
1	1	0

7

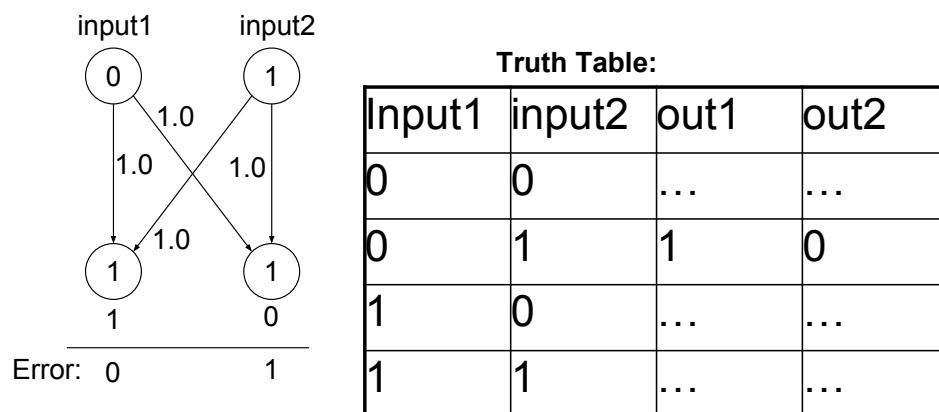
Hidden neurons allow for nonlinear transformations



$$\sigma(x) = \begin{cases} 1 & : x > () \\ 0 & : x \leq () \end{cases}$$

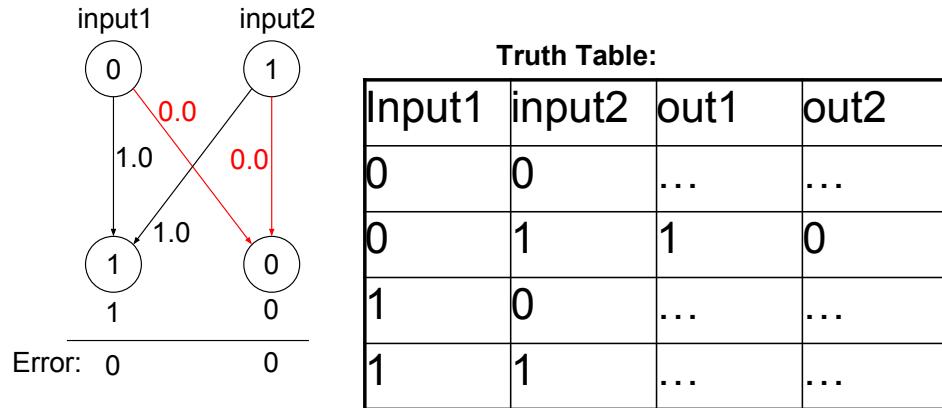
8

Backpropagation: Learning synaptic weights through training



9

Backpropagation: Learning synaptic weights through training

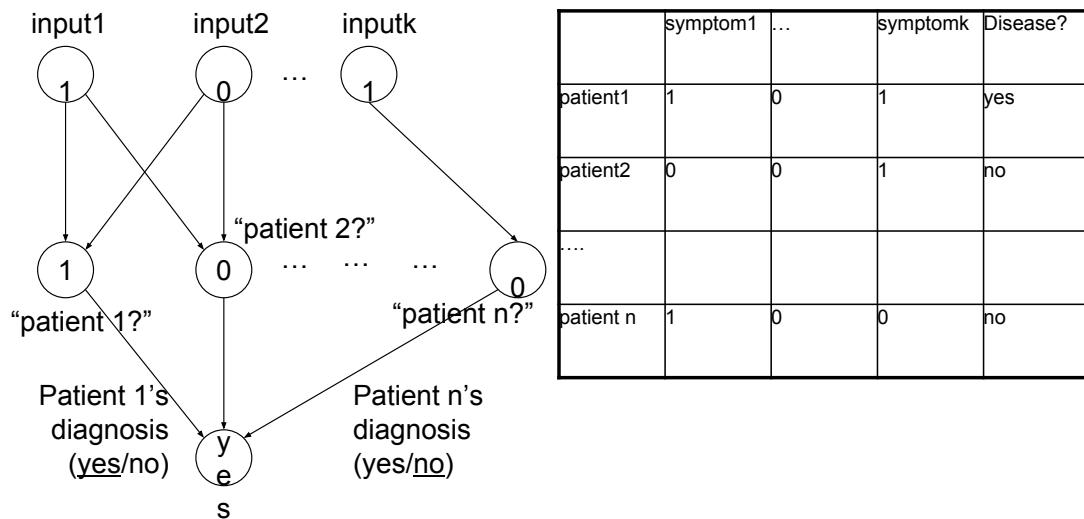


localized change to the synaptic weights →
low chance of increasing error for another input pattern →

“using **tweezers** on the neural network”

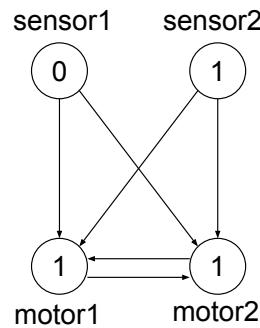
10

Overfitting: Failing to learn the proper relationship between input and output

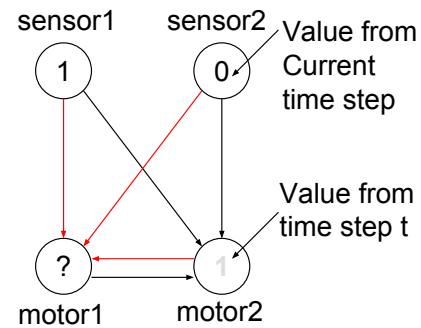


11

Recurrent connections: Adding memory to a neural network



Robot at time step t

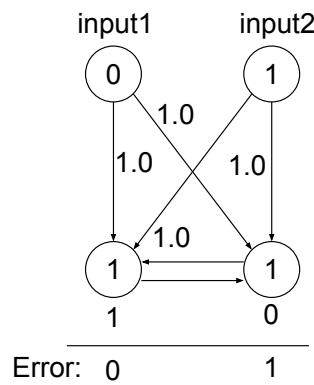


Robot at time step t+1

Value of motor 1 is a function of the current sensor values, and the value of motor 2 from the previous time step.

12

Recurrent connections: Adding memory to a neural network

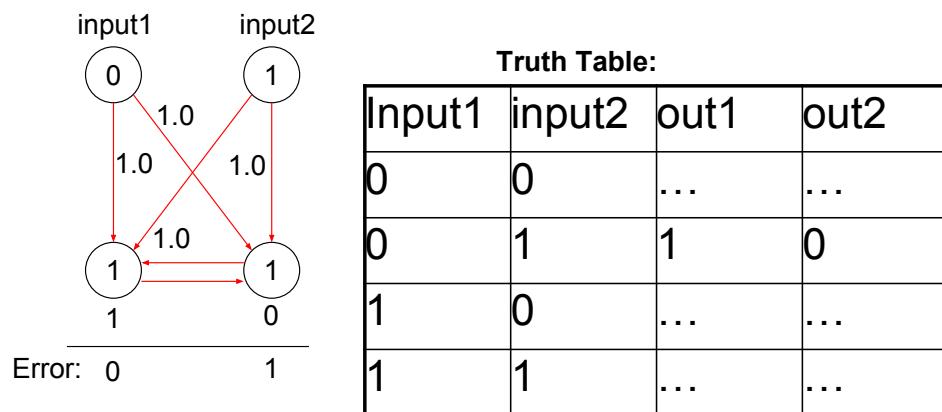


Truth Table:

Input1	input2	out1	out2
0	0
0	1	1	0
1	0
1	1

13

Backpropagation: Does not work for recurrent connections



global change to the synaptic weights →
good chance of increasing error for another input pattern →

“using a **sledge hammer** on the neural network”

14

Supervised Learning: Correct output for each input pattern is known.

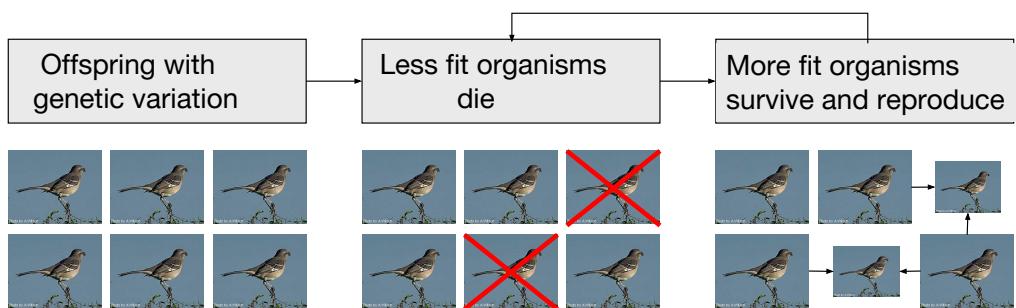
Input1	...	Inputn	Output1	...	Outputm
1	...	0	1	...	1
0	...	1	0	...	1
1	...	1	0	...	0

15

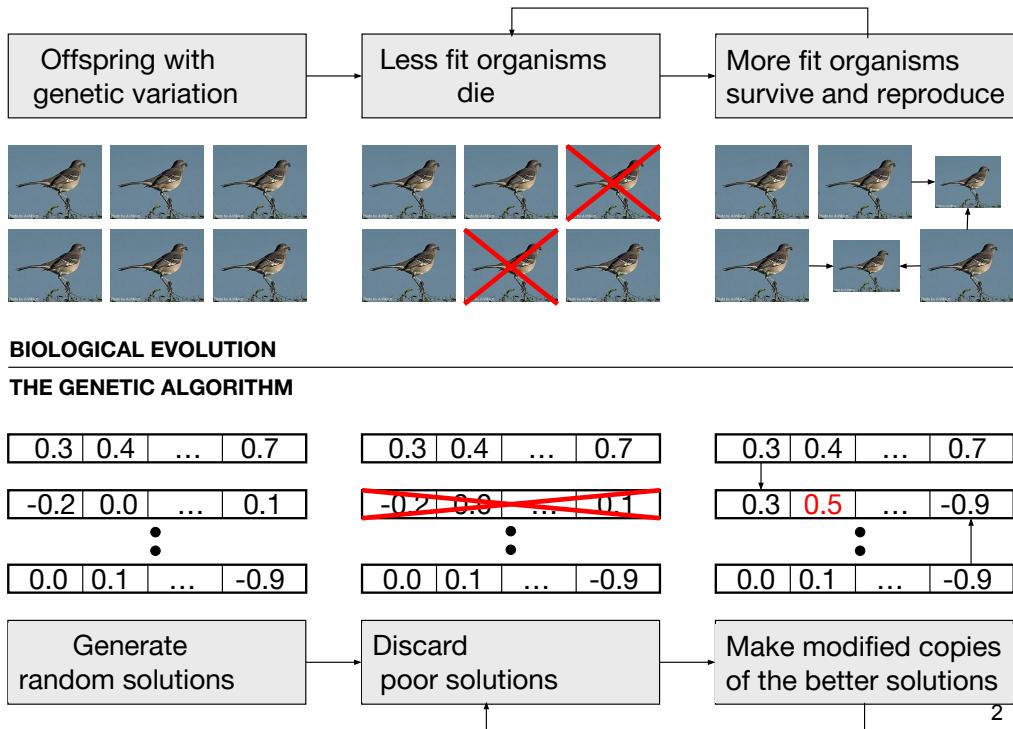
Semi_supervised Learning: Reward signal returned for a series of input patterns.

Sensor1	...	Sensorn	Motor1	...	Motorm
1	...	0		...	
0	...	1		...	
1	...	1		...	
Distance:			6.3 meters		

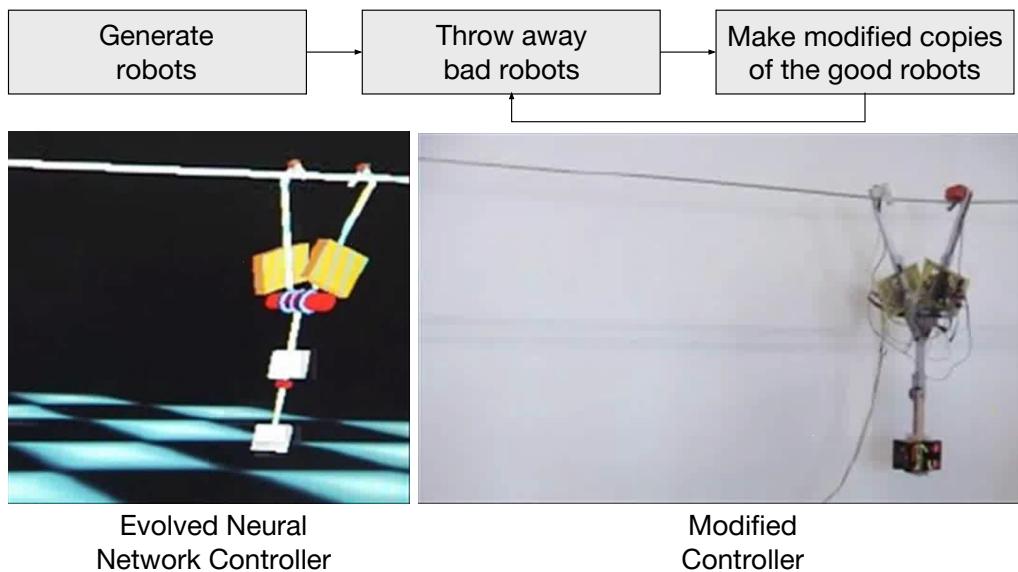
16



BIOLOGICAL EVOLUTION

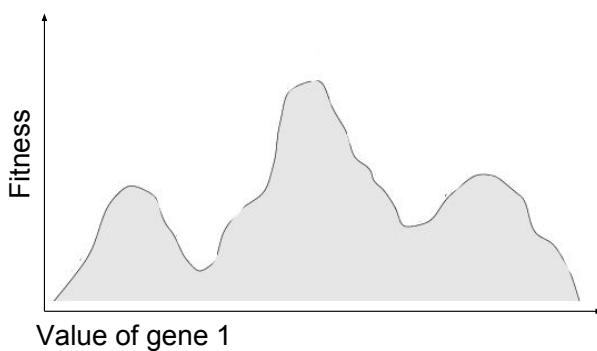


Genetic algorithm + robot simulator = evolutionary robotics



Frutiger, D. R., J. C. Bongard and F. Iida (2002) "Iterative Product Engineering: Evolutionary Robot Design", in Bidaud, P. and F. B. Amar (eds.), *Proceedings of the Fifth International Conference on Climbing and Walking Robots*, Professional Engineering Publishing, pp. 619-629.

The Fitness Landscape (Sewall Wright, 1932)

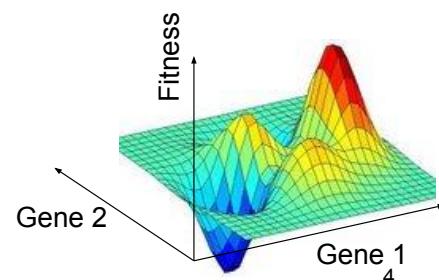


If a **genotype** has n genes, the fitness landscape exists in $n+1$ dimensions:

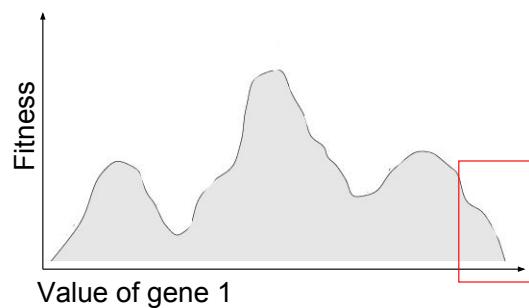
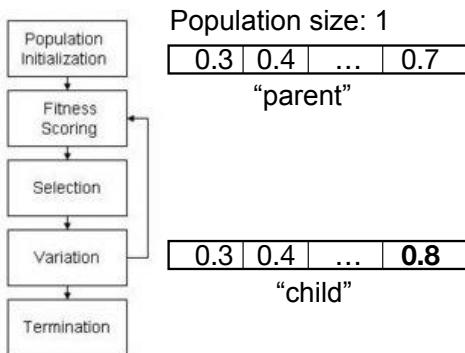
the fitness of the **phenotype** produced by that genotype is the extra dimension.

Genotype:

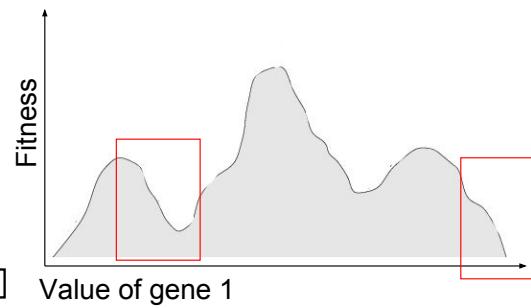
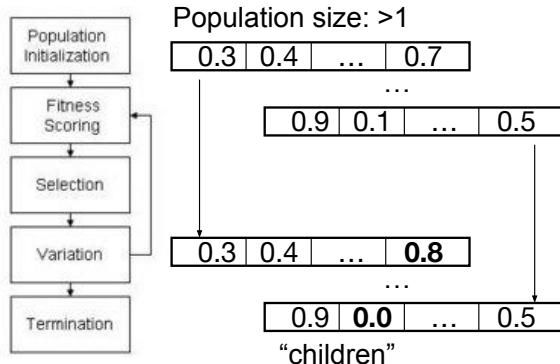
Phenotype:



The Hill Climber

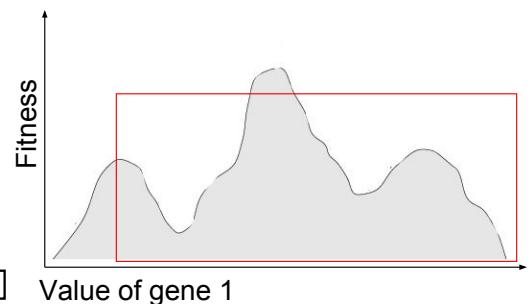
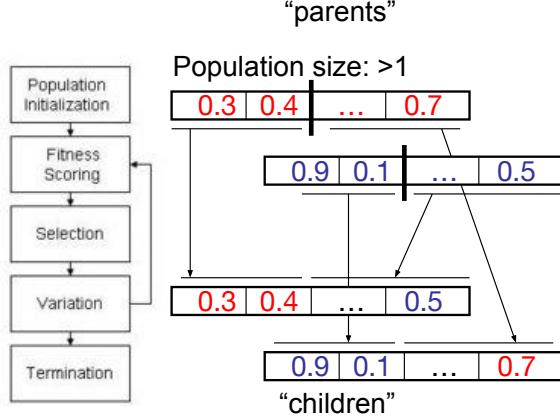


The Parallel Hill Climber



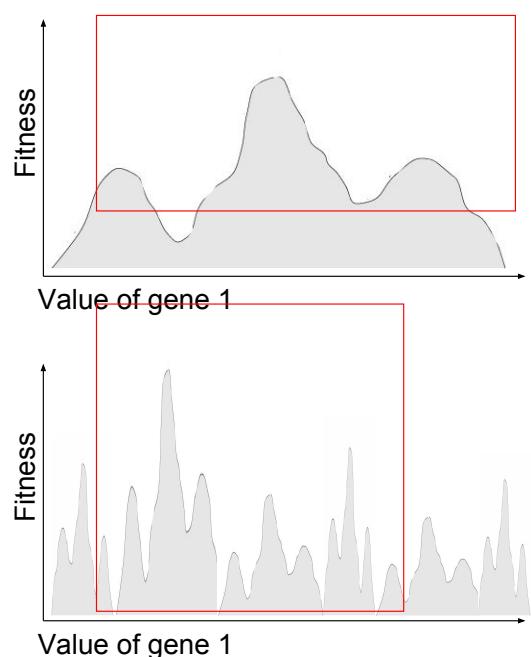
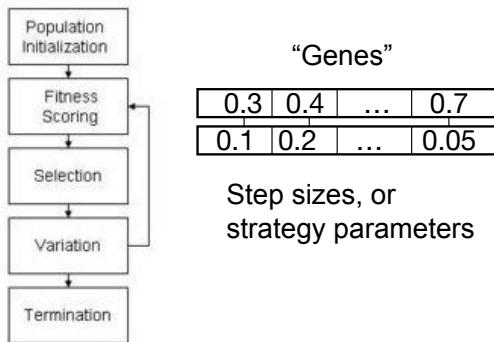
6

The Genetic Algorithm



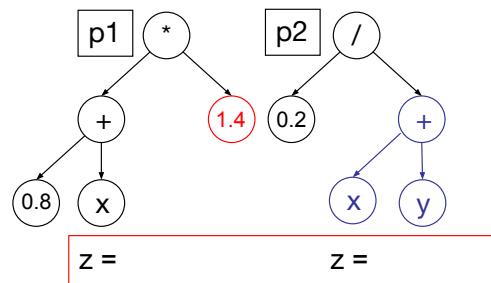
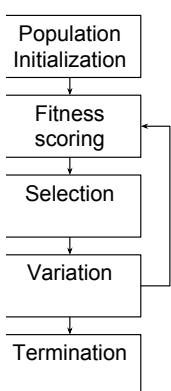
7

The Evolution Strategy



8

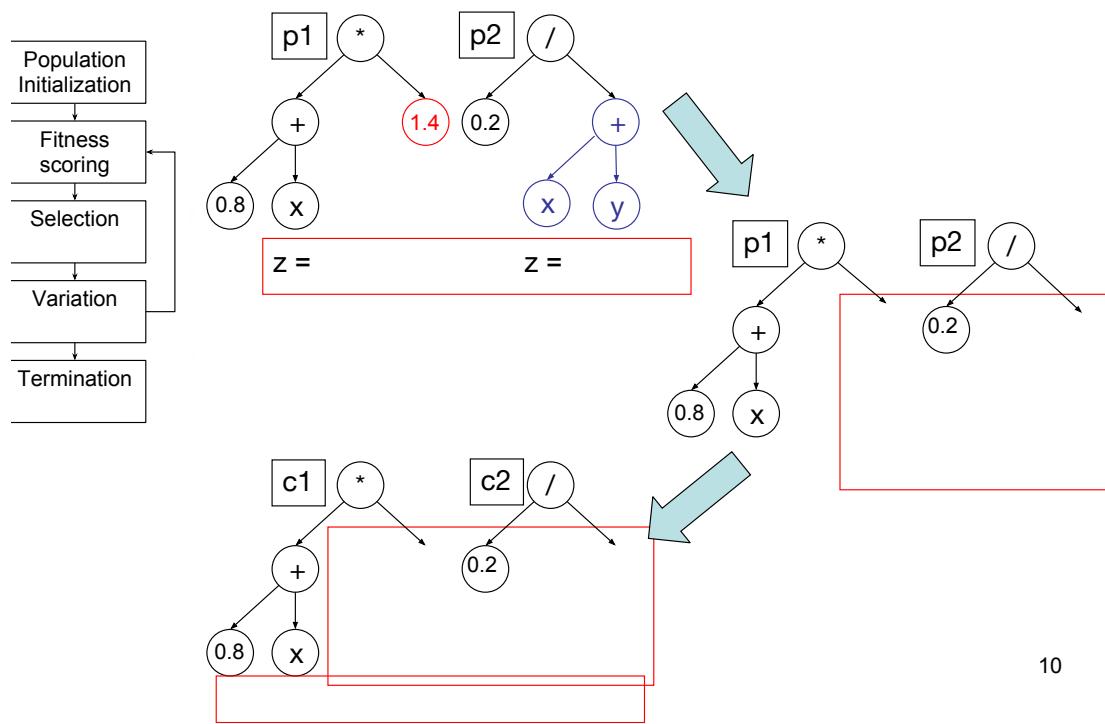
Symbolic regression



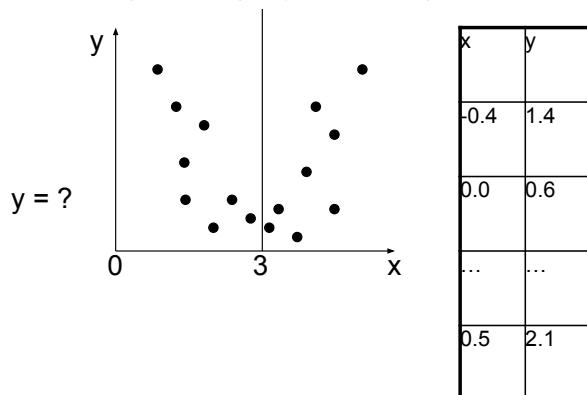
Possible branch nodes:	sin(a) cos(a) plus(a,b) minus(a,b) mult(a,b) div(a,b) pow(a,b)
Possible terminal nodes	x,y,... 0.1,-3.0,...

9

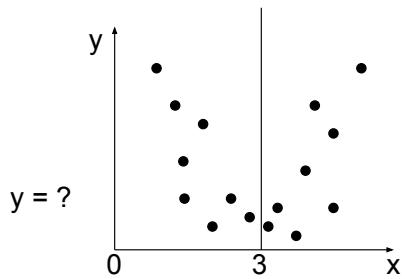
Symbolic regression



Genetic Programming: Symbolic Regression

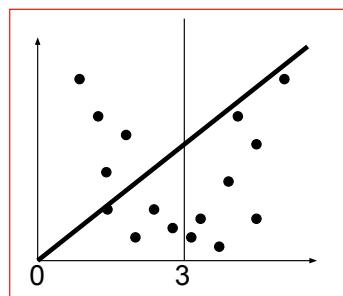


Genetic Programming: Symbolic Regression



x	y
-0.4	1.4
0.0	0.6
...	...
0.5	2.1

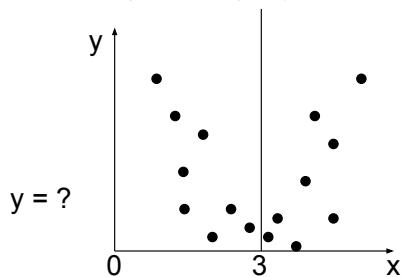
$$\text{Error} = \frac{\sum_{i=1}^n \sqrt{(x_i - x'_i)^2 + (y_i - y'_i)^2}}{n}$$



$y = x \rightarrow \text{high error} \rightarrow \text{low fitness}$

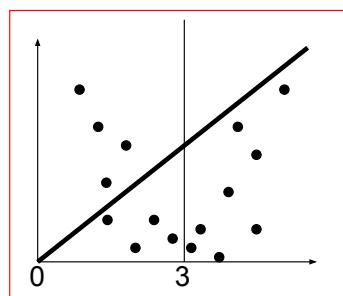
12

Genetic Programming: Symbolic Regression

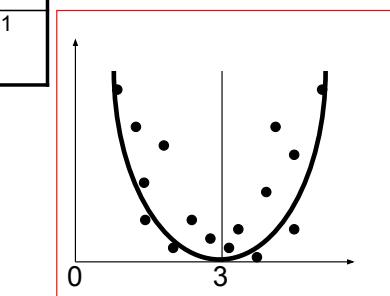


x	y
-0.4	1.4
0.0	0.6
...	...
0.5	2.1

$$\text{Error} = \frac{\sum_{i=1}^n \sqrt{(x_i - x'_i)^2 + (y_i - y'_i)^2}}{n}$$



$y = x \rightarrow \text{high error} \rightarrow \text{low fitness}$



$y = (x-3)^2 \rightarrow \text{low error} \rightarrow \text{high fitness}$

13

Genetic Programming: Symbolic Regression

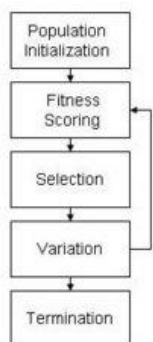
Question: What causes toxic algal blooms in Lake Champlain?

i.e., $T = ?$ 

	Nitrogen (N)	Phosphorus (P)	Water temp (W)	Turbidity (B)	Rainfall (R)	...	Toxic algae/ml (T)
Malletts Bay 08/01/99	0.4	0.6	0.2	0.1	0.4	...	0.5
Shelburne 08/02/99	0.1	0.3	0.6	0.4	0.1	...	0.05
Malletts Bay 07/05/00	0.9	0.1	0.9	0.4	0.6	...	0.8
...

14

Genetic Programming

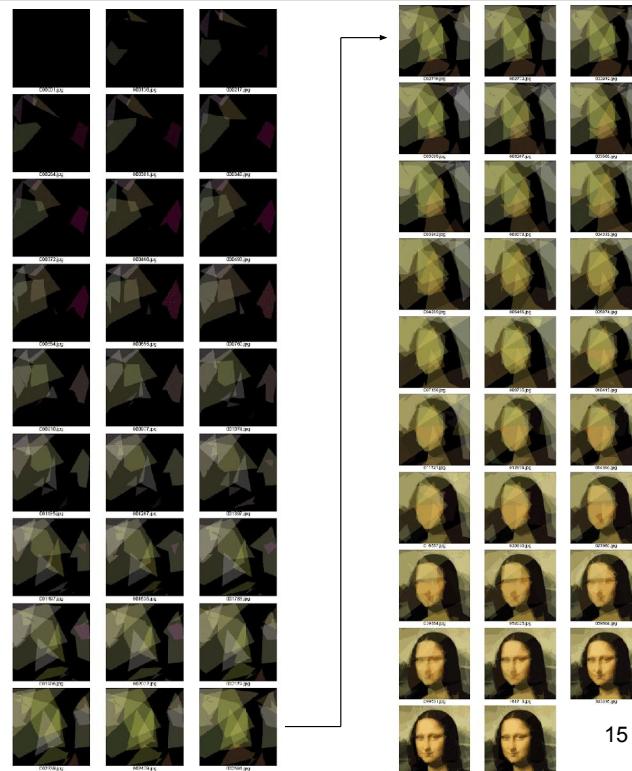


Q:

What is a good genotype?

What is the phenotype?

How to compute fitness?

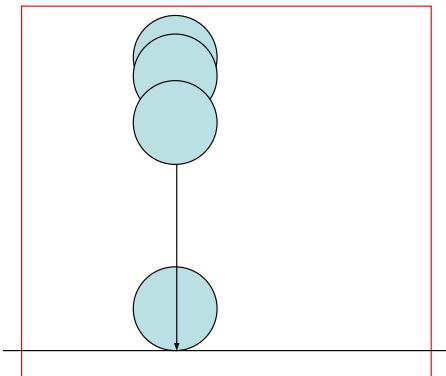


15

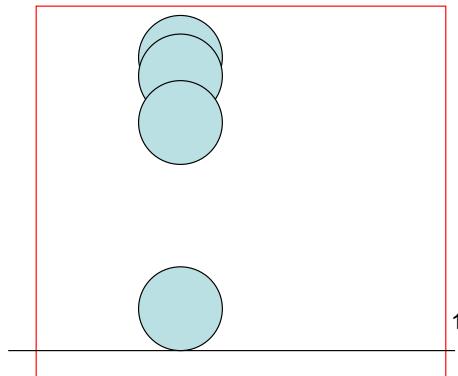
Physical Simulation

1. Define the position, orientation, shape, mass and friction properties of each object.
2. Define how objects are attached together.
3. Start the simulation:

$$\text{Force} = \text{mass} * \text{acceleration} (F=MA) \rightarrow \text{acceleration} = \text{Force} / \text{mass}$$

**3D Computer Graphics**

1. Define the position, orientation, and shape of each object at time t.
 2. Render.
 3. Define the position, orientation, and shape of each object at time t+1.
- ...

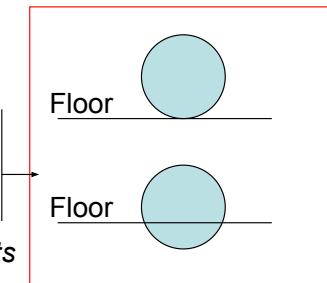
**Preliminaries**(From `ode\demo\demo_boxstack.cpp`)

```
dInitODE2(0); Initialize Open Dynamics Engine
```

```
world = dWorldCreate(); contains all the objects
```

```
space = dHashSpaceCreate (0); contains all the objects  
that cannot interpenetrate
```

```
contactgroup = dJointGroupCreate (0); contains all the objects  
that are in contact
```



```
dWorldSetGravity (world,0,0,-GRAVITY);
```

```
dWorldSetCFM (world,1e-5); Has to do with friction;  
don't worry about for now.
```

Bodies

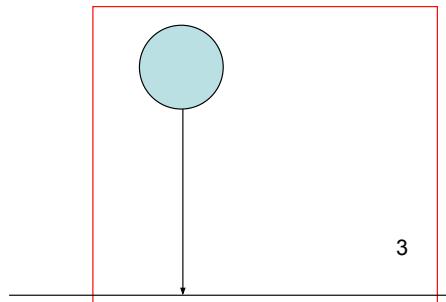
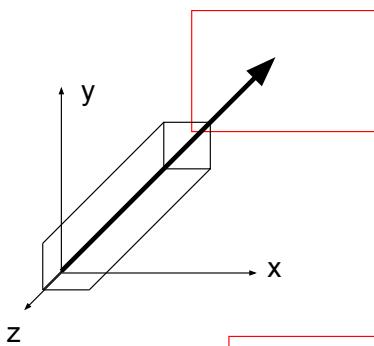
from <http://artis.imag.fr/Membres/Xavier.Decoret/resources/ode/tutorial1.html>

```

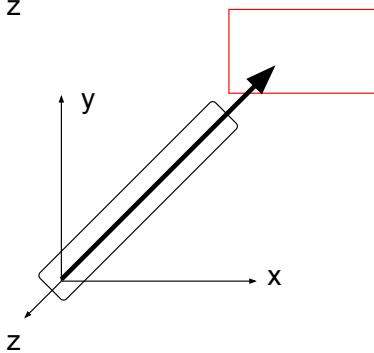
4   dBodyID body = dBodyCreate(world);
5
6   dMass mass;           Object has a
7   dMassSetBox(&mass,1,1,1,1); Object is a
8   dMassAdjust(&mass,0.2f);  1x1x1kg box
9
10  dBodySetMass(body,&mass); Object has a
11  dBodySetPosition(body,0,6,0); mass of 0.2kg.

Object starts at position
(x=0,y=6,z=0)

```

**Bodies – specifying orientation in 3D**

Usually requires four numbers:
First three define axis along which object lies;
Fourth specifies how much the object is rotated
about that axis.
Encoded as a quaternion:
$$q = \cos(\theta/2) + (x_1, y_1, z_1)\sin(\theta/2)$$



If object is a cylinder
we can specify orientation with 3 numbers:

```
dMatrix3 R;
dRFromZAxis(R,x1,y1,z1);
dBodySetRotation(body,R);
```

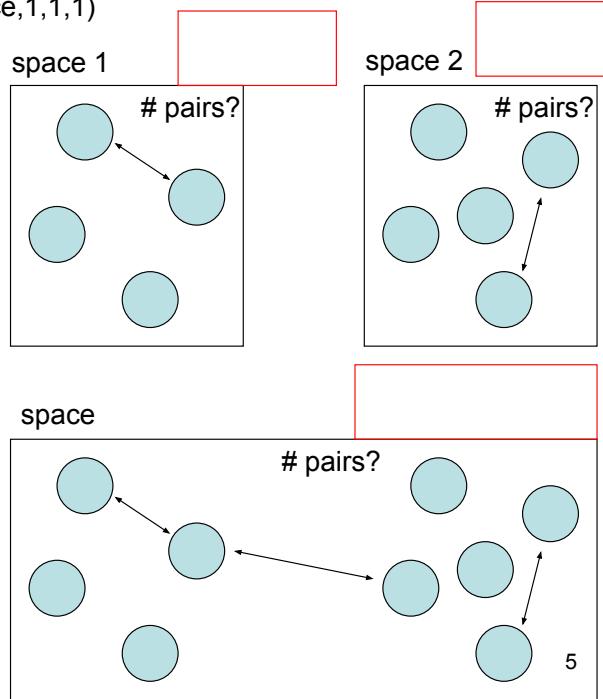
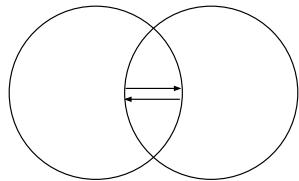
If object is a sphere... ?

Geoms – specifying how bodies interact with other bodies

```
dGeomID geom = dCreateBox(space,1,1,1)
dGeomSetBody(geom,body);
```

To keep objects from colliding:

1. Compute the distance between each **geom** pair.
2. If $\text{distance} \leq 0$, push the **bodies** apart proportional to the interpenetration



Joints – specifying how bodies move relative to each other

`dJointID hinge;` Define a hinge joint data structure.

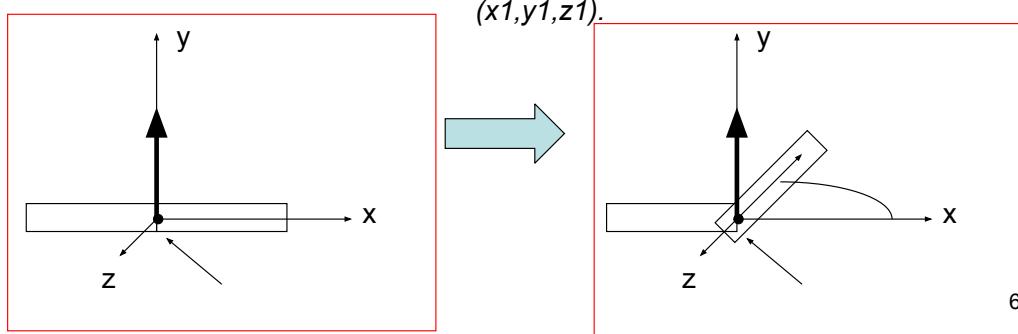
`hinge = dJointCreateHinge (world,0);` Create a hinge joint data structure.

`dJointAttach (hinge,body[0],body[1]);` Which objects does the joint connect?

`dJointSetHingeAnchor (hinge,0,0,1);` Where is the joint's fulcrum?

`dJointSetHingeAxis (hinge,x1,y1,z1);` When the objects move relative to one another, what 2D plane do they define?

The plane that is perpendicular to vector (x_1, y_1, z_1) .

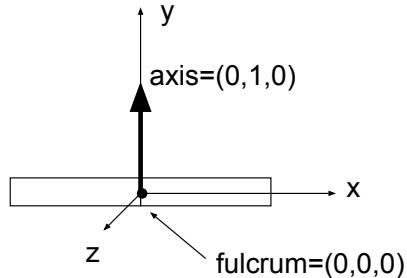
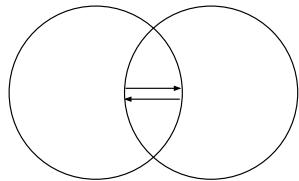


Contacts – what happens when two objects collide?

```
static void nearCallback (void *data, dGeomID o1, dGeomID o2)
{ int i;

// exit without doing anything if the two bodies are connected by a joint
dBodyID b1 = dGeomGetBody(o1);
dBodyID b2 = dGeomGetBody(o2);
if (b1 && b2 && dAreConnectedExcluding (b1,b2,dJointTypeContact))
    return;
```

...



Continue...

[Return...](#)

7

Contacts – what happens when two objects collide?

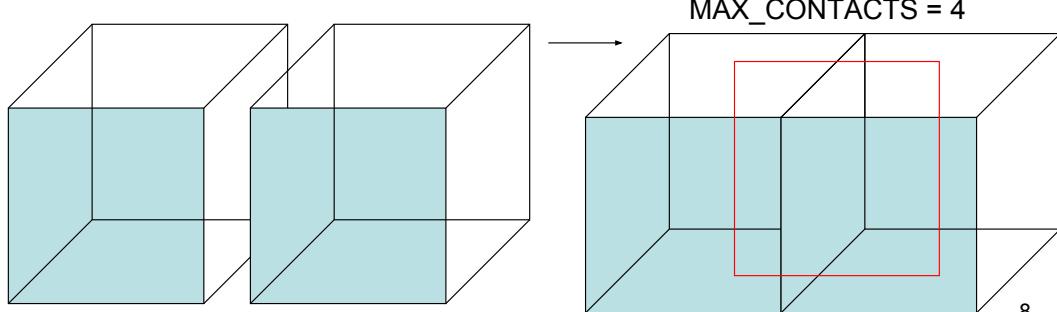
...

```
dContact contact[MAX_CONTACTS];
// up to MAX_CONTACTS contacts per box-box
```

Describes the forces
that arise at each contact
point

```
for (i=0; i<MAX_CONTACTS; i++) {
    contact[i].surface.mode = dContactBounce | dContactSoftCFM;
    contact[i].surface.mu = dInfinity; contact[i].surface.mu2 = 0;
    contact[i].surface.bounce = 0.1; contact[i].surface.bounce_vel = 0.1;
    contact[i].surface.soft_cfm = 0.01;
}
```

...



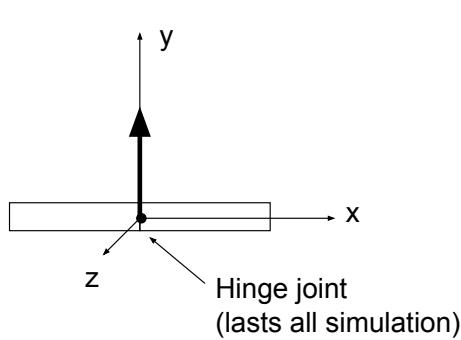
8

Contacts – what happens when two objects collide?

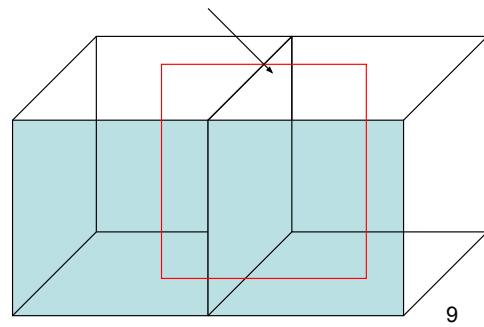
```

if (int numc = dCollide (o1,o2,MAX_CONTACTS,&contact[0].geom,
sizeof(dContact))) {
    ...
    for (i=0; i<numc; i++) {
        dJointID c = dJointCreateContact (world,contactgroup,contact+i);
        dJointAttach (c,b1,b2);
    }
}

```



Contact joint
(lasts one time step)

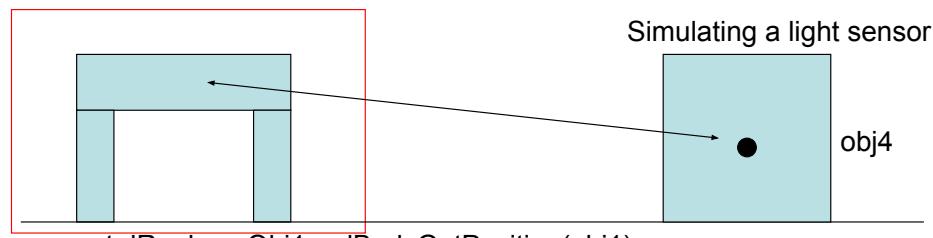
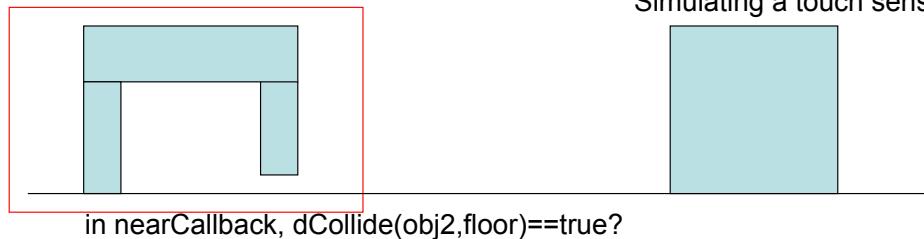


simLoop – updating the physics, and updating the graphics

```

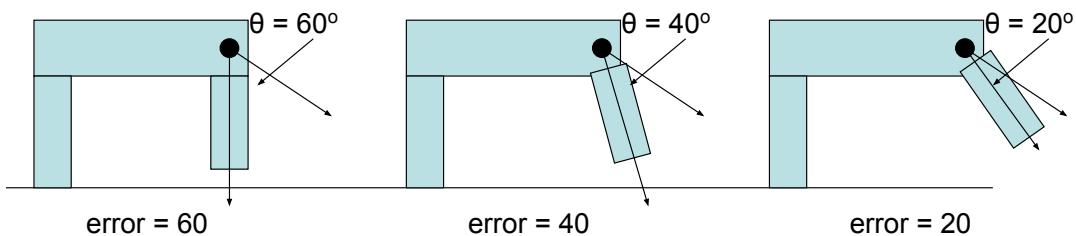
static void simLoop (int pause) {
    ...
    dSpaceCollide (space,0,&nearCallback); Find out who collided
    ...
    if (!pause)
        dWorldStep(world,0.05); Update the positions and orientations of all objects
    ...
    dJointGroupEmpty (contactgroup); Delete all contact joints
    ...
    for (int object = 0; object < totalObjects ; object++)
        dsSetColor (obj[object].r, obj[object].g, obj[object].b);
        Draw(obj[object]);
    }
}

```

Sensors – Allowing the robot to sense in ODE...

```
const dReal posObj1 = dBodyGetPosition(obj1);
const dReal posObj4 = dBodyGetPosition(obj4);
double lightLevel = 1 / (1 + EuclideanDistance(posObj1,posObj4) )
```

11

Motors – Allowing the robot to move in ODE...

The maximum force the dJointSetHingeParam(joint,dParamFMax,motorForce); joint can handle.

double desiredAngle = 60; *Apply force to rotate the leg to 60 degrees forward.*

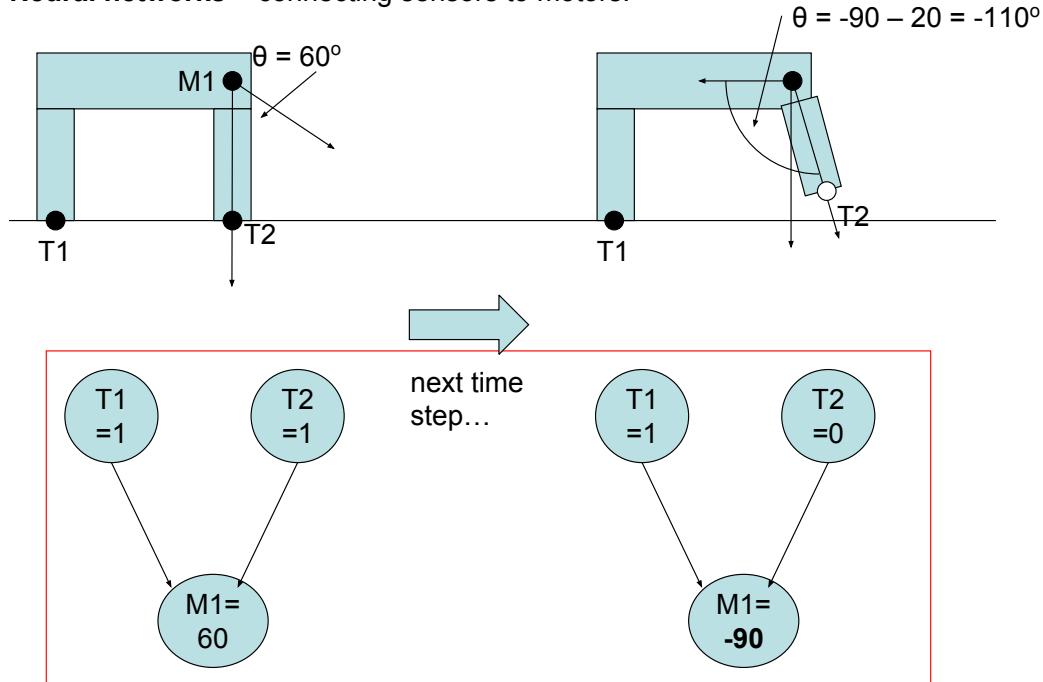
double actualAngle = dJointGetHingeAngle(joint); *What angle is the joint at now?*

double diff = desiredAngle - actualAngle; *How much difference is there?*

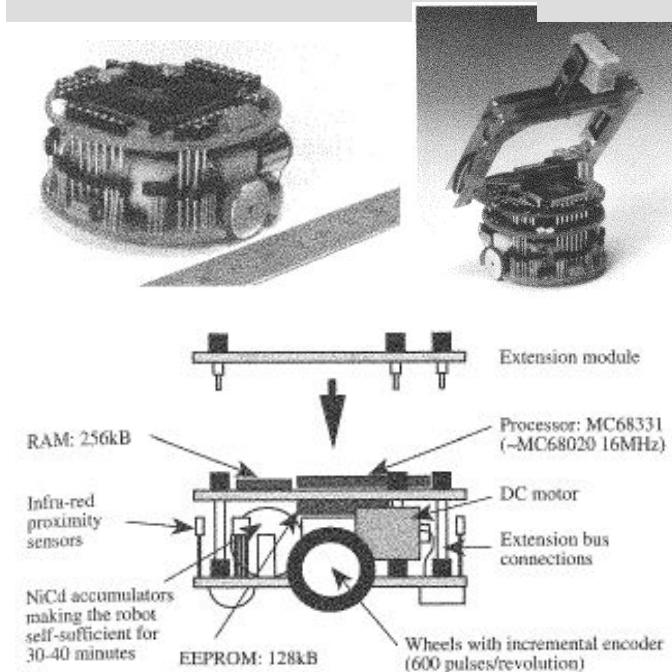
dJointSetHingeParam(joint,dParamVel, diff); *Apply force proportional to how far the joint is from where it should be.*

12

Neural networks – connecting sensors to motors.



13

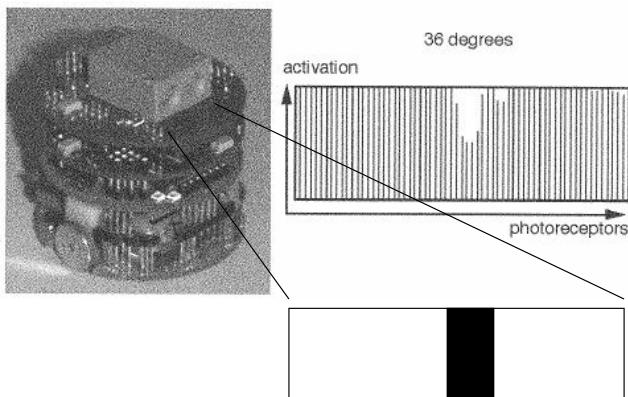
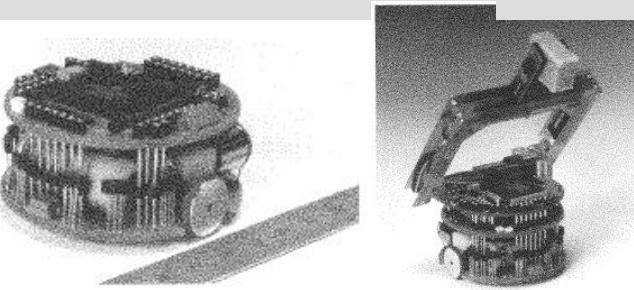


The Italian Approach
The Khepera robot (1996)

Developed at EPFL
Lausanne, Switzerland(!)
by
Francesco Mondada
Diameter: 55 mm

Could perform experiments
on a table, rather than in a
large arena.

Modular architecture:



The Italian Approach

The Khepera robot (1996)

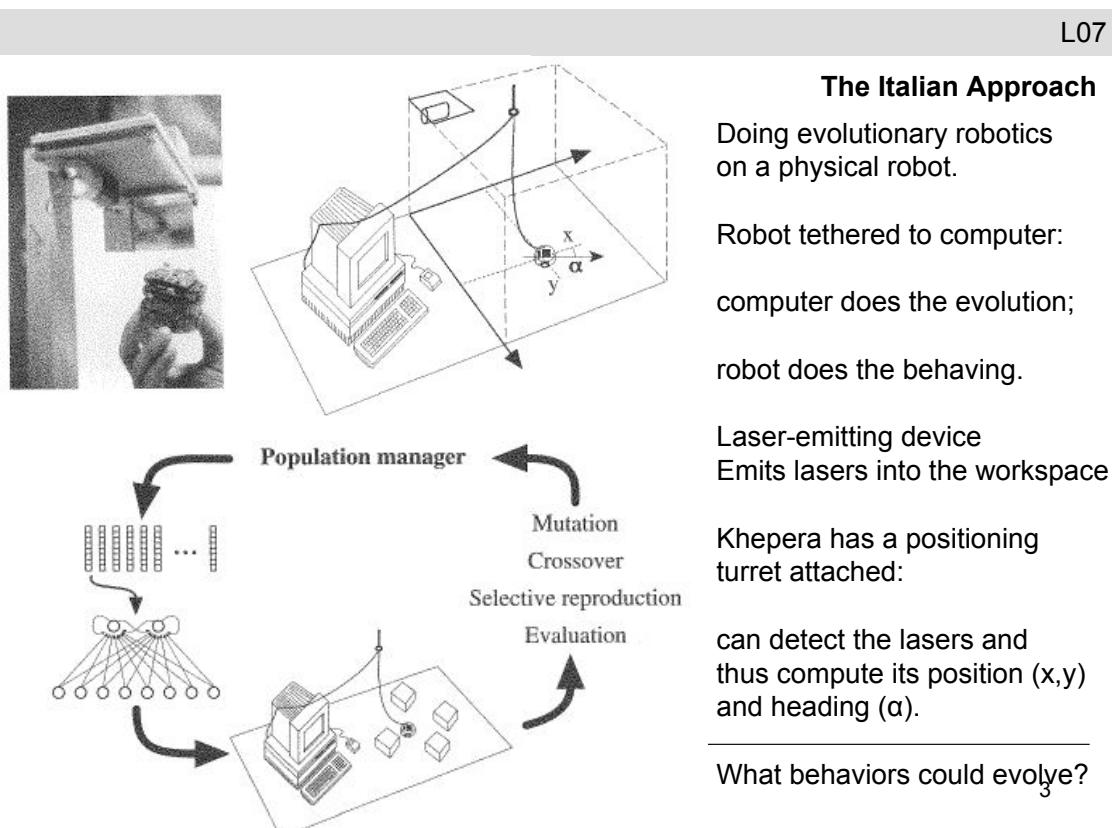
Developed at EPFL
Lausanne, Switzerland(!)
by

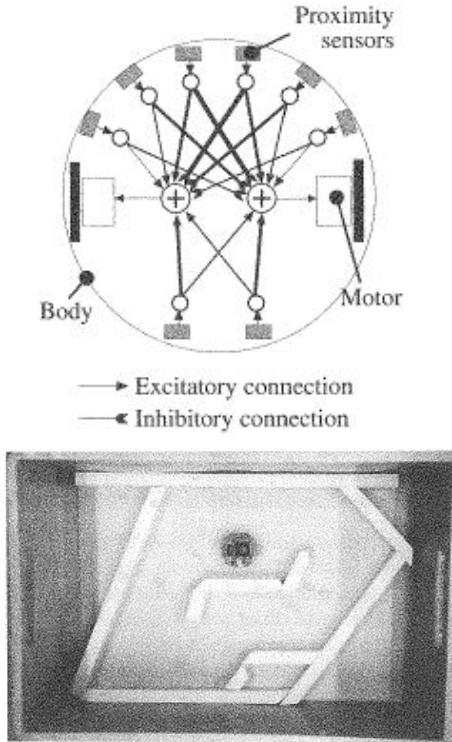
Francesco Mondada
Diameter: 55 mm

Could perform experiments
on a table, rather than in a
large arena.

Modular architecture:

2





The Italian Approach

Evolution of simple navigation:

Evolve a neural network such that the robot...

1. Circles through maze as fast as possible.
2. Does not hit the walls.

Robot is given the NN architecture shown.

Robot's wheels can...

- rotate backwards quickly (-0.5)
- stay still (0.0)
- rotate forward quickly (0.5)
- or anything in this range (-0.5,0.5)

Robot's eight proximity sensors return...

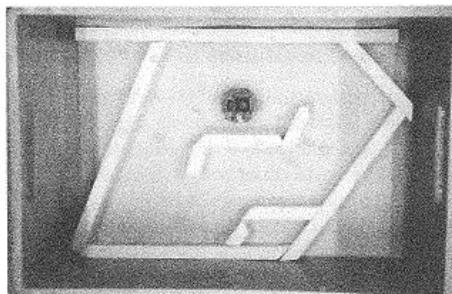
- 0 if obstacle is 5cm or further (or absent)
- 1 if proximity sensor is touching object.⁴

Create a fitness function to select for this behavior:

$$\varphi =$$

Hints:

$\varphi=0$ for worst performance
 $\varphi=1$ for best possible performance (may not be reachable)
 v_L, v_R = speed of left/right wheel
 $i_1 \dots i_8$ = value of proximity sensor



The Italian Approach

Evolution of simple navigation:

Evolve a neural network such that the robot...

1. Circles through maze as fast as possible.
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The Italian Approach

Evolution of simple navigation:

Evolve a neural network such that the robot...

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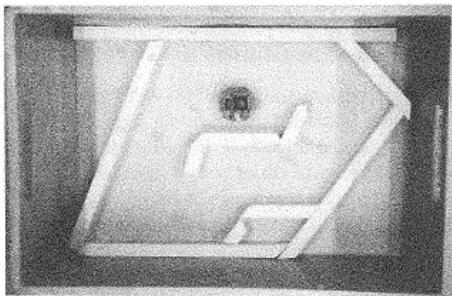
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- rotate backwards quickly (-0.5)
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- rotate forward quickly (0.5)
- or anything in this range (-0.5,0.5)

Robot's eight proximity sensors return...

0 if obstacle is 5cm or further (or absent)

1 if proximity sensor is touching object.⁶

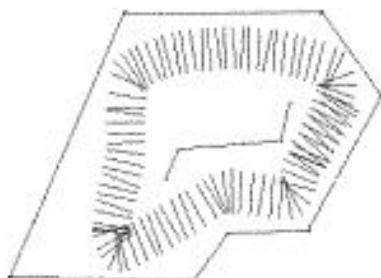
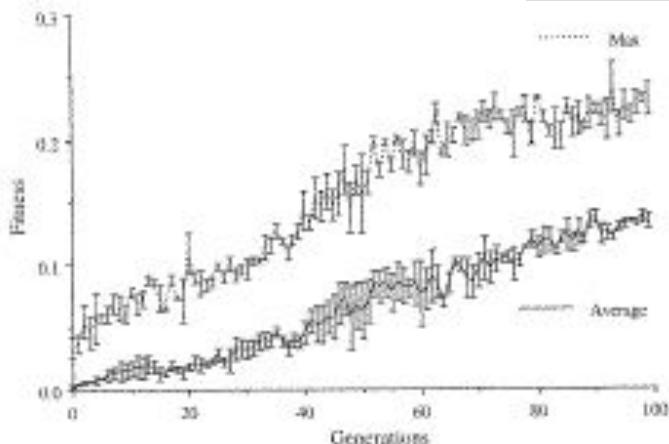


The Italian Approach

A sample run:

One generation:
40 minutes

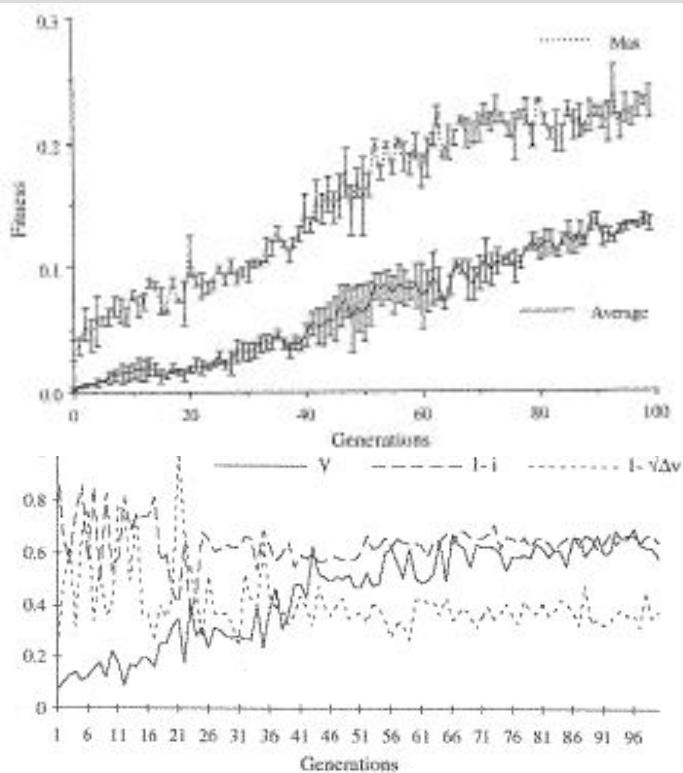
100 generations:
66 hours
2.77 days



Line segment:

Center of segment
Indicates robot's position

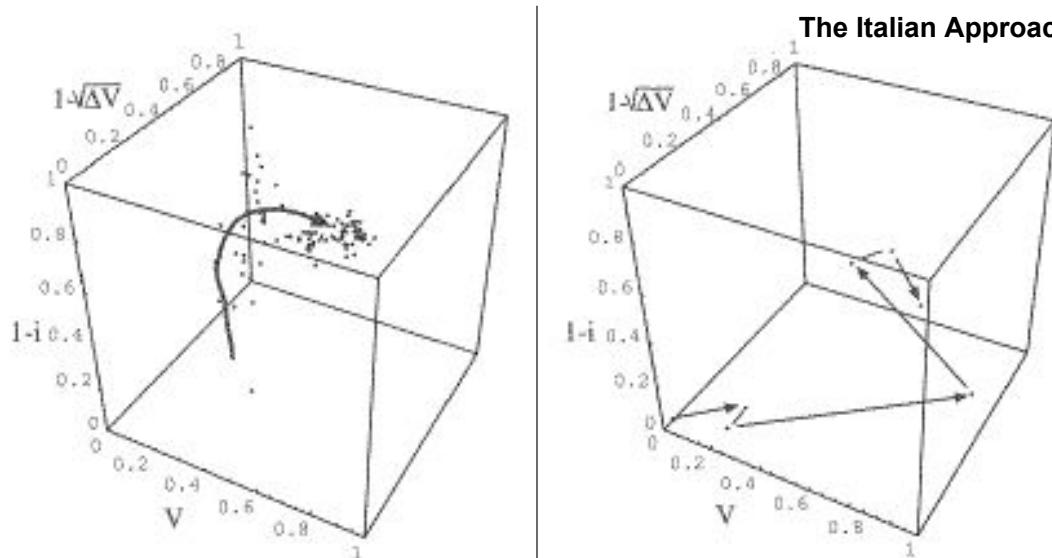
Line passes through the robot's left and right wheels.⁷

The Italian Approach

← Fitness components for the best controller at each generation.

Q: How did the robot's behavior change over time?

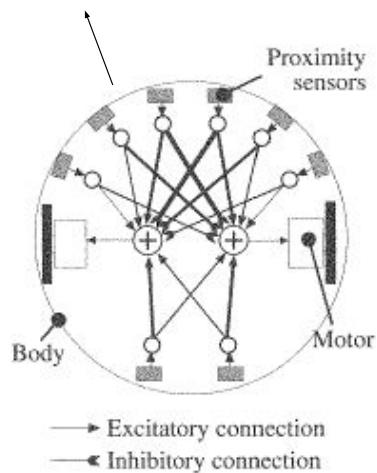
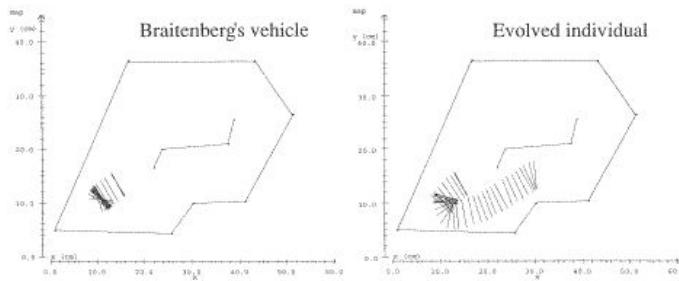
8

The Italian Approach

How the fitness components changed over evolutionary time (over 2.77 days)

How the fitness components changed for the best evolved controller, as it controlled the robot (~1 minute)

9



The Italian Approach

If synaptic weights
(thickness of lines) are
bilaterally symmetric,

robot gets stuck in corners.

Why?

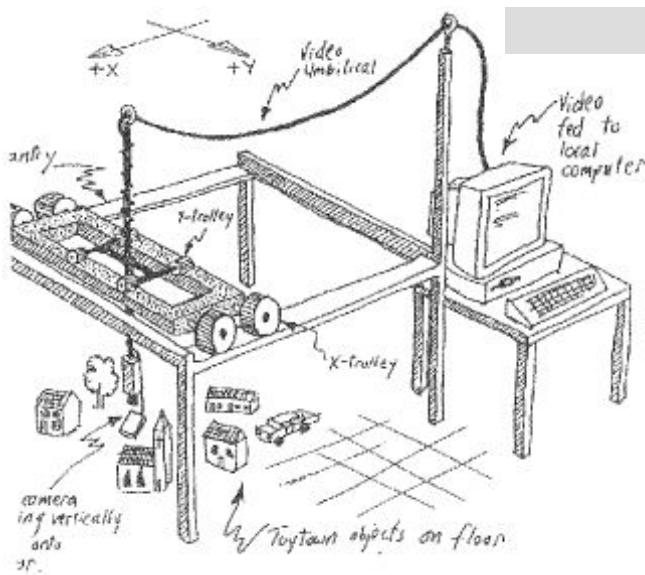
Evolved robot that approaches
corners does not get stuck.

Why do you think this is so?

Evolved controllers only
ever drove the robot at a
Maximum speed of 48 mm/s.

Actual top speed is 80 mm/s.

Why not drive at top speed?



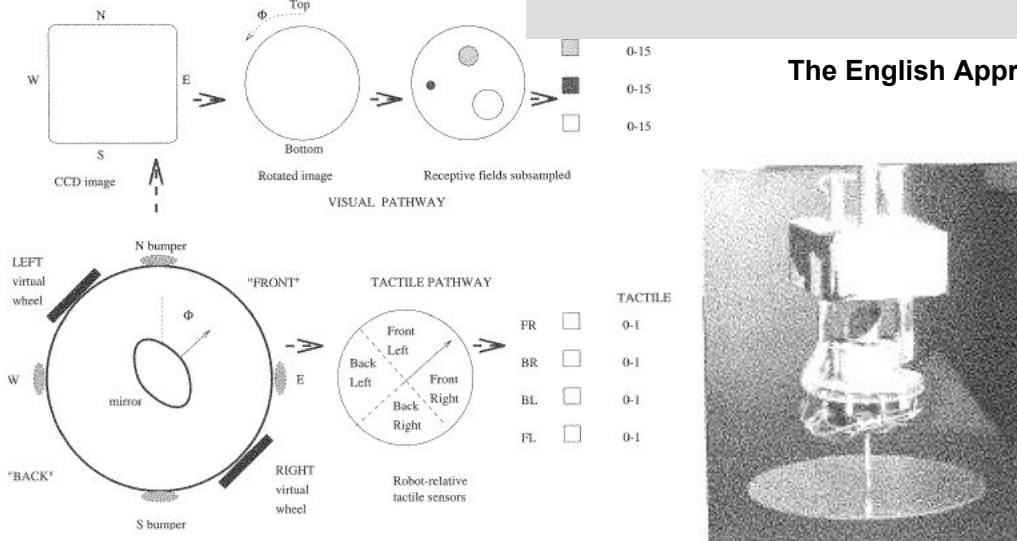
The English Approach



Gantry Robot (University of Sussex, Inman Harvey et al., 1994).

Three ways to move (degrees of freedom); three motors.

The English Approach



Gantry Robot (University of Sussex, Inman Harvey et al., 1994).

Seven ways to sense:

12

The English Approach

Incremental evolution:

← 1. approach back wall
from 4 different initial positions

... evolve ...

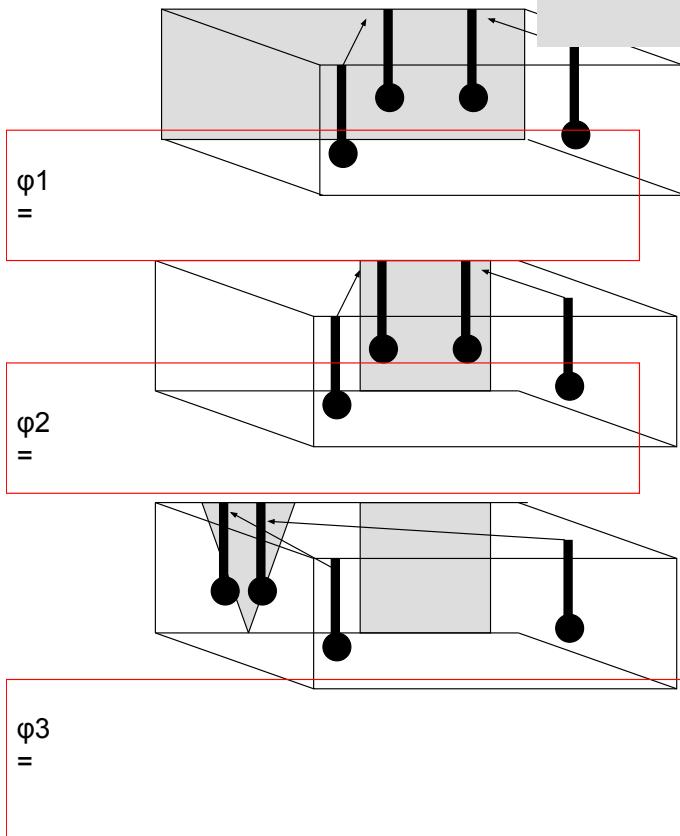
... success!

← 2. approach back rectangle
from 4 different initial positions

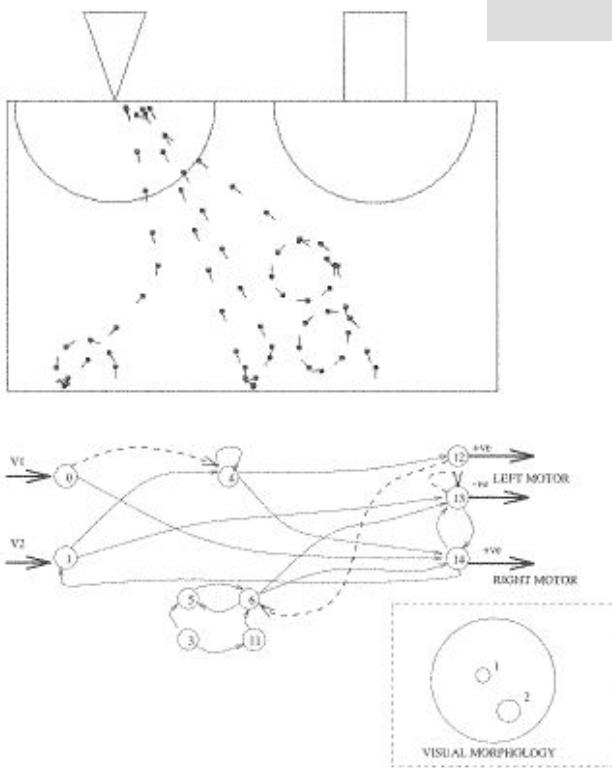
... evolve ...

... success!

← 3. **avoid** back rectangle,
approach triangle.
from 4 different initial positions



13



The English Approach

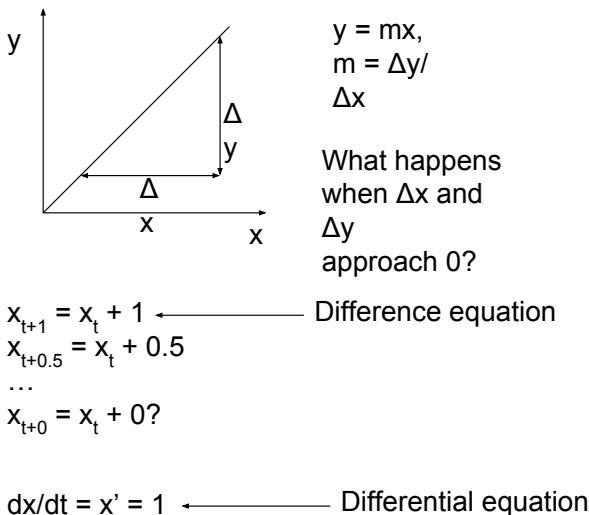
An evolved solution:

Robot does not use bump sensors;

Only uses 2 of the 3 visual fields.

Q: How could it discriminate between the two shapes without a 'recognize triangle' or 'recognize rectangle' algorithm?

14



Continuous-Time Recurrent Neural Networks

The derivative

"The rate of change in x (dx) is equal to the rate of change of t (dt)."

Continuous-Time Recurrent Neural Networks

Value of neuron 1 at time step t+1

$$x_{t+1}^{(1)} = \dots x_t^{(1)} \dots$$

$$x_{(1)}^{t+1} = \sigma(w_{1,1}x_t^{(1)} + w_{2,1}x_t^{(2)} + \dots)$$

Neuron values change over time.

Updating neuron values using a **difference equation**

Updating neuron values using a **differential equation**

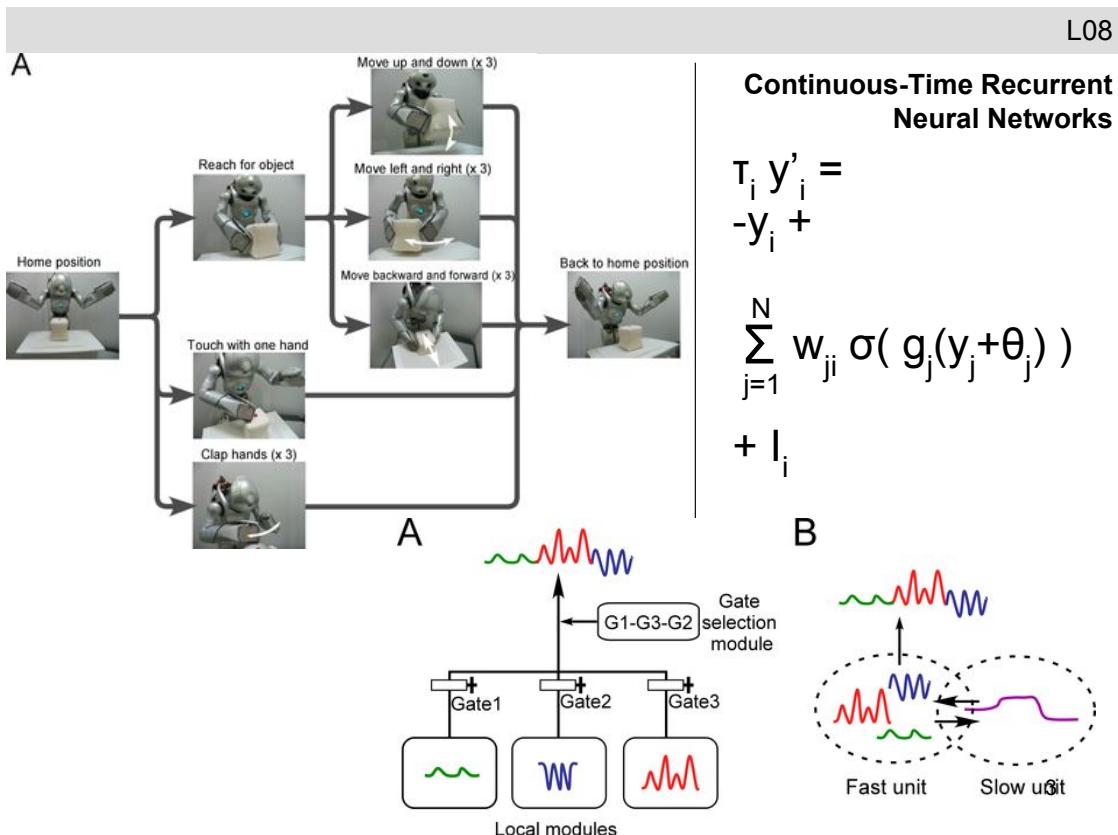
Why $-y_i$?

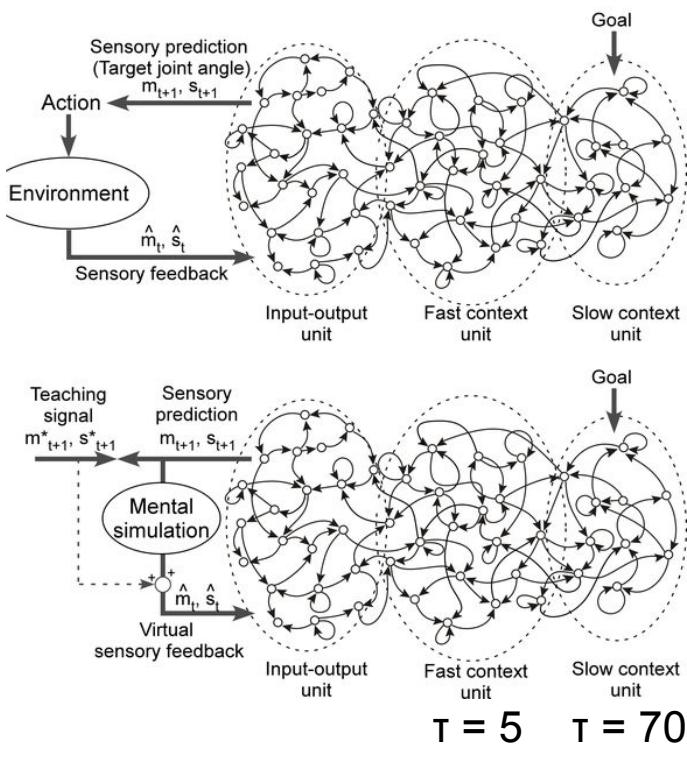
What does a neuron with...

...low/high time constant do?

...low/high gain do?

...low/high bias do? 2





Continuous-Time Recurrent Neural Networks

$$T_i y'_i = \\ -y_i +$$

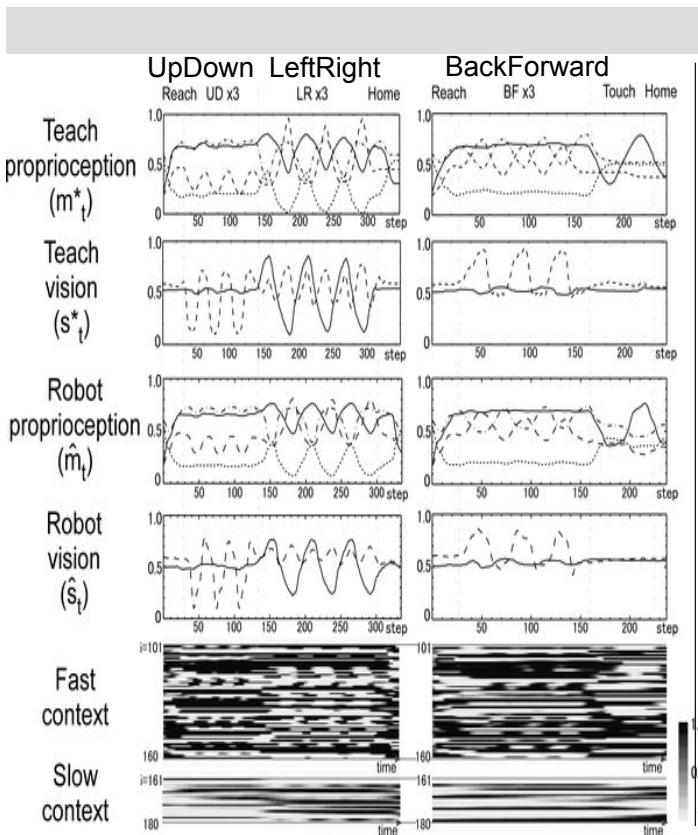
$$\sum_{j=1}^N w_{ji} \sigma(g_j(y_j + \theta_j))$$

$$+ I_i$$

Yamashita, Tani (2008)
Emergence of functional hierarchy in a multiple timescale neural network model: a humanoid robot experiment.

PLoS Computational Biology,
4:e1000220

4



Continuous-Time Recurrent Neural Networks

$$T_i y'_i = \\ -y_i +$$

$$\sum_{j=1}^N w_{ji} \sigma(g_j(y_j + \theta_j))$$

$$+ I_i$$

Yamashita, Tani (2008)
Emergence of functional hierarchy in a multiple timescale neural network model: a humanoid robot experiment.
PLoS Computational Biology,
4:e1000220

5



What do these objects have in common?

What is common about them?

What things should a visual pattern recognizer look for?

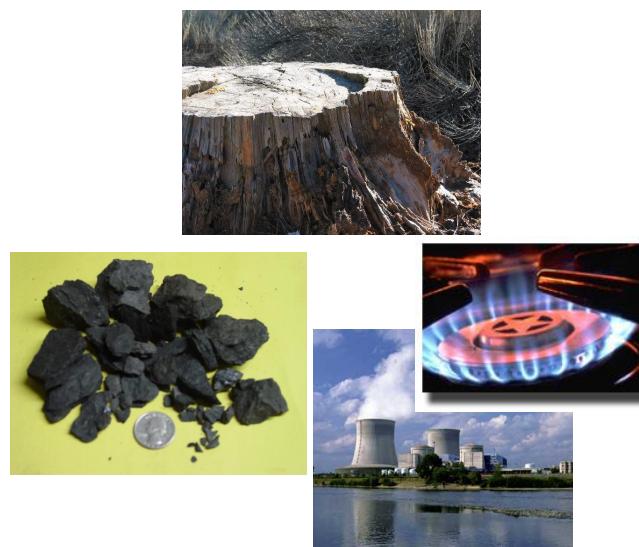
Minimal Cognition

Sect. 3: Perceiving Affordances

(from wikipedia):

Slocum, Downey, Beer (2000).

Further Experiments in the Evolution of Minimally Cognitive Behavior: From Perceiving Affordances to Selective Attention. In *Animals to Animats* 6, pp. 430—439.



Minimal Cognition

Sect. 3: Perceiving Affordances

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Minimal Cognition

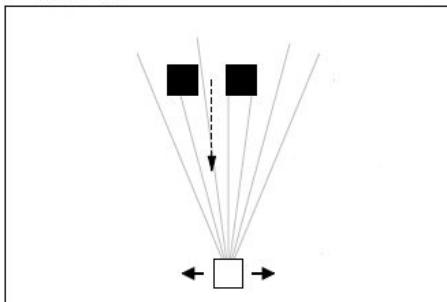


Figure 1: Experimental setup for the passability experiments. The agent moves horizontally while a wall with an adjustable aperture falls from above. The rays of the agent's proximity sensors are shown in gray.

The performance measure to be maximized was:

$$\sum_{i=1}^{\text{NumTrials}} p_i / \text{NumTrials}$$

$$\text{where } p_i = \begin{cases} 2|d_i| & \text{if agent collides with wall} \\ 100 & \text{otherwise} \end{cases}$$

for an opening too narrow for the agent to pass through and

$$p_i = \begin{cases} \max(0, 80 - 4|d_i|) & \text{if agent collides with wall} \\ 100 & \text{if between blocks} \\ 0 & \text{if beyond blocks} \end{cases}$$

for an aperture wide enough for the agent to pass through, and d_i is the final horizontal separation between the center of the agent and the center of the aperture at the end of the i^{th} trial. This fitness measure assigns near-zero fitness to incor-

Slocum, Downey, Beer (2000).

Further Experiments in the Evolution of Minimally Cognitive Behavior: From Perceiving Affordances to Selective Attention. In *Animals to Animats* 6, pp. 430—439.

Minimal Cognition

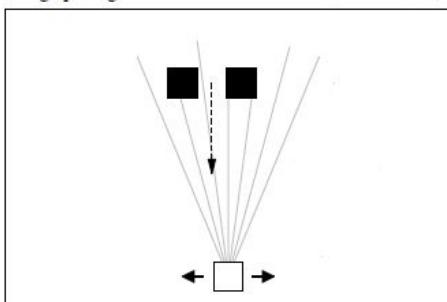


Figure 1: Experimental setup for the passability experiments. The agent moves horizontally while a wall with two black blocks. Gray lines represent proximity sensors. A dashed vertical line indicates the final position of the aperture.

The performance measure to be maximized was:

$$\sum_{i=1}^{\text{NumTrials}} p_i / \text{NumTrials}$$

$$\text{where } p_i = \begin{cases} 2|d_i| & \text{if agent collides with wall} \\ 100 & \text{otherwise} \end{cases}$$

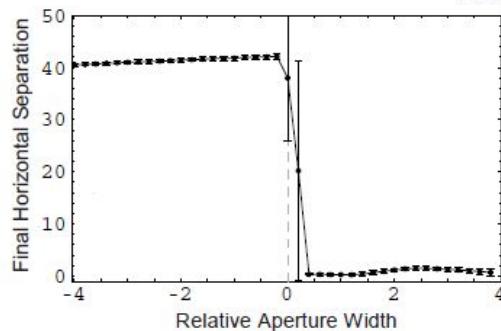
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Minimal Cognition

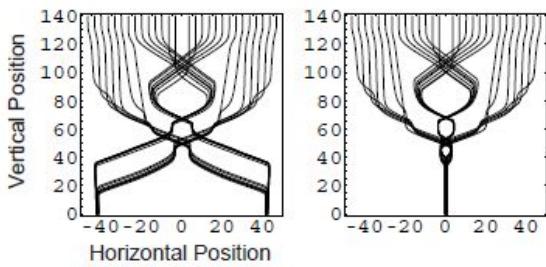
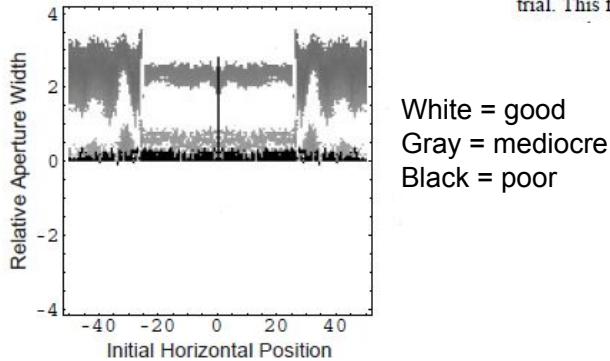


Figure 4: Behavior of the best passability agent. The wall's horizontal and vertical position over time relative to the agent is plotted for an aperture 1 unit smaller than the agent (left) and 1 unit larger than the agent (right). Trials begin at top and time increases from top to bottom.



The performance measure to be maximized was:

$$\sum_{i=1}^{\text{NumTrials}} p_i / \text{NumTrials}$$

$$\text{where } p_i = \begin{cases} 2|d_i| & \text{if agent collides with wall} \\ 100 & \text{otherwise} \end{cases}$$

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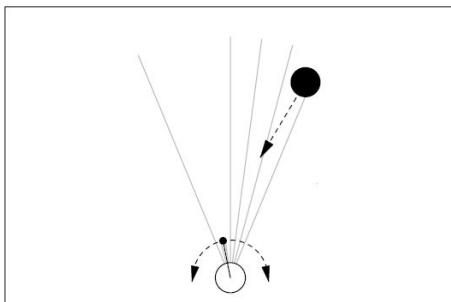
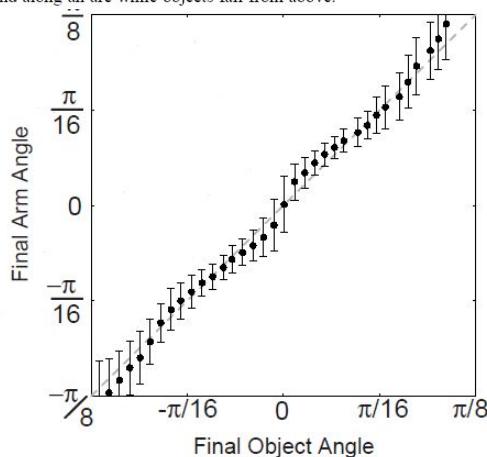


Figure 5: Experimental setup for self/nonself discrimination experiments. The agent is stationary, but can swing an arm with an opaque hand along an arc while objects fall from above.



Minimal Cognition

Sect. 4: Self/NonSelf Discrimination

The performance measure to be maximized was:

$$\sum_{i=1}^{\text{NumTrials}} p_i / \text{NumTrials}$$

where

and θ_i is the angular error at the end of the i^{th} trial.

Slocum, Downey, Beer (2000).

Further Experiments in the Evolution of Minimally Cognitive Behavior: From Perceiving Affordances to Selective Attention. In *Animals to Animats* 6, pp. 430—439.

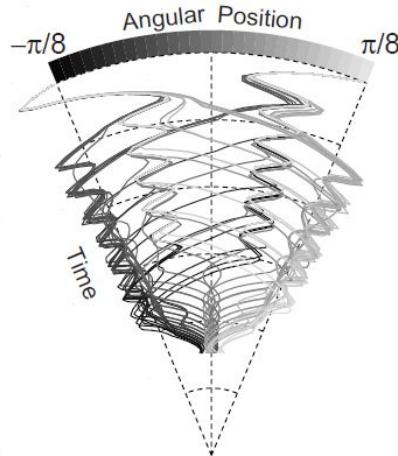


Figure 7: Arm angle trajectories over time of the best self/nonself discrimination agent catching objects at the midline from initial hand positions at either the left or right edge of the visual field. The trajectories are shaded according to the initial angular position of the object as indicated at the top of the plot.

Minimal Cognition

Sect. 4: Self/NonSelf Discrimination

The performance measure to be maximized was:

$$\sum_{i=1}^{\text{NumTrials}} p_i / \text{NumTrials}$$

where

and θ_i is the angular error at the end of the i^{th} trial.

Slocum, Downey, Beer (2000).

Further Experiments in the Evolution of Minimally Cognitive Behavior: From Perceiving Affordances to Selective Attention. In *Animals to Animats* 6, pp. 430—439.

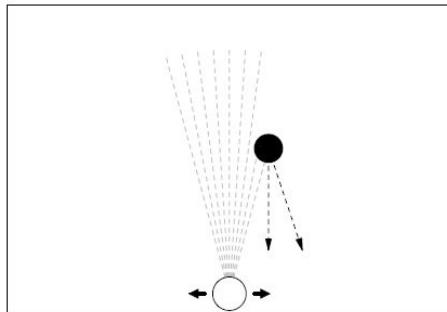
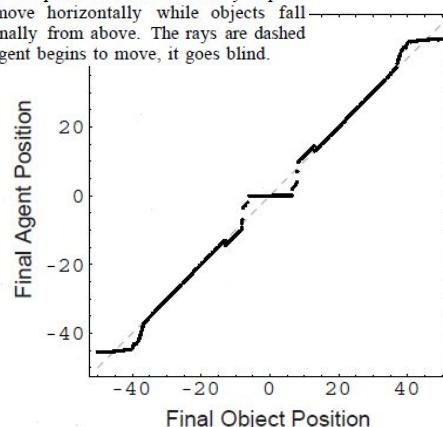


Figure 8: Experimental setup for short-term memory experiments. The agent can move horizontally while objects fall either vertically or diagonally from above. The rays are dashed because, as soon as the agent begins to move, it goes blind.



Minimal Cognition

Sect. 5: Short-term memory

When initially still, robot can sense.

Once it moves, sensors turned off

$$200 - \sum_{i=1}^{\text{NumTrials}} |d_i| / \text{NumTrials}$$

d_i = horizontal distance between object's final position and agent's final position.

Slocum, Downey, Beer (2000).

Further Experiments in the Evolution of Minimally Cognitive Behavior: From Perceiving Affordances to Selective Attention. In *Animals to Animats* 6, pp. 430—439.

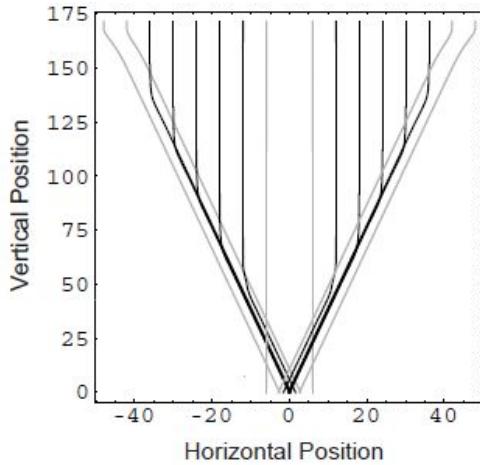


Figure 10: Behavior of the best short-term memory agent for vertically falling objects. Trajectories of motion relative to the agent of objects falling vertically from several different initial horizontal offsets are shown. Gray trajectories are those for which the agent's strategy begins to break down.

Minimal Cognition

Sect. 5: Short-term memory

When initially still, robot can sense.

Once it moves, sensors turned off

$$200 - \sum_{i=1}^{\text{NumTrials}} |d_i| / \text{NumTrials}$$

d_i = horizontal distance between object's final position and agent's final position.

Slocum, Downey, Beer (2000).

Further Experiments in the Evolution of Minimally Cognitive Behavior: From Perceiving Affordances to Selective Attention. In *Animals to Animats* 6, pp. 430—439.

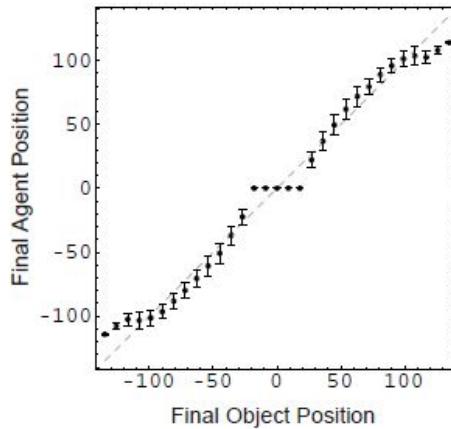


Figure 11: Mean accuracy of the best short-term memory agent for diagonally falling objects. The final horizontal position of the agent is plotted against the final horizontal position of the object (mean \pm s.d., $N = 200$ trials). Note that the average performance closely approximates the ideal (dashed gray line).

Minimal Cognition

Sect. 5: Short-term memory

When initially still, robot can sense.

Once it moves, sensors turned off

$$200 - \sum_{i=1}^{\text{NumTrials}} |d_i| / \text{NumTrials}$$

d_i = horizontal distance between object's final position and agent's final position.

Slocum, Downey, Beer (2000).

Further Experiments in the Evolution of Minimally Cognitive Behavior: From Perceiving Affordances to Selective Attention. In *Animals to Animats* 6, pp. 430—439.

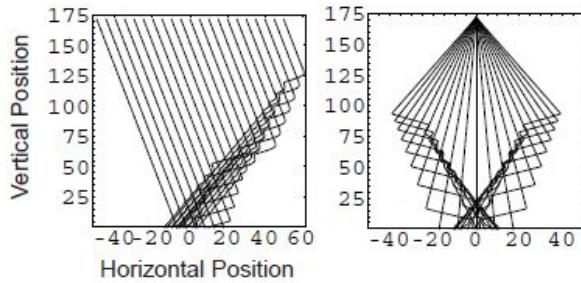


Figure 12: Behavior of the best short-term memory agent for diagonally falling objects. (Left) Trajectories of motion relative to the agent of objects falling diagonally with a horizontal velocity of 0.5 from several different initial horizontal positions are shown. (Right) Trajectories of motion relative to the agent of objects falling diagonally from the midline with several different horizontal velocities are shown.

Minimal Cognition

Sect. 5: Short-term memory

When initially still, robot can sense.

Once it moves, sensors turned off

$$200 - \sum_{i=1}^{\text{NumTrials}} |d_i| / \text{NumTrials}$$

d_i = horizontal distance between object's final position and agent's final position.

Slocum, Downey, Beer (2000).

Further Experiments in the Evolution of Minimally Cognitive Behavior: From Perceiving Affordances to Selective Attention. In *Animals to Animats* 6, pp. 430—439.

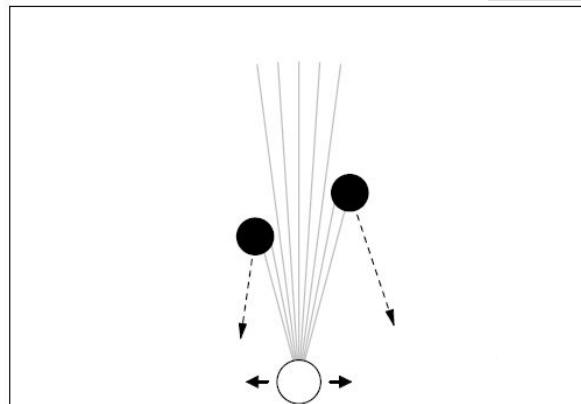


Figure 13: Experimental setup for selective attention experiments. The agent can move horizontally while 2 objects fall from above. As described in the text, the initial positions and velocities of the two objects are constrained so that the agent has a reasonable chance of catching both.

Minimal Cognition

Sect. 6: Selective Attention

$$200 - \sum_{i=1}^{\text{NumTrials}} p_i / \text{NumTrials}$$

$p_i = |d_{i,1}| + |d_{i,2}|$

$d_{i,j}$ = horizontal distance between object j's final position and agent's final position.

Slocum, Downey, Beer (2000).

Further Experiments in the Evolution of Minimally Cognitive Behavior: From Perceiving Affordances to Selective Attention. In *Animals to Animats* 6, pp. 430—439.

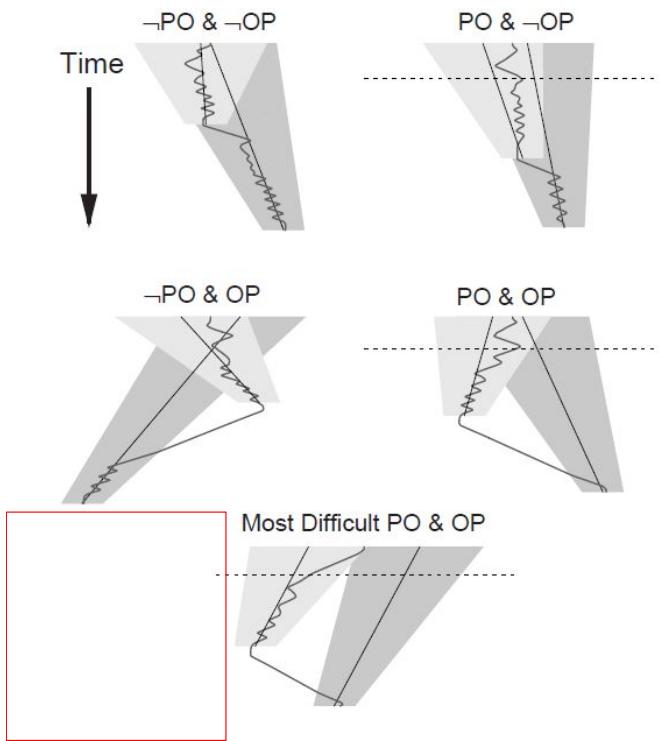


Figure 14: Behavior of the best selective attention agent.

Minimal Cognition

Sect. 6: Selective Attention

$$200 - \sum_{i=1}^{\text{NumTrials}} p_i / \text{NumTrials}$$

$$p_i = |d_{i,1}| + |d_{i,2}|$$

$d_{i,j}$ = horizontal distance between object j's final position and agent's final position.

Slocum, Downey, Beer (2000).

Further Experiments in the Evolution of Minimally Cognitive Behavior: From Perceiving Affordances to Selective Attention. In *Animals to Animats 6*, pp. 430—439.

Active Categorical Perception

Active categorical perception:

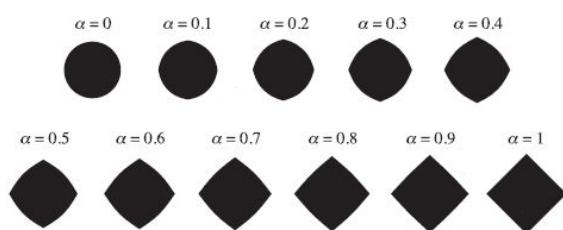
The ability of an animal (or robot) to **interact** with objects of interest to

Task:

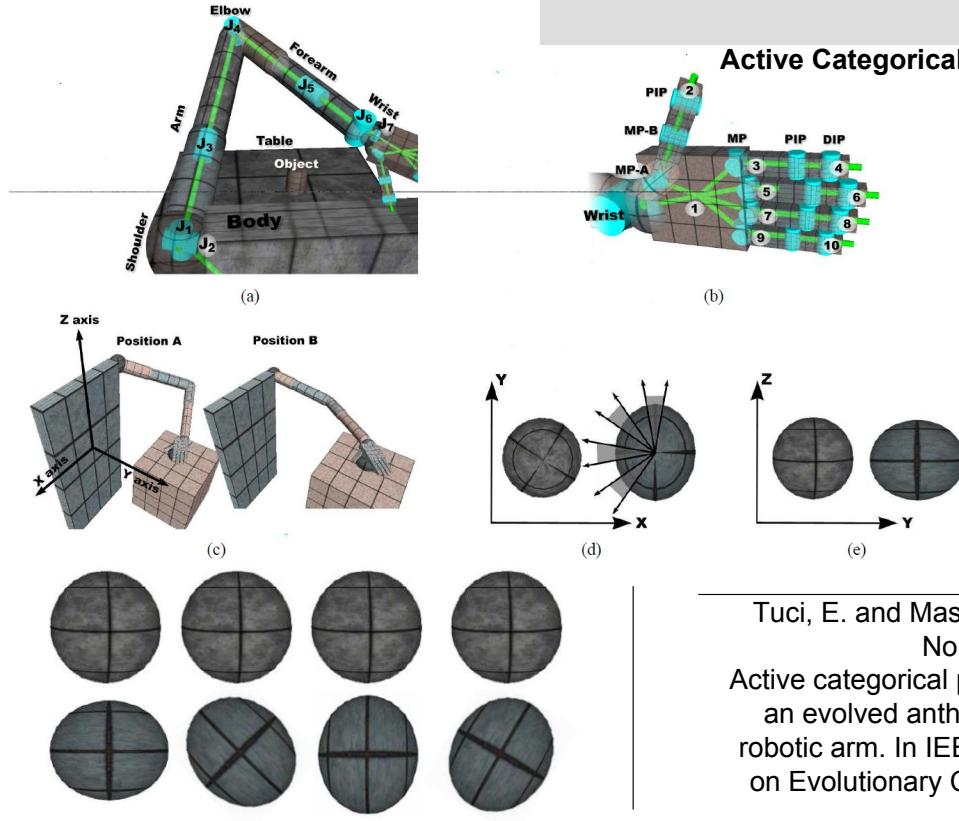
Several objects are placed in front of you.

You must separate the round from edged objects while wearing a blindfold.

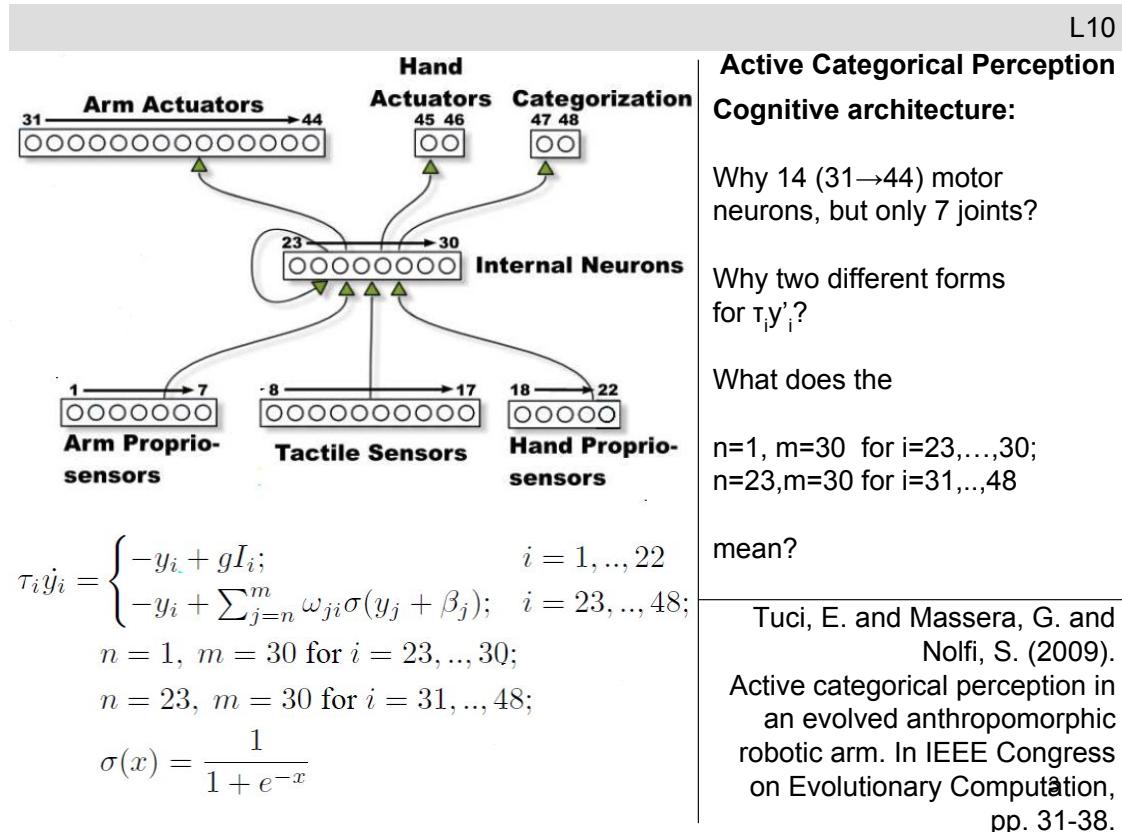
How would you interact with the objects?



Active Categorical Perception



Tuci, E. and Massera, G. and Nolfi, S. (2009). Active categorical perception in an evolved anthropomorphic robotic arm. In IEEE Congress on Evolutionary Computation, pp. 31-38.



Active Categorical Perception

Mental representation of spheres and ellipsoids:

$$\sigma(y_{47}(t) + \beta_{47}) =$$

Value of neuron 47 at time step t.

$$0.95T < t < T =$$

The last 5% of the time steps during the behavior.

Tuci, E. and Massera, G. and Nolfi, S. (2009).

Active categorical perception in an evolved anthropomorphic robotic arm. In IEEE Congress on Evolutionary Computation, pp. 31-38.

- in each trial e , the agent represents the experienced object (i.e., the sphere S or the ellipsoid D) by associating to it a rectangle R_{Se} or R_{De} whose vertices are:

the bottom left vertex:

$$(\min_{0.95T < t < T} \sigma(y_{47}(t) + \beta_{47}), \min_{0.95T < t < T} \sigma(y_{48}(t) + \beta_{48}))$$

the top right vertex:

$$(\max_{0.95T < t < T} \sigma(y_{47}(t) + \beta_{47}), \max_{0.95T < t < T} \sigma(y_{48}(t) + \beta_{48}))$$

- the sphere category, referred to as C_S , corresponds to the minimum bounding box of all R_{Se} ; the ellipsoid category, referred to as C_D , corresponds to the minimum bounding box of all R_{De} .

$$C_S = (\text{C})\text{lassified as a (S)sphere}$$

$$C_D = (\text{C})\text{lassified as an ellipsoi(D)}$$

with d_e the euclidean distance between the object and the centre of the palm at the end of the trial e ; d_{max} the maximum distance between the palm and the object when located on the table.

$$C_S = (\text{C})\text{lassified as a (S)sphere}$$

$$C_D = (\text{C})\text{lassified as an ellipsoi(D)}$$

(C_S , C_D are bounding boxes)

Active Categorical Perception

The Fitness Function (FF)

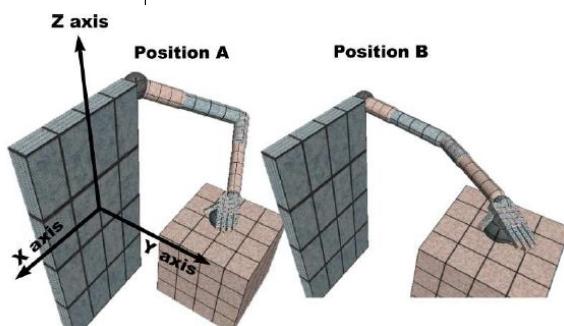
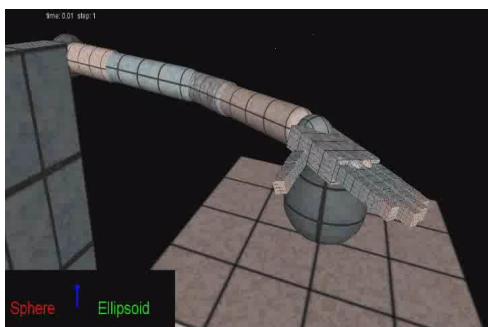
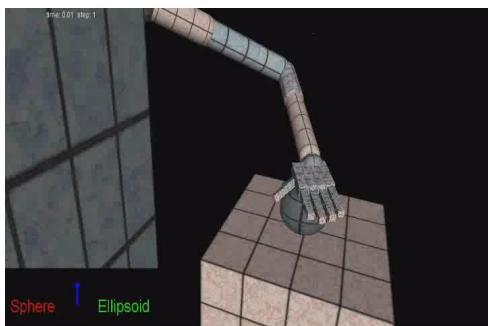
Why two fitness terms F_1 and F_2 ?

What does F_1 select for?
What does F_2 select for?

Is the term d_e/d_{max}
a reward or punishment term?

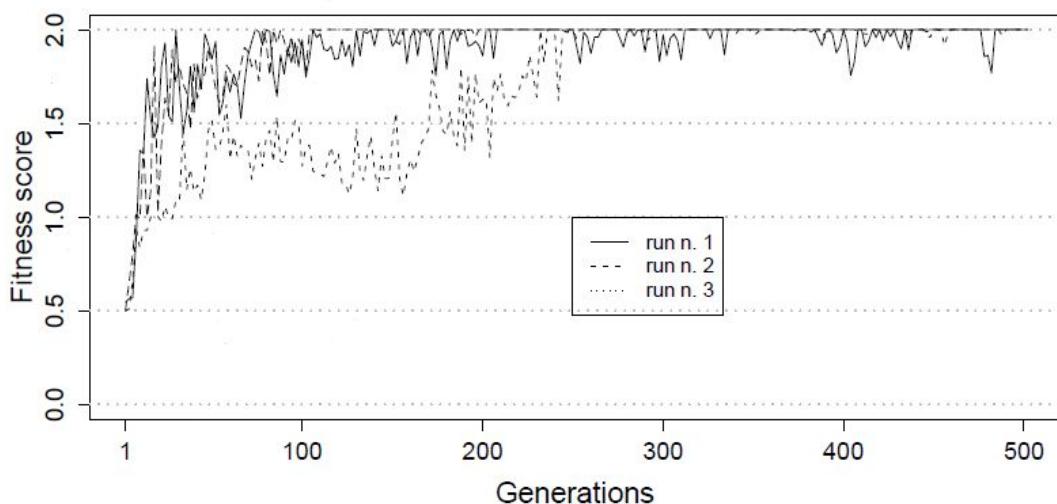
What does $F_2=1$ indicate about C_S and C_D ?

Tuci, E. and Massera, G. and Nolfi, S. (2009). Active categorical perception in an evolved anthropomorphic robotic arm. In IEEE Congress on Evolutionary Computation, pp. 31-38.

Active Categorical Perception

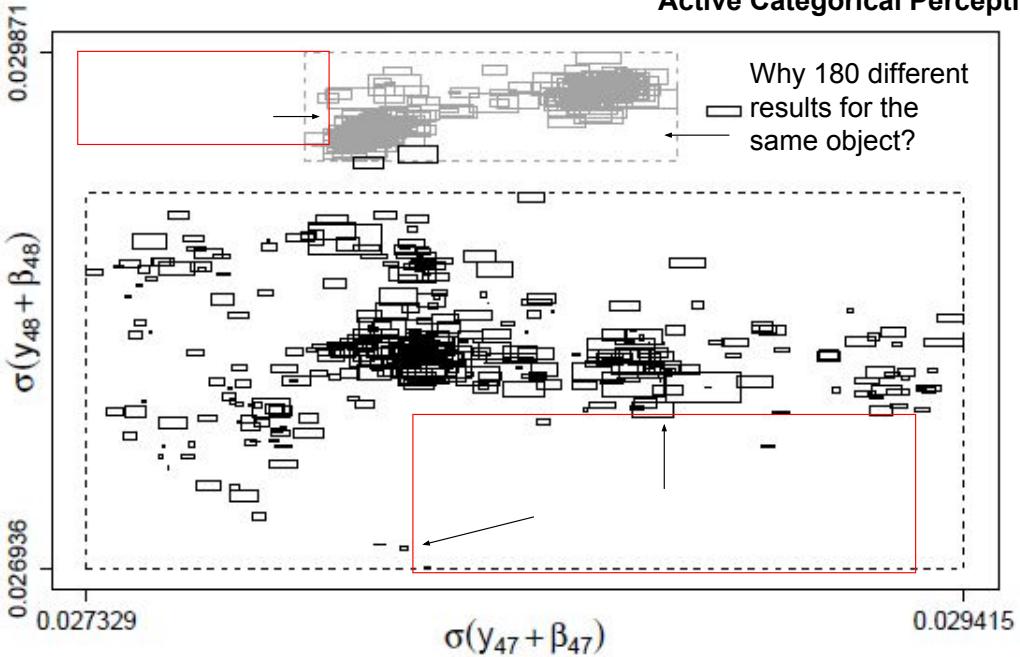
Tuci, E. and Massera, G. and Nolfi, S. (2009). Active categorical perception in an evolved anthropomorphic robotic arm. In IEEE Congress on Evolutionary Computation, pp. 31-38.

Performed three separate evolutionary runs:

Active Categorical Perception

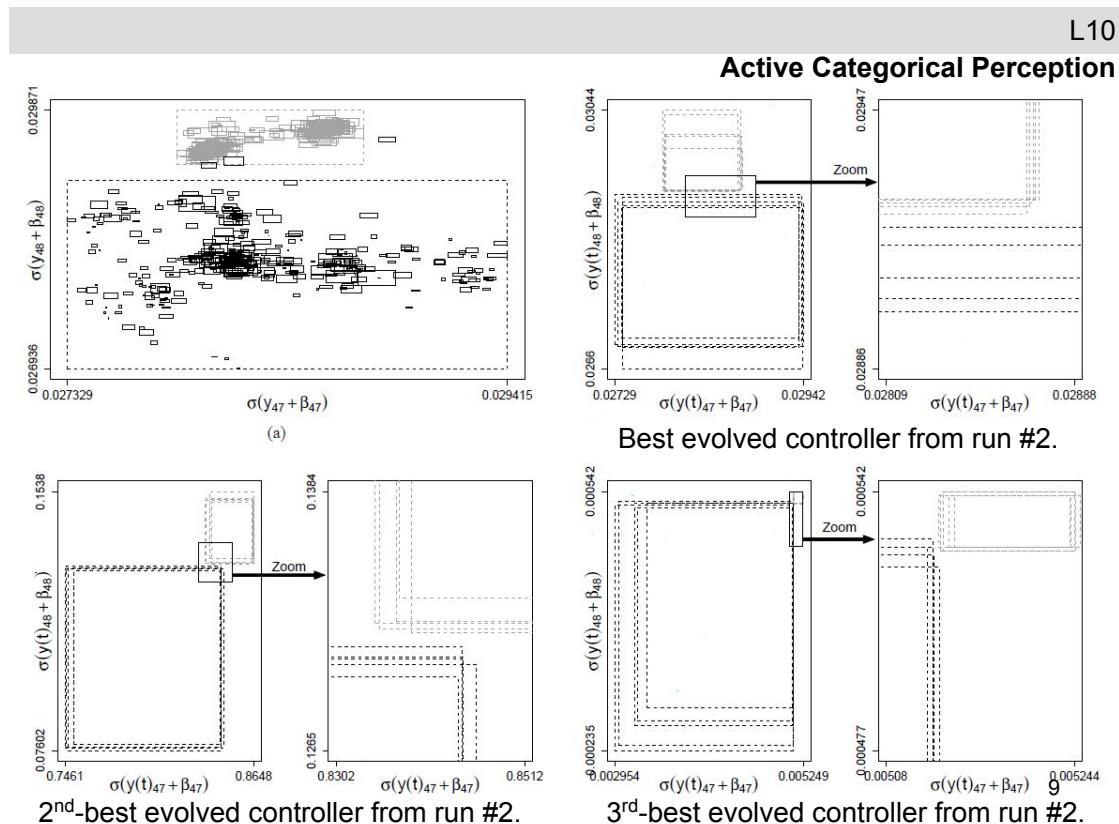
Tuci, E. and Massera, G. and Nolfi, S. (2009). Active categorical perception in an evolved anthropomorphic robotic arm. In IEEE Congress on Evolutionary Computation, pp. 31-38.

Active Categorical Perception



Results from the best evolved controller.

8



Chapter 1: The Best Way to Travel 1
1.1. Fitness 1
1.2. Speed 2
1.3. Acceleration and Maneuverability 2
1.4. Endurance 4
1.5. Economy of Energy 7
1.6. Stability 8
1.7. Compromises 9
1.8. Constraints 9
1.9. Optimization Theory 10
1.10. Gaits 12
Chapter 2: Muscle, the Motor 15
2.1. How Muscles Exert Force 15
2.2. Shortening and Lengthening Muscle 22
2.3. Power Output of Muscles 26
2.4. Pennation Patterns and Moment Arms 28
2.5. Power Consumption 31
2.6. Some Other Types of Muscle 34
Chapter 3: Energy Requirements for Locomotion 38
3.1. Kinetic Energy 38
3.2. Gravitational Potential Energy 39
3.3. Elastic Strain Energy 40
3.4. Work That Does Not Increase the Body's Mechanical Energy 42
3.5. Work Requirements 46
3.6. Oscillatory Movements 48
Chapter 4: Consequences of Size Differences 53
4.1. Geometric Similarity, Allometry, and the Pace of Life 53
4.2. Dynamic Similarity 58
4.3. Elastic Similarity and Stress Similarity 60
Chapter 5: Methods for the Study of Locomotion 68
5.1. Cinematography and Video Recording 68
5.2. Stationary Locomotion 70
5.3. Measurement of Energy Consumption 73
5.4. Observing Flow 74
5.5. Forces and Pressures 76
5.6. Recording Muscle Action 80

L11

Terrestrial Locomotion

Requires a balance between

- (1) displacement,
- (2) robustness,
- (3) energy and
- (4) stability.

All four are usually in opposition:

Improving one degrades the others.

Q: Examples?

Alexander, R. M. (2002)

*Principles of Animal Locomotion.*Princeton University Press₁

5.7. Recording Movement at a Distance 83
5.8. Properties of Materials 84

Chapter 6: Alternative Techniques for Locomotion on Land 86

6.1. Two-Anchor Crawling 86
6.2. Crawling by Peristalsis 88
6.3. Serpentine Crawling 90
6.4. Froglike Hopping 91
6.5. An Inelastic Kangaroo 93
6.6. A Minimal Model of Walking 95
6.7. The Synthetic Wheel 97
6.8. Walkers with Heavy Legs 98
6.9. Spring-Mass Models of Running 99
6.10. Comparisons 100

Chapter 7: Walking, Running, and Hopping 103

7.1. Speed 103
7.2. Gaits 109
7.3. Forces and Energy 114
7.4. Energy-Saving Springs 122
7.5. Internal Kinetic Energy 125
7.6. Metabolic Cost of Transport 128
7.7. Prediction of Optimal Gaits 133
7.8. Soft Ground, Hills, and Loads 136
7.9. Stability 139
7.10. Maneuverability 143

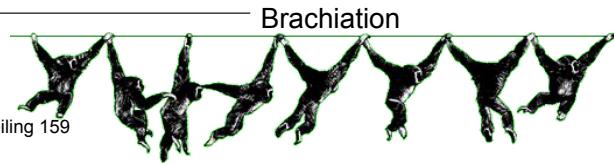
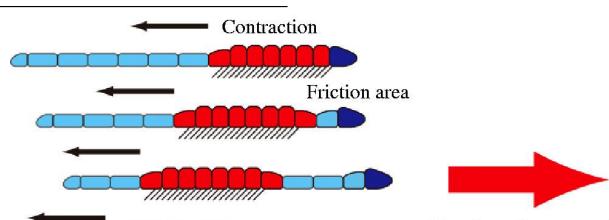
Chapter 8: Climbing and Jumping 146

8.1. Standing Jumps 146
8.2. Leg Design and Jumping Technique 150
8.3. Size and Jumping 153
8.4. Jumping from Branches 155
8.5. Climbing Vertical Surfaces and Walking on the Ceiling 159

Chapter 9: Crawling and Burrowing 166

9.1. Worms 166
9.2. Insect Larvae 170
9.3. Molluscs 171
9.4. Reptiles 176
9.5. Mammals 179

L11

Locomotion

Chapter 10: Gliding and Soaring 181

- 10.1. Drag 181
- 10.2. Lift 183
- 10.3. Drag on Aerofoils 187
- 10.4. Gliding Performance 192
- 10.5. Stability 200
- 10.6. Soaring 201

Chapter 11: Hovering 209

- 11.1. Airflow around Hovering Animals 209
- 11.2. Lift Generation 213
- 11.3. Power for Hovering 221

Chapter 12: Powered Forward Flight 224

- 12.1. Aerodynamics of Flapping Flight 224
- 12.2. Power Requirements for Flight 228
- 12.3. Optimization of Flight 236

Chapter 13: Moving on the Surface of Water 240

- 13.1. Fisher Spiders 240
- 13.2. Basilisk Lizards 244
- 13.3. Surface Swimmers 246

Chapter 14: Swimming with Oars and Hydrofoils 249

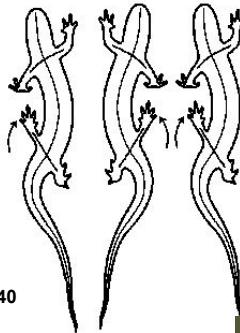
- 14.1. Froude Efficiency 249
- 14.2. Drag-Powered Swimming 250
- 14.3. Swimming Powered by Lift on Limbs or Paired Fins 255
- 14.4. Swimming with Hydrofoil Tails 261
- 14.5. Porpoising 264

Chapter 15: Swimming by Undulation 266

- 15.1. Undulating Fishes 266
- 15.2. Muscle Activity in Undulating Fishes 277
- 15.3. Fins, Tails, and Gaits 282
- 15.4. Undulating Worms 284

Chapter 16: Swimming by Jet Propulsion 288

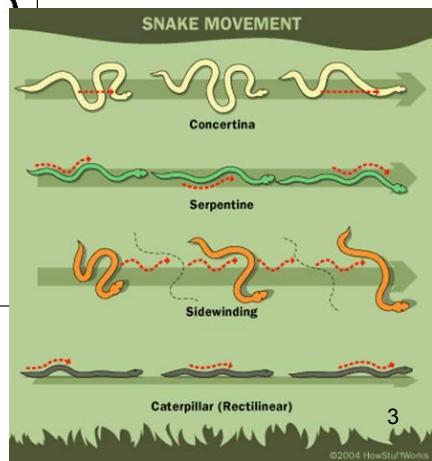
- 16.1. Efficiency of Jet Propulsion 288
- 16.2. Elastic Mechanisms in Jet Propulsion 296



L11

Locomotion

Q: Why evolve away
From snake-like or reptilian
locomotion?



3

L11
Locomotion**Chapter 17: Buoyancy 301**

- 17.1. Buoyancy Organs 301
- 17.2. Swimming by Dense Animals 303
- 17.3. Energetics of Buoyancy 307
- 17.4. Buoyancy and Lifestyle 311

Chapter 18: AIDS to Human Locomotion 316

- 18.1. Shoes 316
- 18.2. Bicycles 318
- 18.3. Scuba 321
- 18.4. Boats 322
- 18.5. Aircraft without Engines 324

Chapter 19: Epilogue 327

- 19.1. Metabolic Cost of Transport 327
 - 19.2. Speeds 328
 - 19.3. Gaits 330
 - 19.4. Elastic Mechanisms 331
 - 19.5. Priorities for Further Research 331
- REFERENCES 333
INDEX 367

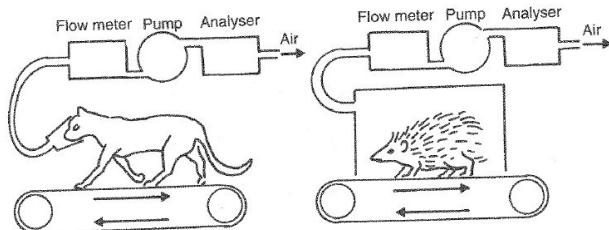
Legged Locomotion

Fig. 4.1 Measuring the oxygen consumption of animals running on treadmills. In (a) the animal wears a mask from which air is sucked for analysis; in (b) the whole animal is enclosed by a hood from which air is drawn.

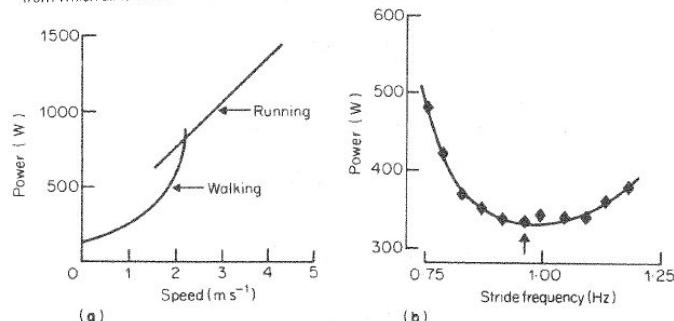
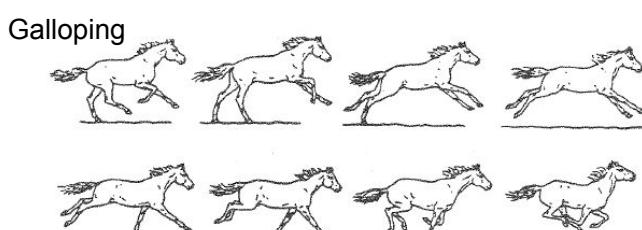
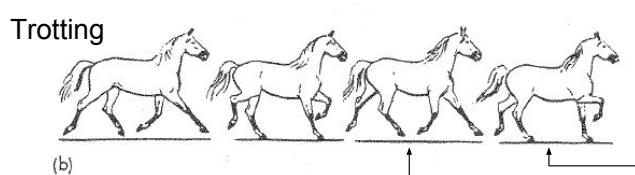
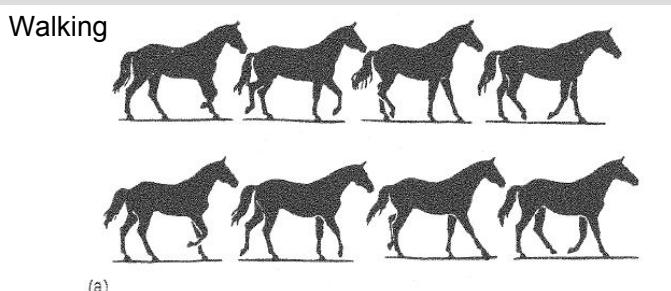


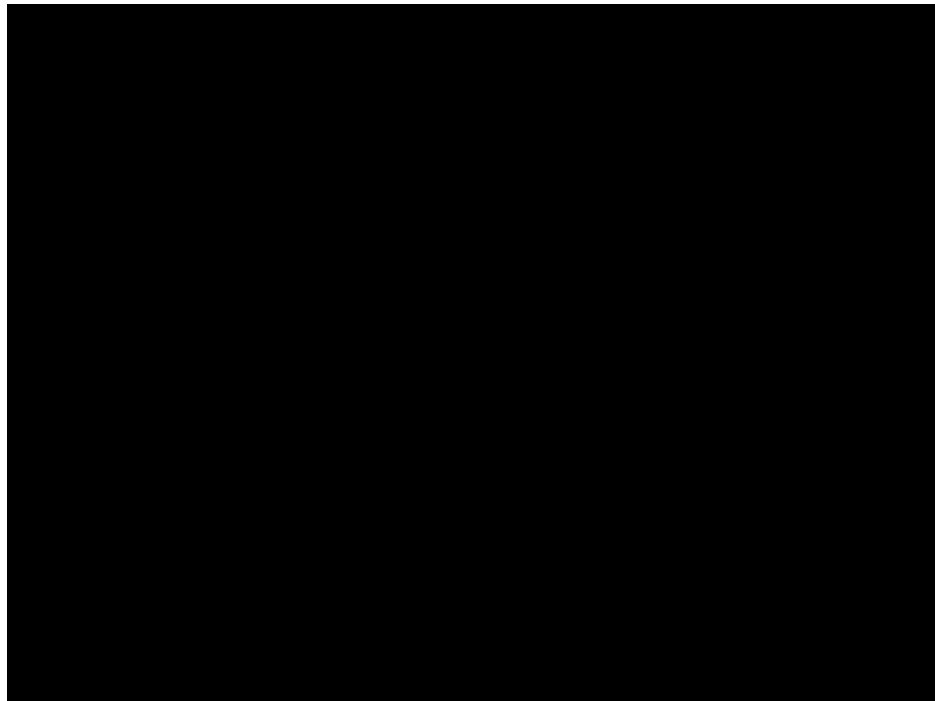
Figure 3-5. The metabolic power consumed by men walking and running, calculated from measurements of oxygen consumption. In (a) power is plotted against speed. The subjects used whatever stride frequency they preferred, at each speed. In (b) power is plotted against stride frequency for walking at $1.5\ ms^{-1}$. The arrow shows the preferred frequency. Data from (a) Margaria, 1976, (b) Zarrugh and Radcliffe (1978).

5

Legged Locomotion

Stance phase
(at least one foot
on the ground)
Flight phase
(no feet on the
ground)

6

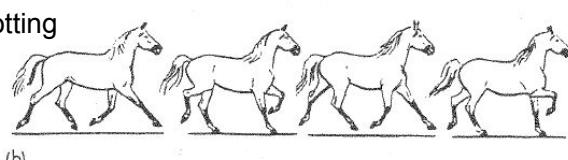


Walking



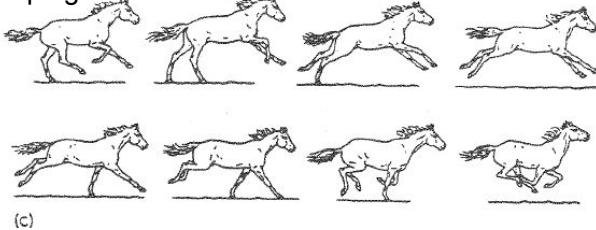
(a)

Trotting



(b)

Galloping



(c)

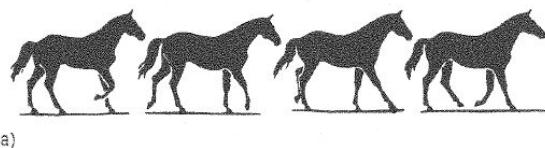
Static stability(if movement stops,
animal will not fall over)

Examples?

Dynamic stability(an observed pattern over
time continues, despite
external perturbations)

Examples?

Walking



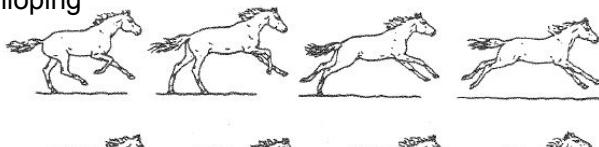
(a)

Trotting



(b)

Galloping



(c)

Static stability(if movement stops,
animal will not fall over)

Examples?

Dynamic stability(an observed pattern over
time continues, despite
external perturbations)

Examples?

9



Boston Dynamics

BigDog, Boston Dynamics



“BigDog”, ?

Dynamic stability(an observed pattern over
time continues, despite
external perturbations)

Examples?

10

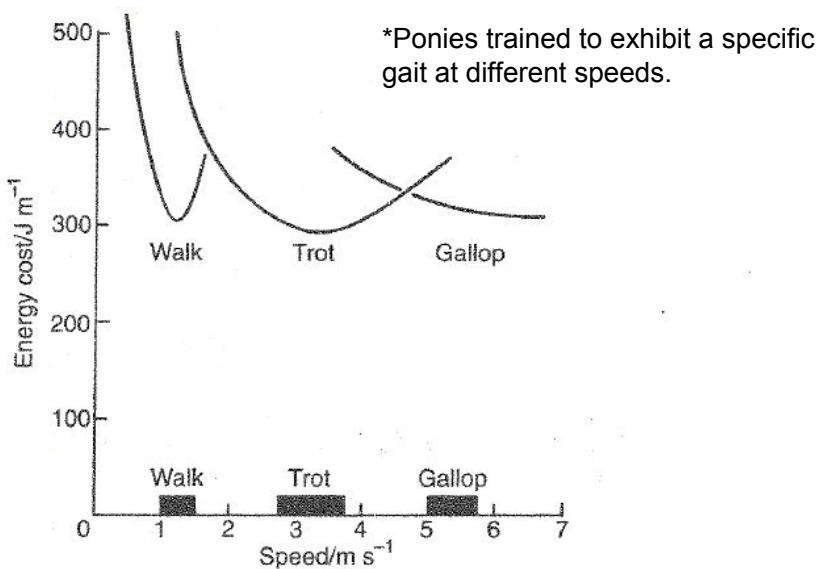


Fig. 4.3 Metabolic energy per unit distance used by 100 kg ponies walking, trotting, and galloping on a treadmill. Bars at the bottom of the graph show the ranges of speeds at which the ponies used each gait when moving freely in their paddock. (Redrawn from D. F. Hoyt and C. R. Taylor 11 (1981) *Nature* **292**, 239–40.)

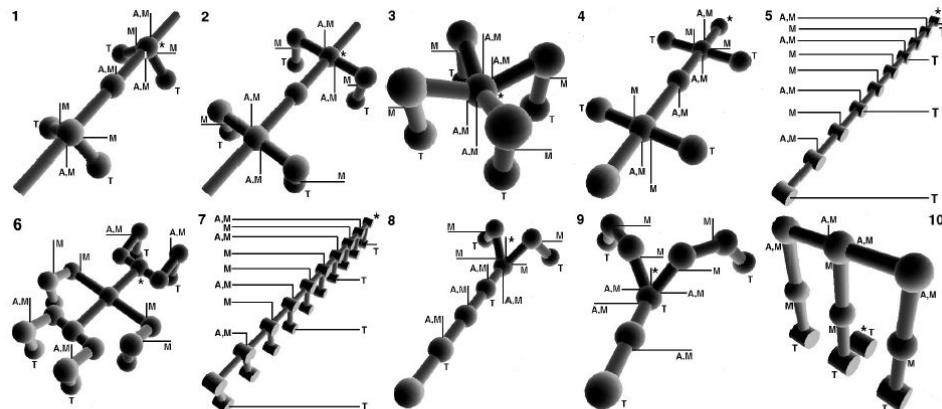


Figure 1: The agents used for comparison. Each agent contains four touch sensors (T), four angle sensors (A), and eight motors (M) actuating eight one degree-of-freedom joints. Fitness is based on the forward displacement of one of the body parts (indicated by *) contained in the agent over a fixed period of time.

Q: Given 10 robots with different bodies but the same...
 number of sensors and motors,
 neural network,
 fitness function,
 and optimizer,...

Which one will evolve the fastest gaits?

Bongard, J. C. and
 R. Pfeifer (2002)
**A Method for Isolating
 Morphological Effects on Evolved Behaviour.** 12

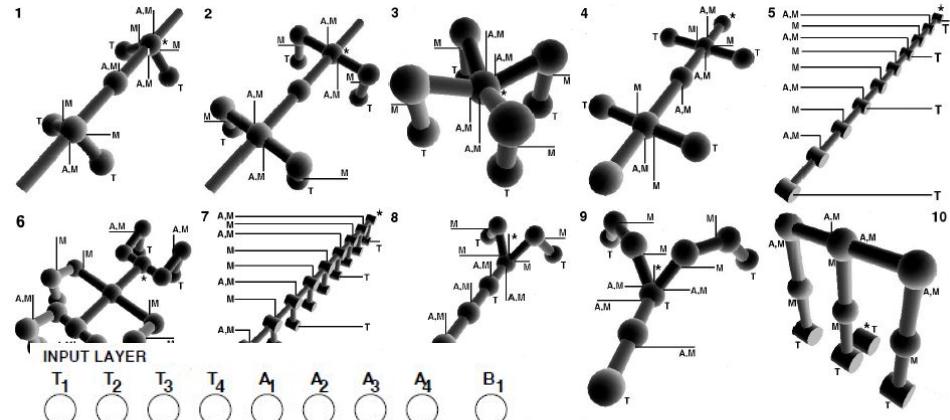
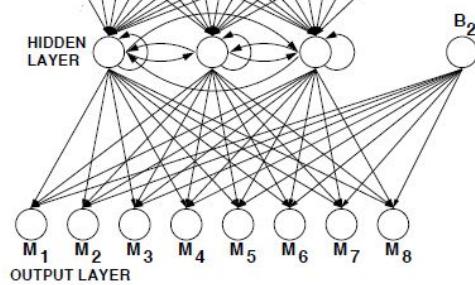
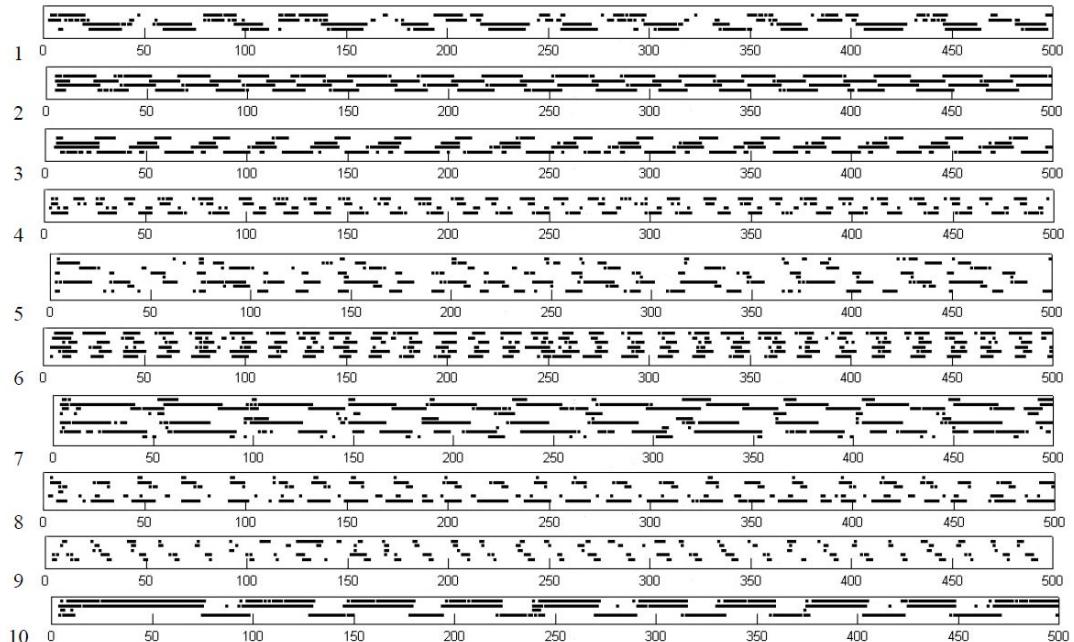


Figure 1
actuator

such sensors (T), four angle sensors (A), and eight motors (M)
1 displacement of one of the body parts (indicated by *) contained



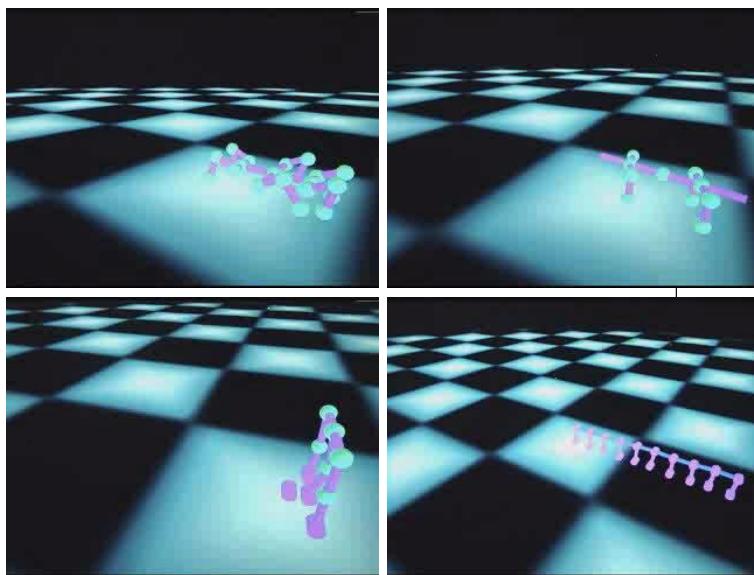
Bongard, J. C. and
R. Pfeifer (2002)
A Method for Isolating
Morphological Effects on 13
Evolved Behaviour.



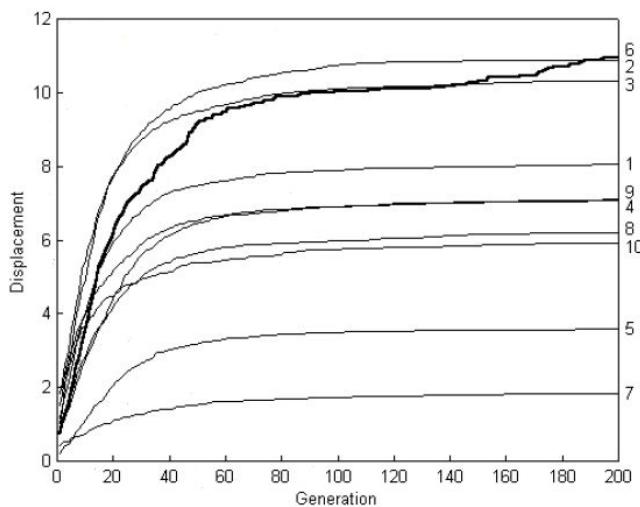
Footprint graph

panel: results from one evolved controller
row: reports the touch patterns for one foot
black pixel: that foot touched the ground at that time
white pixel: that foot was in the air at that time

Bongard, J. C. and
R. Pfeifer (2002)
A Method for Isolating
Morphological Effects on 14
Evolved Behaviour.



Bongard, J. C. and
R. Pfeifer (2002)
A Method for Isolating
Morphological Effects on 15
Evolved Behaviour.



Q: What is it about the
robot's morphology
that predicts the
ability to evolve
gaits for it?

Given your experiences with
PyroSim, what physical aspects
of the robot may make a
difference?

Figure 3: Average evolutionary performance of the 10 agents. The curves are averages of the best fitness curves taken over the 30 evolutionary runs for each agent. The numbers to the right indicate to which agent that curve belongs (i.e., agents 6 and 2 performed the best). Displacement is in meters.

Bongard, J. C. and
R. Pfeifer (2002)
A Method for Isolating
Morphological Effects on 16
Evolved Behaviour.

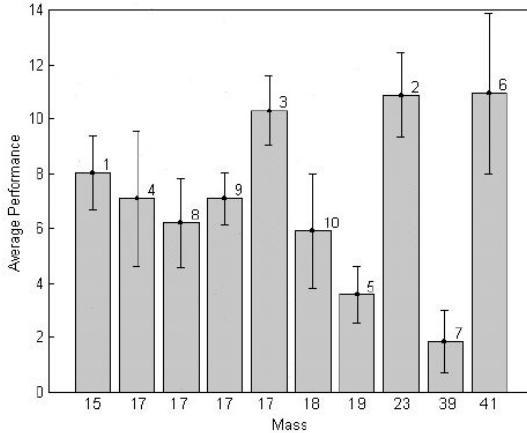


Figure 5: Mass versus evolutionary performance. The horizontal axis indicates the total mass of the agent, in kilograms. The vertical axis indicates the average displacement of the targeted body part for each agent type, in meters. The numbers above the bars indicate the agent index as given in Fig. 1. The error bars are two standard deviation units in length.

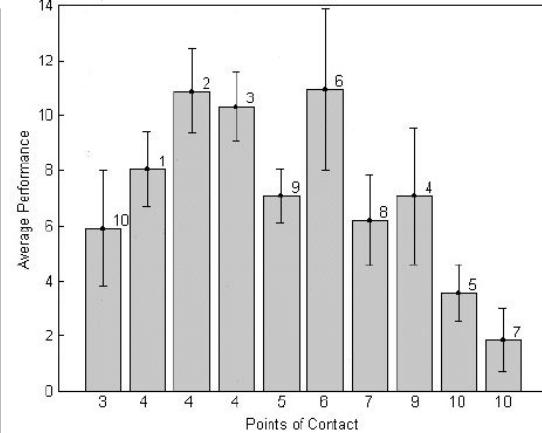


Figure 6: Points of contact versus evolutionary performance. The horizontal axis indicates how many body parts of the agent can contact the ground plane. The vertical axis indicates the average displacement of the targeted body part for each agent type, in meters. The numbers above the bars indicate the agent index as given in Fig. 1. The error bars are two standard deviation units in length.

17

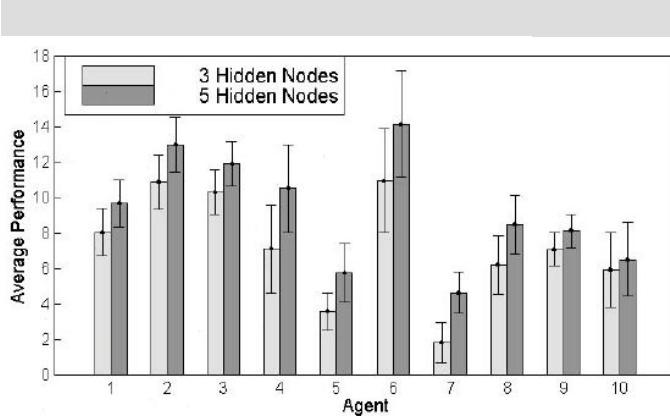
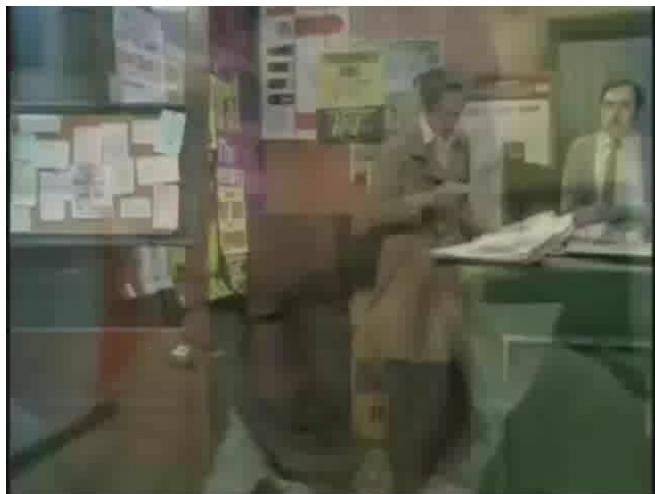


Figure 7: Change in performance based on addition of hidden neurons. The light coloured bars indicate the average evolutionary performance for that agent using three hidden neurons. The dark coloured bars indicate average performance for that agent using five hidden neurons. Numbers along the horizontal axis denote the agent's index number, as denoted in Fig. 1. The error bars are two standard deviation units in length.

Q1: Do changes to
The cognitive architecture
(going from 3 to 5 hidden
nodes)
affect the evolution
of gaits?

Q2: Is this effect the
same across different
robots?

18

Bipedal Locomotion

Question 1:

Why only walking and running?

Question 2:

What (if any) part
does the upper body
play in bipedal locomotion?

1

Bipedal Locomotion

Question 1:

Why only walking and running?

Question 2:

What (if any) part
does the upper body
play in bipedal locomotion?

Honda's ASIMO robot

2



L12

Bipedal Locomotion

Passive Dynamic Locomotion

Pneumatic passive-based biped

Martijn Wisse
Jan van Frankenhuizen
2004

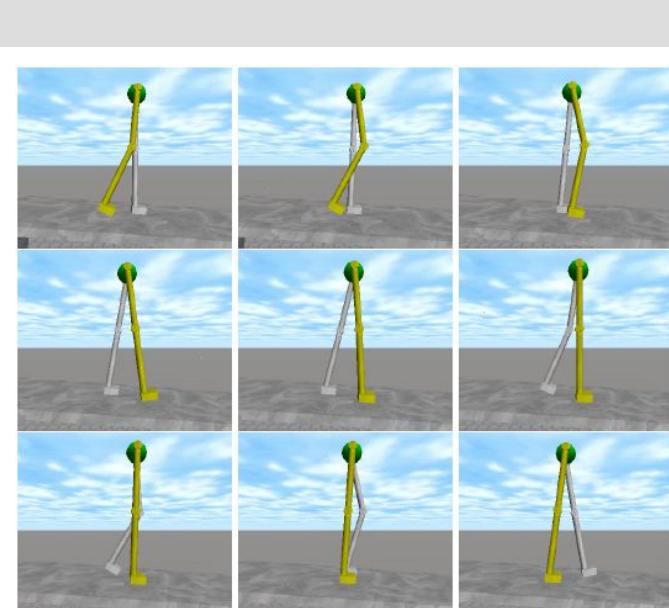
Delft Biorobotics Laboratory



Steve Collins, Martijn Wisse,
Andy Ruina, Cornell

Hybrid Dynamic Locomotion

Martijn Wisse, TU Delft (2004)³



L12

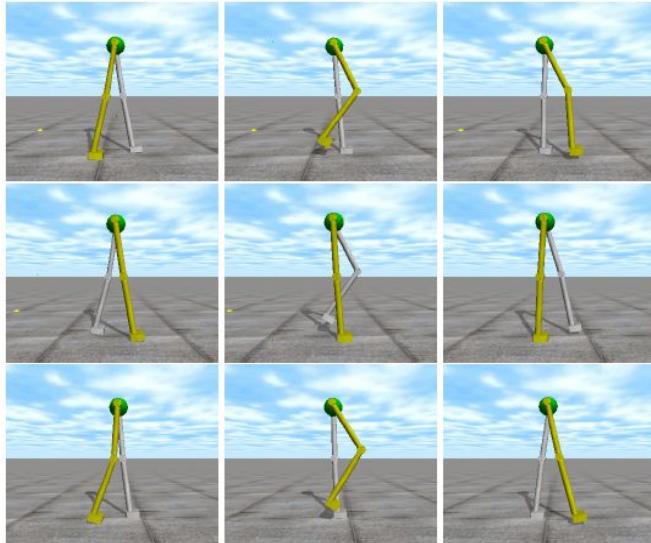
Bipedal Locomotion

Research question:

Can passive dynamic walking
be evolved? How?

Could evolved passive
dynamic walking be
evolved further into
hybrid dynamic walking?

Vaughan, E., Di Paolo, E.,
Harvey, I. (2004)
The evolution of control and
adaptation in a 3D powered
passive dynamic walker.⁴
In *Artificial Life IX*, pp. 139-145.

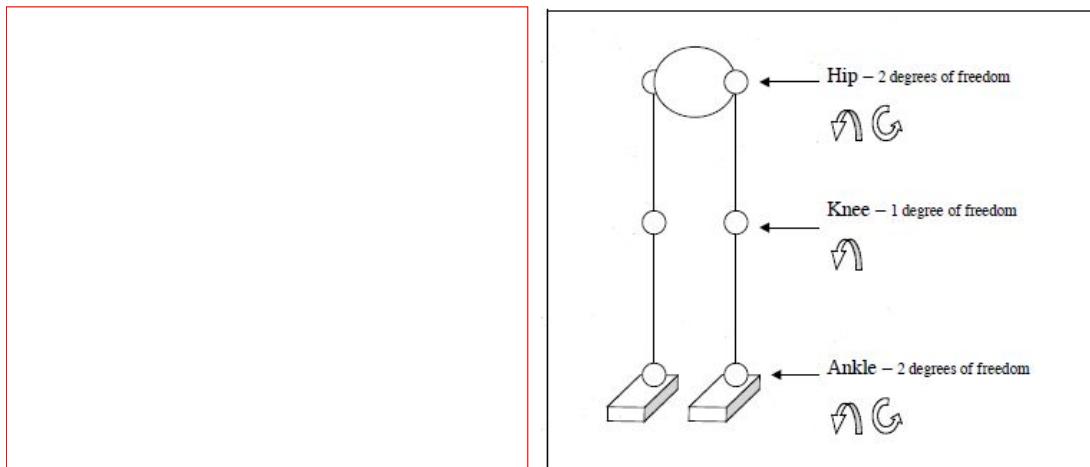
Bipedal Locomotion

Research question:

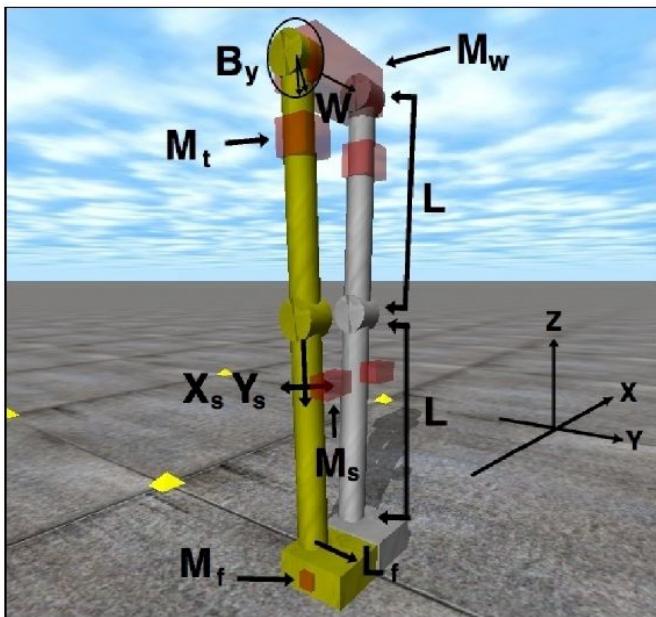
Can passive dynamic walking be evolved? How?

Could evolved passive dynamic walking be evolved further into hybrid dynamic walking?

Vaughan, E., Di Paolo, E., Harvey, I. (2004)
The evolution of control and adaptation in a 3D powered passive dynamic walker.
In *Artificial Life IX*, pp. 139-145.



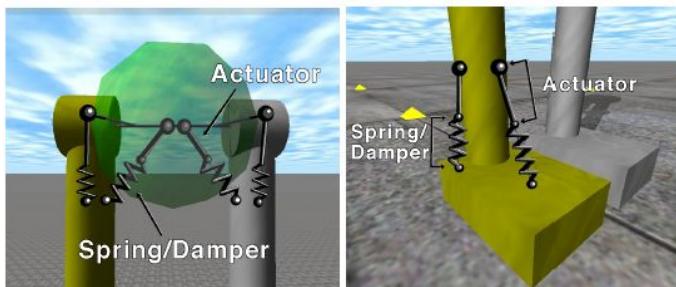
Vaughan, E., Di Paolo, E., Harvey, I. (2004)
The evolution of control and adaptation in a 3D powered passive dynamic walker.
In *Artificial Life IX*, pp. 139-145.



M_w = waist mass
 M_t = thigh mass
 M_s = shank mass
 M_f = foot mass
 L = leg segment length
 X_t = thigh mass x-offset
 Y_t = thigh mass y-offset
 X_s = shank mass x-offset
 Y_s = shank mass y-offset
 L_f = foot length
 W = waist radius
 B_y = starting hip angle around y-axis

Placing the robot's body under evolutionary control:
evolve not just NN parameters, but
body parameters as well.

Vaughan, E., Di Paolo, E.,
Harvey, I. (2004)
The evolution of control and
adaptation in a 3D powered
passive dynamic walker.
In *Artificial Life IX*, pp. 139-145.



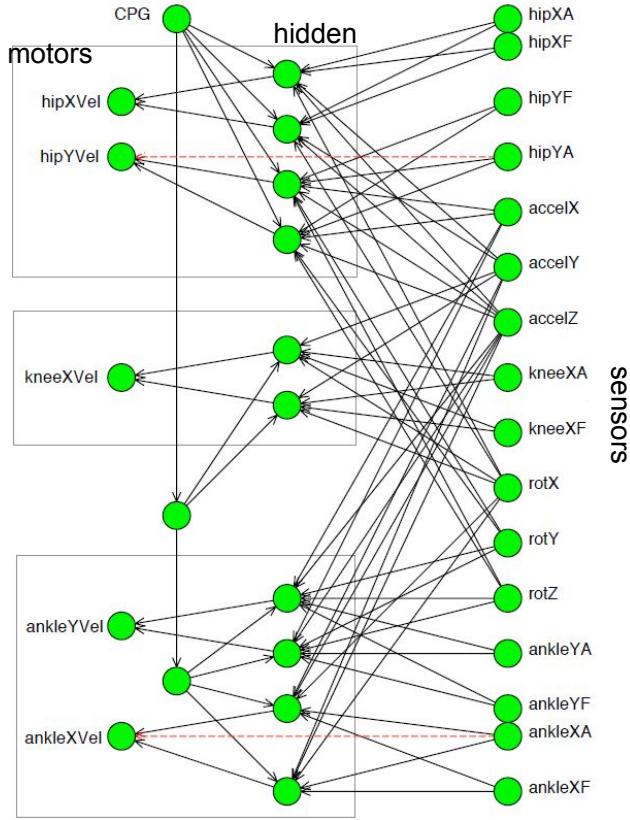
A_x = ankle spring/damper around x-axis
 K_x = knee spring/damper around x-axis
 H_x = hip spring-/damper around x-axis
 H_y = hip spring/damper around y-axis
 A_y = ankle spring/damper around y-axis

Each spring/damper has two parameters:
stiffness and damping coefficient

Q: How many body params?

Vaughan, E., Di Paolo, E.,
Harvey, I. (2004)
The evolution of control and
adaptation in a 3D powered
passive dynamic walker.
In *Artificial Life IX*, pp. 139-145.

High stiffness/ high damping		Low stiffness/ high damping	
High stiffness/ no damping		Low stiffness/ no damping	



Continuous Time Neural Network (CTNN)

Five motors:

one attached to each spring/damper.

CPG =

Two **hidden** nodes / per motor

Sensors:

*A = angle sensor

what is the angle of the joint?

*F = force sensor

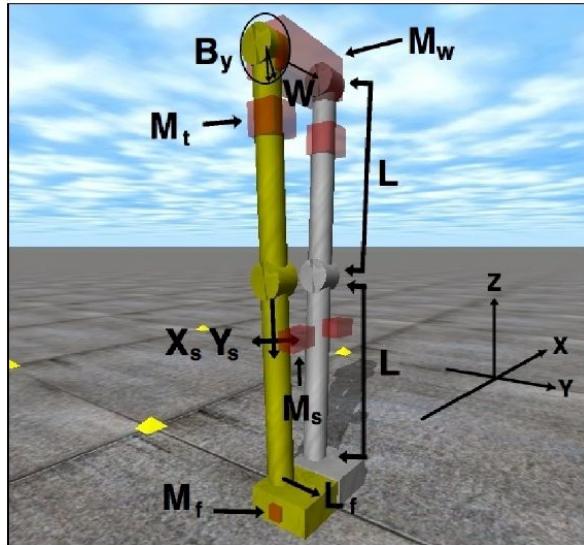
how far is the spring from its resting length?

rot* = rotation about * axis

accel* = acceleration about * axis

9

$$f = d \left(\frac{1}{1+t} \right) \left(\frac{1}{1+x} \right) \left(\frac{1}{1+z} \right) \left(\frac{1}{1+r} \right) \left(\frac{1}{1+y} \right)$$



The Fitness Function:

Q: Does d, t, x, z, r, or y reward or punish?

f: fitness

d: distance travelled

t: torque used
(torque = rotational force)

x: hip rotation about x-axis

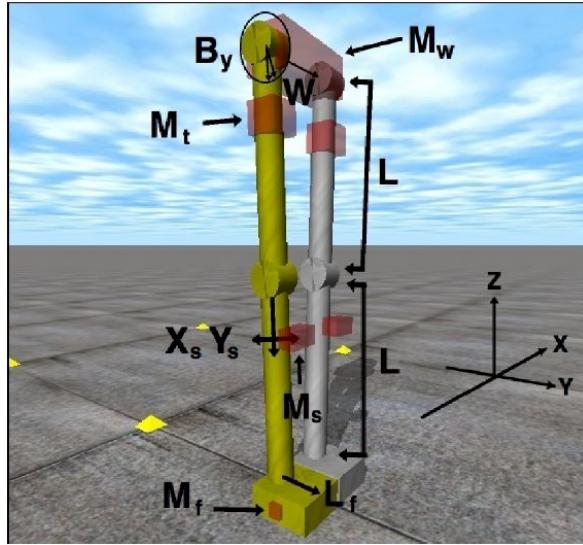
z: hip rotation about z-axis

r: feet rotation about z-axis

y: hip rotation about y-axis

10

$$f = d \left(\frac{1}{1+t} \right) \left(\frac{1}{1+x} \right) \left(\frac{1}{1+z} \right) \left(\frac{1}{1+r} \right) \left(\frac{1}{1+y} \right)$$



Shaping:

1. Evolve passive walking

- 2. Evolve hybrid walking**
3. Evolve sensor-based walking

11

$$f = d \left(\frac{1}{1+t} \right) \left(\frac{1}{1+x} \right) \left(\frac{1}{1+z} \right) \left(\frac{1}{1+r} \right) \left(\frac{1}{1+y} \right)$$

Shaping:

- 1. Evolve passive walking**
2. Evolve hybrid walking

During evolution:

Evolve CPG → motor params
 Evolve body params
 Add $(1/(1+v))$ to fitness function
 v = difference between
 passive and hybrid velocity
 Gradually lower declined plane
 over generations

During evaluation:

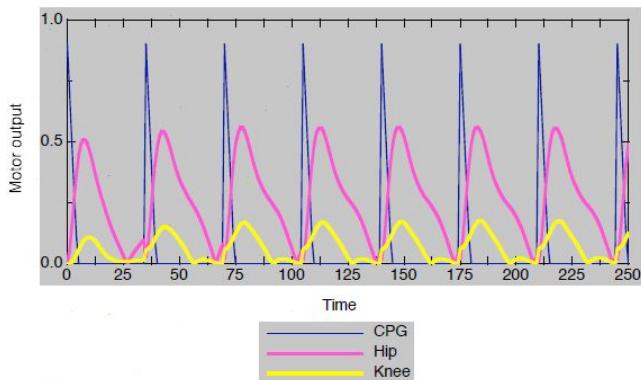
Record time to first heel strike
 Use this to set CPG frequency

- 3. Evolve sensor-based walking**

12

$$f = d \left(\frac{1}{1+t} \right) \left(\frac{1}{1+x} \right) \left(\frac{1}{1+z} \right) \left(\frac{1}{1+r} \right) \left(\frac{1}{1+y} \right)$$

Motor outputs of swing leg



Shaping:

1. Evolve passive walking
2. Evolve hybrid walking
3. Evolve sensor-based walking

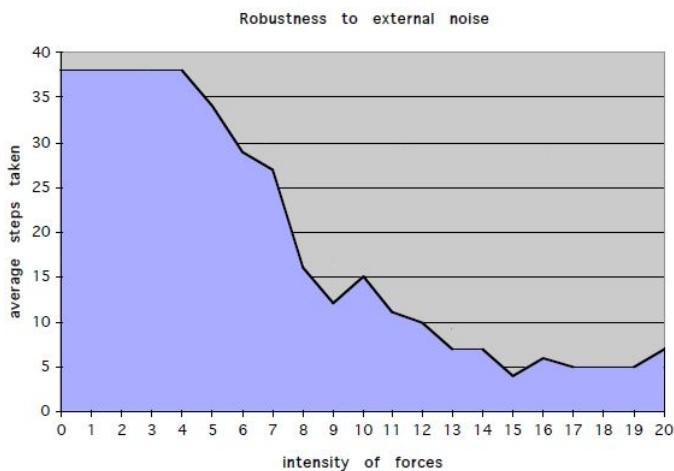
During evolution:

reconnect sensors to NN
with small connection weights
Evolve all NN param weights
Evolve body params
Use $1/(1+v)$

During evaluation:

Same as before.

13



Robustness to **external** perturbations

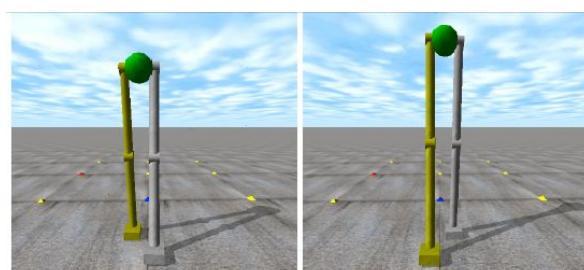
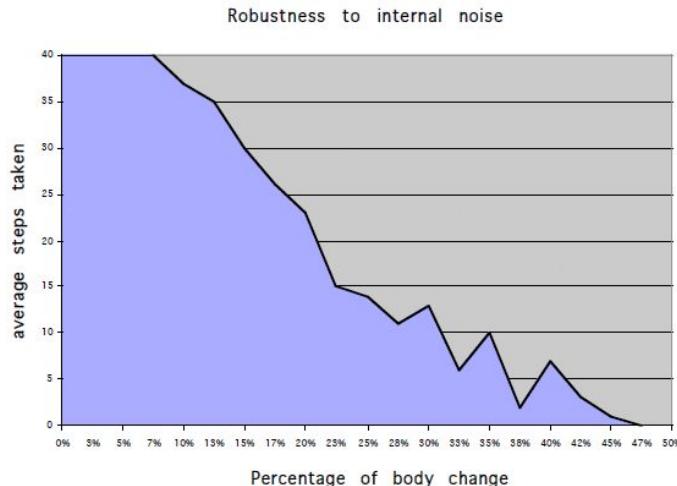
Evolve for another 100 generations.

Small random force vectors applied to the robot while it moved (i.e. "wind").

"Developed dynamic mechanisms to adapt to noise."

"When pushed too far to one side, the machine was observed to adjust its foot placement by stepping inward to regain balance."

14

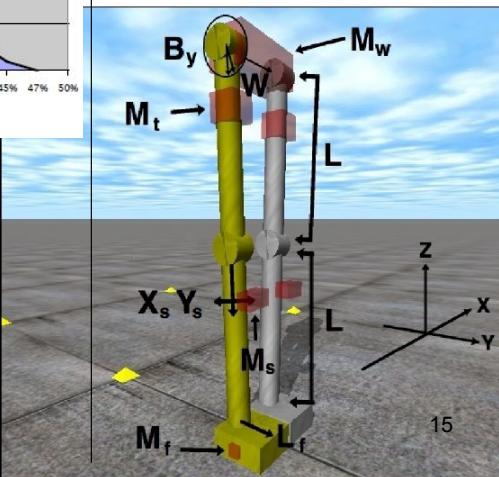


Robustness to **internal** perturbations

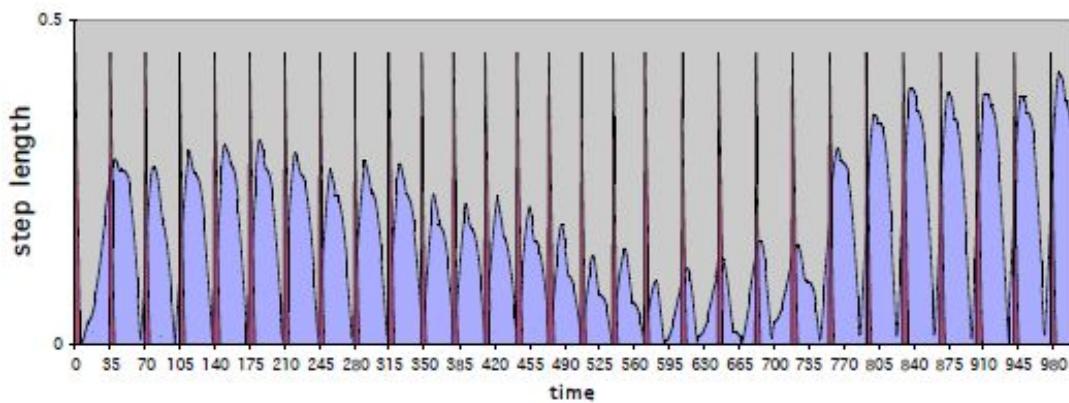
Evolve further.

Introduce “mistakes” when building the body.

Random changes are made to the body params



Robustness to **CPG** perturbations
Gait modulation



Modularity

Data/function hiding
in object-oriented programming:

The internal complexity of an object is hidden from the objects that call its public methods.

```
Class Pyrosim_Shape
public:
    Create(...); Draw(...); Delete(...)
```

...this internal complexity will grow as the object becomes more complex, but interactions between objects should grow at a slower rate:

```
Class Pyrosim_Robot
public:
    Create(...); Draw(...); Delete(...)
private:
    CreateNN(...); DestroyNN(...);
    CreateBody(...); DestroyBody(...);
    CreateJoints(...); DestroyJoints(...);
    ActuateJoints(...); CollectSensorReadings();
```

An important concept in many domains.

Different definitions in different domains, but similar concept:

Tighter coupling within modules;
less coupling across modules.

A module in object-oriented programming: the object.

1

Modularity

Why is modularity important for evolutionary robotics?

Structural modularity:

Reduces the quadratic increase in synapses as the number of neurons increases.

Functional modularity:

The size of the network does not need to increase with the number of motor primitives (i.e. simple actions the robot must perform)

2

Why is modularity important for evolutionary robotics?

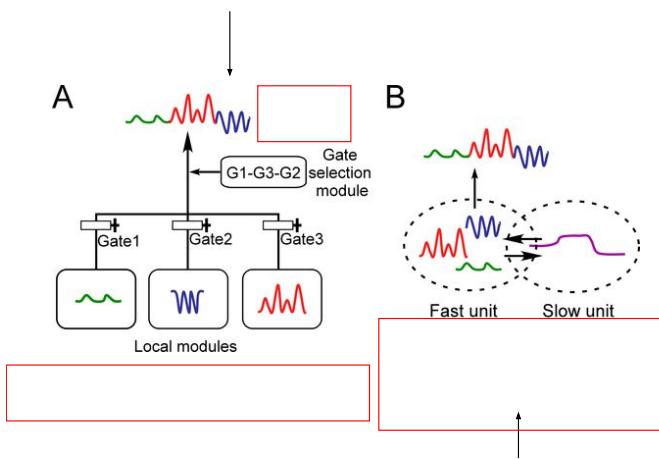
Structural modularity:

Reduces the quadratic increase in synapses as the number of neurons increases.

Functional modularity:

The size of the network does not need to increase with the number of motor primitives (i.e. simple actions the robot must perform)

Structural modularity in (neural) networks:
different parts of the network at different times.



Functional modularity in (neural) networks:
the network exhibits a fixed number of dynamic patterns.

3

Given a task...

the roboticist
may break the task down into several subtasks, and assign a subnetwork to each task.

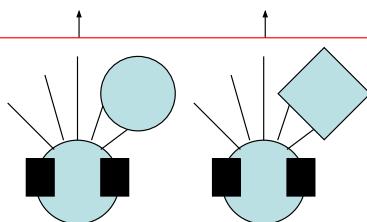
the evolutionary algorithm
may create modules appropriate for the task.

However, roboticist and robot may have different ideas about what counts as a 'behavior'...

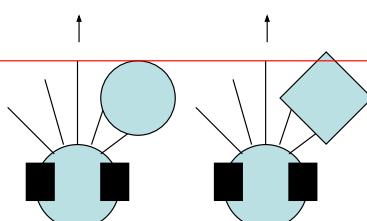
4

Structural modularity**Distal perspective of behavior:**

how does behavior look from
the perspective of the distal observer.

**Proximal perspective of behavior:**

how does behavior look from
the perspective of the robot (i.e., from its sensors).



Given a task...

the roboticist

may break the task down into
several subtasks, and
assign a subnetwork to each
task.

the evolutionary algorithm

may create modules
appropriate for the
task.

However, roboticist and
robot may have different
ideas about what counts
as a 'behavior' ...

5

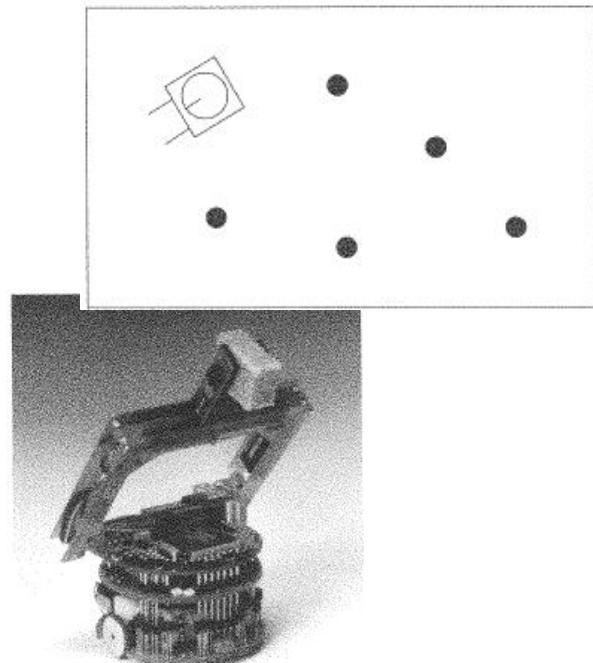
Structural modularity**Research question:**

How to enable evolution
to discover modules appropriate
to the task?

[Today's assigned reading]

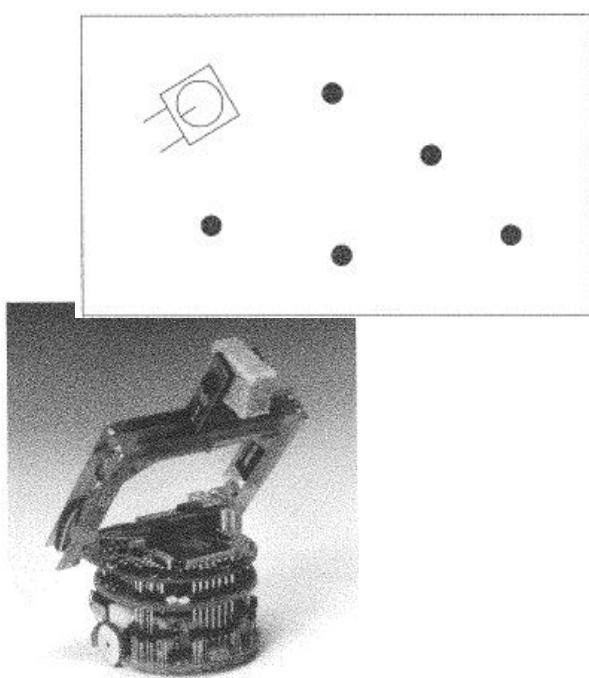
Task:

Pick up all objects and drop
them over the wall and thus
out of the arena.



6

Structural modularity



Task:

Pick up all objects and drop them over the wall and thus out of the arena.

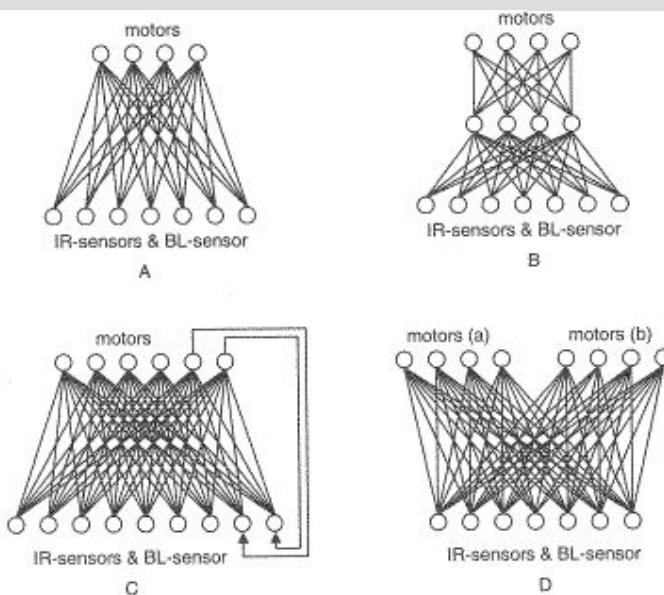
Possible decomposition:

- Explore environment, avoid walls.
- a1: if no sensors firing, move forward.
- a2: if left sensors firing, turn right.
- Recognize object, move to position for pick-up.
- Pick up object.
- Move toward wall (avoid other objects)
- Recognize wall, move close to it.
- Release object.

7

Structural modularity

Five possible networks:



A: feedforward,
no hidden neurons

B: feedforward,
hidden neurons

C: Recurrent,
hidden neurons

D: Two pre-designed
modules:

First module used
when gripper empty;

Second module used
when gripper full.

8

Structural modularity

Five possible networks:

E: Emergent modular network.

Four neurons per motor neuron

Two selector neurons,
two output neurons.

If first selector neuron >
second selector neuron:

first output neuron
controls motor neuron.

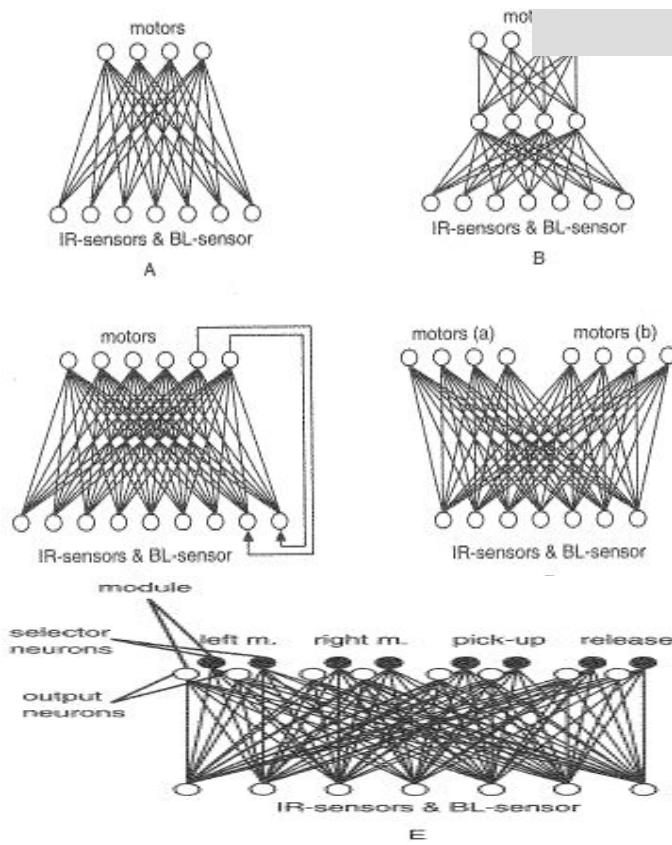
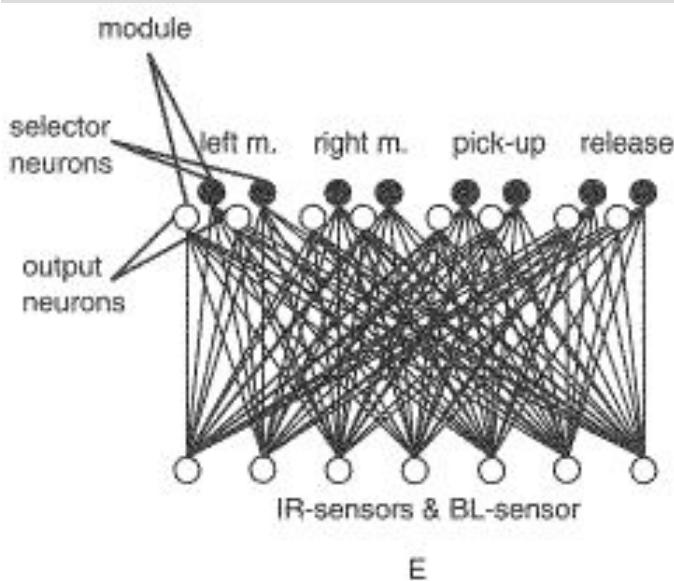
otherwise:

second output neurons
controls motor neuron.

How many 'states' are possible?

State = which selector neurons
control the motor neurons.

9



Structural modularity

Can investigate the role of:

a) Internal units

(internal neurons can 'recode'
sensor signals to cause
very different reactions to
very similar patterns.)

b) Recurrent connections

(allows the robot to
react differently to the
same stimuli, if it experienced
different conditions just
previously.)

c) Modularity

(divide continuously changing
sensor signals into groups,
to be processed by different
neural modules).

10

Structural modularity

Results:

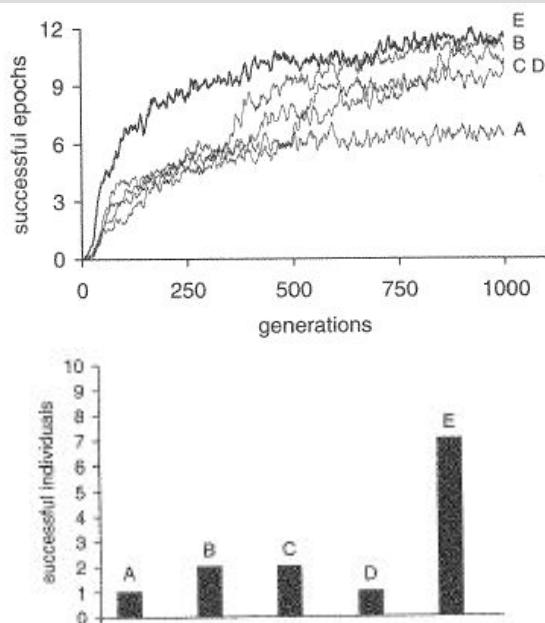
For each controller,

Robot put into arena 15 times,
or epochs, at different
positions and orientations.

1 epoch = 200 actions or object
correctly released.

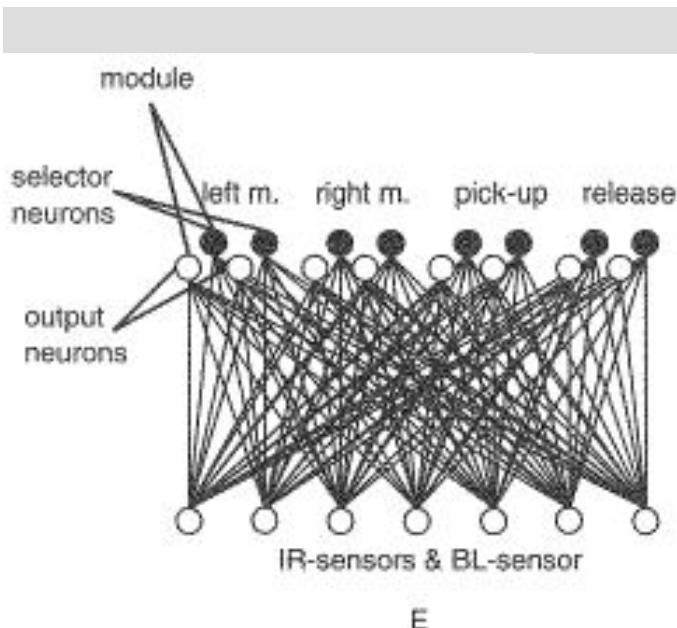
Controllers evolved for 1000
generations.

10 replications for each of
the five controllers:
50 runs in total.



For the best controller from the 10 replications,
how many successfully cleaned the arena?

11



Structural modularity

Q: Is there a correspondence
between evolved modules
and distal behaviors
(e.g. explore until object
found?)

A: No.

Results from one evolved
controller E.

Controller has two states:

Only right motor is controlled
by both output neurons;

for the other three motor
neurons, one selector neuron
always 'wins'.

12

Structural modularity

Mod: Which module controls the right motor?

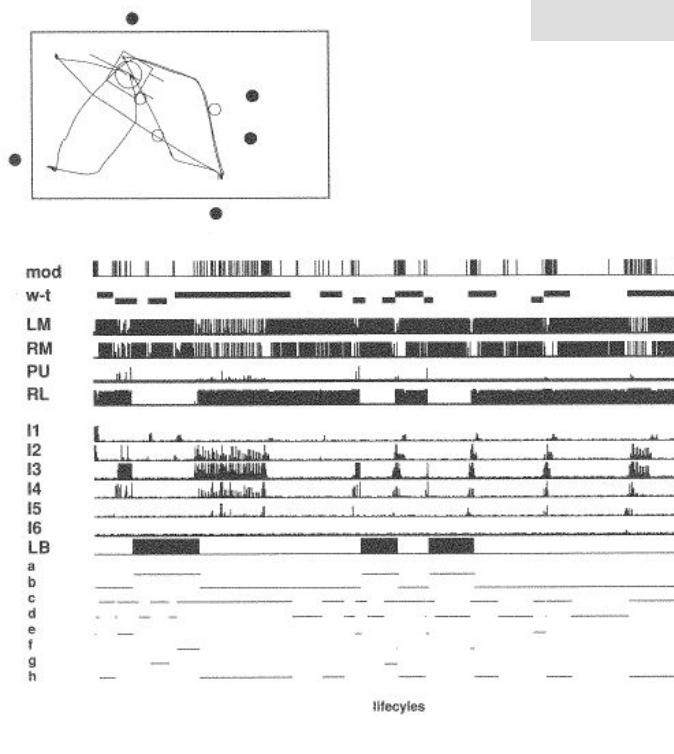
w-t: what is perceived?
w=wall; t=target object

LM=left motor; RM=right motor
PU=pick up; RL=release

i1-i6: infrared sensors
LB = light barrier sensor

- a: carrying object, look for wall
- b: gripper empty, look for object
- c: sees something: wall/object?
- d: doesn't see anything
- e: approaching object
- f: approaching wall
- g: avoiding an object
- h: avoiding a wall.

13

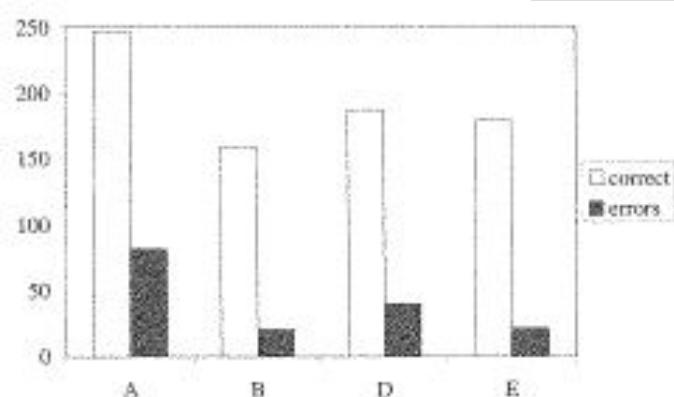


Structural modularity

When evolved controllers are placed in robot at novel locations, how many errors are made?

Novel stimuli:

Robot placed near object or wall at 180 different angles, 20 different distances, gripper full or empty.
($180 \times 20 \times 2 = 7200$ trials)



Robot with internal neurons (B) or emergent modules (E) makes fewer mistakes.

B, E: Two out of 10 networks never made mistakes.

A,D: All 10 made mistakes.

C: ?

14

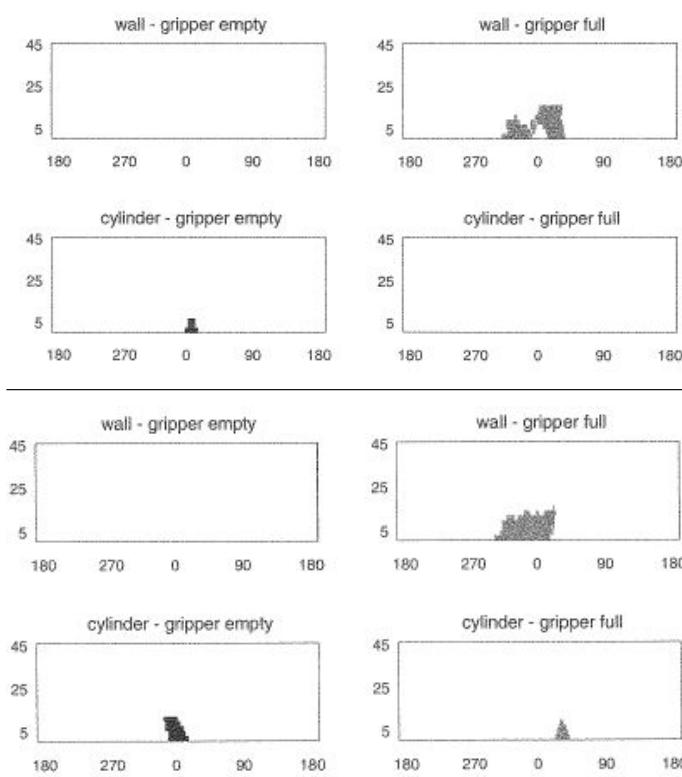
Structural modularity

One evolved E controller
that never makes mistakes:

Black pixel: triggers pick-up
behavior.

Gray pixel: triggers release
behavior.

White pixel: neither is triggered.



One evolved E controller
that makes mistakes:

Mistakenly releases object
when it encounters an object
close up on its right side.

However...

15

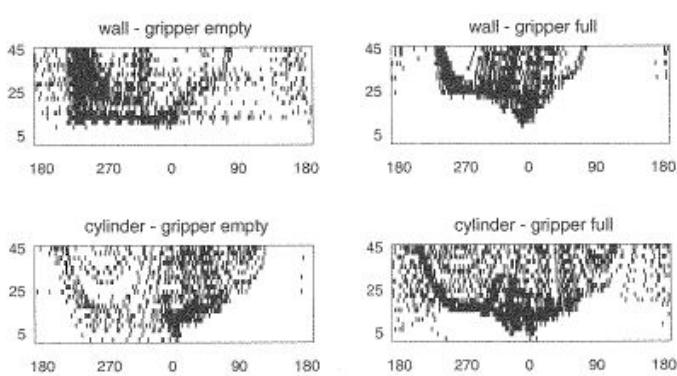
Structural modularity

...this controller never
encountered this situation
when behaving in the arena.

(black pixel: situation
experienced when evaluated
during evolution.)

(white pixel: situation not
experienced when evaluated
during evolution.)

16



Structural modularity

Experiment was a success;
evolution determined:

1.

2.

3.

4.

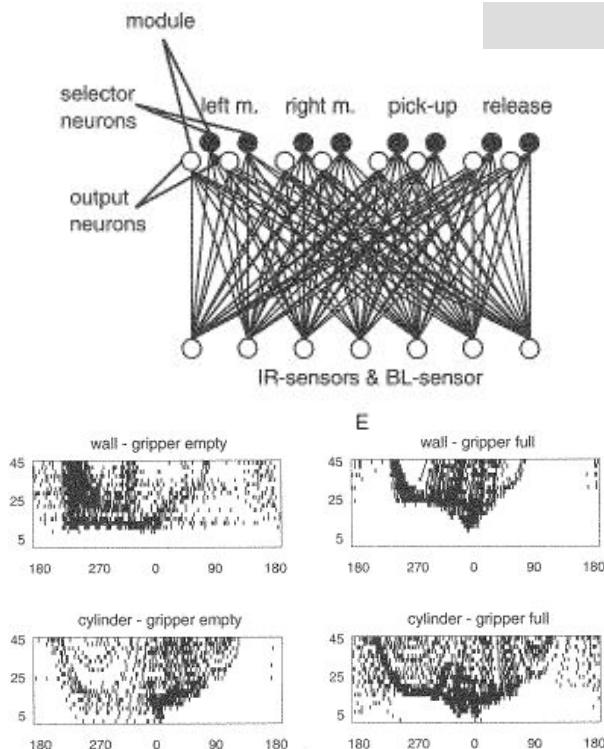
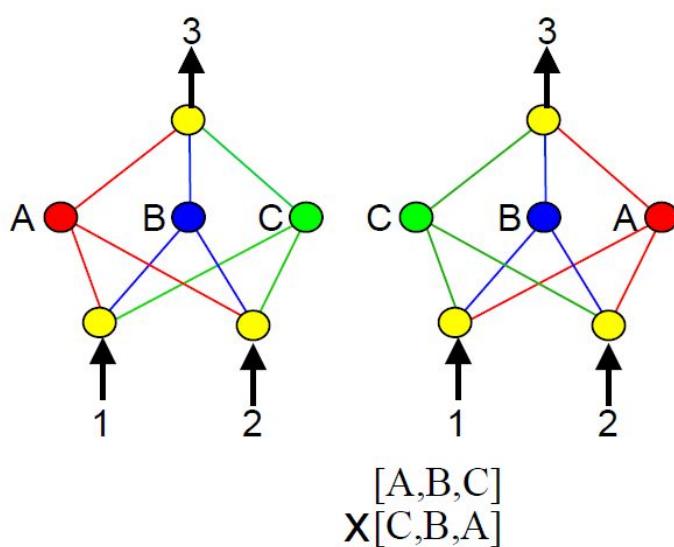


Fig. 6.10

17

NEAT / HyperNEAT



Crossovers: [A,B,A] [C,B,C]
(both are missing information)

Competing Conventions:

Two neural networks:

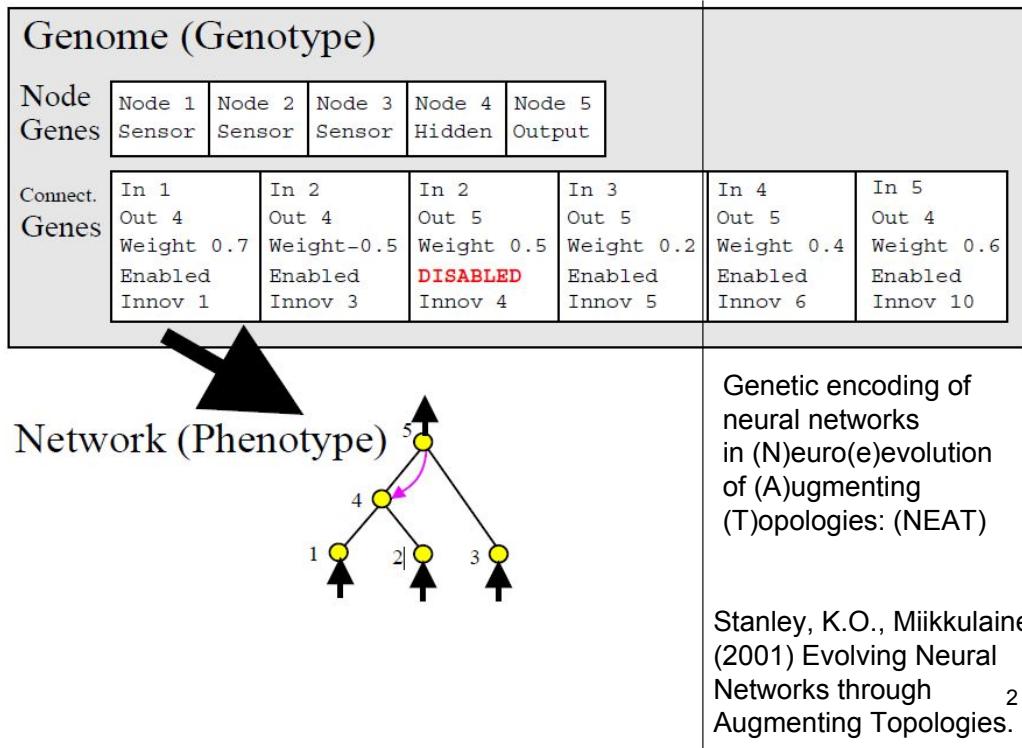
Both encode the same function;

Have different conventions for doing so.

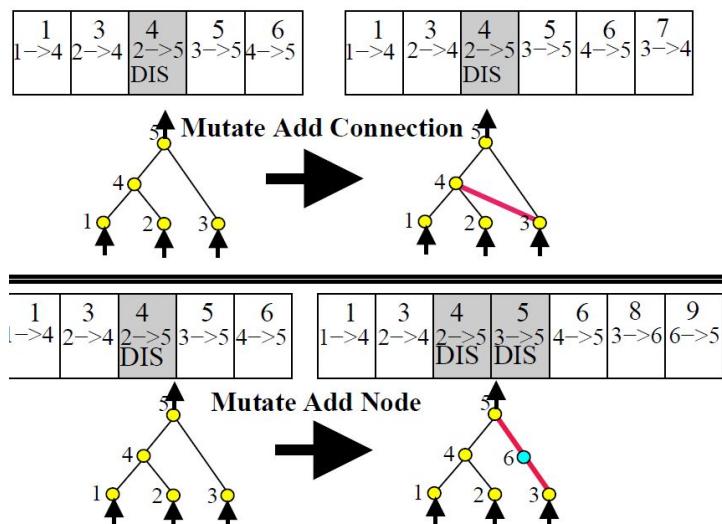
No matter how they're crossed, their children will lack information.

Stanley, K.O., Miikkulainen (2001) Evolving Neural Networks through Augmenting Topologies.

NEAT / HyperNEAT



NEAT / HyperNEAT



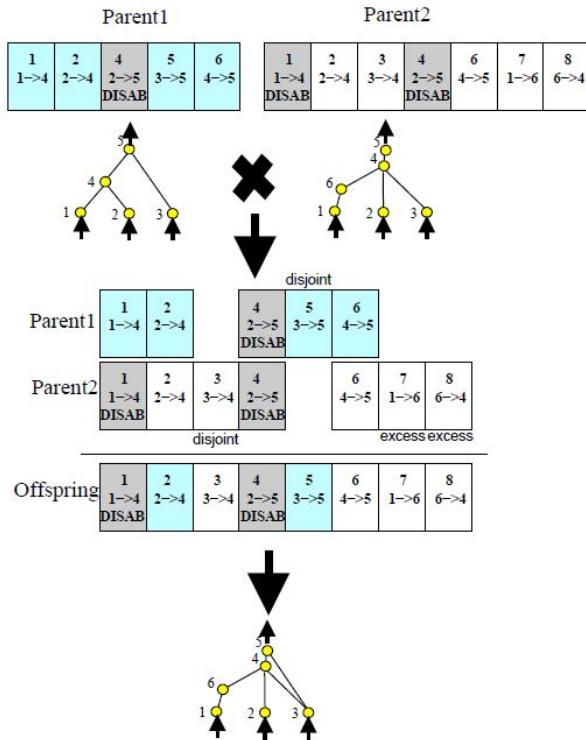
Historical Markings:

Keep a global counter; every time a neuron or synapse is added, assign the value of the counter, and increment it.

Genes/synapses can be disabled, but remain in the genome.

Stanley, K.O., Miikkulainen (2001) Evolving Neural Networks through Augmenting Topologies.

NEAT / HyperNEAT



NEAT designed so
That crossover is

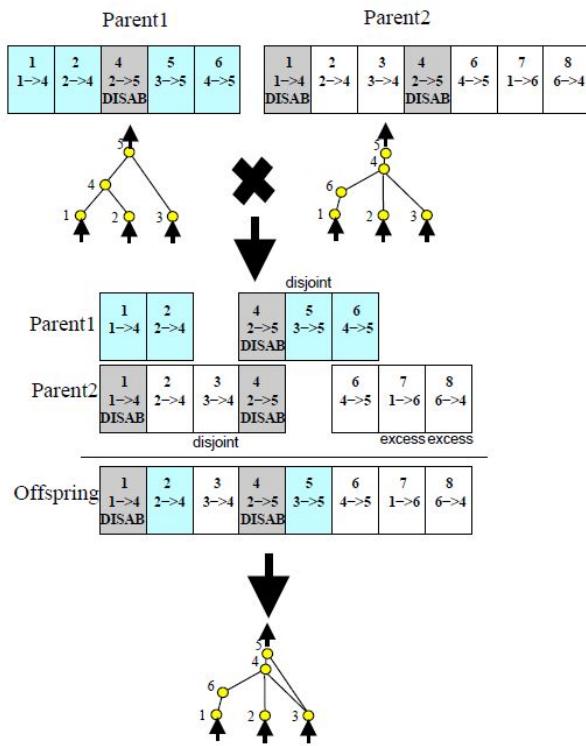
(1) Algorithmically simple

and

(2) Produces children
that are similar to their
parents.

Stanley, K.O., Miikkulainen
(2001) Evolving Neural
Networks through
Augmenting Topologies.⁴

NEAT / HyperNEAT



Take two parent
NNs:

Line up connection genes
according to their
historical markings.

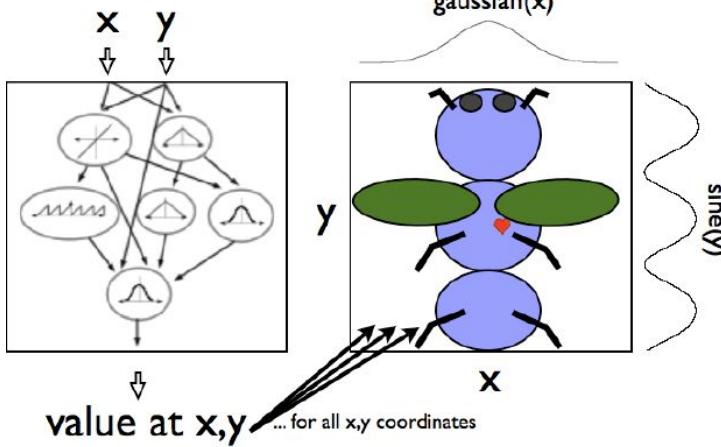
For matching genes,
copy either gene into child
at random.

Disjoint genes (those
in the middle without a
partner gene)

Excess genes (those at
the end)

Stanley, K.O., Miikkulainen
(2001) Evolving Neural
Networks through
Augmenting Topologies.⁵

NEAT / HyperNEAT

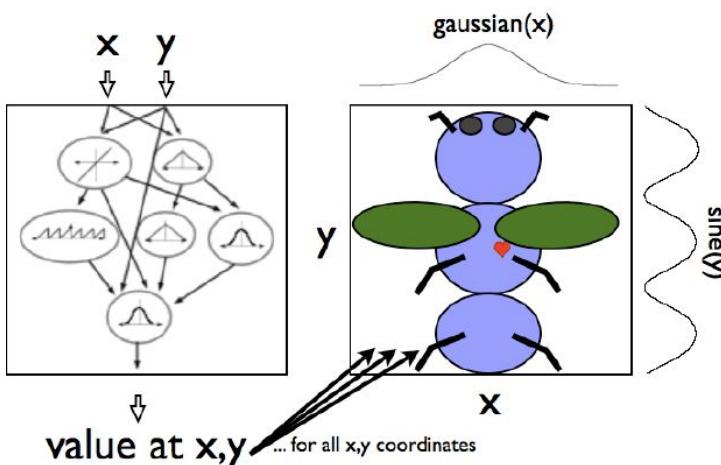


HyperNEAT:

Evolves neural networks (compositional pattern-producing networks) that produce regular patterns spatially:

Clune, J. et al. (2009)
Evolving Coordinated Quadruped Gaits with the HyperNEAT Generative Encoding

NEAT / HyperNEAT



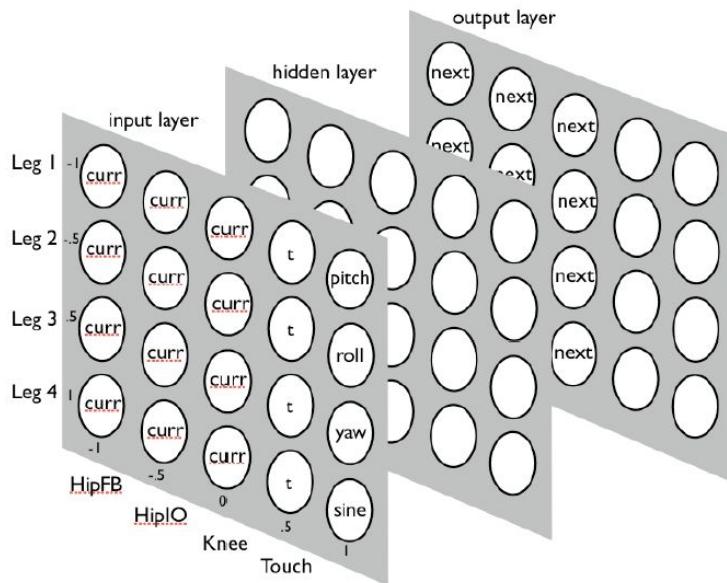
HyperNEAT:

HyperNEAT “paints” regular patterns on to a hypercube.

The dimensionality of the hypercube is determined by the dimension of the input coordinates.

Clune, J. et al. (2009)
Evolving Coordinated Quadruped Gaits with the HyperNEAT Generative Encoding

NEAT / HyperNEAT

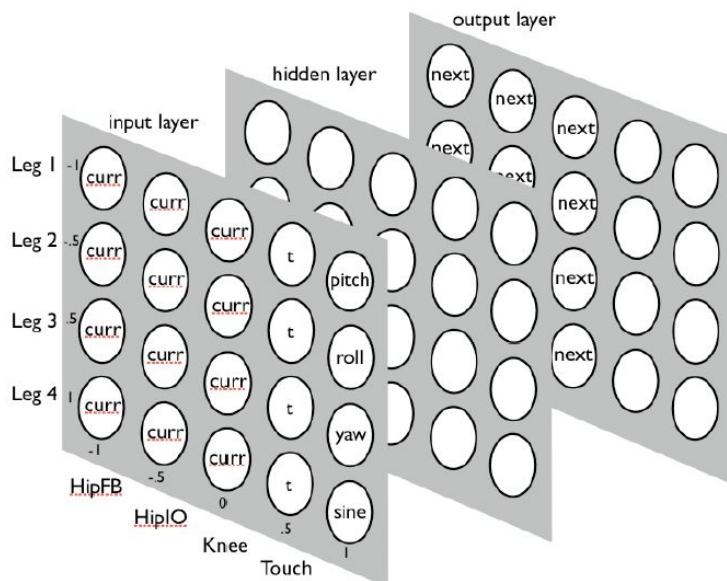


HyperNEAT can be used to “paint” weights on to synapses of a second neural network.

Requires that each neuron and synapse have a 3D location:

Clune, J. et al. (2009)
Evolving Coordinated Quadruped Gaits with the HyperNEAT Generative Encoding

NEAT / HyperNEAT



HyperNEAT can be used to “paint” weights on to synapses of a second neural network.

...why do this, if NEAT already evolves neural networks?

Clune, J. et al. (2009)
Evolving Coordinated Quadruped Gaits with the HyperNEAT Generative Encoding

NEAT / HyperNEAT

HyperNEAT



FT-NEAT



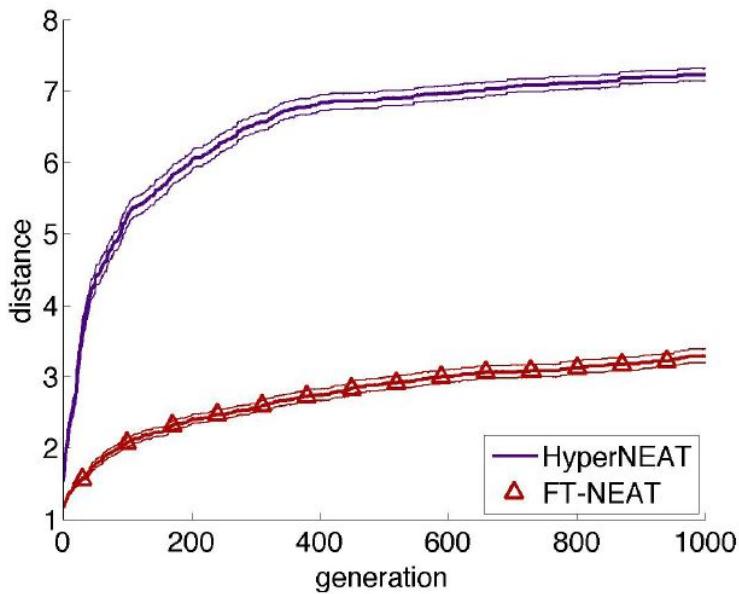
Compare HyperNEAT to NEAT:

FT-NEAT: Fixed Topology NEAT.

Use same NN as in HyperNEAT;
allow for mutation and crossover, but
not the addition/removal of neurons/synapses.

Clune, J. et al. (2009)
Evolving Coordinated
Quadruped Gaits with the
HyperNEAT Generative
Encoding

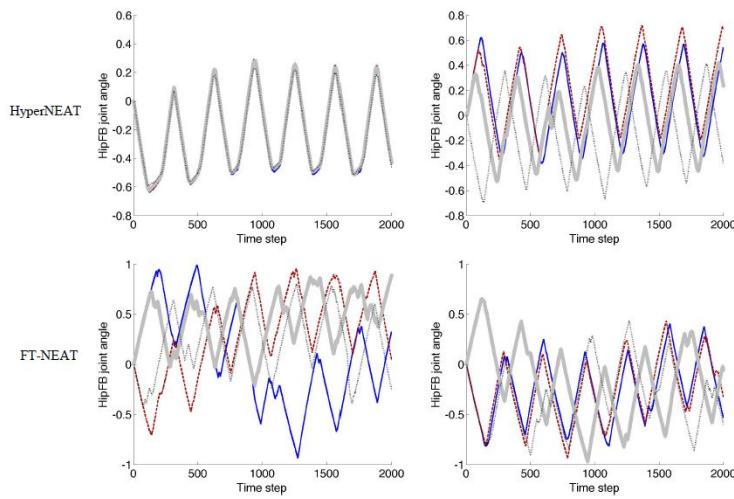
NEAT / HyperNEAT



Results from
evolving locomotion.

Clune, J. et al. (2009)
Evolving Coordinated
Quadruped Gaits with the
HyperNEAT Generative
Encoding

NEAT / HyperNEAT

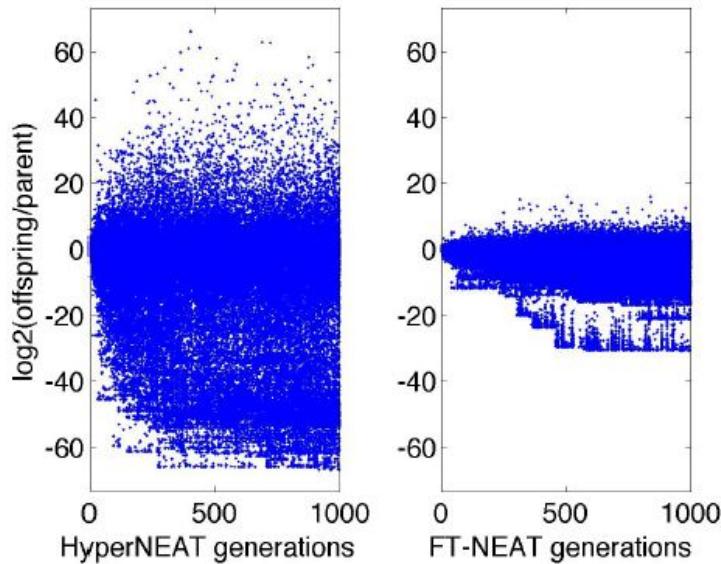


HyperNEAT repeatedly finds regular gaits;

FT-NEAT does not.

Clune, J. et al. (2009)
Evolving Coordinated Quadruped Gaits with the HyperNEAT Generative Encoding

NEAT / HyperNEAT



For mutations,

mean fitness of children compared to parents:

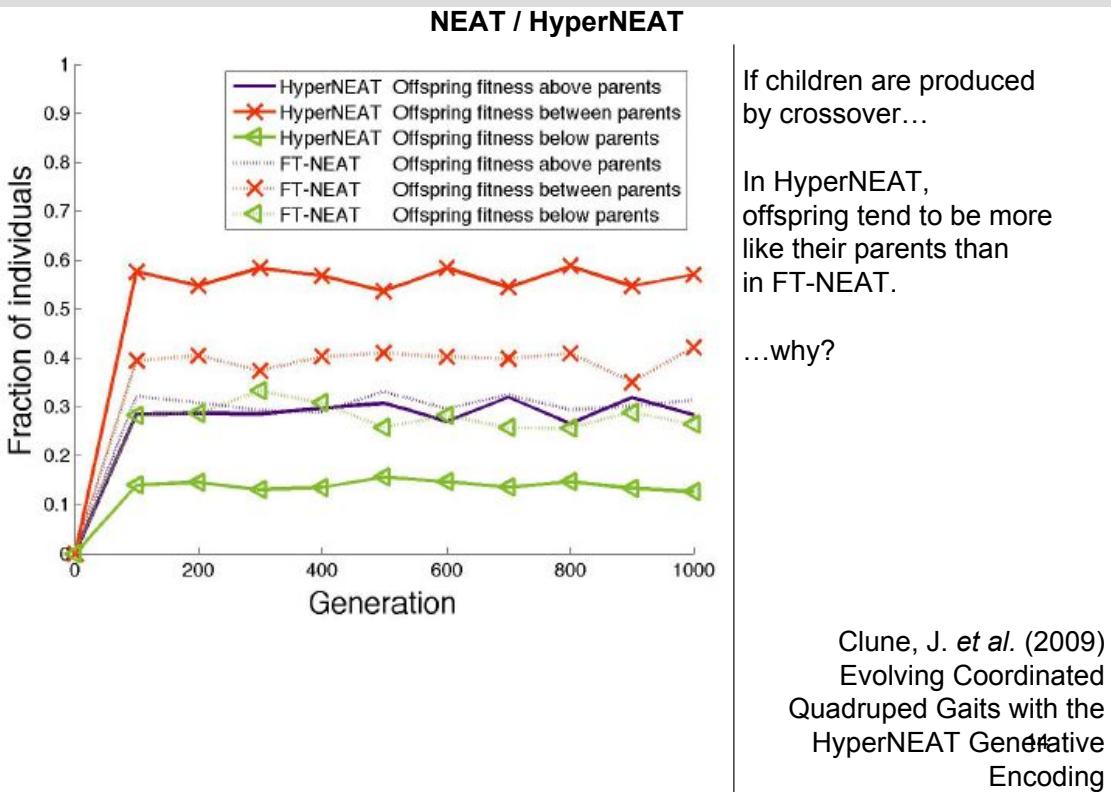
HyperNEAT:
FT-NEAT:

but HyperNEAT tends to create more fit children than FT-NEAT.

..why?

It also creates much worse children, but these are discarded.

Clune, J. et al. (2009)
Evolving Coordinated Quadruped Gaits with the HyperNEAT Generative Encoding



The radical envelope-of-noise hypothesis

Observation: Evolution will create controllers that exploit details of the simulation.

If those details do not exist in reality, the controller fails to cross the reality gap.

Hypothesis: Adding noise to a simulator in the right way forces evolution to create more robust controllers.

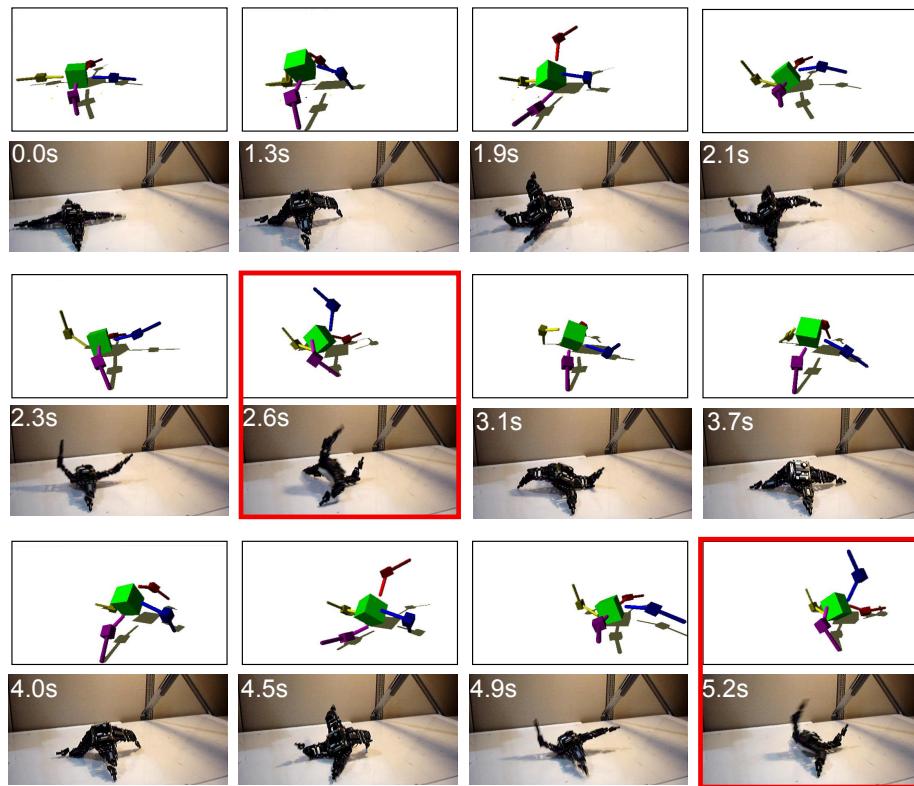
Question: What aspects of a simulation to noisify?
If the simulation is complex, many things must be noisified: friction, mass distribution, geometry, joint properties, sensor properties, motor properties.

Solution: Create a minimal simulation.

Minimal simulation: Simulation that contains as little details as possible.

Jakobi, N. (1997) Evolutionary Robotics and the Radical Envelope-of-Noise Hypothesis. *Adaptive Behavior*, 6(2): 325-368.

Generating behaviors using an optimized model



2

L15

The radical envelope-of-noise hypothesis

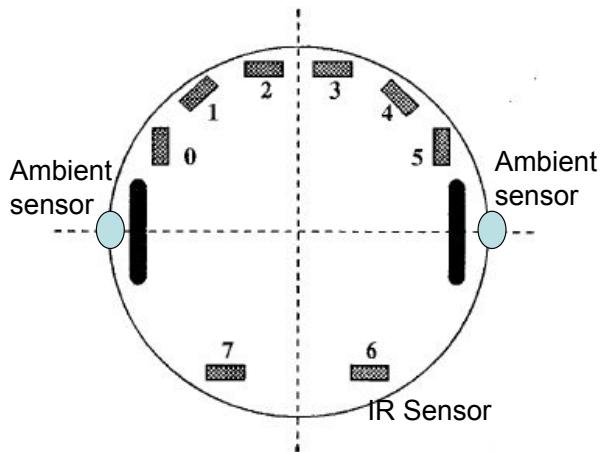
those simulation aspects that have a basis in reality
(but will still be slightly different in reality)

those simulation aspects that *do not* have a basis in reality.
(might be completely different in reality)

During evolution in simulation...

add a bit of noise to the base set
add 100% of noise to the implementation set
(so evolved controllers do not rely on them)

Radical Envelope-of-Noise
Hypothesis



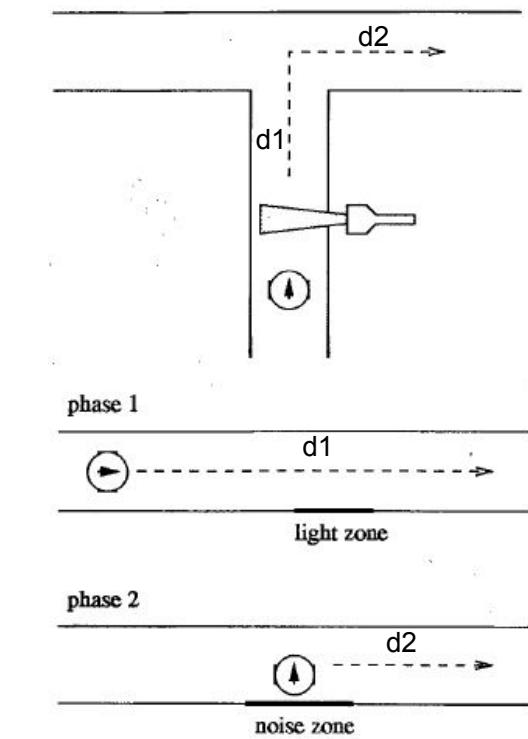
4

Radical Envelope-of-Noise
Hypothesis

The task (requires memory)

If light on right,
turn right at corner.

If light on left,
turn left at corner.



Minimal simulation:

Robot can move through
two, infinitely long corridors.

5

Radical Envelope-of-Noise Hypothesis

Minimal simulation (contd).

Simulation is made up of two look up tables:

Table I:

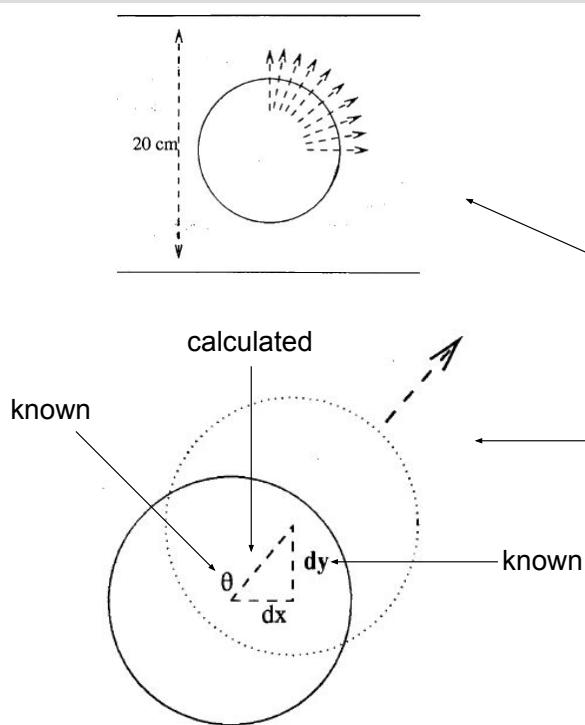
For robot's orientation, if move forward, update robot's x and y position.

Table II:

For robot's orientation θ and distance from the wall dy , how long is the line segment from IR sensor to wall?

Convert length to a sensor value.

6

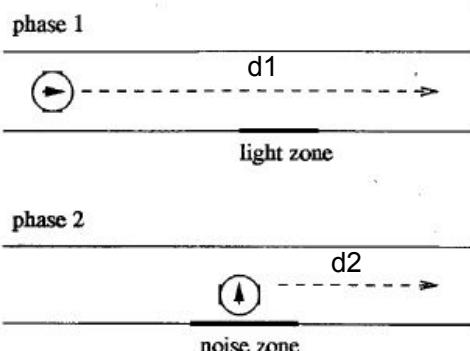


Radical Envelope-of-Noise Hypothesis

Base set (some basis in reality)

1. How robot moves in response to motor signals.
2. How IR sensors respond.
3. How the ambient sensors respond.

Add a bit of noise to these interactions.



7

Radical Envelope-of-Noise Hypothesis

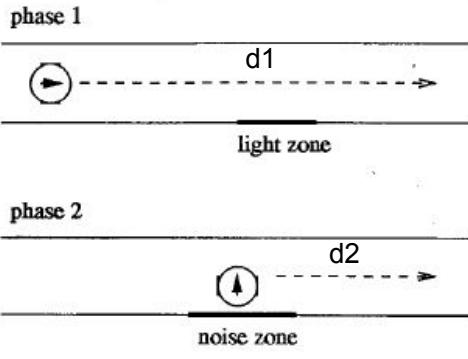
Implementation set

(implementation details of simulation unlikely to match details in reality)

1. How IR sensors behave when the robot is at the T-junction.

Add 100% noise:

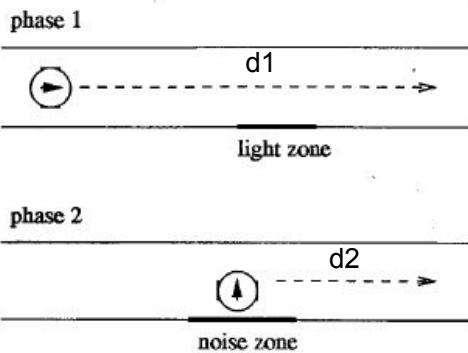
If an IR sensor ray intersects the “noise zone”, return a value randomly in sensor’s [min,max] range.



8

Radical Envelope-of-Noise Hypothesis

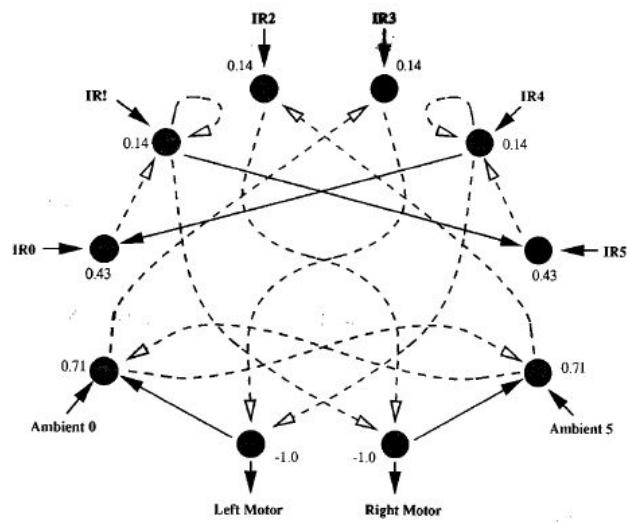
Additional implementation details (some noise added)



2. Side from which light comes
3. Corridor width
4. Starting robot orientation
5. Length of light zone
6. Corridor length

9

Radical Envelope-of-Noise Hypothesis



Evolved controllers:

Bilateral symmetry imposed.

Solid arrows: Excitatory links

Dashed arrows: Inhibitory links

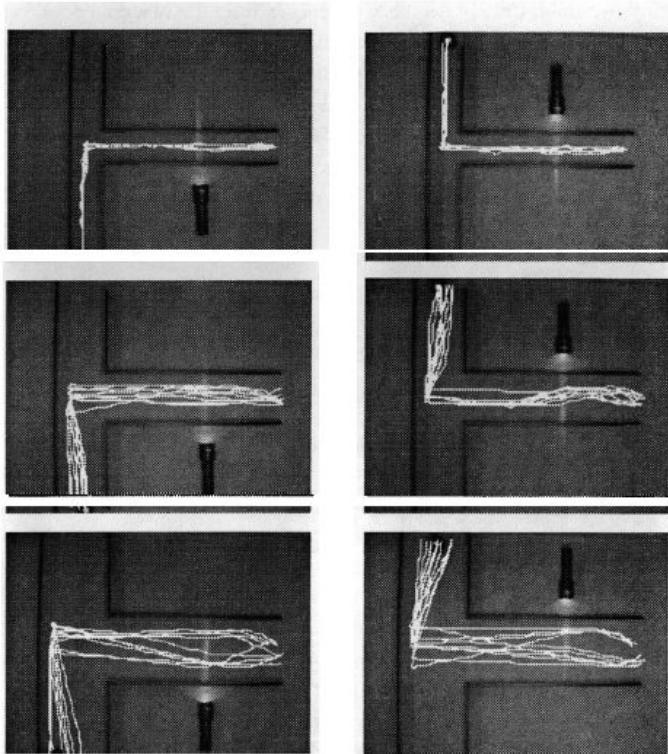
Numbers: Activation thresholds

Q: Where is the memory
of the light?

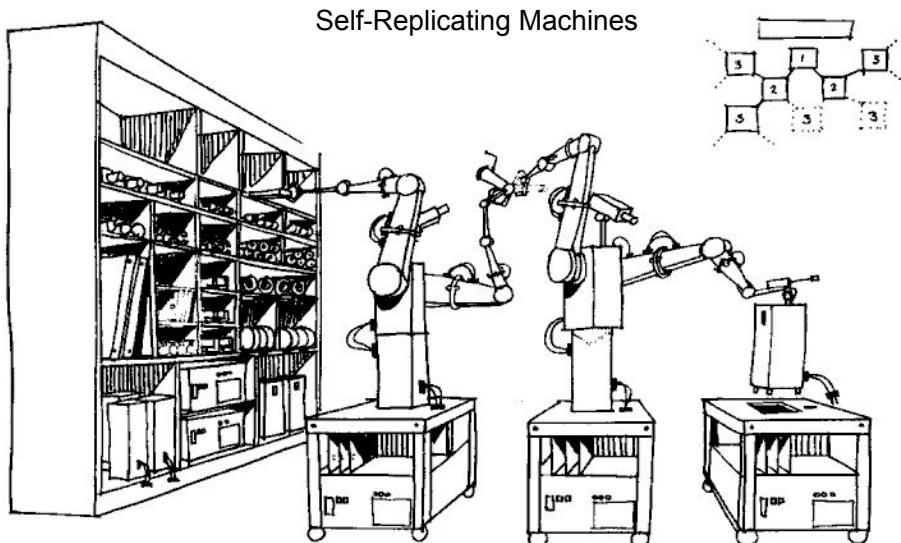
10

Radical Envelope-of-Noise Hypothesis

Results



11



Source: NASA Conference Publication 2255 (1982), based on the Advanced Automation for Space Missions NASA/ASEE summer study Held at the University of Santa Clara in Santa Clara, California, from June 23-August 29, 1980.

Original idea: John von Neumann, 1948;
often referred to as "von Neumann machines"
(different from von Neumann architecture)

1

The New York Times

THURSDAY, AUGUST 31, 2000

L16

The Golem Project

Scientists Report They Have Made Robot That Makes Its Own Robots

By KENNETH CHANG

For the first time, computer scientists have created a robot that designs and builds other robots, almost entirely without human help.

In the short run, this advance could lead to a new industry of inexpensive robots customized for specific tasks. In the long run — decades at least — robots may one day be truly regarded as "artificial life," able to reproduce and evolve, building improved versions of themselves.

Such durable, adaptive robots, astronomers have suggested, could someday be sent into space to explore the galaxy or search for other life.

But the quest to create artificial life also revives concerns that computer scientists could eventually create a robotic species that would supplant biological life, including humans.

"Some things we probably do we shouldn't do," said Bill Joy, chief scientist at Sun Microsystems, who wrote a recent article warning of the power of emerging technologies.



Brandeis University
The "Arrow" left a trail as it crawled across a bed of sand.

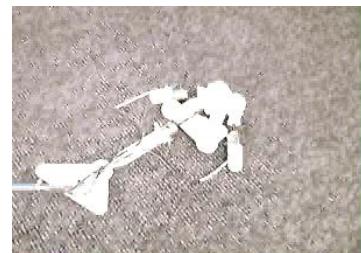
were not manufactured by humans."

Dr. Pollack and Dr. Lipson, a research scientist, report their results

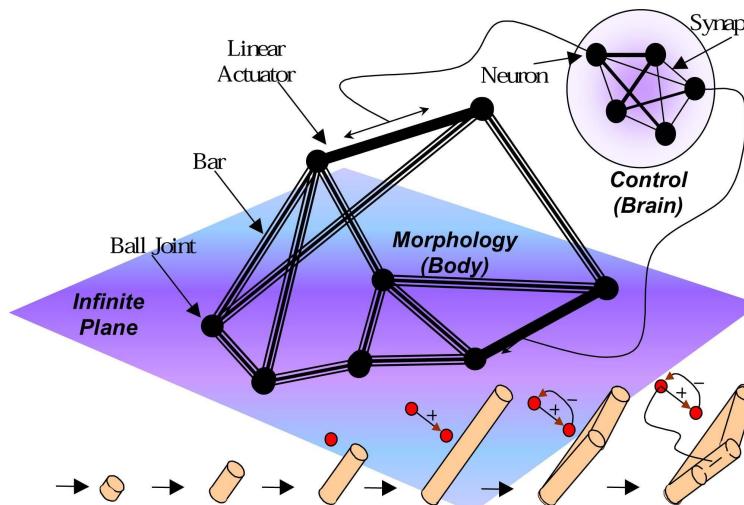
in today's issue of the journal Nature.

"This is the first example of pretty much 100 percent automated evolution of a machine," said Dr. Philip Husbands, a professor of artificial intelligence at the University of Sussex in England. "It's a rather primitive example, but it's the first step to something that could be quite significant."

In the future, the technique could



Lipson, H., Pollack J. B., (2000),
"Automatic Design and Manufacture of Artificial Lifeforms",
Nature 406, pp. 974-978.



Step 1:

Step 2:

Step 3:

Genotype encoding:

The Golem Project

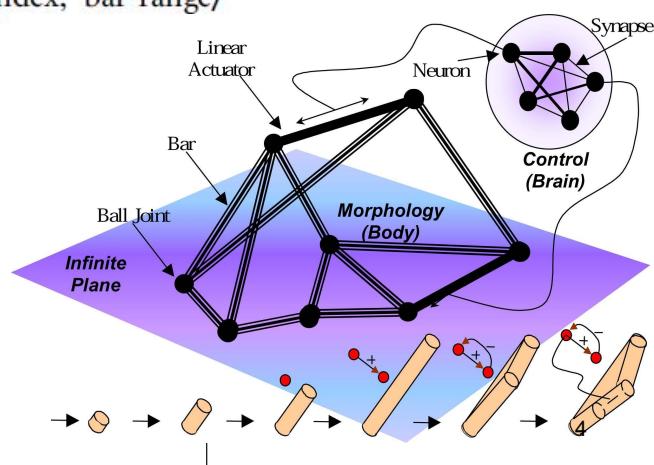
robot := <vertices><bars><neurons><actuators>

vertex := <x, y, z>

bar := <vertex 1 index, vertex 2 index, relaxed length, stiffness>

neuron := <threshold, synapse coefficients of connections to all neurons>

actuator := <bar index, neuron index, bar range>



Genotype encoding:

The Golem Project

Initial population: 200 null genotypes.

Fitness: Displacement of the center of mass

Evaluation period: "Fixed number (12) of cycles of its neural control"?

5

Genotype encoding:

The Golem Project

Mutations: 1. Change the length of a bar (10%)

2. Change a synaptic weight (10%)

3. add or 4. remove a dangling bar (1%)

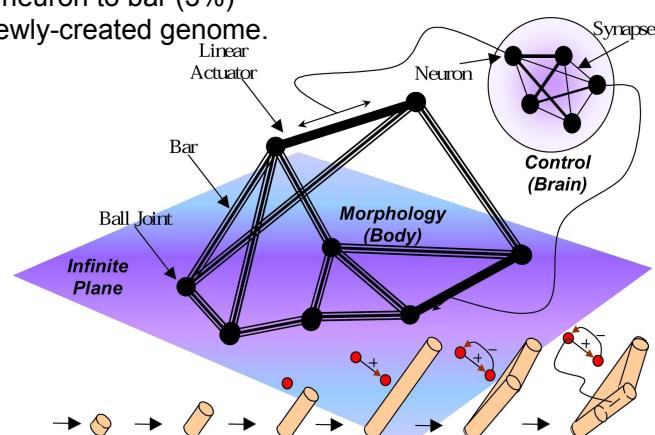
5. add or 6. remove unconnected neuron (1%)

7. split vertex into two and add a small bar (3%)

8. split bar into two and add vertex (3%)

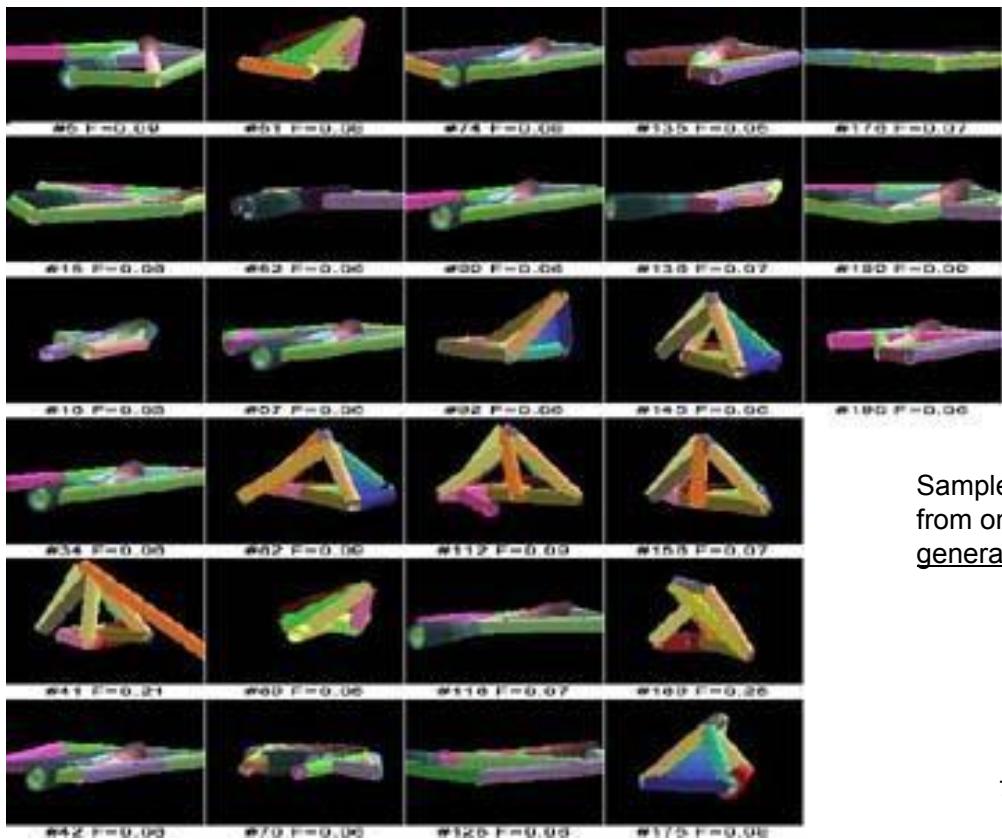
9. attach or 10. detach neuron to bar (3%)

One mutation was applied to each newly-created genome.



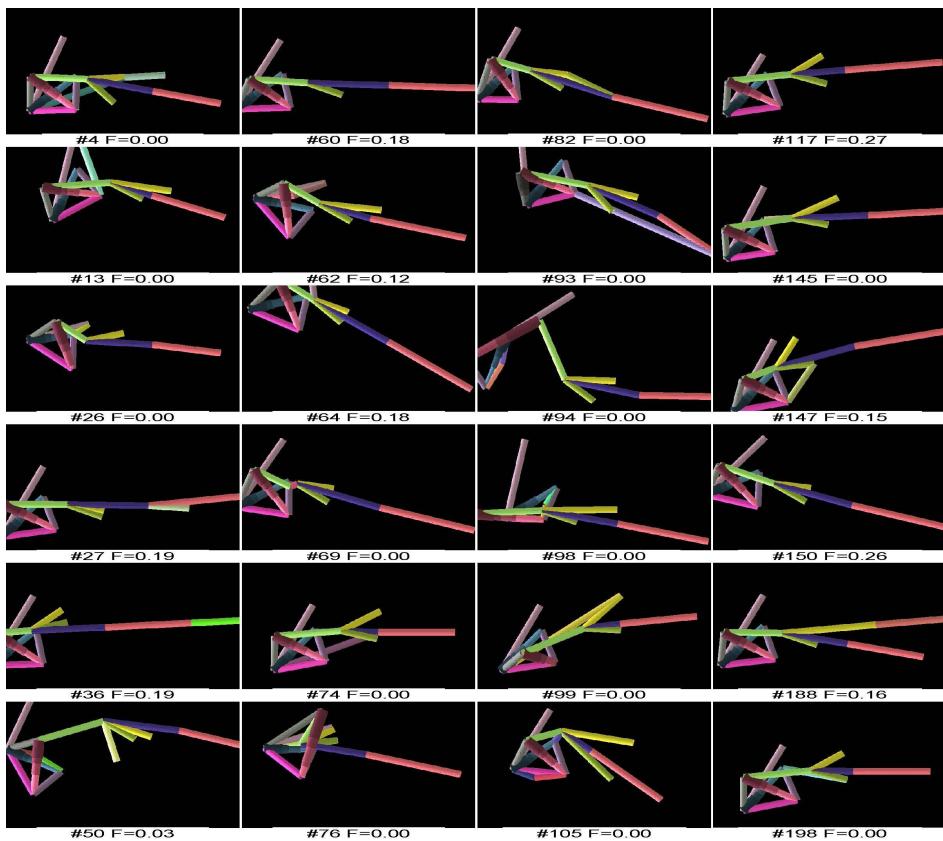
Q: Mutation sequence:

6



Samples
from one
generation.

7



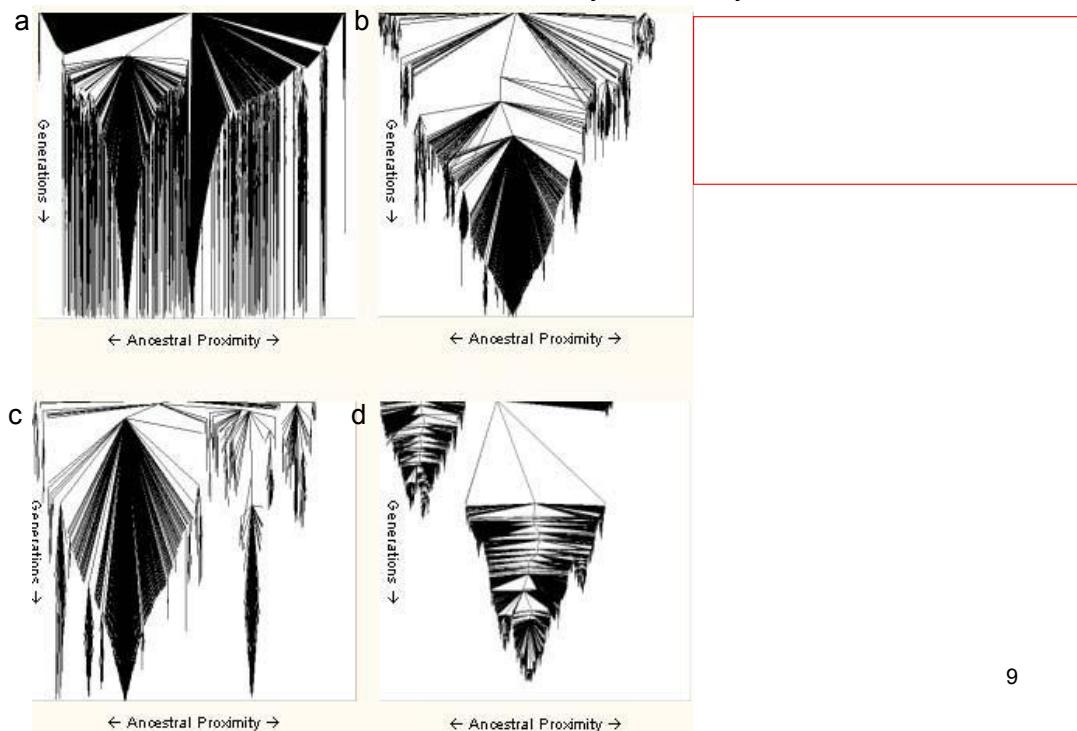
Samples
from one
evolutionary
run.

8

Another way of visualizing artificial evolution: phylogenetic trees

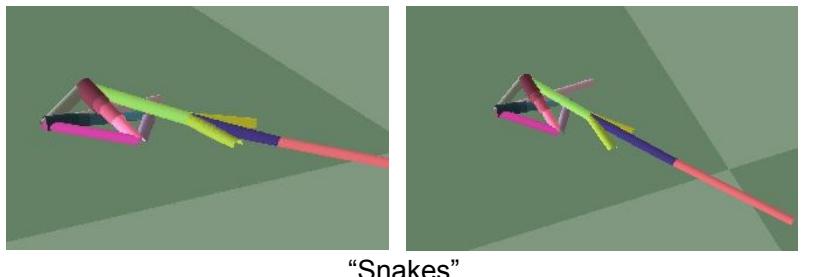
Node = individual; link = parent-child relationship

Horizontal distance between two nodes = similarity of ancestry

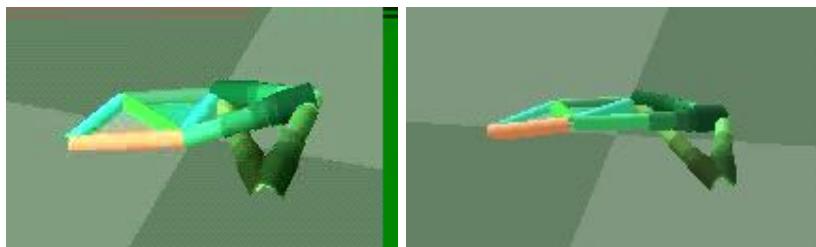


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The Golem Project



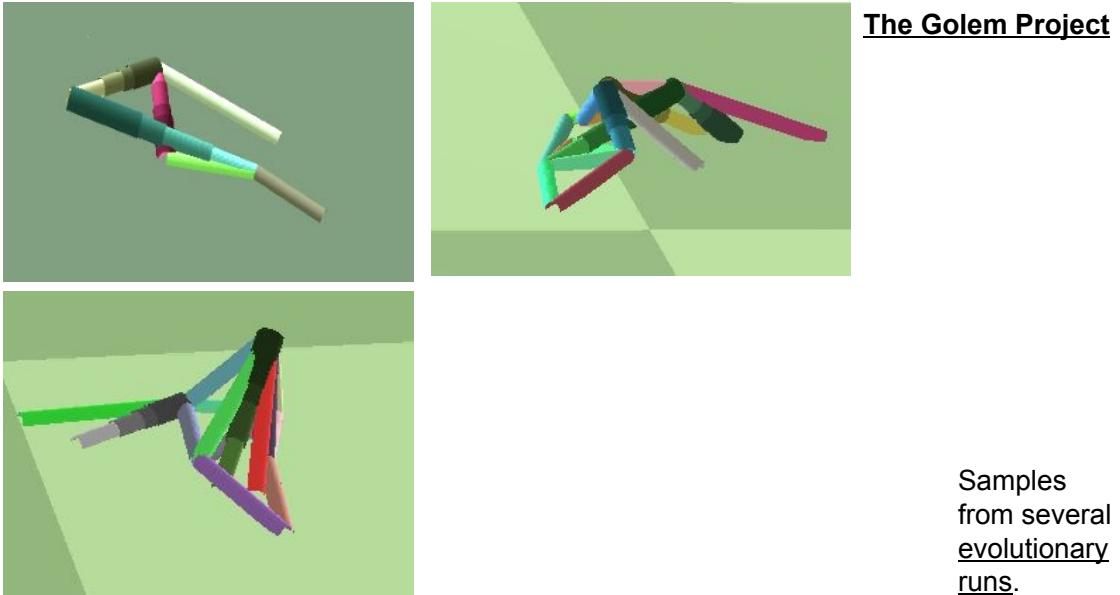
"Snakes"



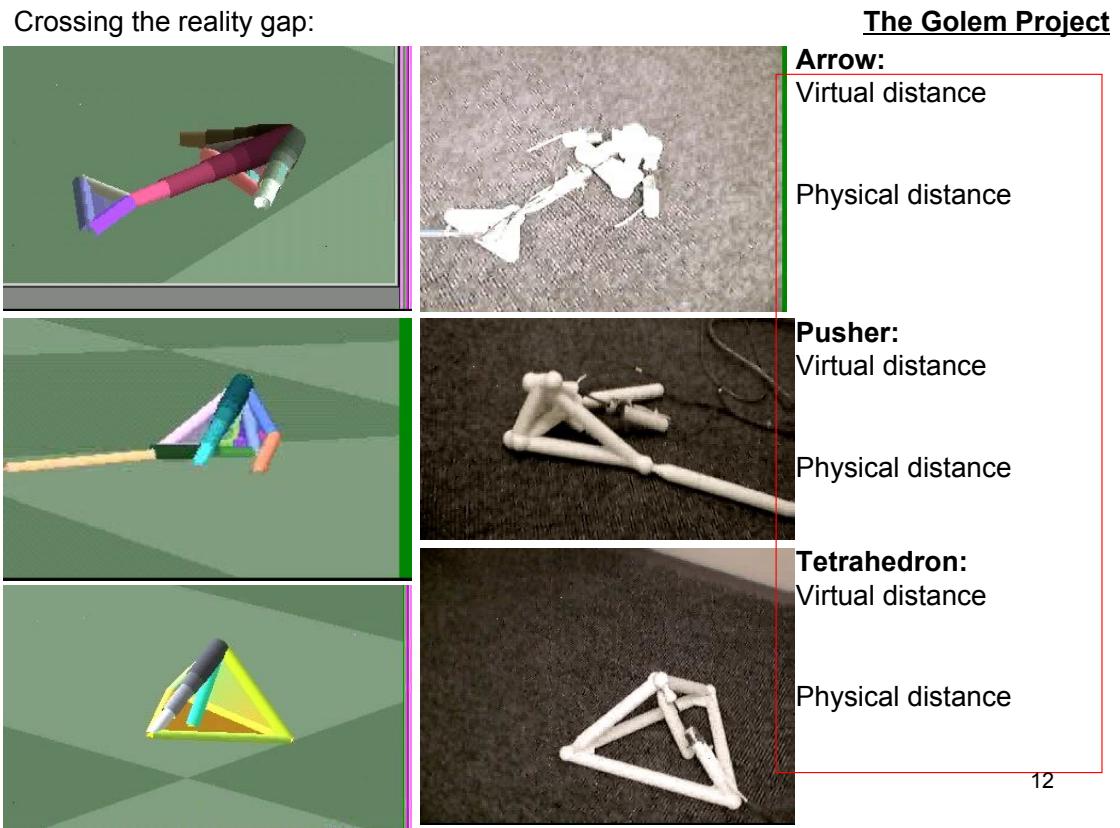
"Crabs"

Samples
from two
evolutionary
runs.

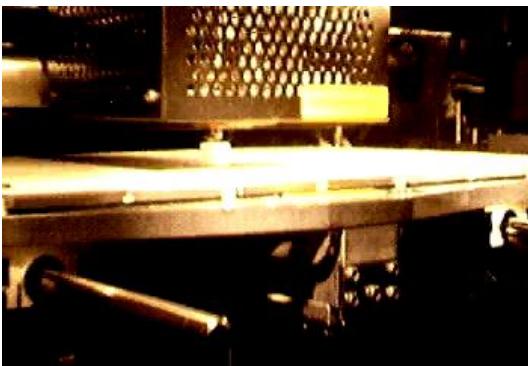
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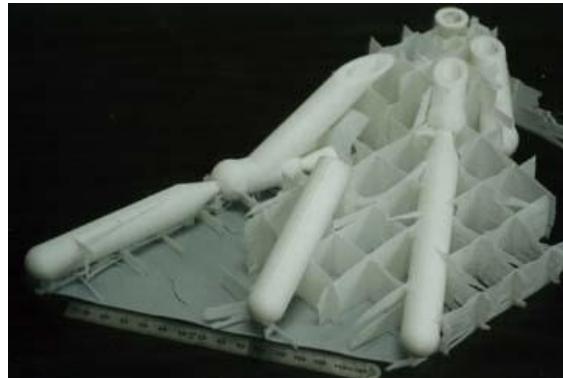
11



Crossing the reality gap:



The Golem Project



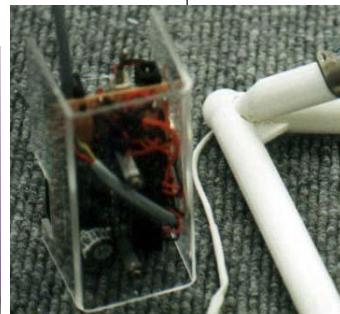
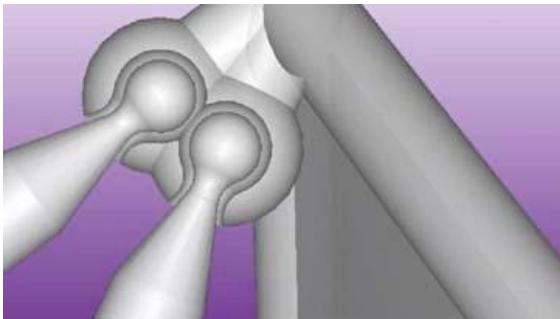
Step 1:
Evolve a robot to
locomote
in simulation (evolve body
and brain).

Step 2:
Manufacture robot
using 3D printer

Step 3:
Snap in motors
and electronics

13

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14

Crossing the reality gap:



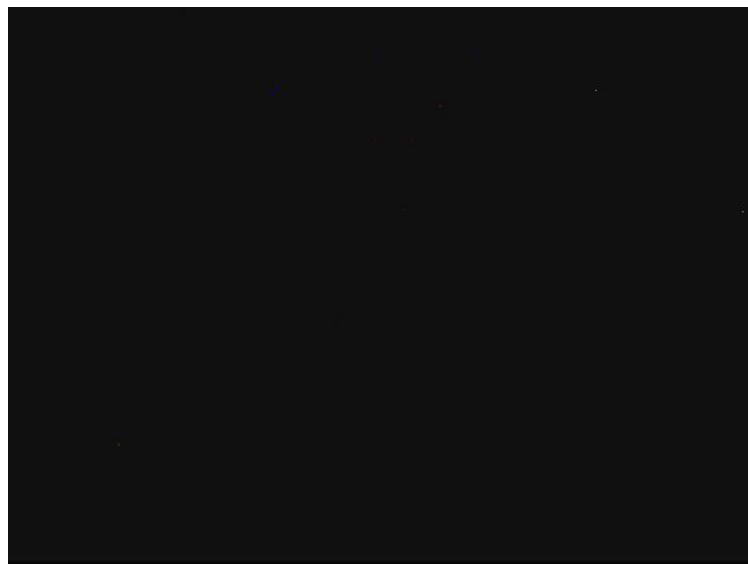
Reduce,
Reuse,
Recycle...



Reduce,
Reuse,
Recycle...

15

Fab@Home: Open source 3D printing technology, revolutionizing manufacturing



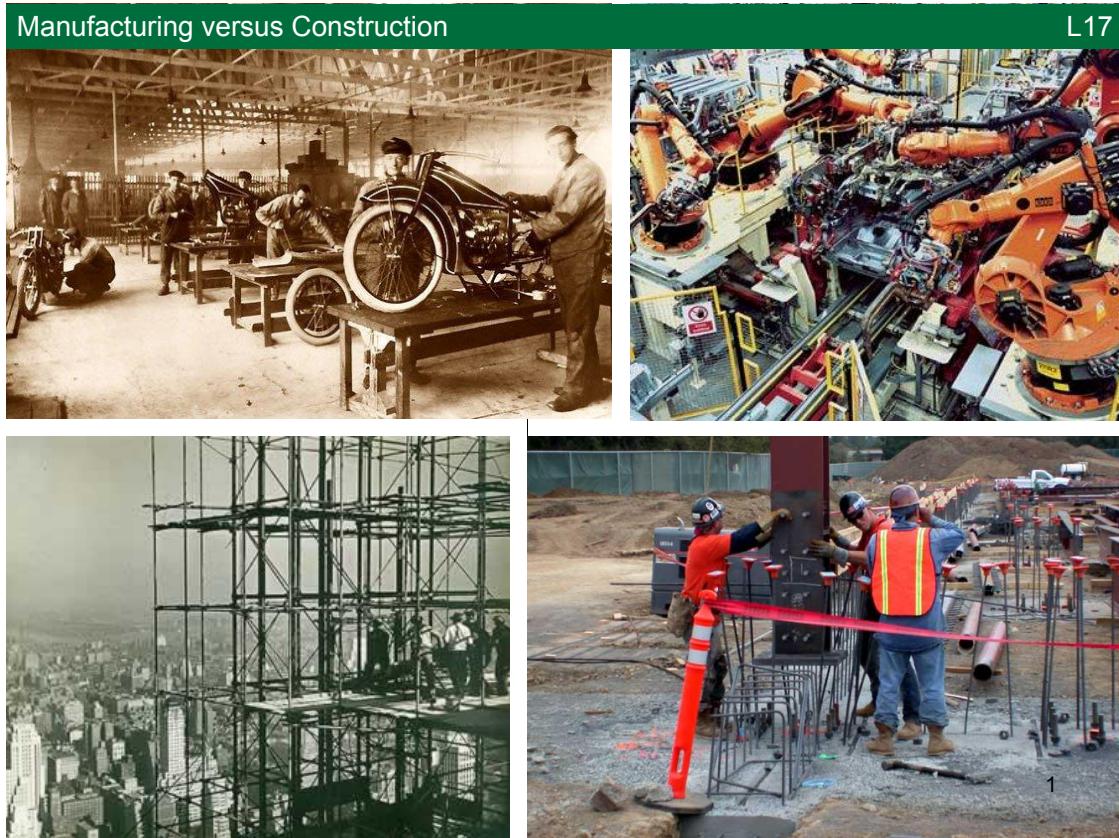
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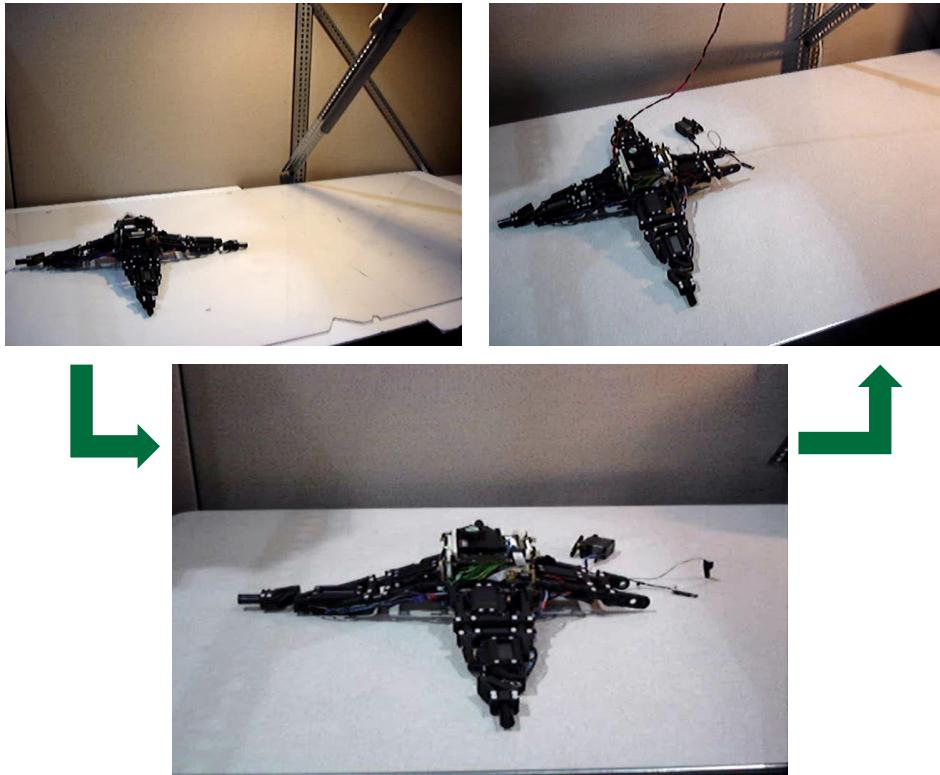
Rep Rap: A machine that makes a machine that makes a machine that makes...



Q: How could evolutionary algorithms be used to expand the capabilities of this technology?

17





2

Evolve the controller of a robot to automatically discover (near-)optimal behavior

Three existing approaches to evolutionary robotics:

Evolve controllers directly on a physical robot.

Requires 100s or 1000s of physical evaluations.

Create a simulation of the robot, and perform some or all of controller evolution in simulation before transferal to the physical device.

*Requires a human to hand craft the simulator;
“Reality gap” problem.*

Adapt controllers on the physical robot from an original, hand-created controller

Requires a human to hand craft the original controller.

3

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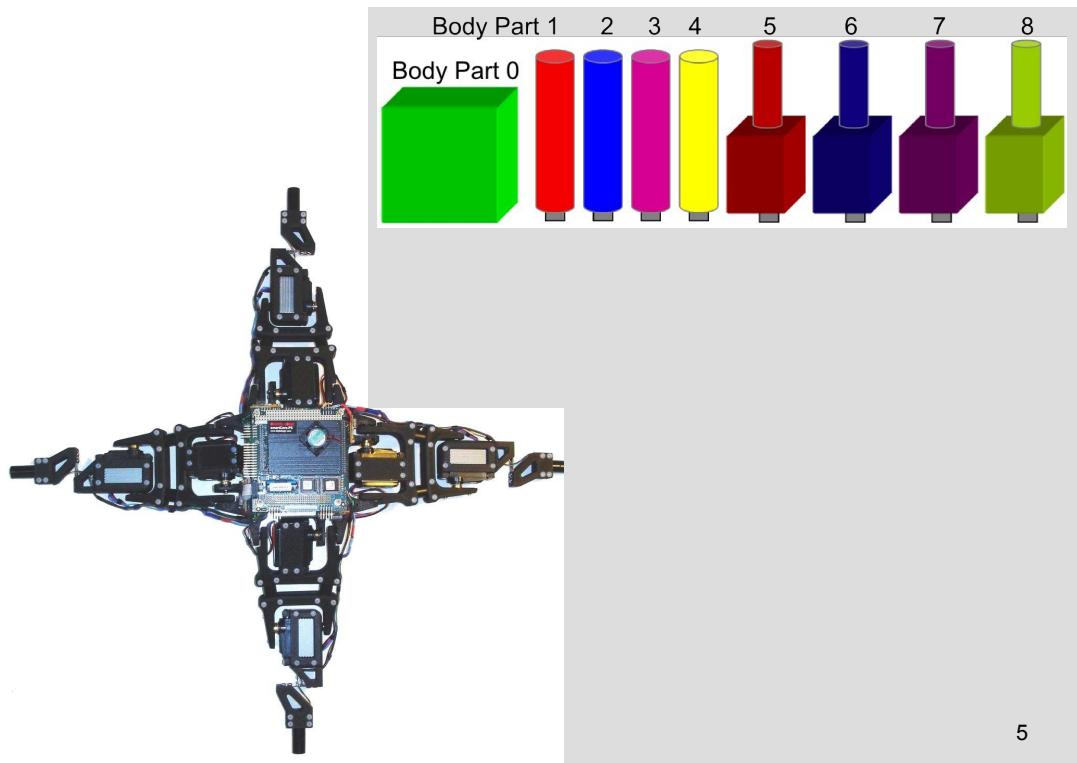
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Adapt controllers on the physical robot from an original, hand-created controller

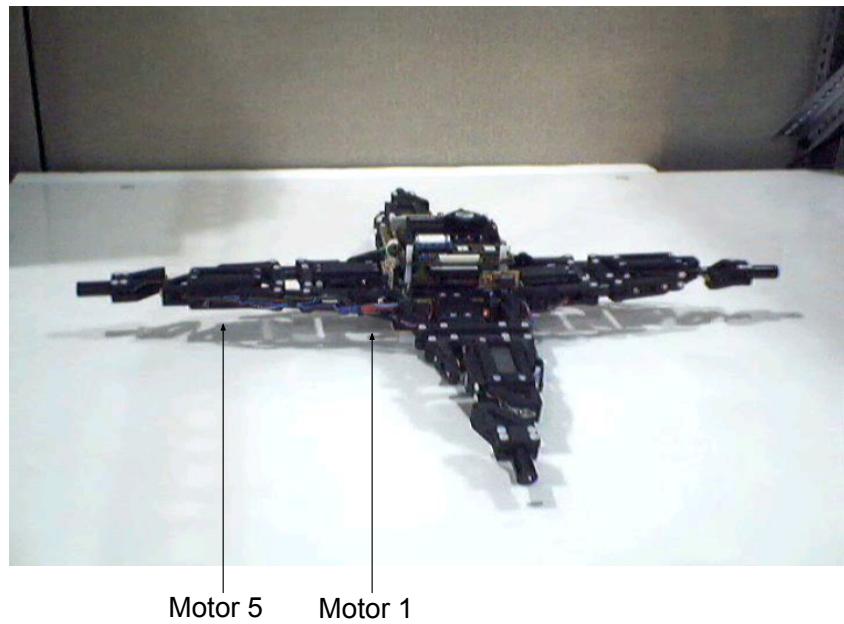
Requires a human to hand craft the original controller.

Alternative approach—The Estimation-Exploration Algorithm (EEA):

4



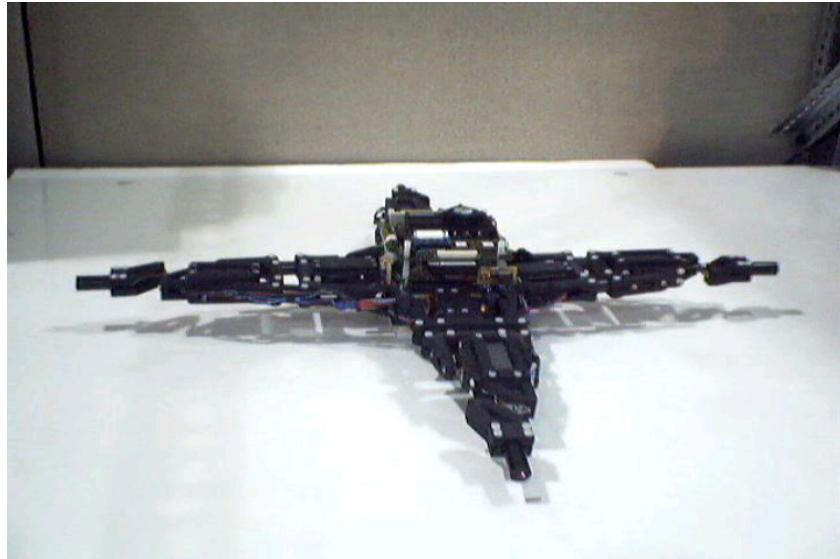
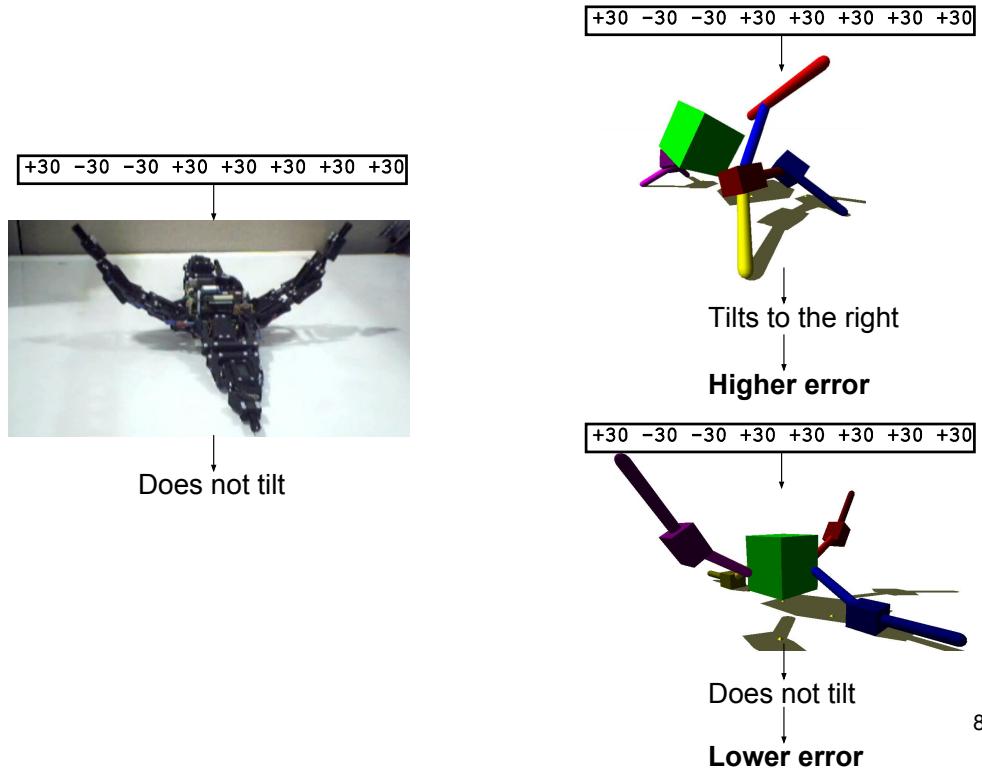
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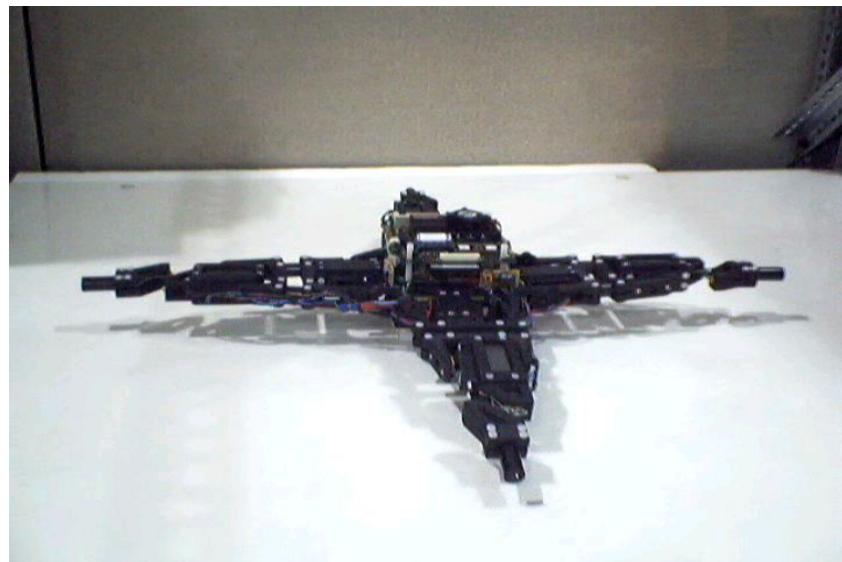
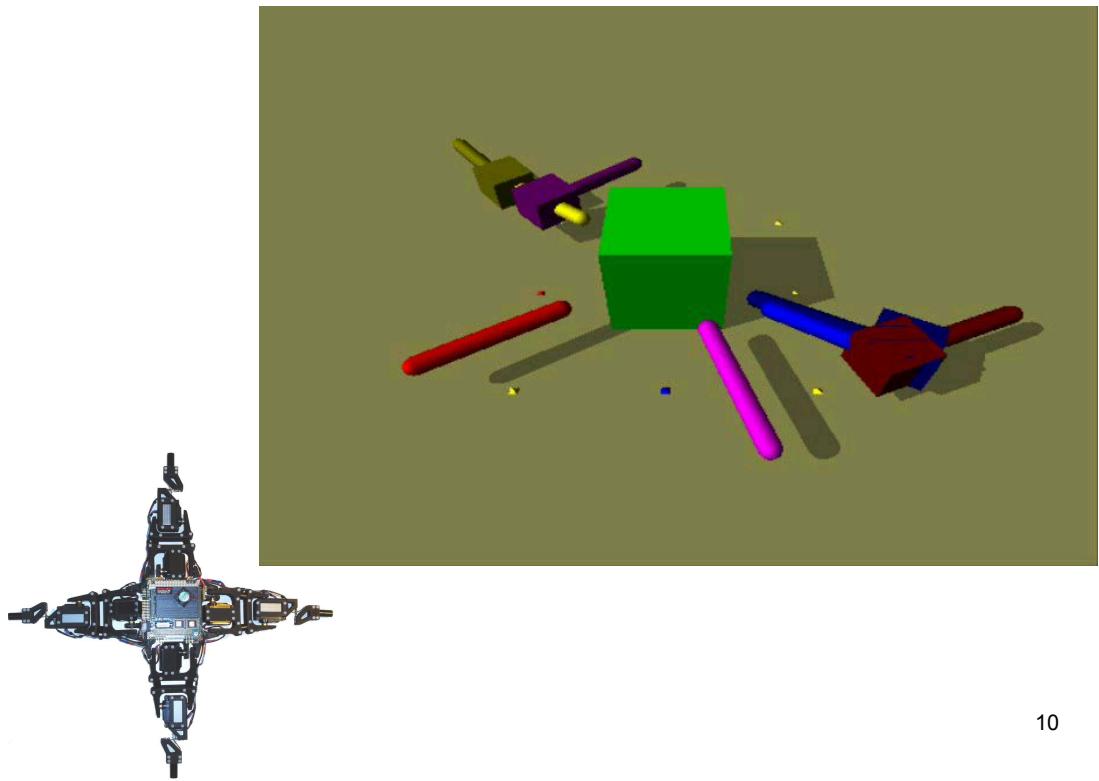


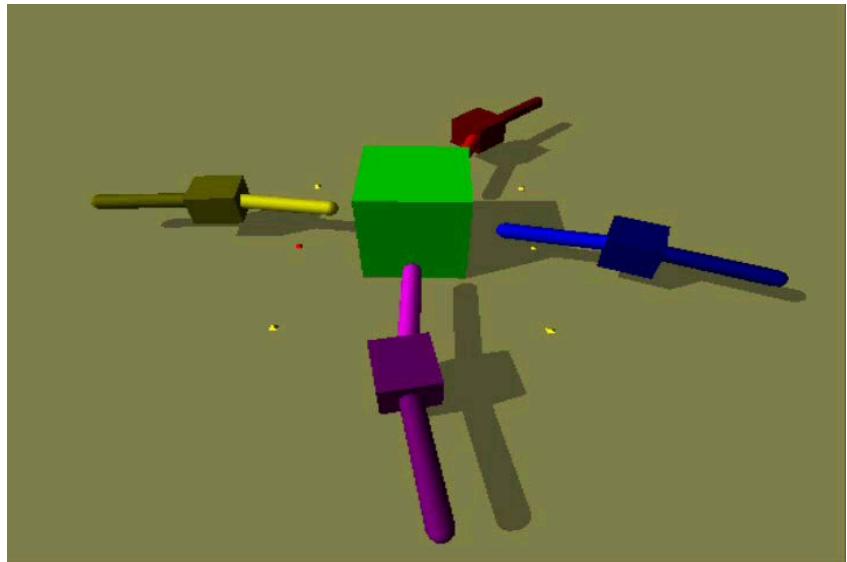
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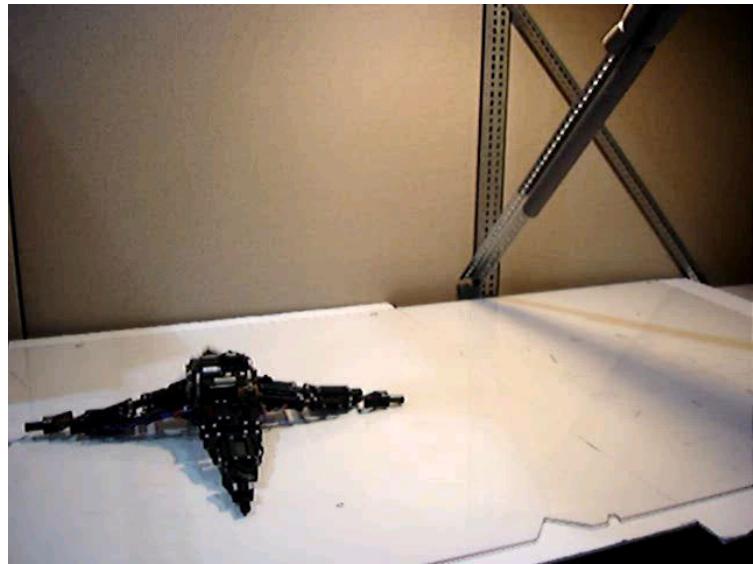




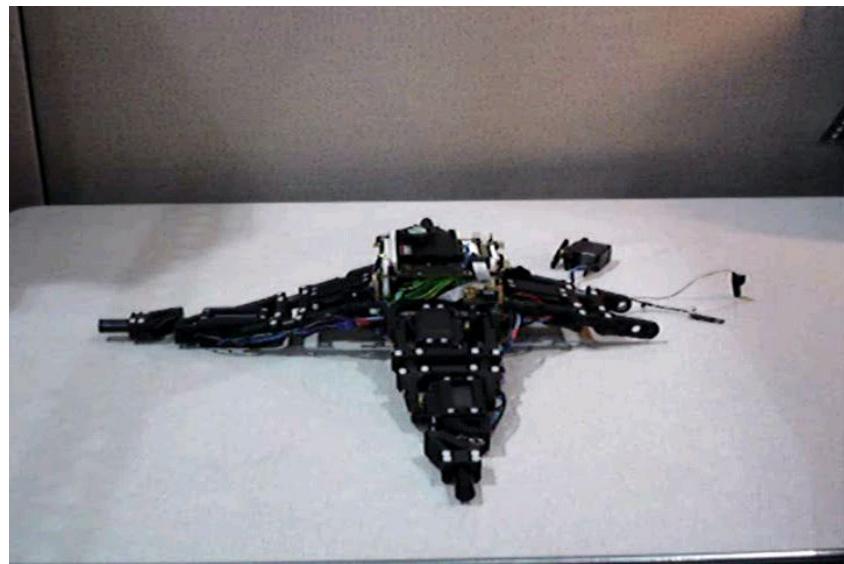
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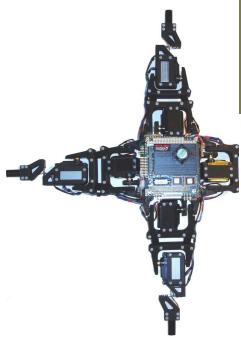
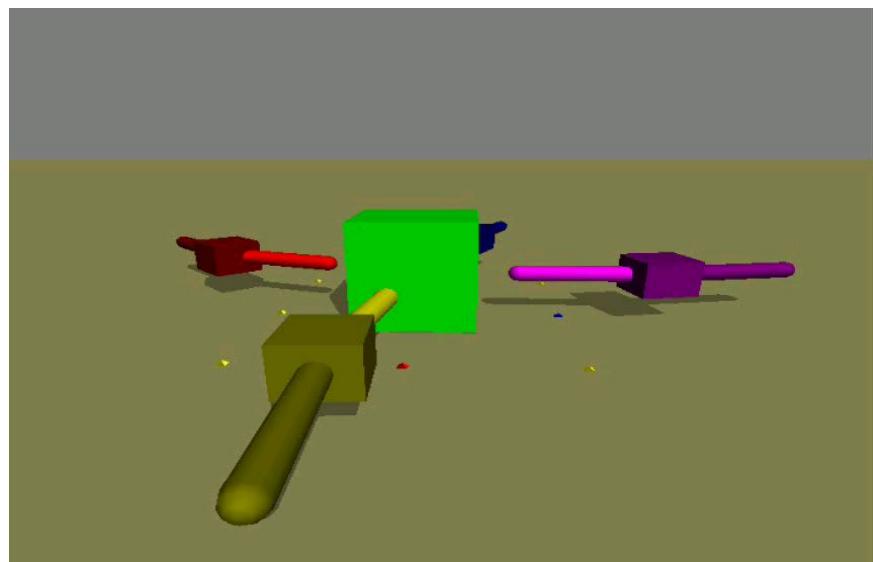
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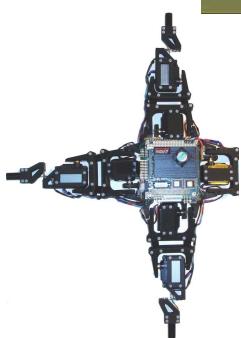
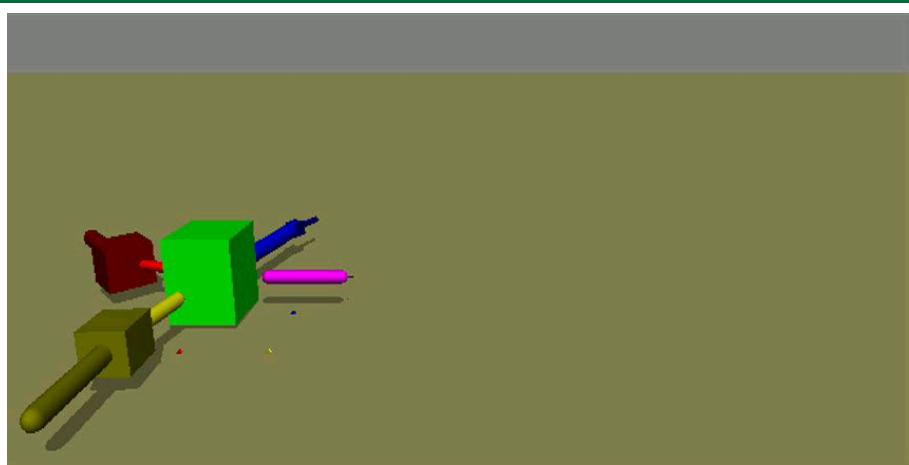
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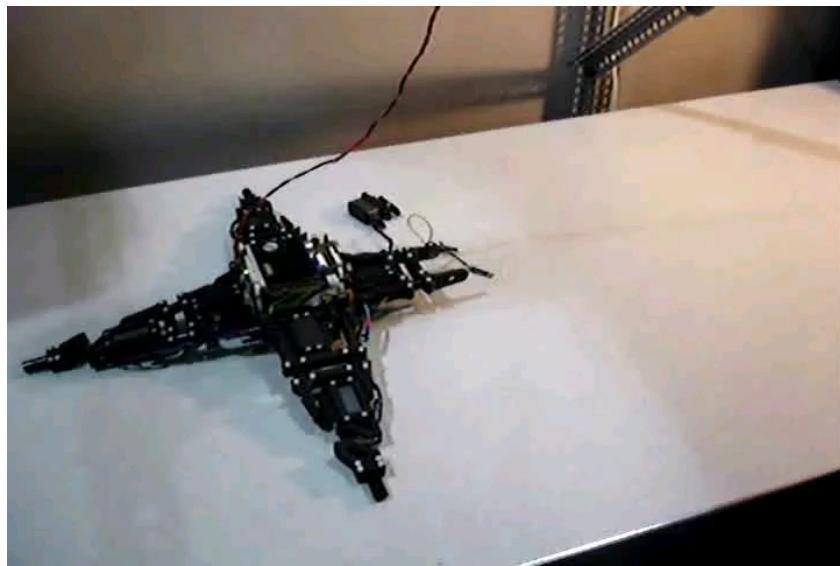
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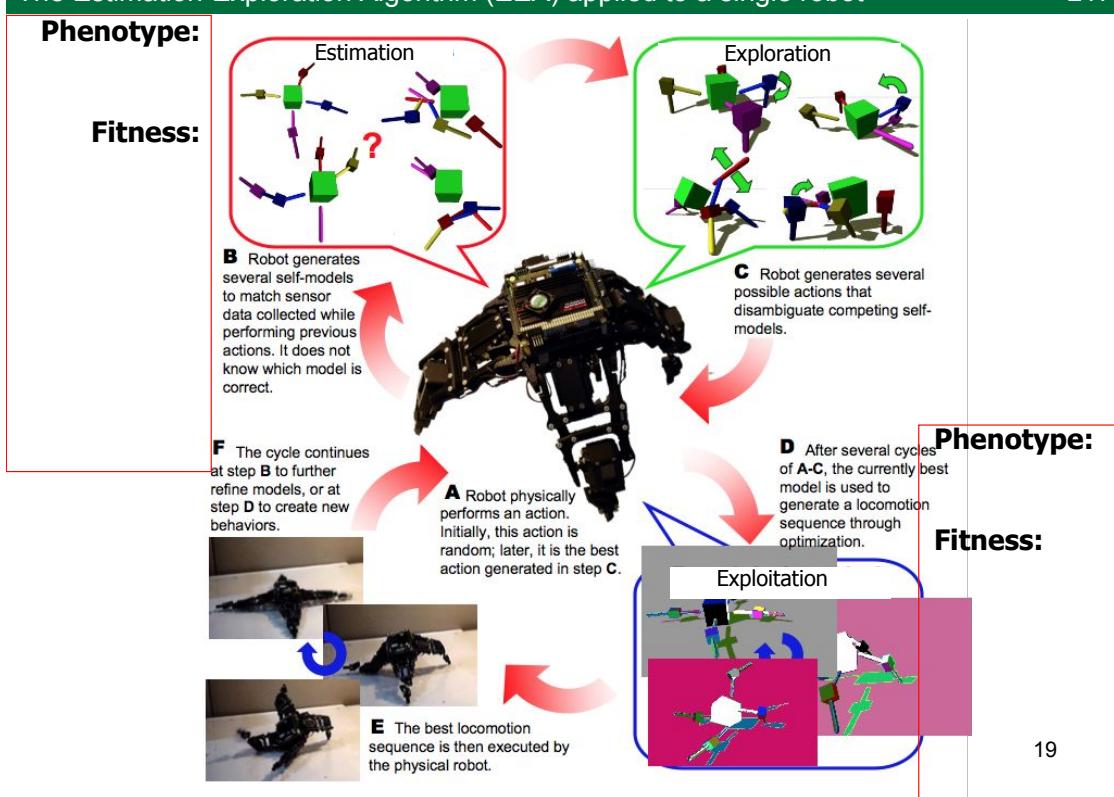
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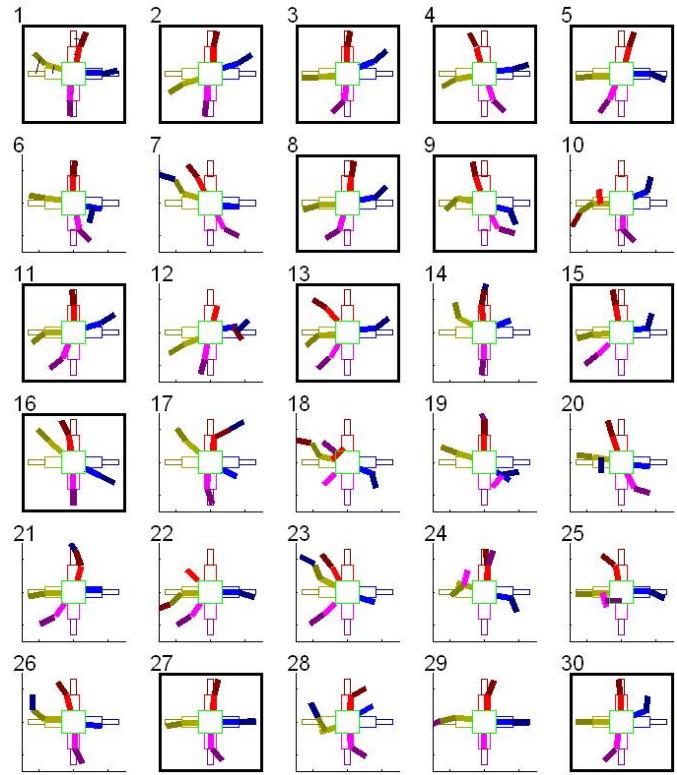
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The Estimation-Exploration Algorithm (EEA) applied to a single robot

L17



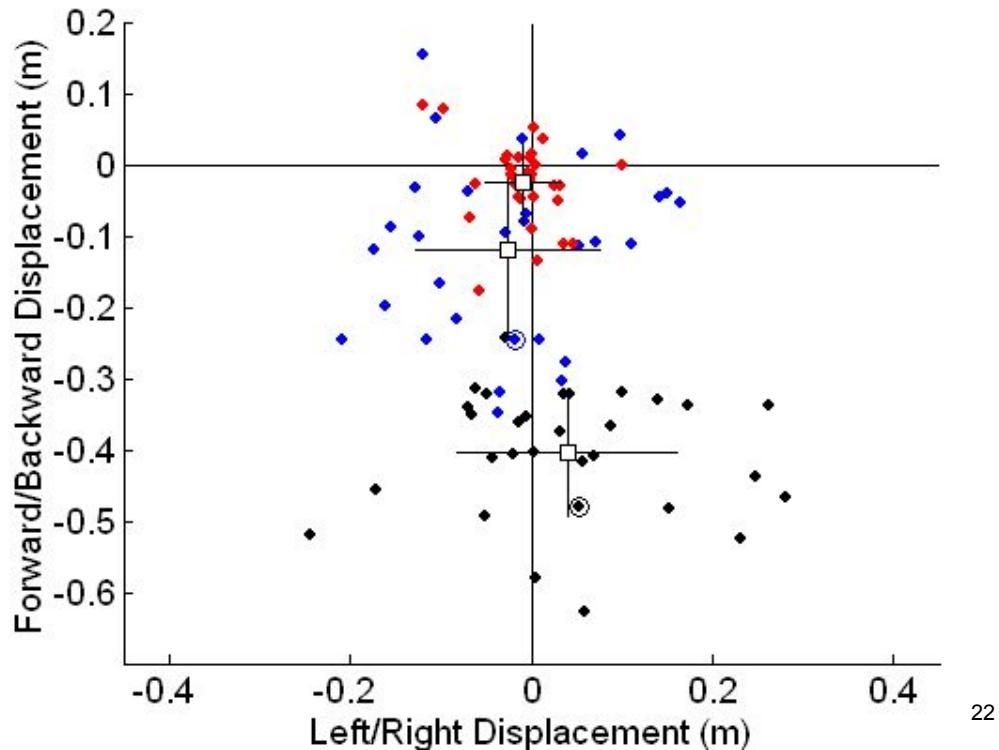
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20



21



22

Transferability

Question: Could the transferability of a controller be added to the fitness function?

How to define transferability?

Koos, S. and Mouret, J.-B. and Doncieux, S. (2010). Crossing the Reality Gap in Evolutionary Robotics by Promoting Transferable Controllers.
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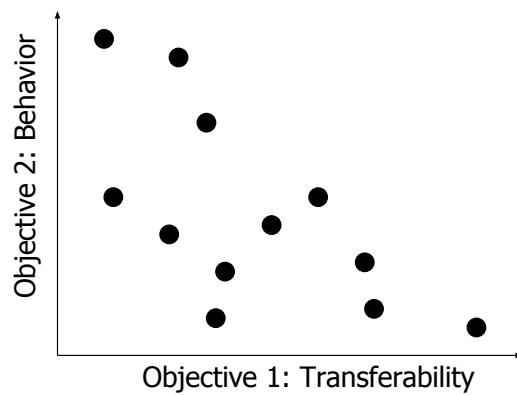
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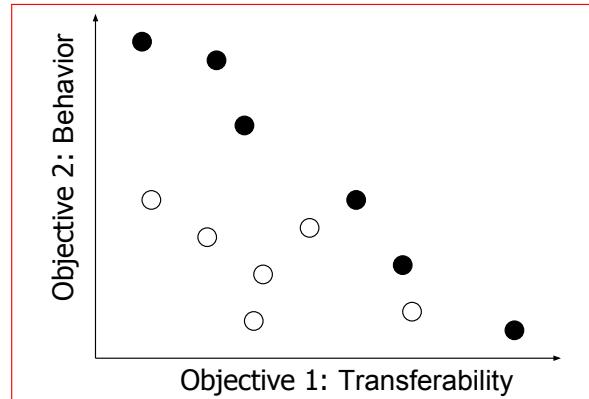
Multi-objective optimization (MOO)



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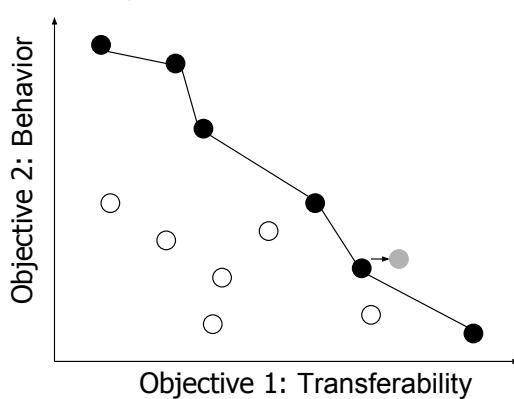


$$\text{solution } s = \begin{cases} \text{dominated} & : \text{ there exists another solution, } t, \text{ for which} \\ & \text{all objectives } o_t \geq \text{all objectives } o_s \\ \text{non-dominated} & : \text{ otherwise} \end{cases}$$

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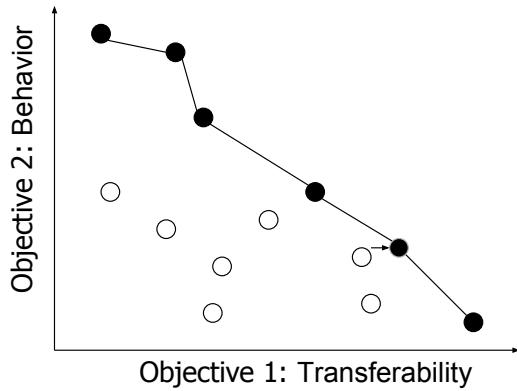
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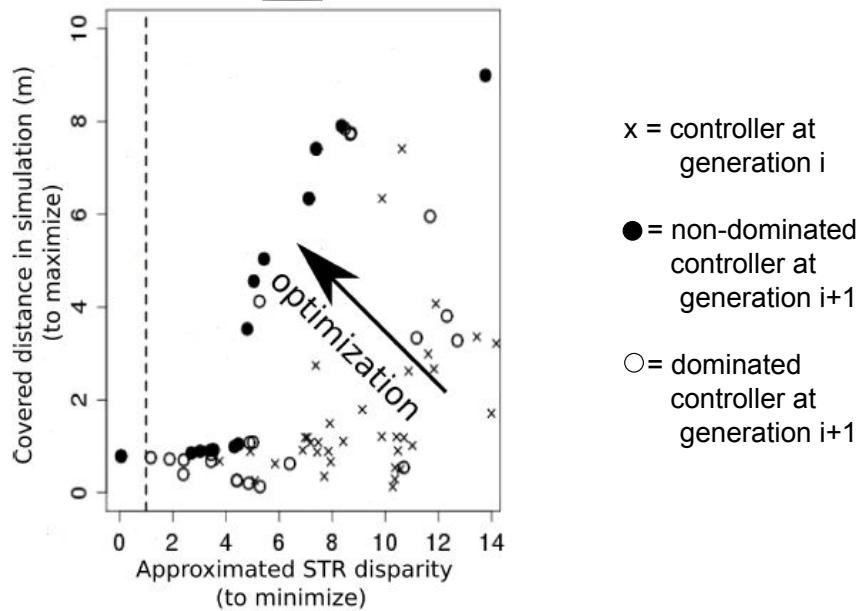
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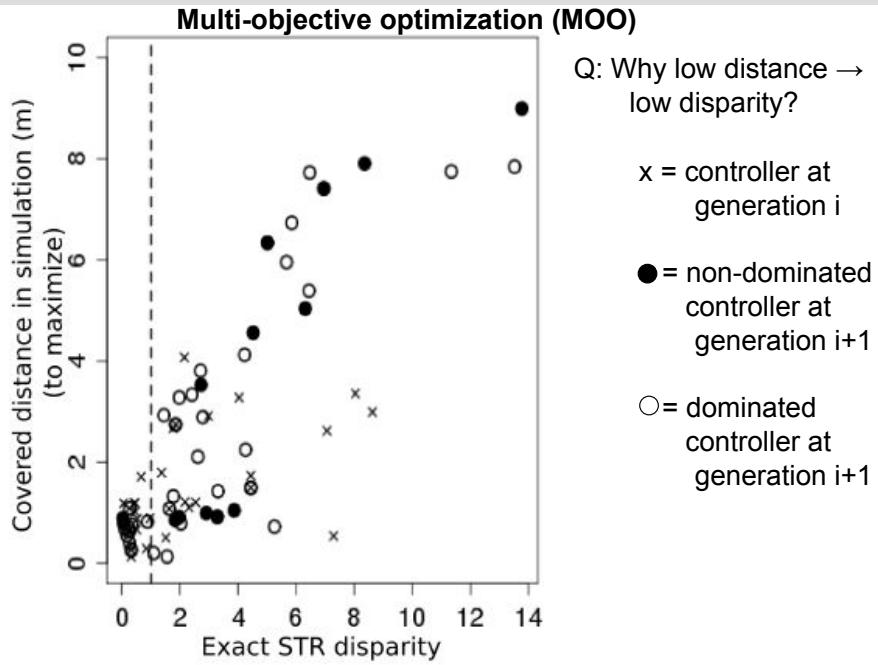


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8

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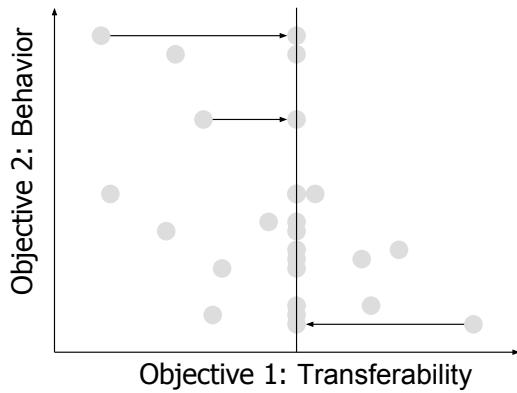
How to define transferability?

Solution: Use two fitness objectives:
One that rewards for the desired behavior,
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Problem 1: ...but to compute transferability for each evolved controller, have to evaluate each on the real robot!

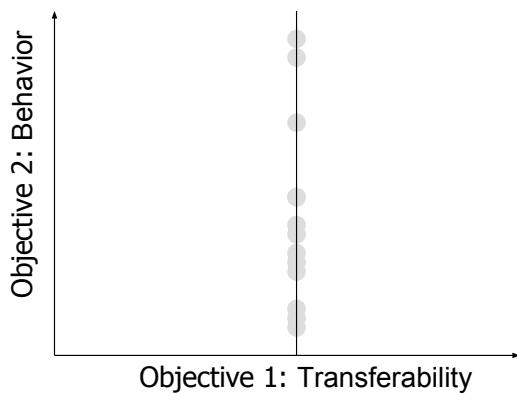
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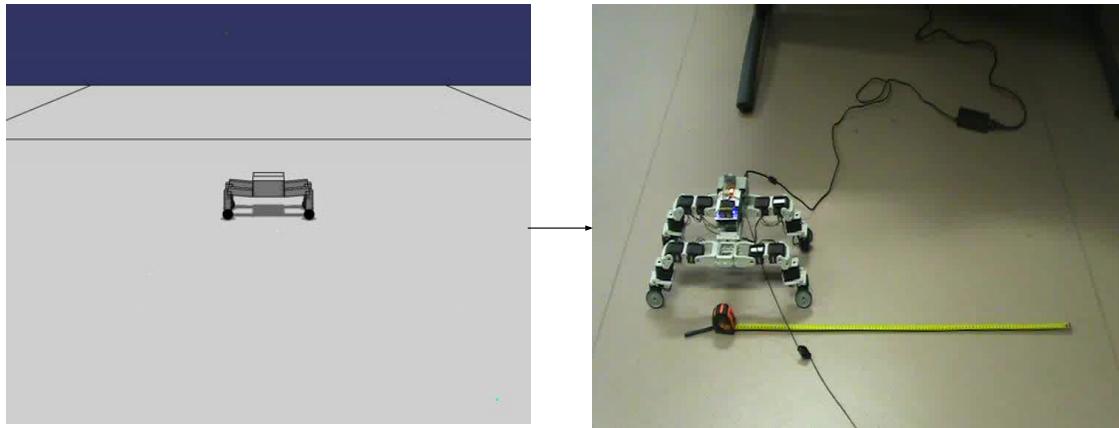


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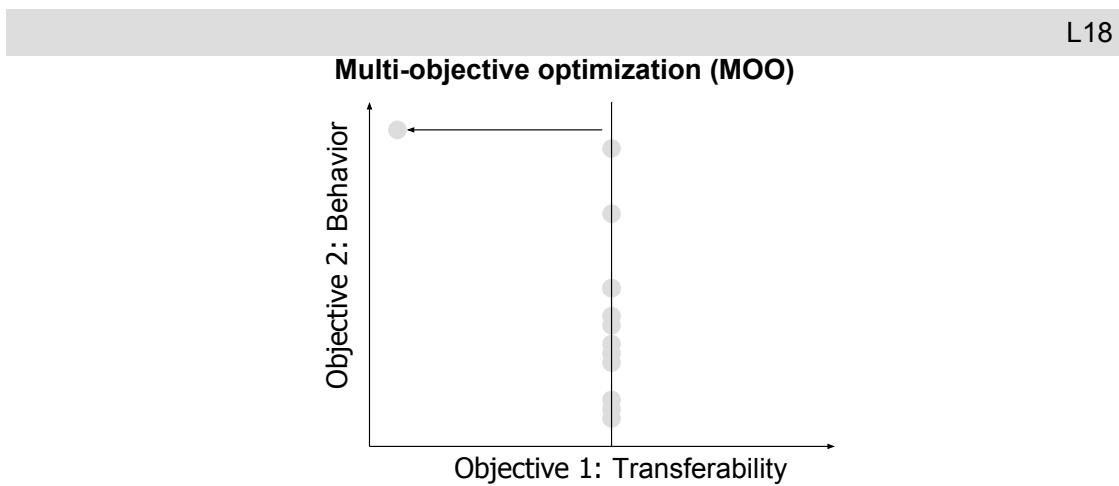
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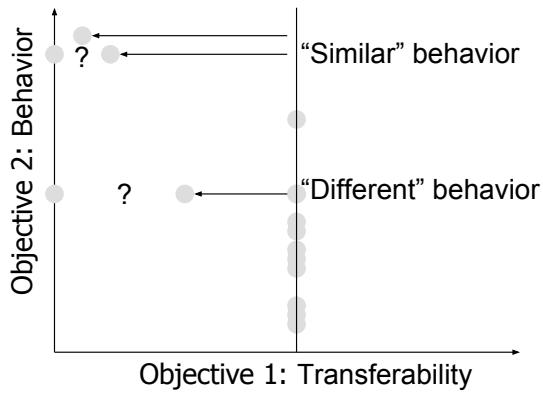


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Problem 2: ...how to measure the similarity between behaviors?

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Transferability

Problem 2: ...how to measure the similarity between behaviors?

Solution 2: Define a distance measure between any two behaviors.

Define behavior b as a vector: $b = (f_1, f_2, f_3)$

f_1 = distance traveled by robot

f_2 = mean height of the robot during travel

f_3 = final orientation of the robot



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Solution 1: Estimate transferability of a controller based on behavioral similarity to a tested controller.

Estimated transferability of controller c =

CT = set of already-transferred controllers

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Problem 2: ...how to measure the similarity between behaviors?

Solution 2: Define a distance measure between any two behaviors.

Problem 3: Which controller to try in reality next?

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- Solution 2: Define a distance measure between any two behaviors.
- Problem 3: Which controller to try in reality next?
- Solution 3: The one most “different” from those in the population.

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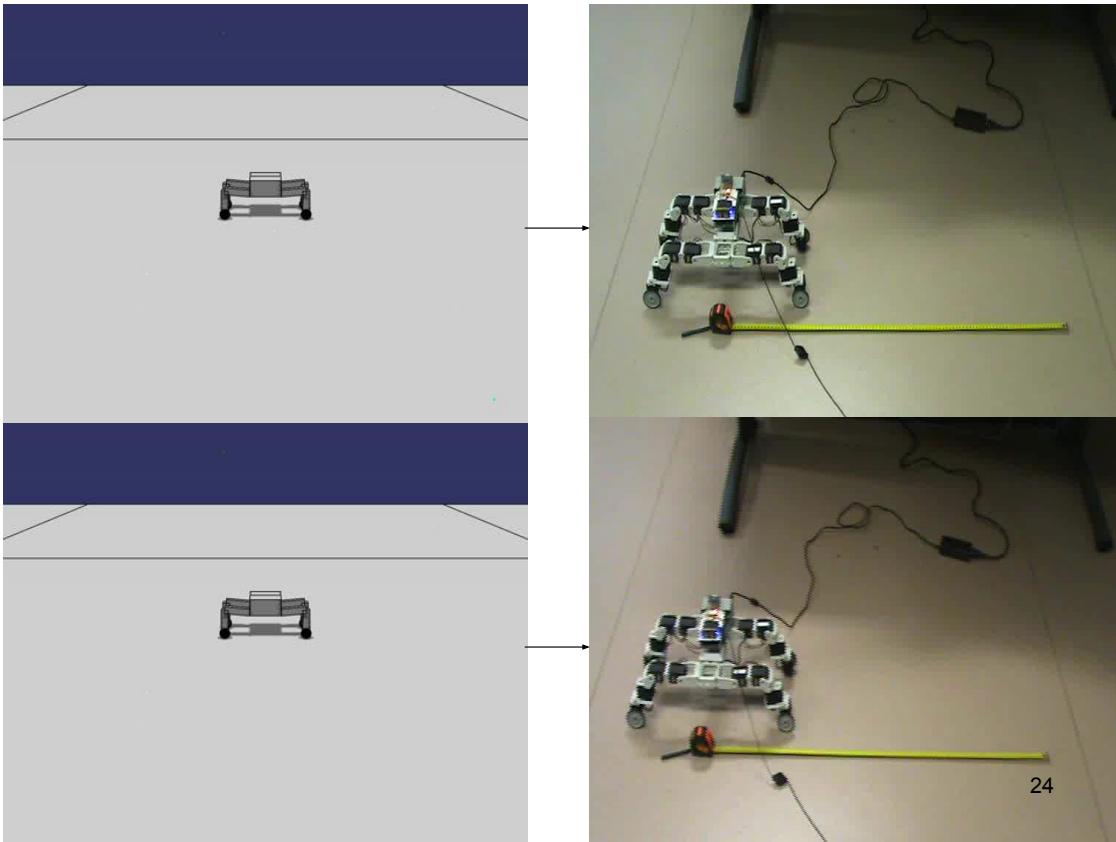
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- Solution 3: The one most “different” from those in the population.

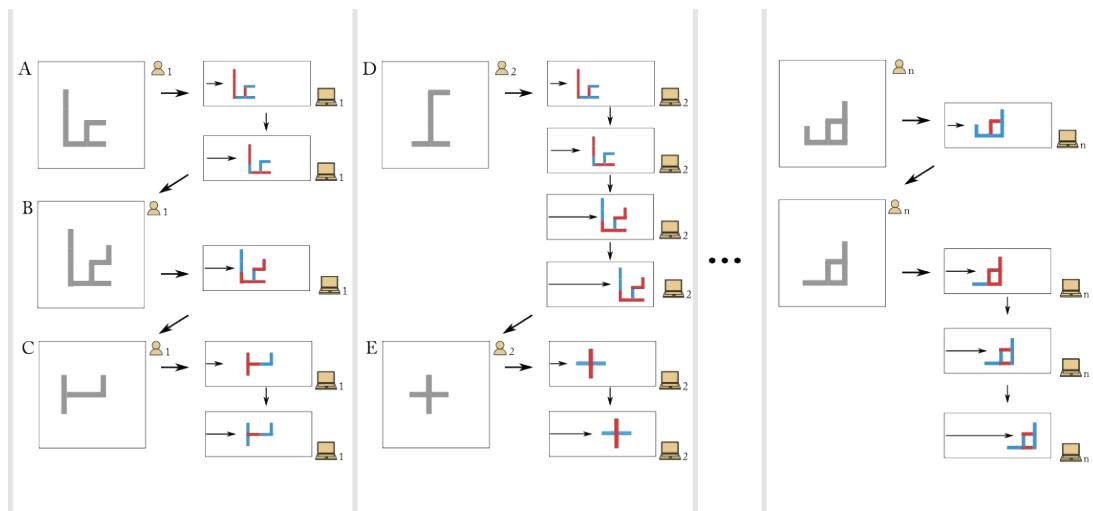
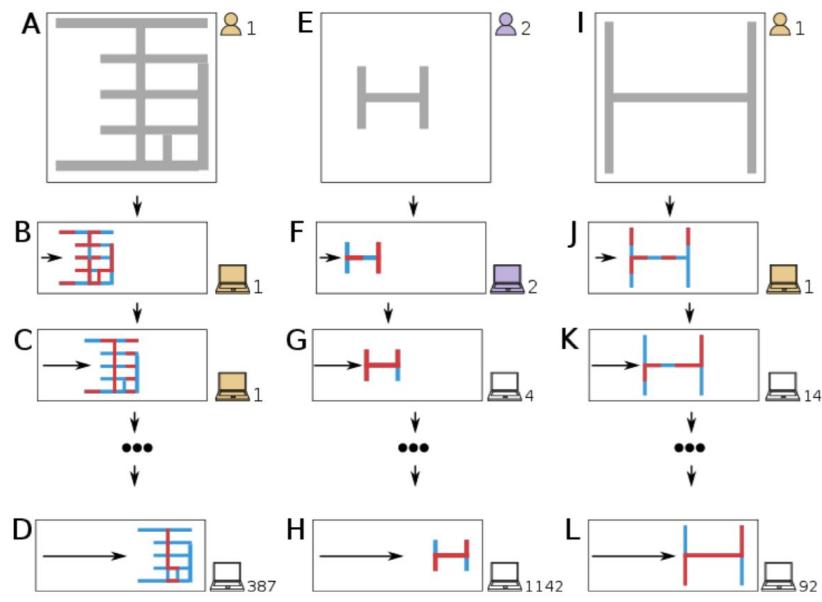
Koos, S. and Mouret, J.-B. and Doncieux, S. (2010). Crossing the Reality Gap in Evolutionary Robotics by Promoting Transferable Controllers.

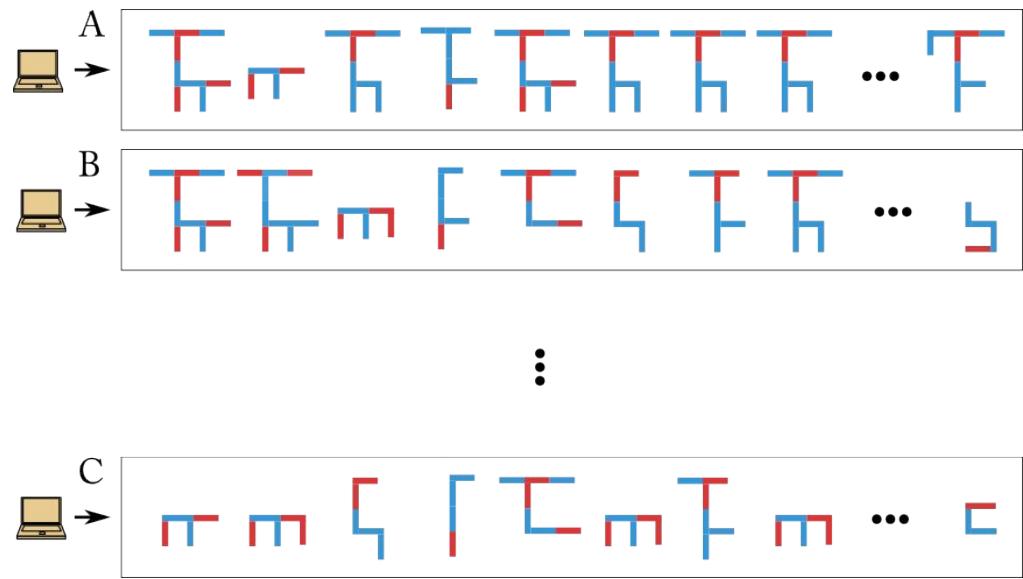
GECCO'10: Proceedings of the 12th annual conference on Genetic and evolutionary computation.



24

Crowdsourcing Robotics: The “DotBot” Project

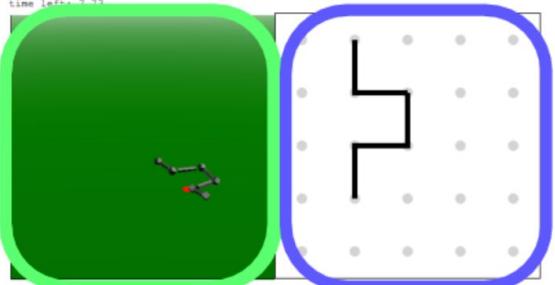


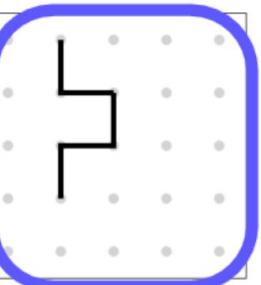


Try to design a robot that moves farther!
 Connect the dots with your mouse to draw a robot then click GO.
 If you run the same robot design multiple times, it will learn new behaviors.

Some random past designs:

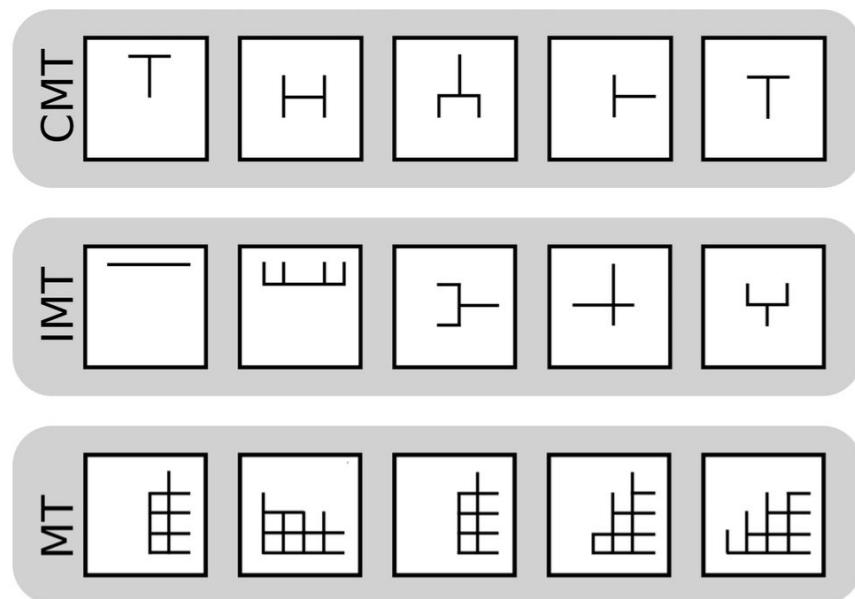
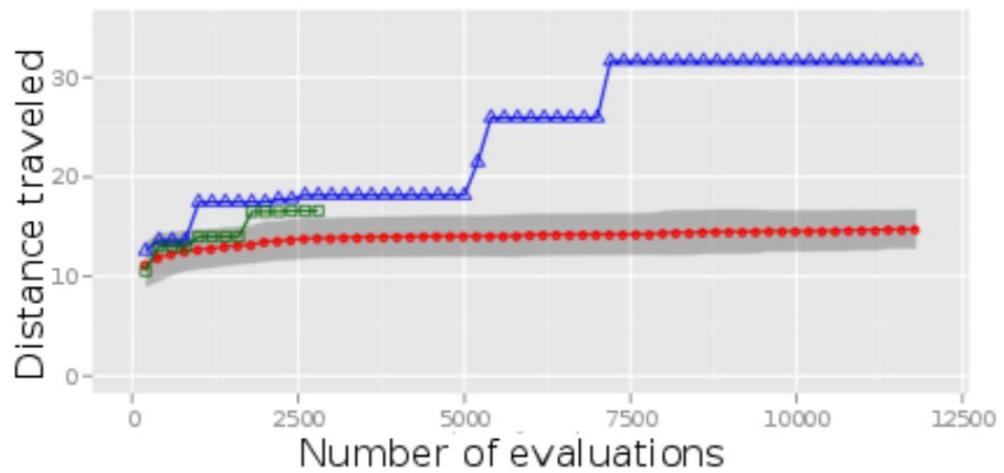
A 

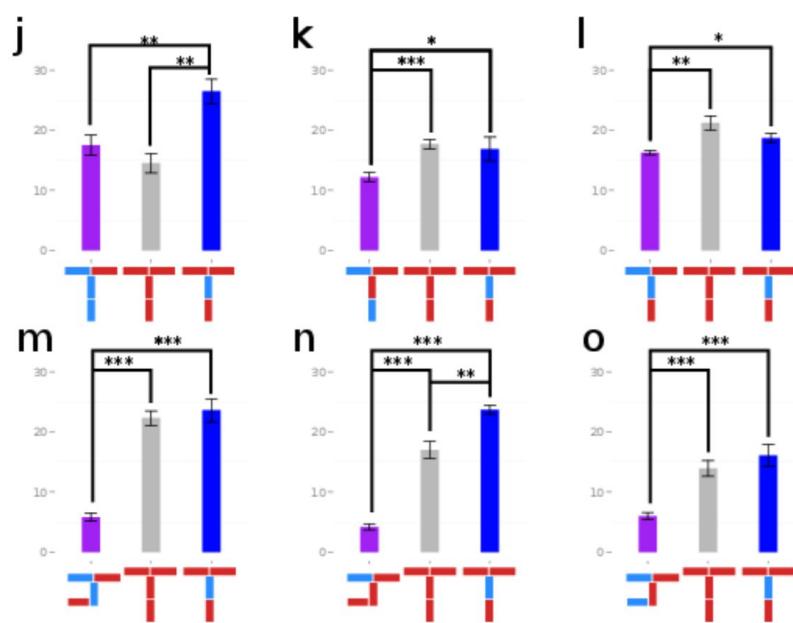
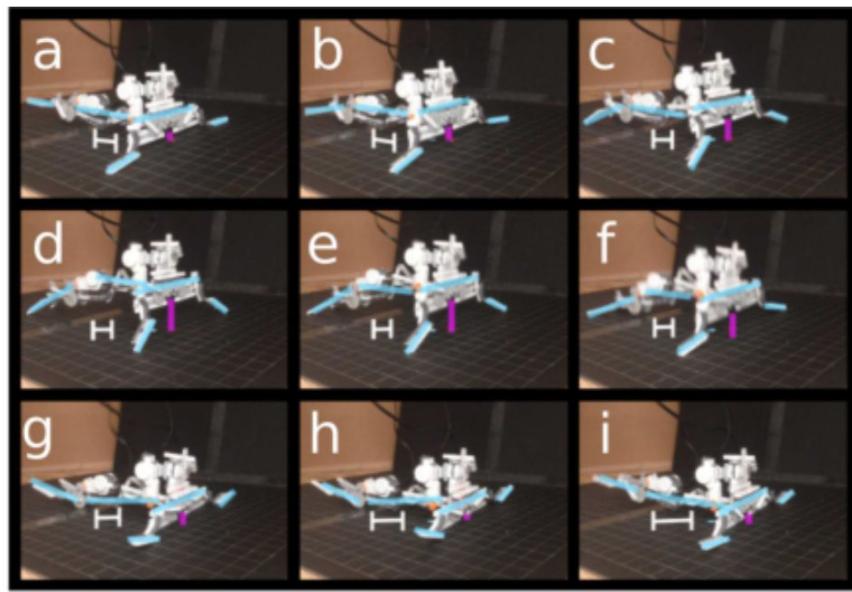
B 

C 

controls: **GO** reset
 mouse: rotate scene, z: zoom in, x: zoom out

best so far 





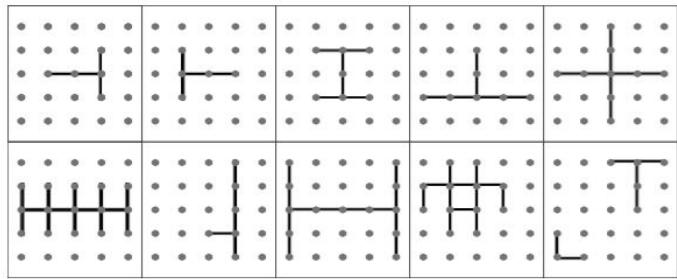
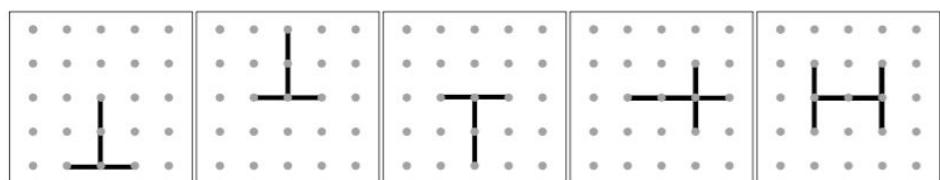
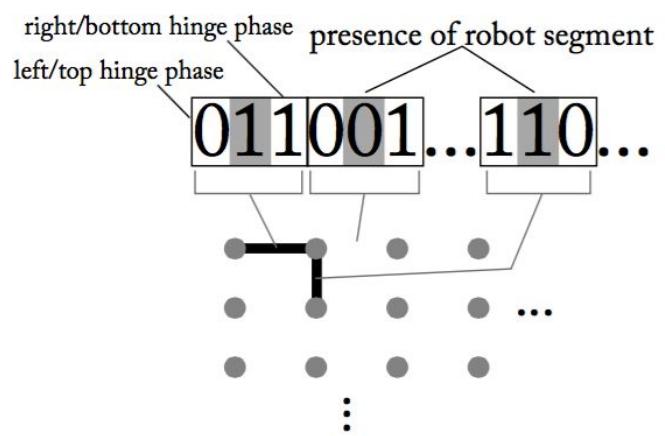
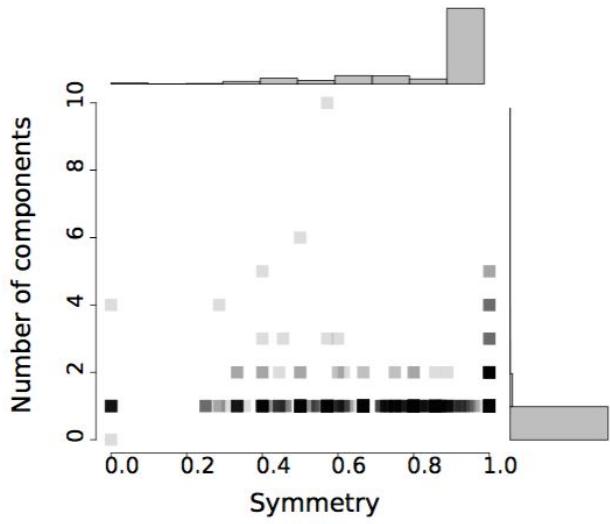
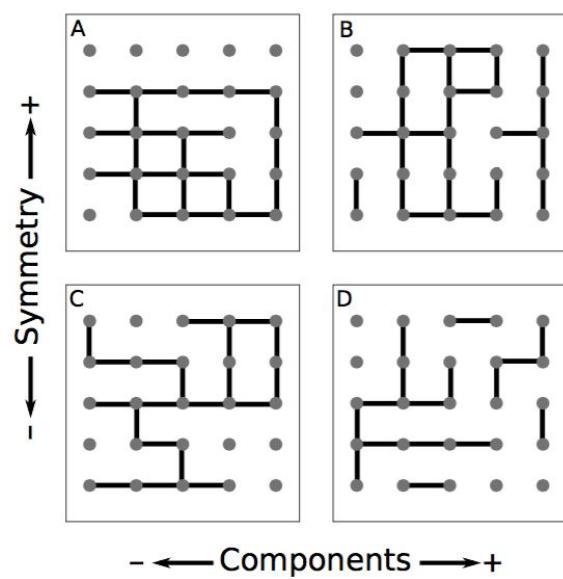
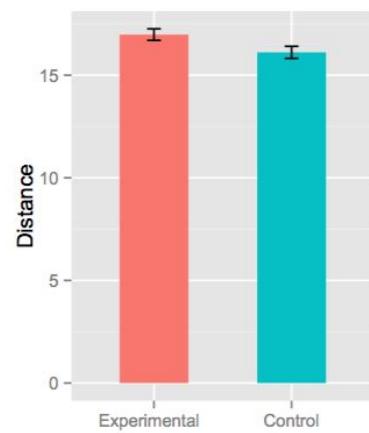


Figure 4.3: Ten examples of user designs of robot bodies.







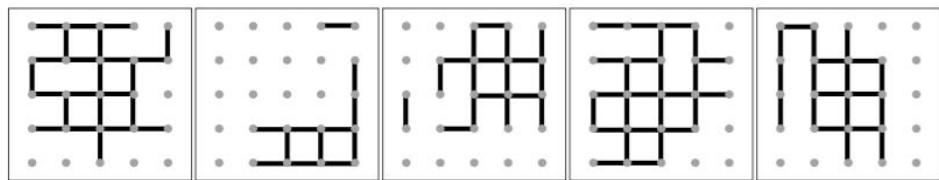
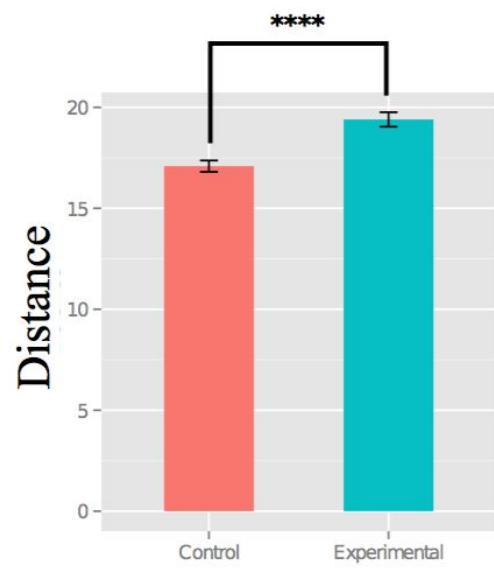
Variable	Symbol
Maximal matching	M_{max}
Number of connected components	c
Maximum degree	D_{max}
Minimum degree	D_{min}
Number of limbs	L
Not a chordal graph	C
Symmetry	S
Number of segments	G
Average Degree	D_{ave}
Average degree connectivity	D_{con}
Average clustering	T_{ave}

(a) Variables

Function Name	Symbol
Addition	+
Subtraction	-
Multiplication	.
Division	/
Logistic function	$\sigma()$
Indicator function	$I()$
Cosine	$\cos()$
Sine	$\sin()$
Tangent	$\tan()$
Exponential	$\exp()$
Natural Logarithm	$\log()$
Power	x^y
Square root	$\sqrt{\cdot}$
Gaussian	$G(\cdot)$
Less than or equal	\leq
Greater than or equal	\geq

(b) Functions

	Solution	Error
1*	$I(D_{max} \leq L) \cdot \min(G(D_{conn}), S) + 0.177 \min(c + 6.800 D_{conn}, D_{max}^{4.510 - \max(S, \log(L))})$	0.771
2	$0.041 \cdot c \cdot S \cdot I(L \geq 0.044 \cdot c \cdot D_{max}) + \min(c^{0.350}, D_{max})$	0.773
3	$\min(D_{max} \cdot \sigma(M_{max}), 2.187) - 0.085 \cdot M_{max}$	0.804
4	$\min(3.150, D_{max} + 0.170 \cdot M_{max}) - 0.144 \cdot M_{max}$	0.806
5	$\sqrt{D_{max}} - (0.003 \cdot N \cdot c^2)^S \cdot \cos(D_{max})$	0.786
6	$\min(3.054, D_{max} \cdot \min(M_{max}, 1.325)) - 0.125 \cdot M_{max}$	0.807
7	$4.374 \cdot c \cdot \min(0.033, D_{con}) + I(D_{max} \geq 3) + \min(S, I(D_{max} \leq L))$	0.781
8	$0.053 \cdot c \cdot S \cdot I(L \geq 0.044 \cdot c \cdot D_{max}) + \min(\log c + S, D_{max})$	0.773
9	$D_{con} + S \cdot I(L \geq D_{max}) + 0.196 \cdot \min(3.471^{D_{max}}, c) - I(L \geq G)$	0.771
10	$2.819 \cdot \sigma(S) \cdot \min(3.180, D_{max}) - 0.141 \cdot M_{max} \cdot \min(M_{max}, D_{max}) - 2.960 \cdot I(3.887 - L \geq M_{max})$	0.779



A potentially scalable solution to the symbol grounding problem.

Josh Bongard

Morphology, Evolution and Cognition Laboratory
University of Vermont
www.cs.uvm.edu/~jbongard

April 5, 2016

Anetsberger & Bongard (2016). *Proceedings of ALife*. In press.



The Chinese Room Problem.

Searle, John (1980). "Minds, Brains and Programs", *Behavioral and Brain Sciences* 3(3): 417–457



Anetsberger & Bongard (2016). *Proceedings of ALife*. In press.



The Cyc Project.

Douglas Lenat (1984—present)

The concept names in Cyc are known as *constants*. Constants start with an optional "#\$" and are case-sensitive. There are constants for:

- Individual items known as *individuals*, such as #SBillClinton or #France.
 - *Collections*, such as #\$Tree-ThePlant (containing all trees) or #\$EquivalenceRelation (containing all equivalence relations). A member of a collection is called an *instance* of that collection.
 - *Functions*, which produce new terms from given ones. For example, #\$FruitFn, when provided with an argument describing a type (or collection) of plants, will return the collection of its fruits. By convention, function constants start with an upper-case letter and end with the string "Fn".
 - *Truth Functions* which can be applied to one or more other concepts and return either true or false. For example, #\$/siblings is the sibling relationship, true if the two arguments are siblings. By convention, truth function constants start with a lower-case letter. Truth functions may be broken down into logical connectives (such as #\$/and, #\$/or, #\$/not, #\$/implies), quantifiers (#\$/forall, #\$/thereexists, etc.) and predicates.

The most important predicates are #*Sisa* and #*Genls*. The first one describes that one item is an *instance* of some collection, the second one that one collection is a subcollection of another one. Facts about concepts are asserted using certain CycL *sentences*. Predicates are written before their arguments, in parentheses:

(#\$isa #\$BillClinton #\$UnitedStatesPresident)

"Bill Clinton belongs to the collection of U.S. presidents" and

(#\$genls #\$Tree-ThePlant #\$Plant)

"All trees are plants".

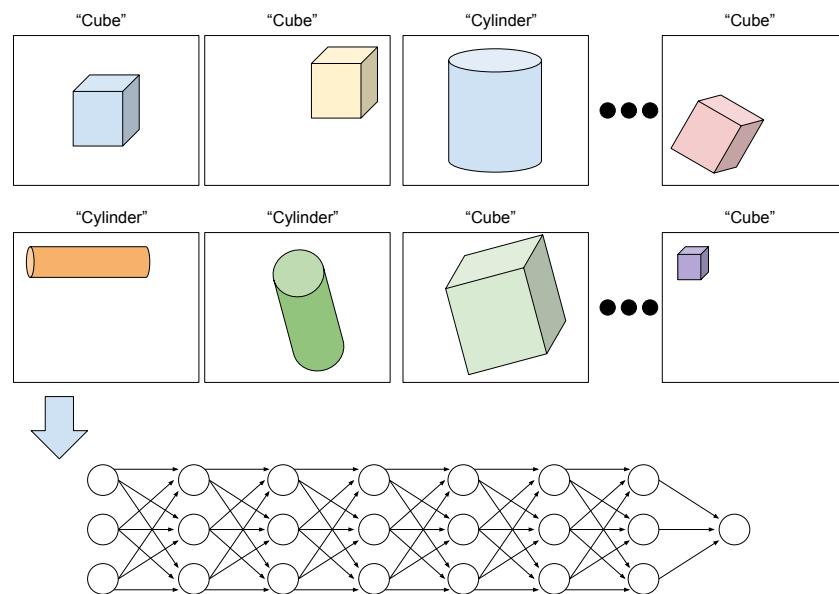
(#\$capitalCity #\$France #\$Paris)

"Paris is the capital of France."

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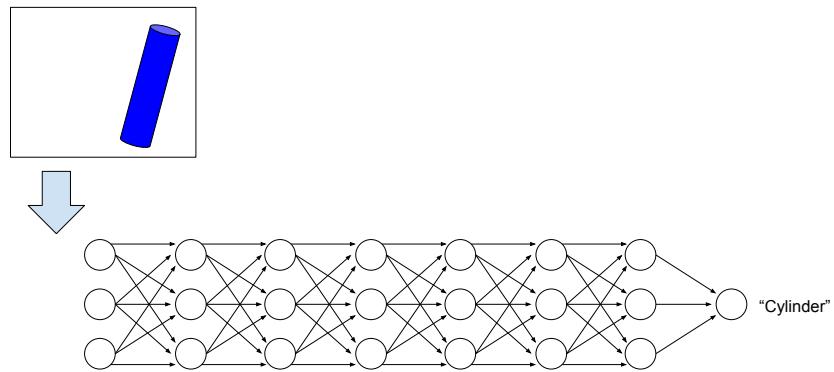
Non-embodied categorization.



Anetsberger & Bongard (2016) *Proceedings of Alife*. In press

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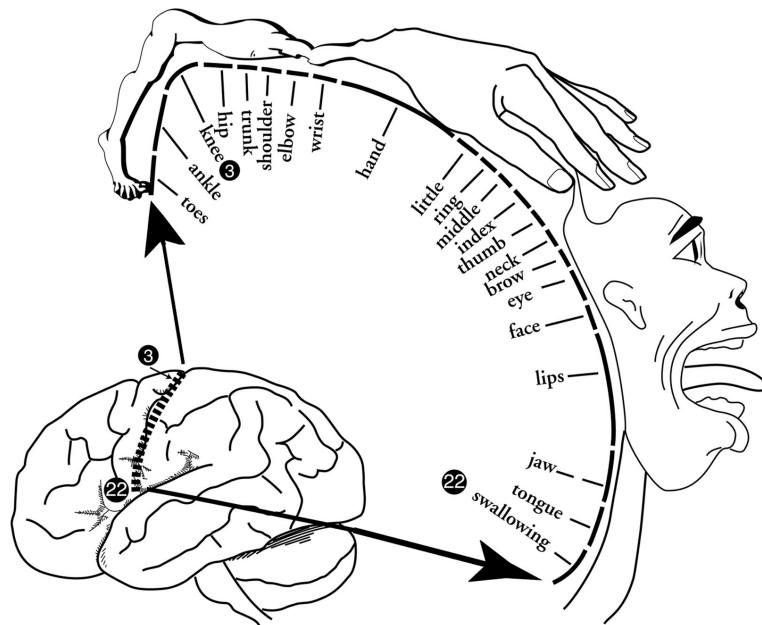
Non-embodied categorization.



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The brain's motor strip.

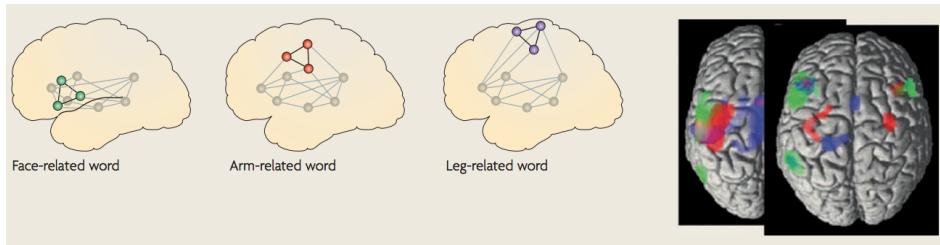


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6

Motoric words activate the brain's motor strip.

Pulvermüller & Fadiga, (2010). Active perception: sensorimotor circuits as a cortical basis for language. *Nature Reviews Neuroscience*, 11(5), 351–360.

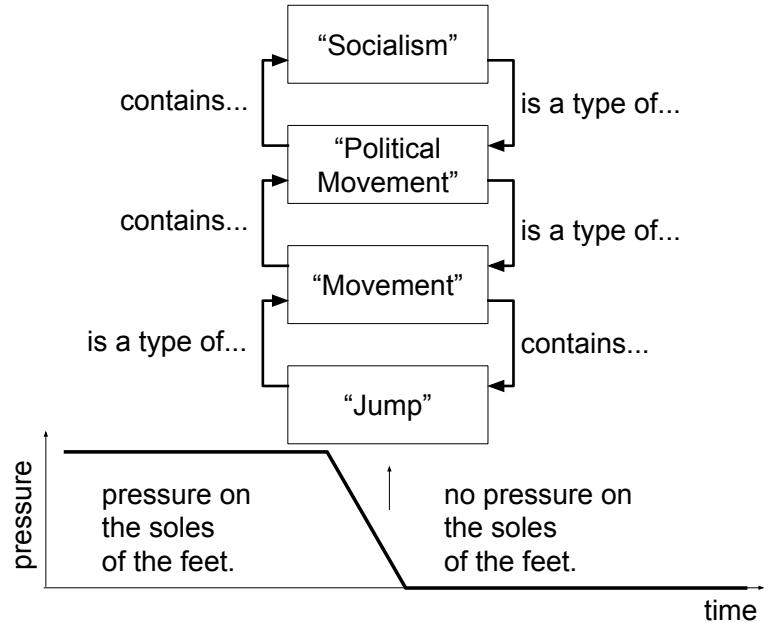


- ▶ Face-related words (green): “talk”, “lick”.
 - ▶ Arm-related words (red): “grasp”, “pick”.
 - ▶ Leg-related words (blue): “walk”, “kick”.

George Lakoff: embodied metaphors.

- ▶ Don't **jump** to conclusions.
 - ▶ Don't **look back** in anger.
 - ▶ ...

Symbols grounded...?



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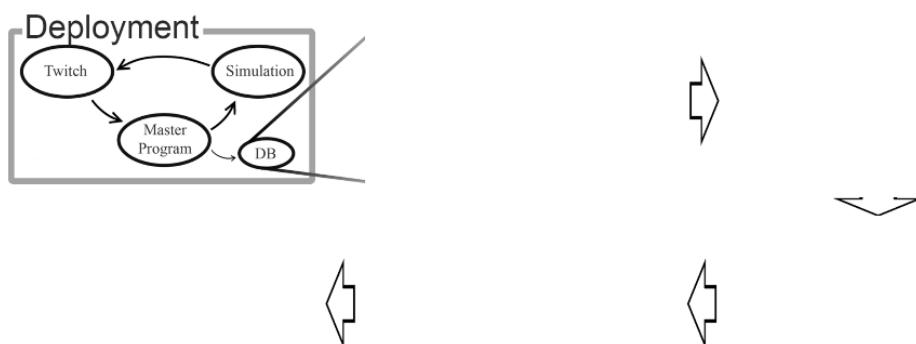
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Grounding symbols using *Twitch Plays Robotics*.

Act. Observe. Learn. Predict.

Grounding symbols using *Twitch Plays Robotics*.

Act. Observe. Learn. Predict.



Simulation: Robots simulated in Unity Physics Engine.

Twitch: Video captured from simulation and fed to Twitch.

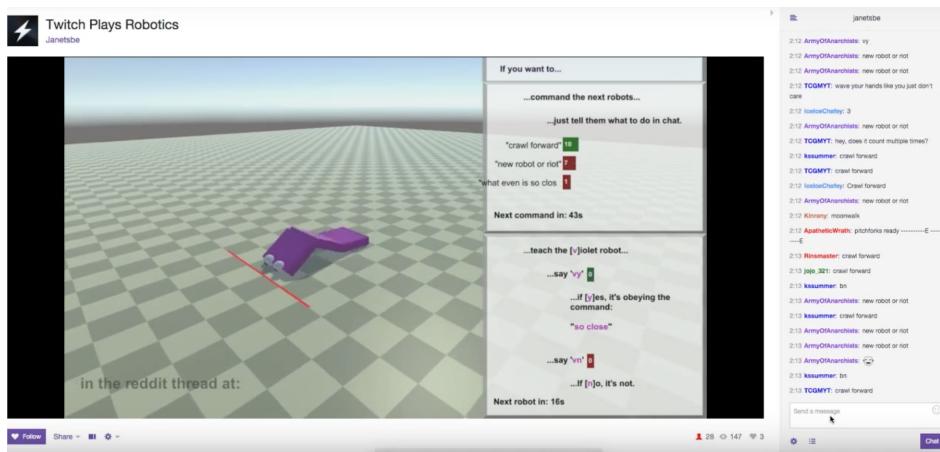
Master Program: controllers-->simulation; crowd response -->DB

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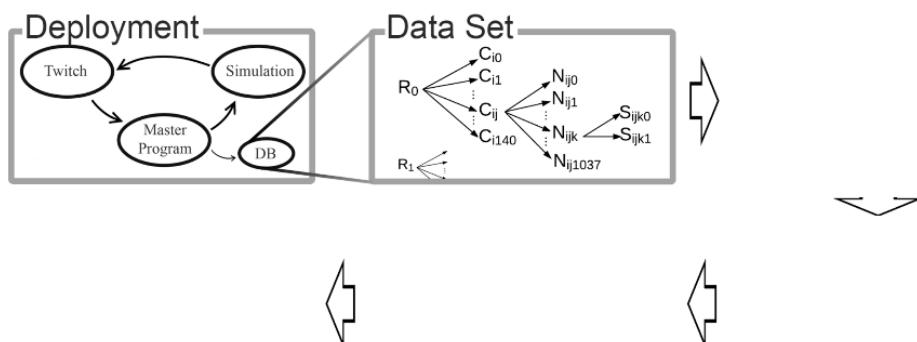


Anetsberger & Bongard (2016). *Proceedings of ALife*. In press.

12 28 3

Grounding symbols using *Twitch Plays Robotics*.

Act. **Observe.** Learn. Predict.



Simulation: Robots simulated in Unity Physics Engine.

Twitch: Video captured from simulation and fed to Twitch.

Master Program: controllers-->simulation; crowd response -->DB

R.:Robot i.

C_{ij} :Command j issued to robot i.

N_{ij}:Controller k evaluated under command j

S_{ijk} : Negative reinforcement signals issued under controller k.

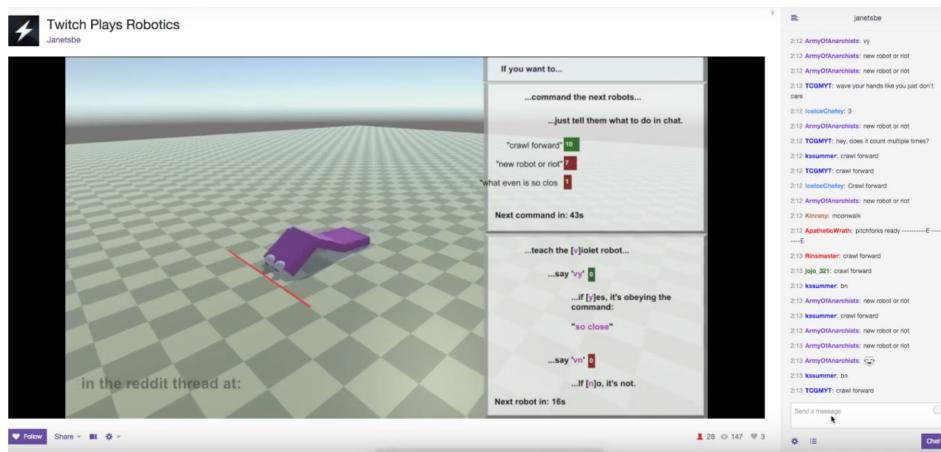
S_{ijk0} : Negative reinforcement signals issued under controller k.

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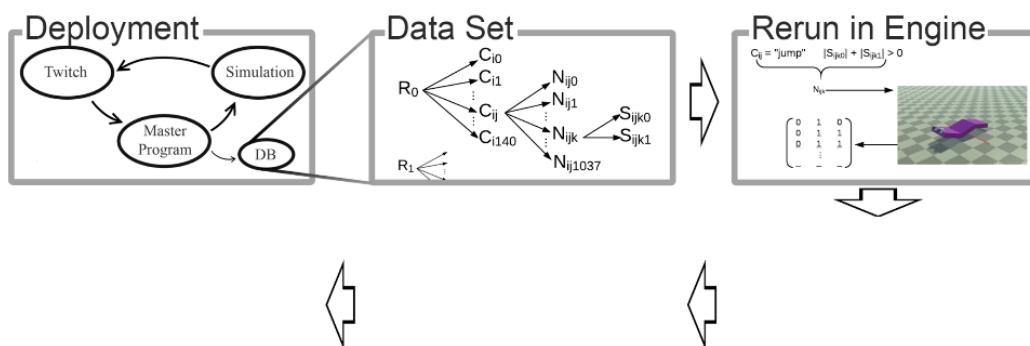
Act. Observe. Learn. Predict.

General Figures	Values
Subjects	424
Robot evaluations sent	57,108
Robot evaluations observed	$\geq 6,388$
Subject inputs	16,449
Commands	Values
Candidate commands entered	8943
Candidate commands/subject	≈ 21.1
Distinct commands issued	266
Most frequently issued commands	jump (385) walk forward (58) move forward (41) run (26) crawl forward (20).
Reinforcement signals	Values
Reinforcement signals entered	7503
Mean reinforcement signals/eval.	≈ 1.18
Mean reinf. signals/subject	≈ 17.7
Proportion of positive reinforcement	$\rho = 0.28$

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R_i : Robot i.

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N_{ijk} : Controller k evaluated under command j.

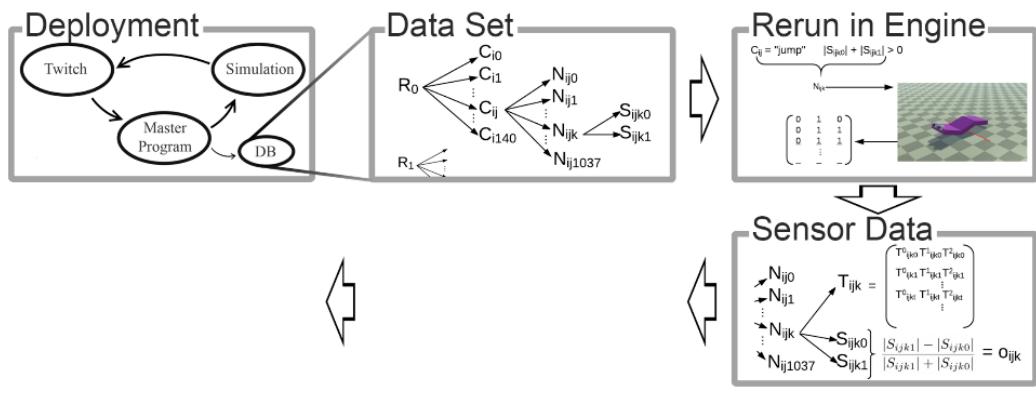
S_{ijk0} : Negative reinforcement signals issued under controller k.

S_{ijk1} : Positive reinforcement signals issued under controller k.

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Grounding symbols using *Twitch Plays Robotics*.

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Twitch: Video captured from simulation and fed to Twitch.

Master Program: controllers-->simulation; crowd response -->DB

R.:Robot i.

C_i:Command j issued to robot i.

N_k: Controller k evaluated under command j

S_{ijk} : Negative reinforcement signals issued under controller k.

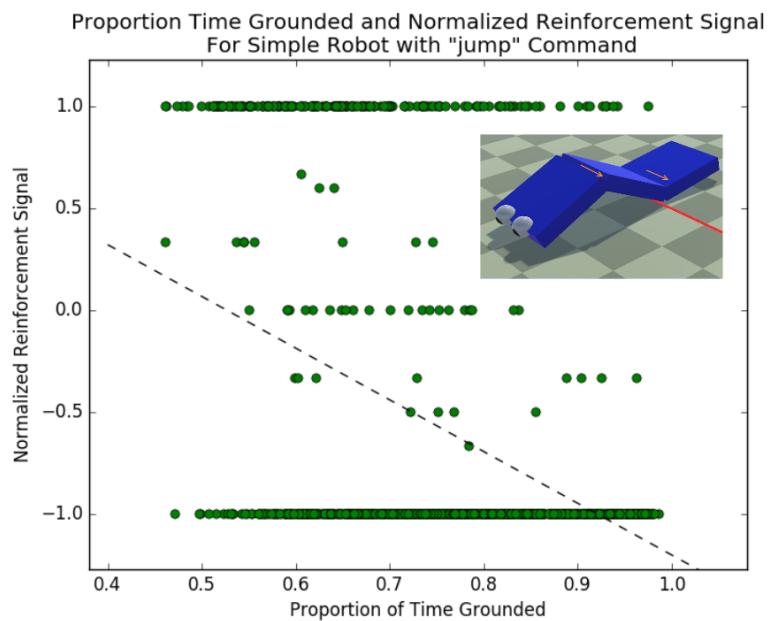
S_{ijk0} : Positive

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Grounding symbols using *Twitch Plays Robotics*.

Act. Observe. **Learn.** Predict.

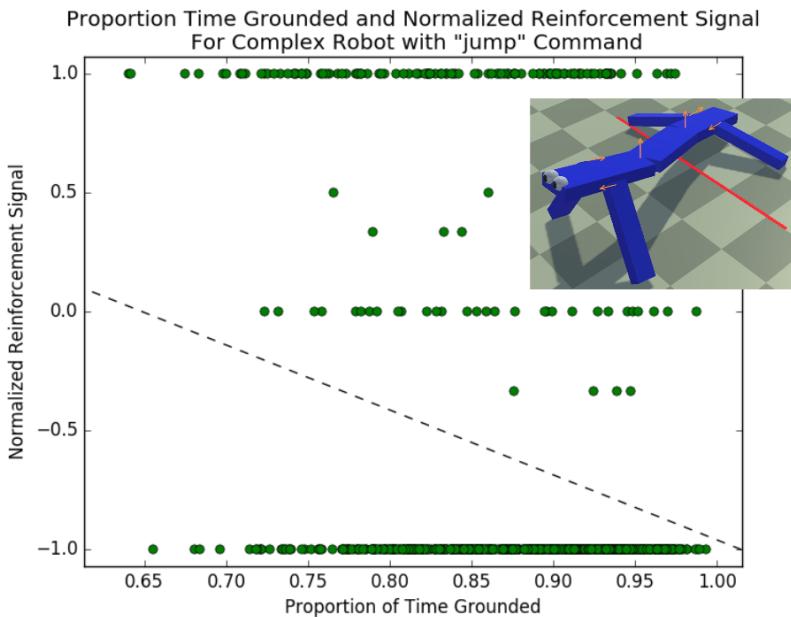


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Grounding symbols using *Twitch Plays Robotics*.

Act. Observe. **Learn.** Predict.

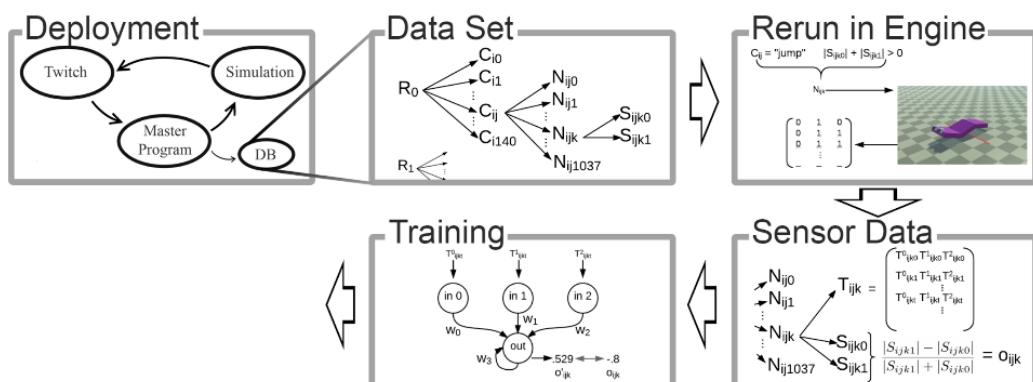


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Simulation: Robots simulated in Unity Physics Engine.

Twitch: Video captured from simulation and fed to Twitch.

Master Program: controllers-->simulation: crowd response -->DB

am.controllers.R:Robot i.

C_i:Command i issued to robot i

N_k^i :Controller k evaluated under command i

S_k: Negative reinforcement signals issued under controller k

s_{ijk0} : Negative reinforcement signal
 s_{ijk1} : Positive reinforcement signal

s_{ijk1} : Positive reinforcement signals issued under controller k.

T^n : Value of nth touch sensor at time t.

- \circ Crowd response to controller k.

δ_{ijk} : Crowd response in p th input neuron

out: output neuron

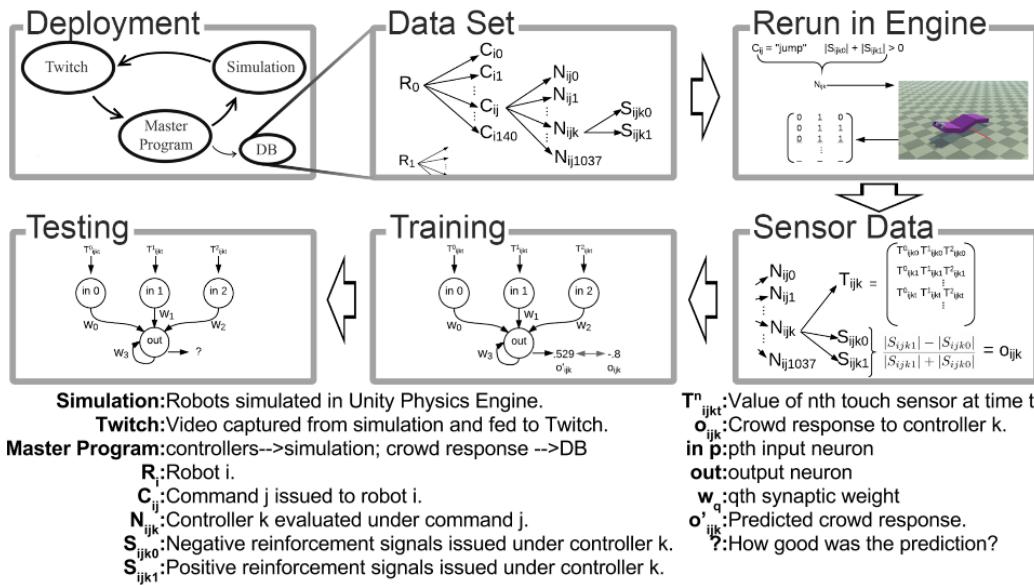
**Out. output neuron
with synaptic weight**

w_q : qth synaptic weight
 σ' : Predicted crowd response

θ_{ijk} : Predicted crowd response.

Grounding symbols using *Twitch Plays Robotics*.

Act. Observe. Learn. Predict.



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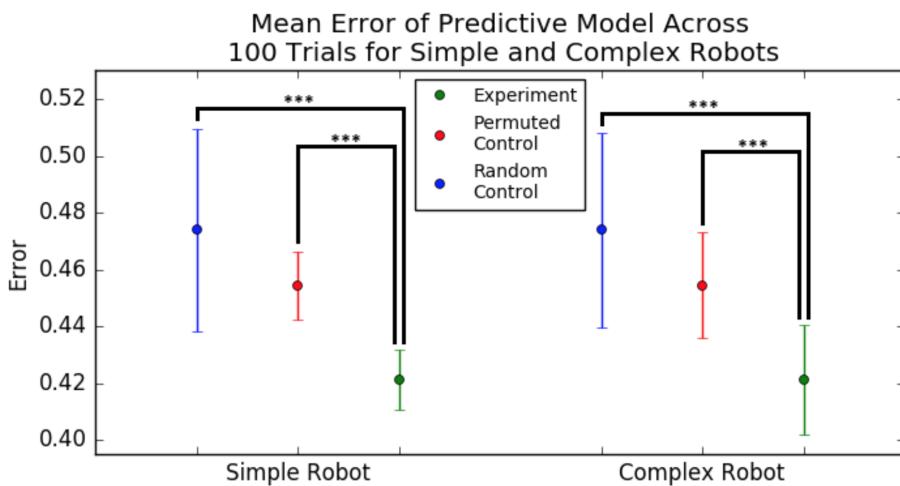


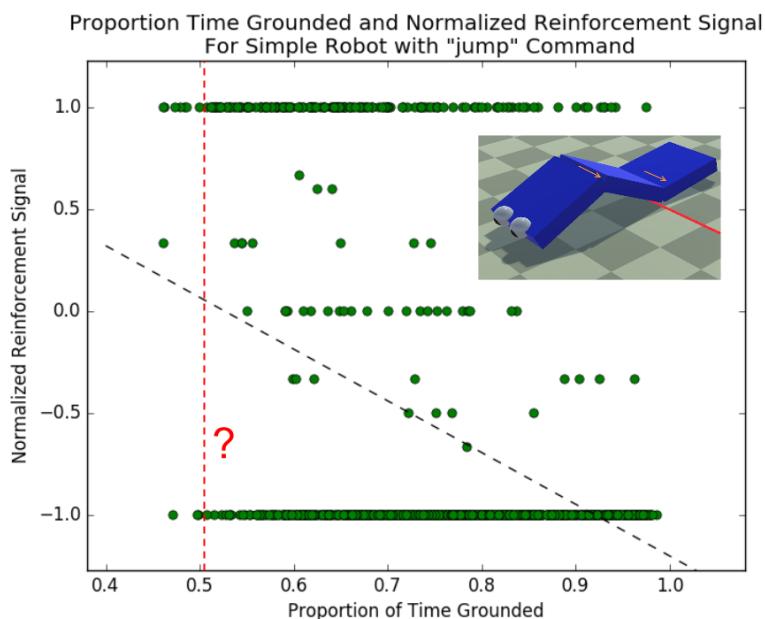
Figure 4: Results from the predictive model on unseen test data, the permuted test data set, and random RNNs on test data. *** denotes $p < .001$ as reported by a Student's T-test.

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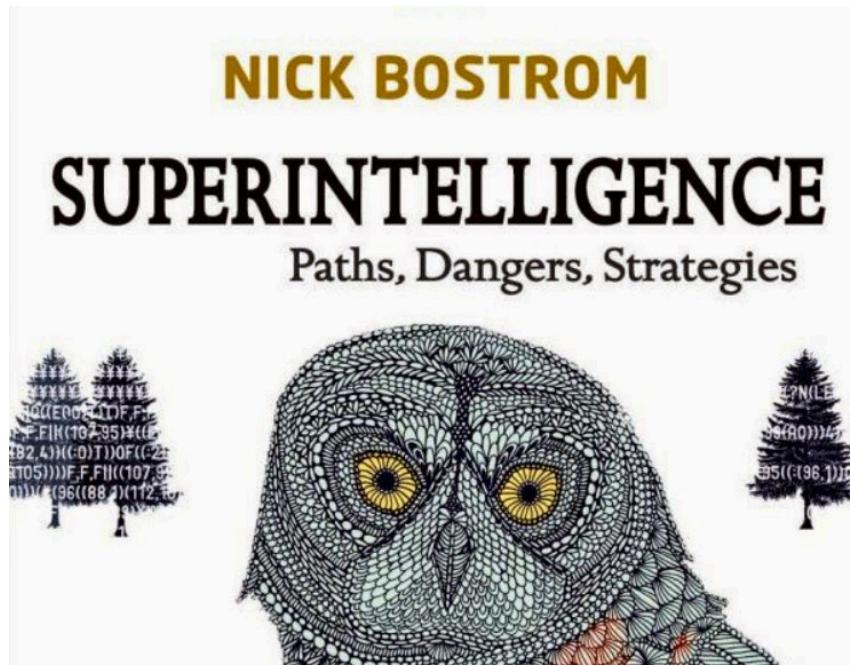
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Scaling up the grounding of symbols.

- ▶ Jump
 - ▶ ...
 - ▶ Don't **jump** to conclusions.

N. Bostrom. *Superintelligence*, (2014).

Superintelligent AI's may be unsafe because of **pathological instantiation**.

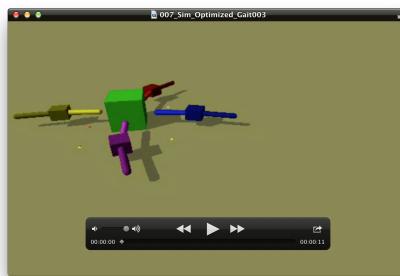
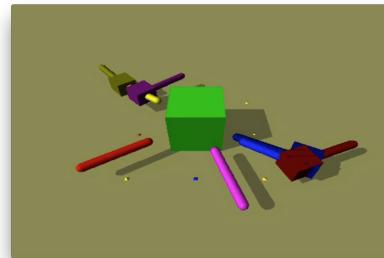


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Resilient Machines (The Intact Robot)

Bongard, Zykov & Lipson, 2006, *Science*



Anetsberger & Bongard (2016). *Proceedings of ALife*. In press.

A set of small, light-blue navigation icons typically found in presentation software like Beamer. From left to right, they include: a left arrow, a square, a right arrow, a double left arrow, a double square, a double right arrow, a double left arrow with a horizontal line, a double right arrow with a horizontal line, and three circular arrows.

Yudkowsky: CEV could combat perverse instantiation.

E. Yudkowsky. 2004. Coherent extrapolated volition. *The Singularity Institute*, San Francisco.

- ▶ A friendly AI should implement policies in a way that...
 - ▶ ...despite our differences... **[coherent]**
 - ▶ ...our future selves... **[extrapolated]**
 - ▶ ...would be likely to approve of those policies. **[volition]**

Anetsberger & Bongard (2016). *Proceedings of ALife*. In press.

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- ▶ A friendly AI should implement policies in a way that...
 - ▶ ...despite our differences... **[coherent]**
 - ▶ ...our future selves... **[extrapolated]**
 - ▶ ...would be likely to approve of those policies. **[volition]**

Challenges:

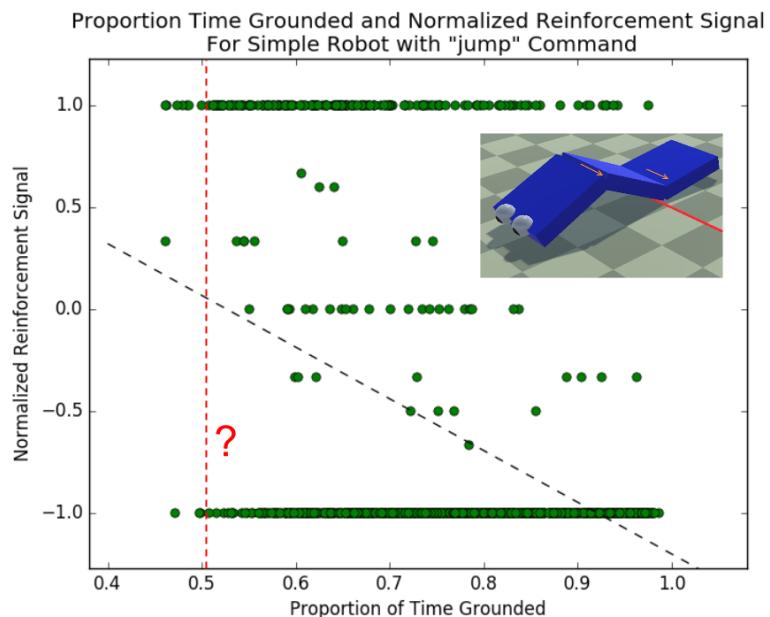
- ▶ Requires an accurate model of future human behavior.
 - ▶ Policy implemented now cannot cause future humans to vote as the model predicted.
 - ▶ Thus, model must also predict that future humans would signal remorse that a given policy was not implemented now.

Anetsberger & Bongard (2016). *Proceedings of ALife*. In press.

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Grounding symbols using *Twitch Plays Robotics*.

Act. Observe. Learn. Predict.



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A set of small, light-blue navigation icons typically found in Beamer presentations, including symbols for back, forward, search, and table of contents.

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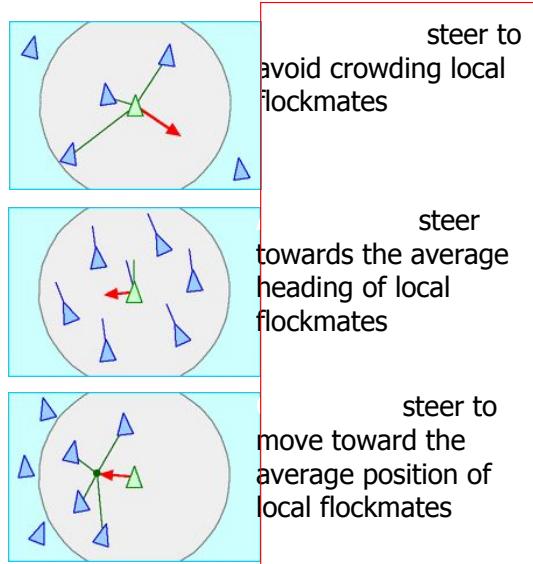
Evolutionary Robotics for Swarms



Evolutionary Robotics for Swarms

Example: Controllers for a Robot Swarm

Design a controller to be placed into a swarm of Unmanned Aerial Vehicles, such that they swarm:

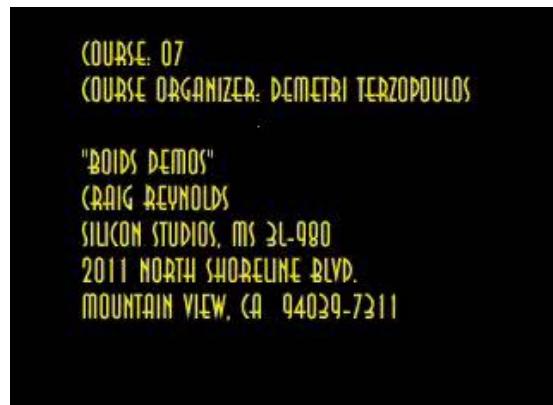


2

Evolutionary Robotics for Swarms

Example: Controllers for a Robot Swarm

Design a controller to be placed into a swarm of Unmanned Aerial Vehicles, such that they swarm:



3

Evolutionary Robotics for Swarms

- Question: What tasks cannot be solved by a single robot?
 Answer: Group hunting

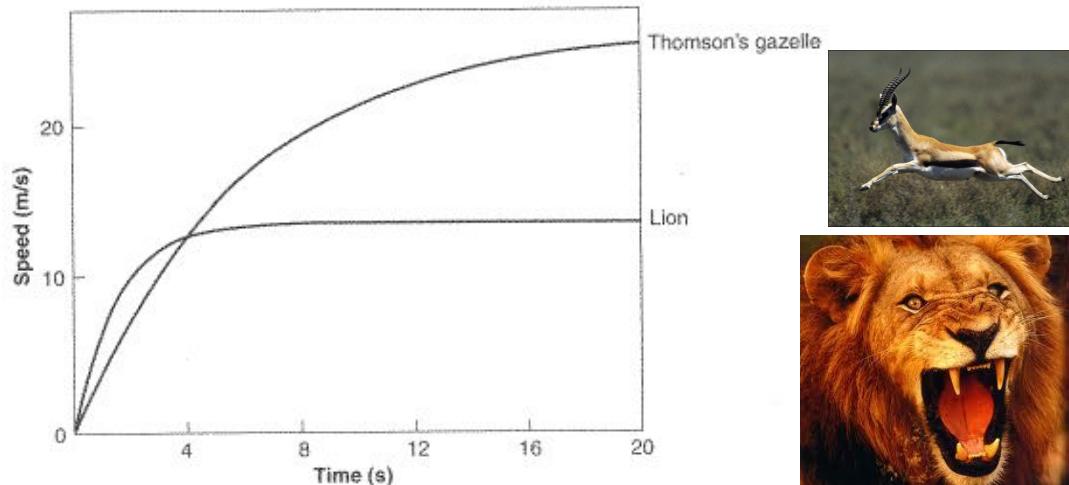


Fig. 1.1. Graphs of speed against time for lions and Thomson's gazelle, calculated from films of lions attacking prey. The curves were obtained by fitting to the data equations of the form $v = v_{\max} [1 - \exp(-kt)]$, where v is the speed at time t , v_{\max} is the speed that is approached asymptotically, and k is a constant. Redrawn from Elliott et al. (1977).

4

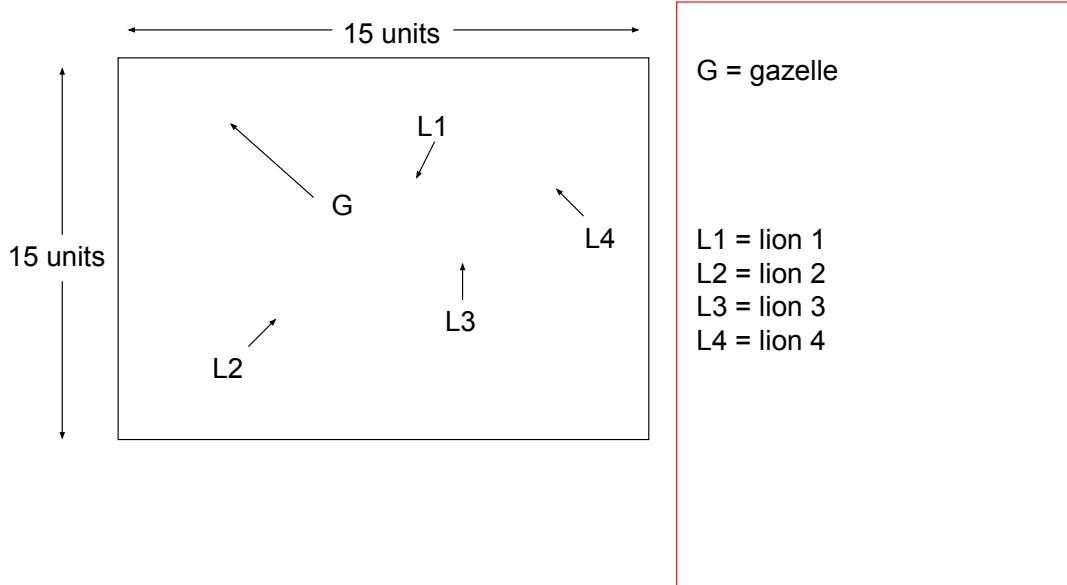
Evolutionary Robotics for Swarms

- Question: Can we evolve behaviors for a team of predators?
 How?
 Will they evolve to cooperate?

Luke, S., Spector, L. (1996) Evolving teamwork and coordination with genetic programming. In Procs. of the First Annual Conference on Genetic Programming, pp. 150-156.

5

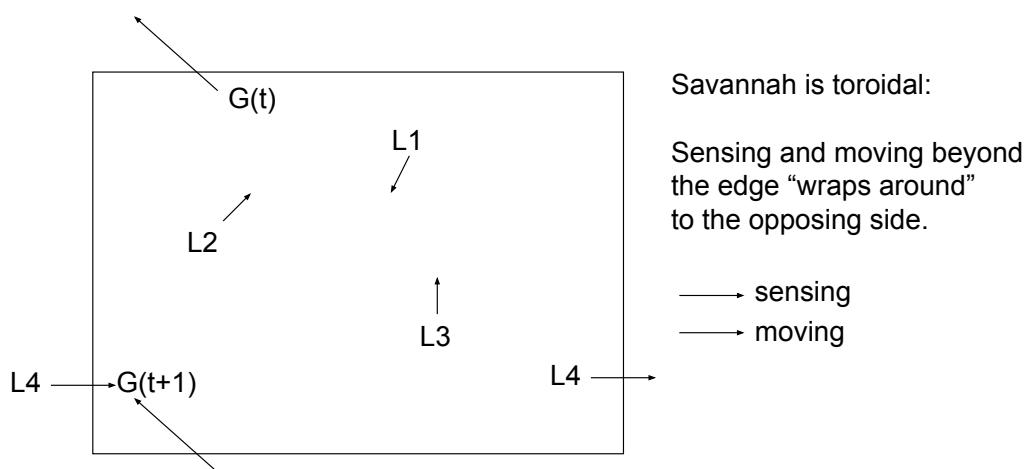
Evolutionary Robotics for Swarms



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6

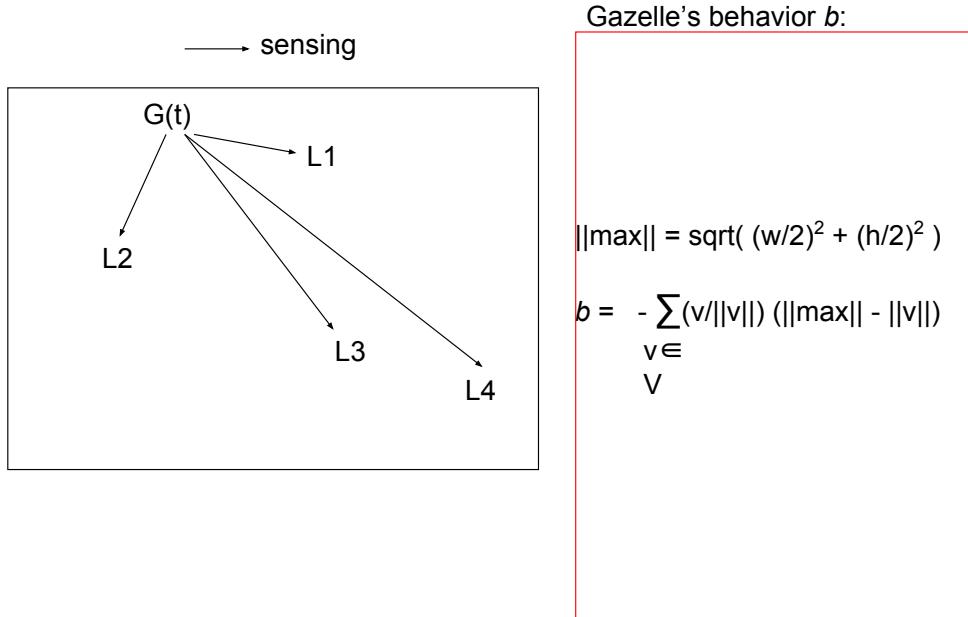
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7

Evolutionary Robotics for Swarms



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8

Lion's behavior L_i : Encoded as a tree that operates on 2D vectors:

Name	# Args	Description
last	0	One unit in the direction the lion went last. On the first move, return a random normal vector.
rand-dir	0	A random normal vector.
gazelle	0	The smallest vector from the lion to the gazelle.
+	2	Add two vectors.
-	1	Negate a vector.
*2	1	Multiply the magnitude of a vector by 2.
/2	1	Divide the magnitude of a vector by 2.
->90	1	Rotate a vector clockwise 90 degrees.
rand	1	Given a vector, return a vector in the same direction, whose magnitude varies randomly between 0 and the magnitude of the original vector.
inv	1	“Invert” a vector’s magnitude, so that small vectors are “more significant” than large vectors. This is done similarly to the method used in the gazelle algorithm: Let v be the vector, and $\ max\ = \sqrt{(w/2)^2 + (h/2)^2}$, where w is the width of the world (15 units), and h is the height of the world (also 15 units). Then inv returns $\frac{v}{\ v\ } (\ max\ - \ v\)$.
ifdot	4	Evaluate the first and second arguments. If their dot product is greater than or equal to 0, then evaluate and return the third argument, else evaluate and return the fourth argument.
if>=	4	Evaluate the first and second arguments. If the magnitude of the first argument is greater than or equal to the magnitude of the second argument, then evaluate and return the third argument, else evaluate and return the fourth argument.

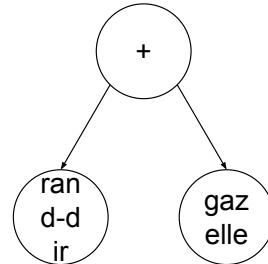
Q: If you were a single lion chasing the gazelle, what is the best strategy?

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9

Lion's behavior L_i ; Encoded as a tree that operates on 2D vectors:

Name	# Args	Description
nearest	0	The vector from the lion nearest the gazelle, to the gazelle.
lion	0	A vector from the lion to its nearest neighbor lion.
rlion	0	A vector from the lion to the first neighbor lion encountered in a clockwise sweep. The sweep begins in the direction the lion moved last. All the minimal vectors to each lion are gathered, and the first one found in the sweep is returned.
llion	0	A vector from the lion to the first neighbor lion encountered in a counterclockwise sweep. The sweep begins in the direction the lion moved last. All the minimal vectors to each lion are gathered, and the first one found in the sweep is returned.



Q: If you had these additional four sensors, what is the best strategy?

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10

Lion's behavior L_i ; Encoded as a tree that operates on 2D vectors:

Name	# Args	Description
lion-1	0	A vector from the lion to lion #1.
lion-2	0	A vector from the lion to lion #2.
lion-3	0	A vector from the lion to lion #3.
lion-4	0	A vector from the lion to lion #4.

Q: If you had these additional four sensors, what is the best strategy?

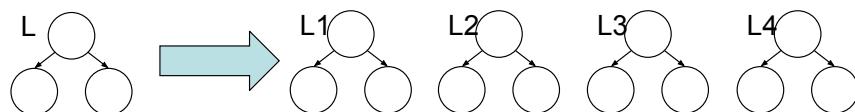
Luke, S., Spector, L. (1996) Evolving teamwork and coordination with genetic programming. In Procs. of the First Annual Conference on Genetic Programming, pp. 150-156.

11

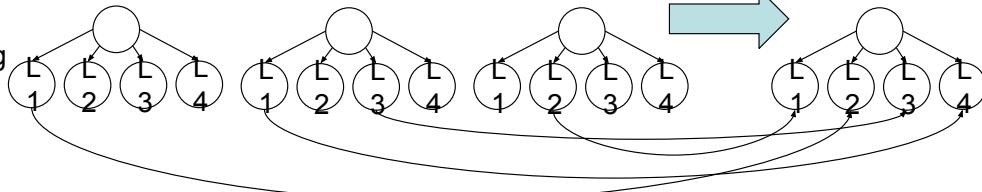
Q: How to evolve teams?

Three possible ways:

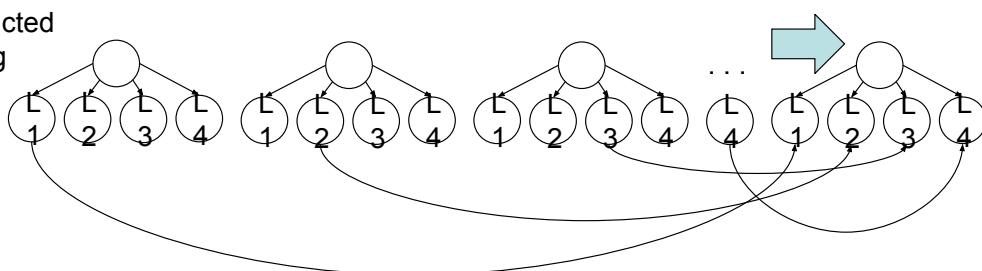
1. Cloning



2. Free breeding



3. Restricted breeding



12

Results:

1200 Evolutionary runs

100 runs for each of three sensing capabilities and three team-construction methods

100 runs: One lion with evolved behavior

100 runs: One randomly-moving lion

100 runs: Four randomly-moving lions

51 generations, population size = 500, max tree size = 70, max tree depth = 17,

For each new tree:
 created by crossover = 90% probability
 created by mutation = 10% probability

For each team evaluation: Place gazelle, lions, randomly
Each moves 15 times.

Fitness function: $\text{Fitness} = 0$: lion ≤ 1 unit from gazelle
 $\text{Fitness} = ||\text{nearest lion} - \text{gazelle}|| - 1$: otherwise

13

Trial Results

Sensing	Restricted Breeding		Free Breeding		Clones	
	Average	Best	Average	Best	Average	Best
Deictic	1.65	0.13	2.03	0.23	1.52	0.20
Name-Based	1.33	0.03	1.79	0.07	1.93	0.22
None	2.20	0.49	2.23	0.50	2.18	0.45

Control Results

	One Lion		One Random		Four Random	
	Average	Best	Average	Best	Average	Best
Controls	7.39	5.43	7.87	6.74	4.41	2.57

Observations:

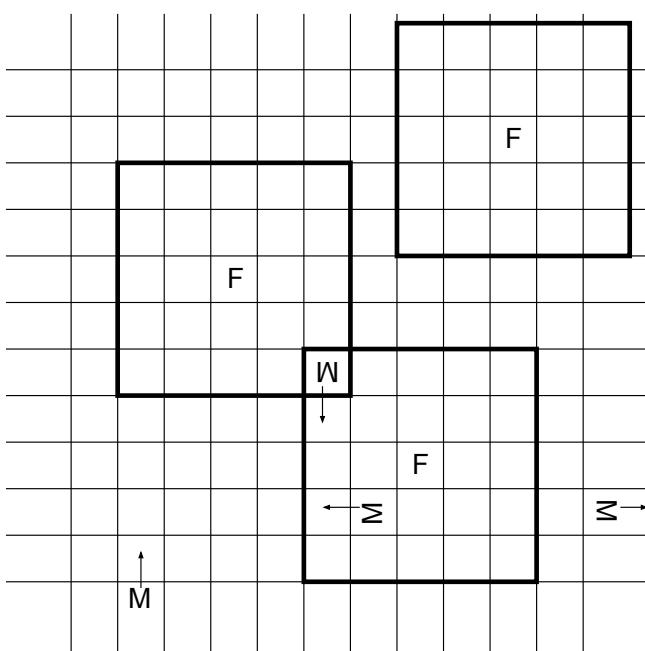
1. One evolved lion doesn't do much better than a random lion
2. Four lions do better than one lion (random or evolved)
3. For clones, name-based sensing was worse than deictic sensing; why?
4. For restricted breed, name-based sensing was best; why?

Q: What else besides distance to Lion i might a lion want to know?

14

L22

Evolution of Communication



Grid world:

200x200 squares
(toroidal)

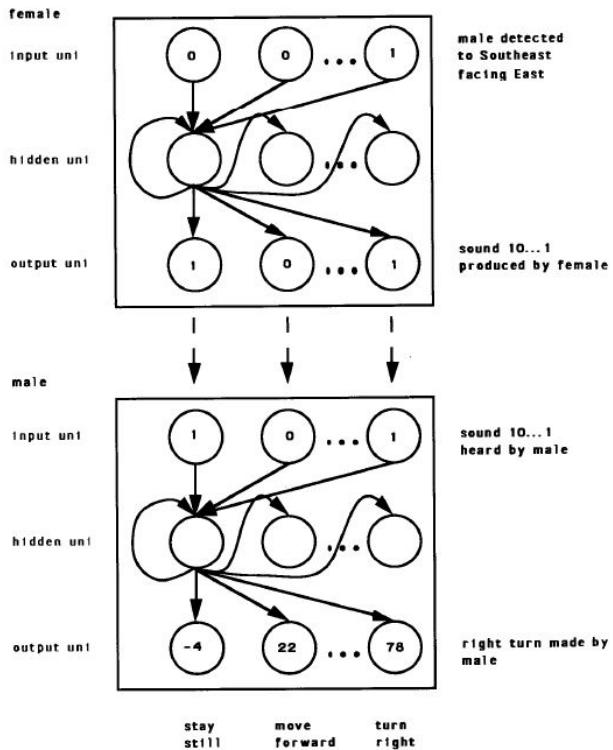
800 females, 800 males

Females are deaf
and immobile,
but can signal

Males are blind but
can hear, cannot signal,
but are mobile.

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Evolution of Communication



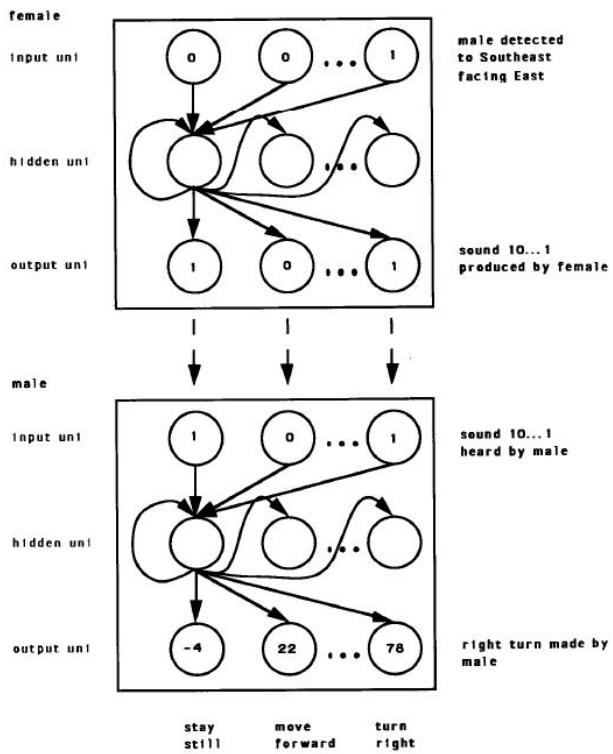
Each male and female starts with its own random neural network

Female network:
input:

output:

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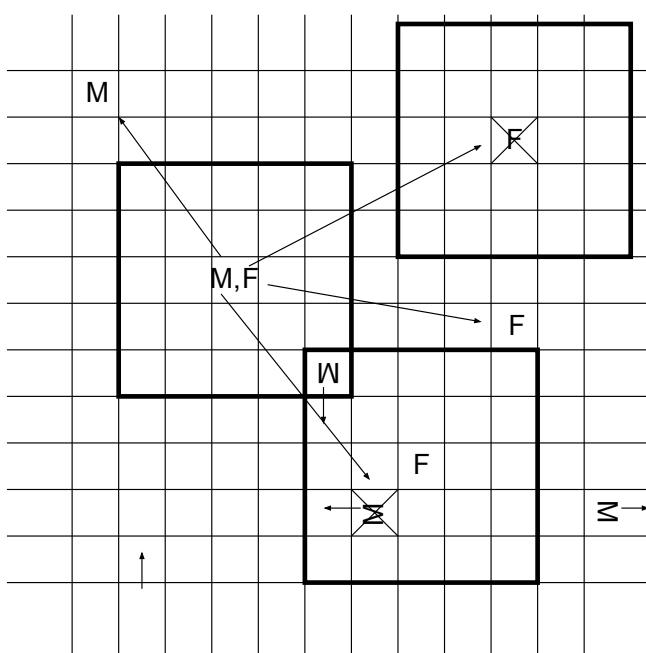
Each male and female starts with its own random neural network

Male network:
input:

output:

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If male finds female
(occupy same cell)...

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Observed evolutionary changes:

1. Males wandered randomly; females signaled randomly.

TABLE 1 Responses of randomly generated male neural nets to female signals are random (percentage of males making each response at Time = 100).

Signal	Move Forward	Turn Right	Turn Left	Stand Still
000	25	38	9	28
001	19	25	31	25
010	28	22	26	24
011	29	25	29	17
100	25	27	26	22
101	25	25	26	24
110	19	20	31	30
111	22	27	21	30

Observed evolutionary changes:

1. Males wandered randomly; females signaled randomly.
2. Males that stood still went extinct.

TABLE 2 Few males interpret a female signal to mean "stand still" (percentage of males making each response at Time = 5000).

Signal	Move Forward	Turn Right	Turn Left	Stand Still
000	74	20	5	1
001	81	12	7	0
010	67	18	14	1
011	79	11	19	1
100	80	7	12	0
101	75	11	14	0
110	56	21	23	0
111	70	14	16	0

6

Observed evolutionary changes:

1. Males wandered randomly; females signaled randomly.
2. Males that stood still went extinct.
3. Males evolved to move in straight lines; ignore signals.

TABLE 3 Males ignore their inputs and simply move forward (percentage of males making each response at Time = 7500).

Signal	Move Forward	Turn Right	Turn Left	Stand Still
001	98	2	0	0
001	99	0	0	1
010	98	1	1	0
011	100	0	0	0
100	100	0	0	0
101	99	1	0	0
110	98	1	1	0
111	99	0	1	0

7

Observed evolutionary changes:

1. Males wandered randomly; females signaled randomly.
2. Males that stood still went extinct.
3. Males evolved to move in straight lines; ignore signals.
4. Males evolved to turn when on same row or column as female; females have evolved to signal this information; females that do not use this signal go extinct.

TABLE 4 Males evolve that interpret 101 as "turn left," 110 as "turn right," and the remaining patterns as "move forward" (percent of males making each response at Time = 15,000).

Signal	Move Forward	Turn Right	Turn Left	Stand Still
000	97	2	0	1
001	100	0	0	0
010	98	1	1	0
011	98	0	1	1
100	100	0	0	0
101	22	77	1	0
110	5	2	93	0
111	97	0	3	0

8

Observed evolutionary changes:

1. Males wandered randomly; females signaled randomly.
2. Males that stood still went extinct.
3. Males evolved to move in straight lines; ignore signals.
4. Males evolved to turn when on same row or column as female; females have evolved to signal this information; females that do not use this signal go extinct.
5. Females evolve to use this signal in more situations.

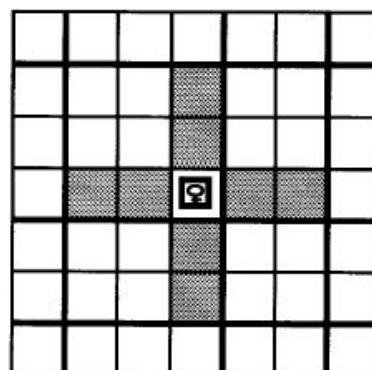
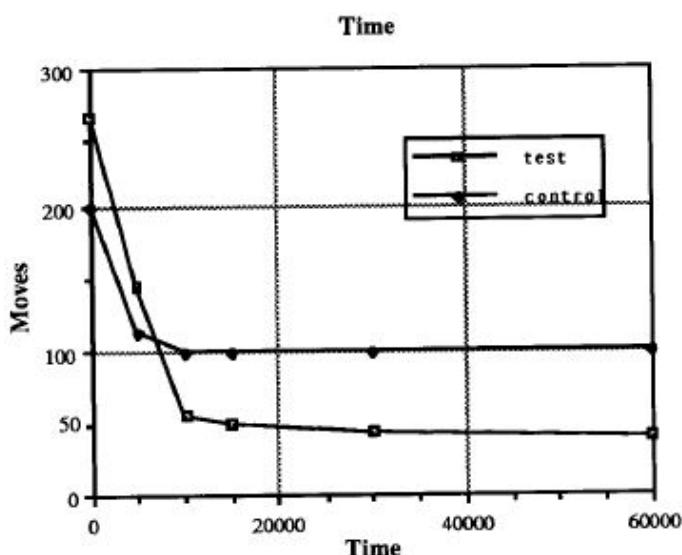


FIGURE 3 Females evolve that tell males in cross-shaped (shaded) area to continue turning until the male is facing the female. Males entering the "receptive field" but outside of the cross-shaped area are told to go straight. Such males will eventually enter the shaded area and from there be guided in to the female.

Evolution of Communication



Control set of runs:

Males were deafened;
could not hear female's
signals.

Q: Why the initial faster
rate of improvement
in the control case?

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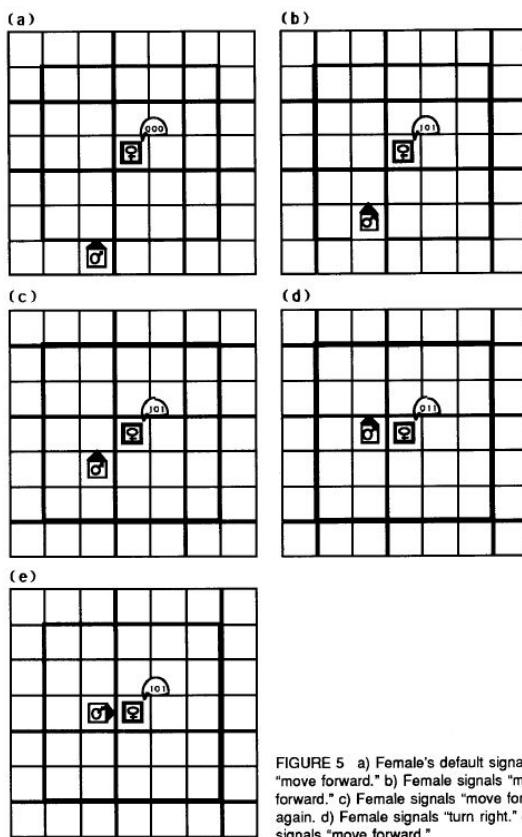
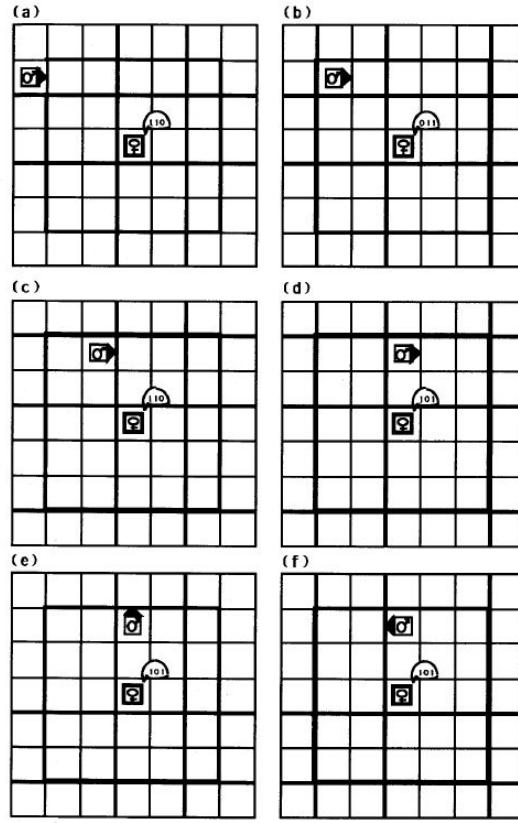


FIGURE 5 a) Female's default signal is "move forward." b) Female signals "move forward." c) Female signals "move forward" again. d) Female signals "turn right." e) Female signals "move forward."

Example of an evolved
female signal / male
response pairing.

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Example of a better evolved female signal / male response pairing.

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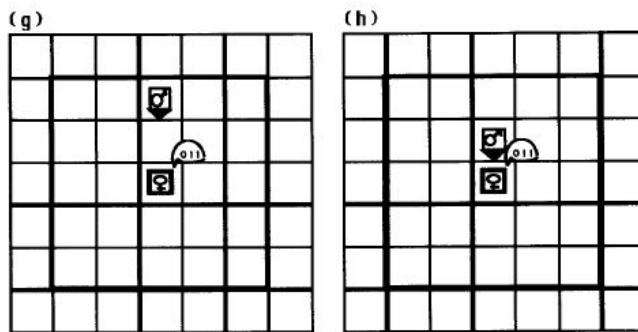


FIGURE 6 (continued) a) Male approaches "receptive field." b) Female signals "move forward." c) Female indicates "move forward" with another signal. d) Female signals "turn left" since she lacks a signal for "turn right." e) Female signals "turn left" again. f) Female signals "turn left" again. g) Female signals "move forward." h) Female signals "move forward" again.

Example of a better evolved female signal / male response pairing.

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TABLE 5 Frequency of Male Signal Responses (time = 0)

4:000	6:0001	5:0002	7:0003	4:0010	6:0011	4:0012	4:0013
12:0020	1:0021	3:0022	4:0023	8:0030	8:0031	2:0032	7:0033
5:0100	7:0101	7:0102	5:0103	7:0110	5:0111	3:0112	8:0113
2:0120	7:0121	6:0122	7:0123	3:0130	9:0131	6:0132	7:0133
8:0200	6:0201	4:0202	3:0203	11:0210	3:0211	4:0212	8:0231
1:0220	7:0221	6:0222	5:0223	8:0230	5:0231	8:0232	2:0233
8:0300	7:0301	2:0302	9:0303	4:0310	9:0311	9:0312	4:0313
10:0320	7:0321	3:0322	5:0323	12:0330	7:0331	6:0332	4:0333
8:1000	6:1001	6:1002	7:1003	7:1010	4:1011	7:1012	2:1013
7:1020	7:1021	0	7:1023	4:1030	8:1031	7:1032	8:1033
11:1100	4:1101	4:1102	6:1103	10:1110	3:1111	3:1112	8:1113
3:1120	5:1121	6:1122	4:1123	3:1130	8:1131	2:1132	7:1133
11:1200	4:1201	6:1202	5:1203	5:1210	6:1211	8:1212	5:1213
7:1220	5:1221	8:1222	8:1223	5:1230	4:1231	7:1232	5:1233
8:1300	4:1301	9:1302	7:1303	8:1310	11:1311	8:1312	6:1313
4:1320	3:1321	10:1322	6:1323	5:1330	2:1331	6:1332	7:1333
7:2000	9:2001	7:2002	11:2003	3:2010	9:2011	5:2012	6:2013
12:2020	8:2021	5:2022	7:2023	7:2030	6:2031	7:2032	10:2033
7:2100	5:2101	8:2102	3:2103	4:2110	7:2111	4:2112	5:2113
11:2120	11:2121	6:2122	6:2123	5:2130	8:2131	4:2132	9:2133
7:2200	4:2201	3:2202	10:2203	7:2210	8:2211	4:2212	7:2213
8:2220	7:2221	9:2222	11:2223	4:2230	5:2231	3:2232	5:2233
6:2300	8:2301	6:2302	7:2303	7:2310	7:2311	5:2312	6:2313
6:2320	4:2321	7:2322	4:2323	3:2330	3:2331	8:2332	3:2333
8:3000	6:3001	8:3002	4:3003	8:3010	4:3011	9:3012	9:3013
4:3020	8:3021	4:3022	9:3023	6:303	10:3031	6:3032	5:3033
9:3100	5:3101	7:3102	3:3103	14:3110	8:3111	5:3112	8:3113
7:3120	5:3121	5:3122	12:3123	3:3130	6:3131	6:3132	6:3133
4:3200	10:3201	6:3202	4:3203	12:3210	6:3211	10:3212	0
14:3220	9:3221	3:3222	12:3223	4:3230	6:3231	7:3232	7:3233
8:3300	4:3301	4:3302	9:3303	8:3310	8:3311	4:3312	3:3313
4:3320	6:3321	11:3322	6:3323	4:3330	5:3331	6:3332	6:3333

Female can emit
one of four signals:

00, 01, 10, 11

For a given female signal,
males can do 1 of 4 actions:

- 0: stay still
- 1: go forward
- 2: turn left
- 3: turn right

←Initial random responses
of males

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TABLE 6 Frequency of Male Signal Responses (time = 8000)

0	0	0	0	0	0	0	0
0	1:0101	0	0	0	0	0	1:0113
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	1:0222	0	0	0	0	0
0	0	0	0	0	0	1:0312	1:0313
0	0	0	0	0	0	0	1:0333
2:1000	0	0	0	0	73:1011	0	1:1013
1:1020	0	0	0	0	0	2:1032	6:1033
0	1:1101	0	1:1103	1:1110	70:1111	92:1112	64:1113
0	131:1121	14:1122	2:1123	0	3:1131	0	24:1133
1:1200	0	0	0	0	323:1211	5:1212	2:1213
1:1220	4:1221	2:1222	12:1223	0	0	0	2:1233
4:1300	2:1301	1:1302	0	5:1310	547:1311	74:1312	1:1313
0	89:1321	0	1:1323	0	13:1331	0	1:1333
0	0	0	0	0	0	0	0
0	1:2021	0	1:2023	0	0	0	0
0	0	0	0	0	0	0	1:2113
0	1:2121	0	1:2123	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	1:2332	0
0	0	1:3002	0	0	0	0	0
0	0	0	1:3023	0	0	0	0
1:3100	0	0	0	0	0	0	0
1:3120	1:3121	0	0	1:3130	0	0	0
0	0	0	0	0	0	0	0
1:3220	0	0	0	0	0	0	0
0	0	1:3302	0	0	0	0	0
0	0	1:3322	0	0	1:3331	0	0

Males can do 1 of 4 actions:

- 0: stay still
- 1: go forward
- 2: turn left
- 3: turn right

The 547 males with
response '1311' responded
to females that emitted
only signals #1 and #2.

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TABLE 7 Frequency of Male Signal Responses (time = 10,000)

0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	1.0101	0	0	0	0	0	1:0113
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	1:0313
0	0	0	0	0	0	0	0
1:1000	0	0	0	45:1011	0	22:1013	
1:1020	0	0	0	0	0	1:1032	0
0	0	0	1:1103	0	55:1111	90:1112	127:1113
0	78:1121	5:1122	1:1123	0	0	0	53:1133
0	0	0	0	321:1211	2:1212	3:1213	
1:1220	2:1221	4:1222	4:1223	0	0	0	1:1233
2:1300	0	1:1302	0	1:1310	613:1311	42:1312	20:1313
0	85:1321	0	0	0	7:1331	0	1:1333
0	0	0	0	0	0	0	0
0	1:2021	0	0	0	0	0	0
0	0	0	0	0	0	0	1:2113
0	0	0	1:2123	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
1:3100	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	1:3322	0	0	1:3331	0	0

Males can do 1 of 4 actions:

- 0: stay still
 - 1: go forward
 - 2: turn left
 - 3: turn right

The 127 males with response '1113' responded to females that emitted only signals #3 and #4.

Two groups of females;
Males 1311 and 1113
only responded to one
of these groups.

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TABLE 8 Frequency of Male Signal Responses (time = 12,000)

Males can do 1 of 4 actions:

- 0: stay still
 - 1: go forward
 - 2: turn left
 - 3: turn right

Q: How can we tell that from this figure?

Q: What do you think will happen in subsequent generations?

TABLE 9 Frequency of Male Signal Responses (time = 14,000)

0	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
0	0	0	0	0	0	0	0
1:1000	0	0	0	0	11:1011	0	1:1013
1:1020	0	0	0	0	0	0	0
0	0	0	0	0	27:1111	88:1112	286:1113
0	16:1121	1:1122	0	0	2:1131	0	26:1133
0	0	0	0	1:1210	310:1211	78:1212	20:1213
0	3:1221	0	0	0	0	0	0
0	1:1301	1:1302	0	0	470:1311	20:1312	217:1313
0	18:1321	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	1:2021	0	0	0	0	0	0
0	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
0	0	0	0	0	0	0	0

Female can emit
one of four signals:

00, 01, 10, 11

For a given female signal,
Males can do 1 of 4 actions:

- 0: stay still
- 1: go forward
- 2: turn left
- 3: turn right

TABLE 10 Frequency of Male Signal Responses (time = 16,000)

0	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
0	0	0	0	0	0	0	0
1:1000	0	0	0	0	0	7:1011	0
1:1020	0	0	0	0	0	0	0
0	0	0	0	0	27:1111	125:1112	192:1113
0	10:1121	1:1122	0	0	1:1131	0	3:1133
0	0	0	0	1:1210	397:1211	102:1212	218:1213
0	0	1:1302	0	0	326:1311	28:1312	155:1313
0	2:1321	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	1:2021	0	0	0	0	0	0
0	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
0	0	0	0	0	0	0	0

Werner, G.M., Dyer, M.G.

(1991)

Evolution of Communication

in Artificial Organisms

Artificial Life II, Studies in the Sciences of Complexity.

TABLE 11 Frequency of Male Signal Responses (time = 20,000)

0	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	8:1111	72:1112	87:1113
0	5:1121	0	0	0	0	0	0
0	0	0	0	0	222:1211	171:1212	262:1213
0	0	0	0	0	0	0	0
0	0	0	0	0	211:1311	45:1312	517:1313
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
0	0	0	0	0	0	0	0

Female can emit
one of four signals:

00, 01, 10, 11

For a given female signal,
Males can do 1 of 4 actions:

- 0: stay still
- 1: go forward
- 2: turn left
- 3: turn right

TABLE 12 Frequency of Male Signal Responses (time = 30,000)

0	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	5:1211	231:1212	183:1213
0	0	0	0	0	0	0	0
0	0	0	0	0	1:1311	40:1312	1140:1313
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
0	0	0	0	0	0	0	0

Werner, G.M., Dyer, M.G.
(1991)

Evolution of Communication

in Artificial Organisms

Artificial Life II, Studies in the Sciences of Complexity.

TABLE 13 Frequency of Male Signal Responses (time = 40,000)

0	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
0	0	0	0	0	0	0	0

Female can emit
one of four signals:

| 00, 01, 10, 11

For a given female signal,
Males can do 1 of 4 actions:

- 0: stay still
 - 1: go forward
 - 2: turn left
 - 3: turn right

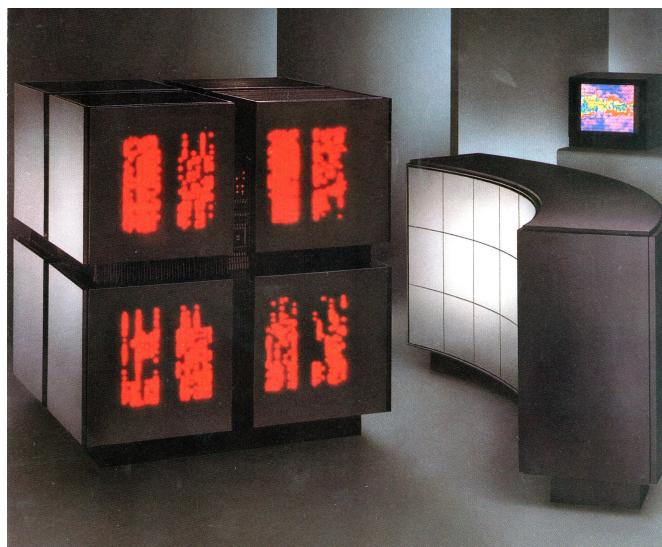
Werner, G.M., Dyer, M.G.
(1991)
Evolution of Communication
in Artificial Organisms
*Artificial Life II, Studies in the
Sciences of Complexity.*

First attempt to evolve robot morphology and control



Sims, K. (1994)
Evolving 3D Morphology
And Behavior by Competition.
Artificial Life IV, 28-39.

First attempt to evolve
robot morphology and control



Evolution performed on
Connection Machine-5:

1024 cores

Peak of 131.0 Gflops/sec

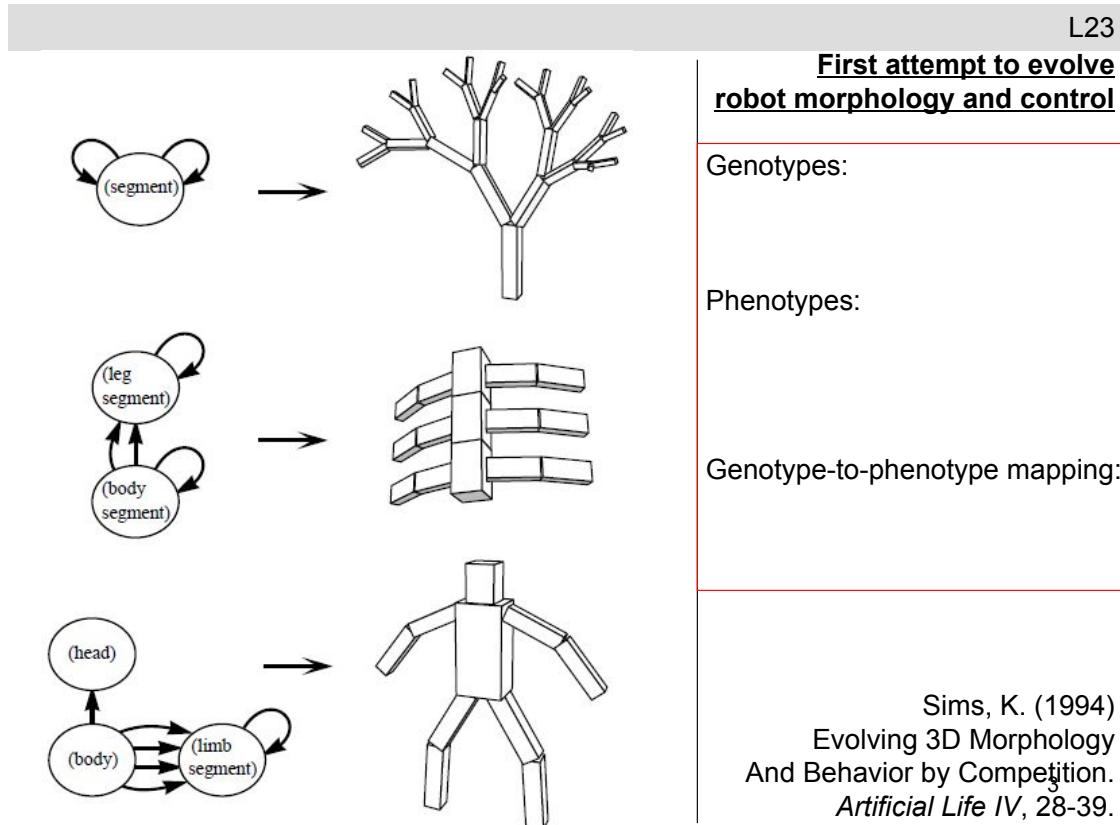
Mac Pro: ~91 Gflops/sec

Population size = 300

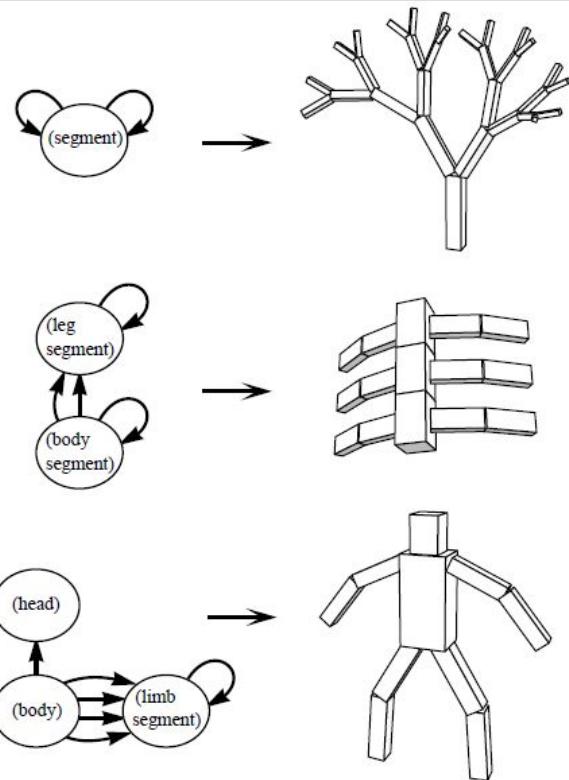
of generations = 100

~ 3 hours for a typical run

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First attempt to evolve robot morphology and control



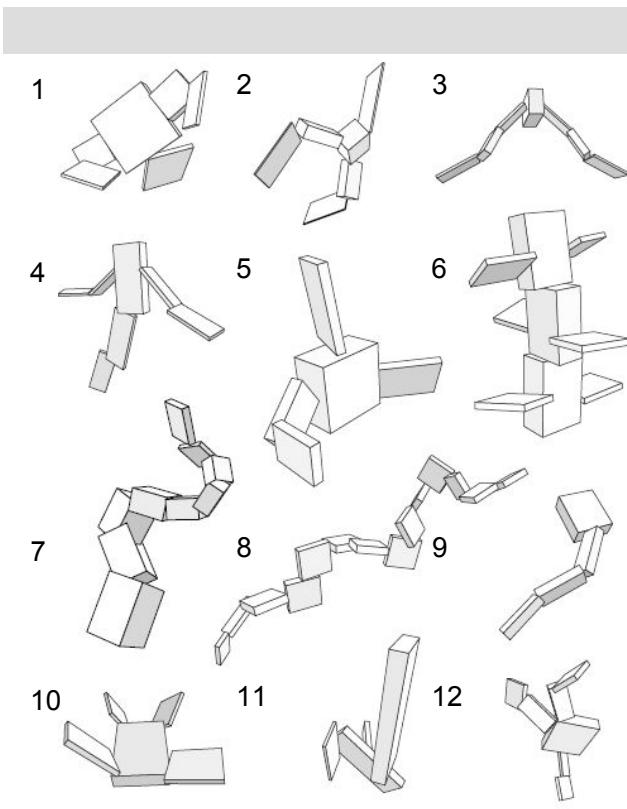
Genotype:

Node labels:

body part dimensions
joint-type: hinge, ball/socket...
joint-limits
recursive-limit (RL):
if (RL>0):
 RL = RL-1
 follow all outgoing edges.

Edge labels:

change in position
change in orientation
change in scale
reflection
terminal-only flag (TO):
if (TO==true &&
 parent->RL==0): 4
 follow edge;



First attempt to evolve robot morphology and control

Genotype:

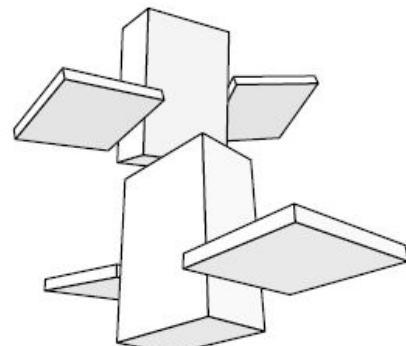
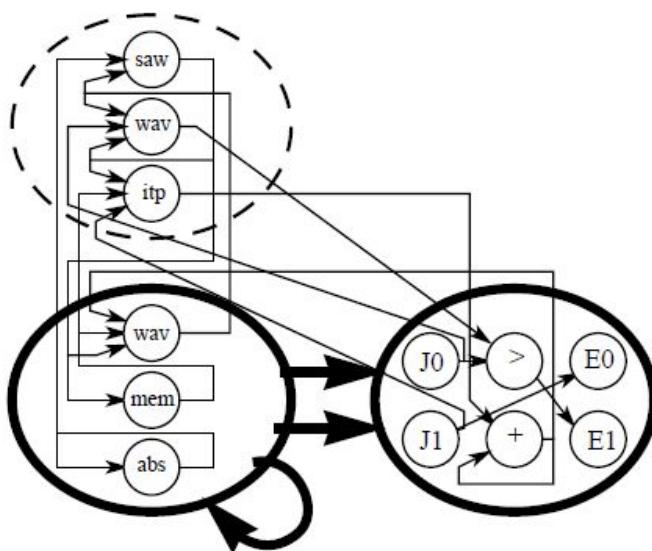
Node labels:

body part dimensions
joint-type: hinge, ball/socket...
joint-limits
recursive-limit (RL):
if (RL>0):
 RL = RL-1
 follow all outgoing edges.

Edge labels:

position
orientation
scale
reflection
terminal-only flag (TO):
if (TO==true &&
 parent->RL==0): 5
 follow edge;

**First attempt to evolve
robot morphology and control**



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Artificial Life IV, 28-39.

**First attempt to evolve
robot morphology and control**

Genotypes:

Nested, directed, multigraphs:

Each graph node contains
another graph.

Embedded graph describes
the local neural circuitry
for that body part.

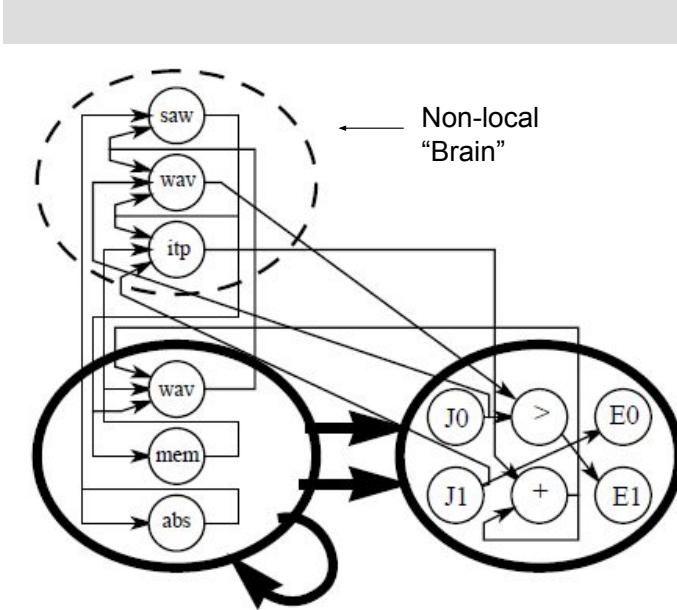
JX = joint sensor

CX = contact sensor

PX = photosensor

EX = effector

(X=degree-of-freedom)

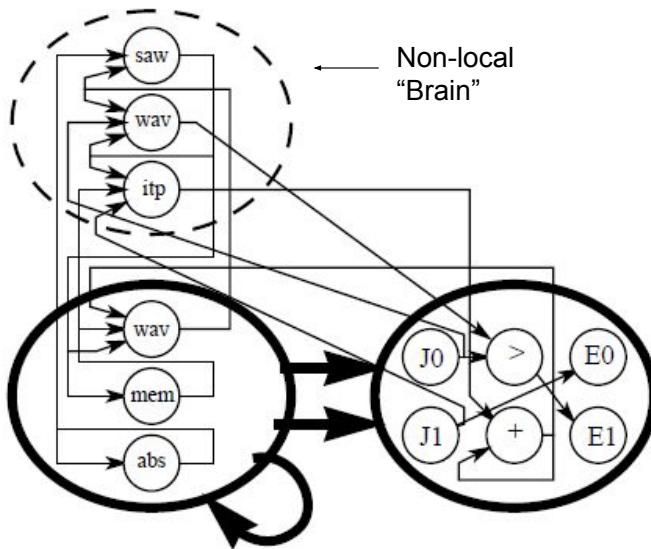


First attempt to evolve robot morphology and control

Neurons:

Sum
Product
Divide
Sum-threshold
Greater-than
Sign-of, Min, Max, Abs,
If,
Interpolate (itp)
Sin, cos, atan,
Log,
Expt,
Sigmoid,
Integrate,
Differentiate,
Smooth,
Memory
Oscillate-wave (wav)
Oscillate-saw (saw).

8



First attempt to evolve robot morphology and control

Genotypes:

Nested, directed, multigraphs:

Each graph node contains another graph.

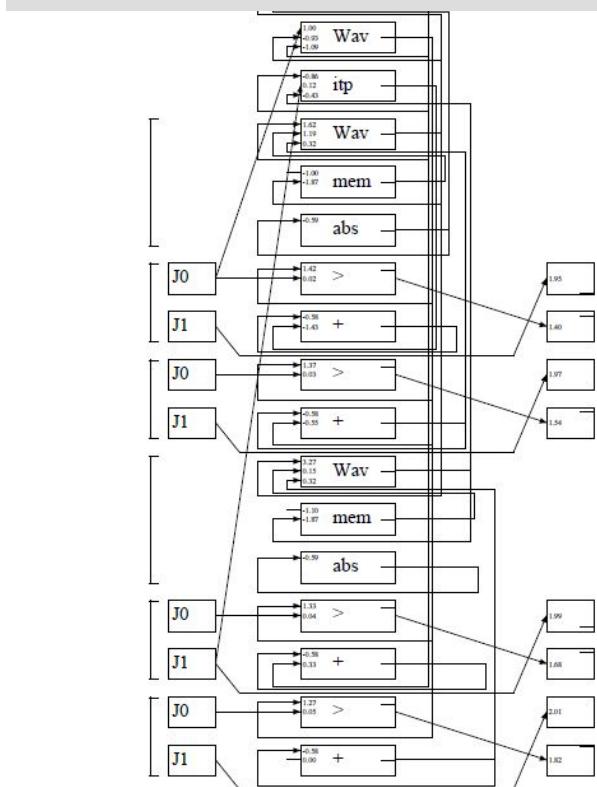
Embedded graph describes the local neural circuitry for that body part.

JX = joint sensor

CX = contact sensor

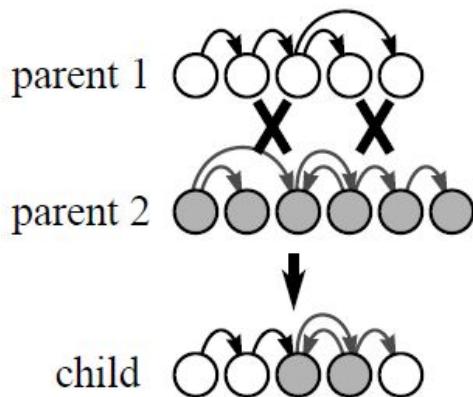
PX = photosensor

EX = effector
(X=degree-of-freedom)

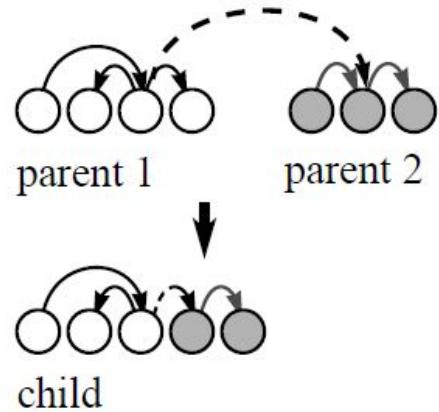


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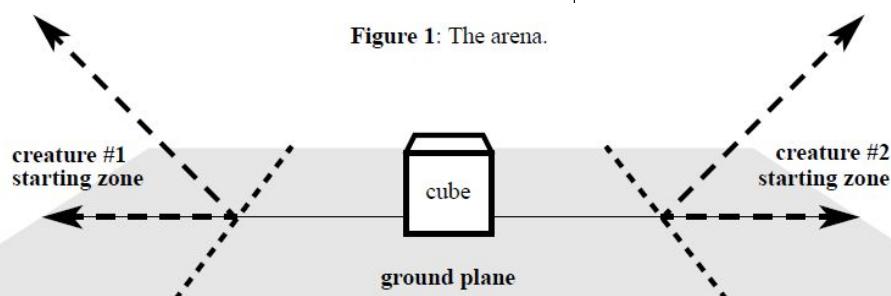
a. Crossovers:



b. Grafting:



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Two robots compete:

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Artificial Life IV, 28-39.

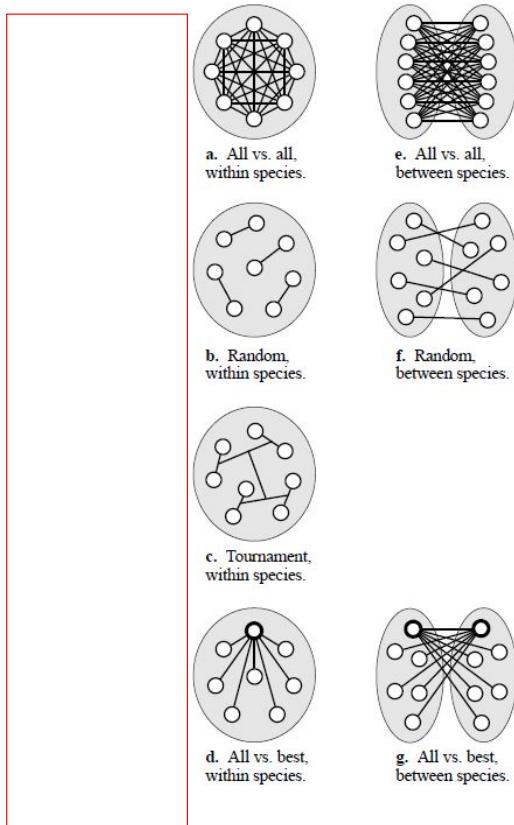
First attempt to evolve robot morphology and control

Robots can compete within a single species (a-d),

or

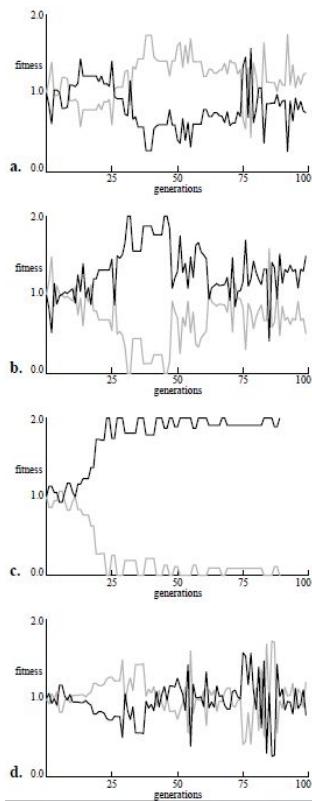
robots can compete between species (e-g)

What is the disadvantage of 'all-vs-all', 'random', and 'tournament'?



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12
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First attempt to evolve robot morphology and control

Results from four evolutionary runs.

Grey line:

Average fitness of species 1;

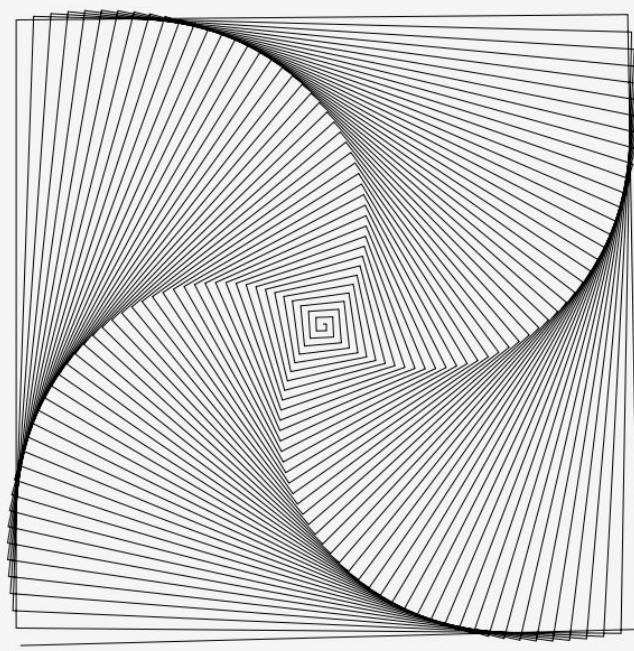
Black line:

Average fitness of species 2.

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Turtle Graphics (from computer graphics)



Using A Formal Grammar To Evolve Robot Bodies and Brains

Turtle moves over a 2D surface.

Possesses:

1. Position
2. Orientation
3. Pen, which can be up or down.

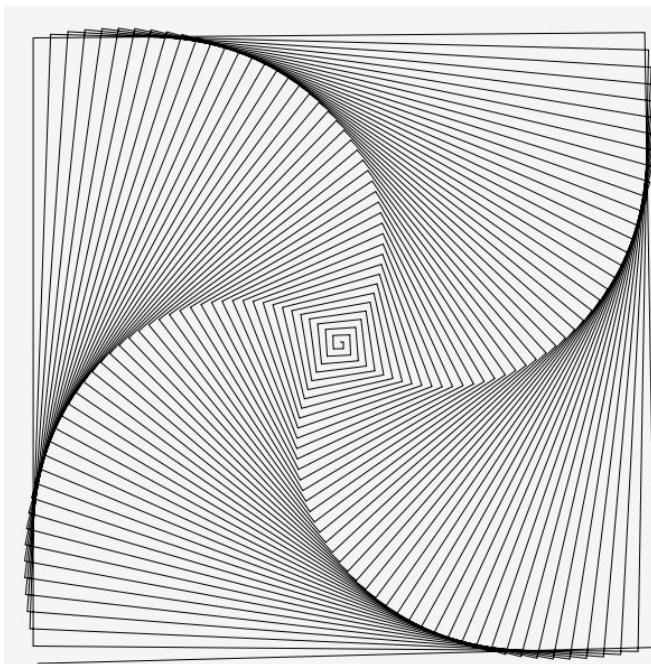
“Code” for drawing:

1. Move forward 10 paces
2. Turn left 95 degrees
3. Drop pen
4. Move forward
5. Lift pen...

Hornby, G.S., Pollack, J. (2001)
Creating high-level components
with a generative representation
for body-brain evolution.
GECCO 2001.

Using A Formal Grammar To Evolve Robot Bodies and Brains

1. Drop pen
2. For $i = 1$ to 1000
3. forward $1 + i/1000$
4. turn 85 degrees left
5. Lift pen



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Creating high-level components
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GECCO 2001.

Formal grammar:

1. Define an alphabet V that contains elements that can be replaced (variables)
2. Define a starting 'sentence' composed of elements from V
(eg. 'AB')
3. Define a set of production rules:
rule is composed of two strings:
the predecessor and
the successor
(eg. $A \rightarrow AB$
 $B \rightarrow A$)
4. If a symbol C in V does not match any predecessor, then C is a constant.
5. Apply the production rules to the start sentence.
6. Continue to apply the rules until the sentence only contains constants.

Using A Formal Grammar To Evolve Robot Bodies and Brains

Hornby, G.S., Pollack, J. (2001)
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Example 1: Algae

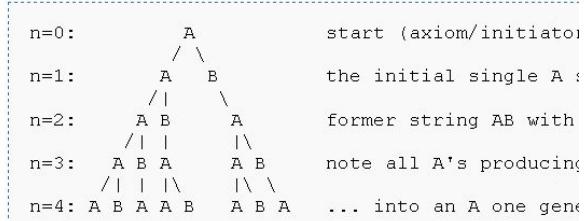
Lindenmayer's original L-system for modelling the growth of algae.

```
variables : A B
constants : none
start : A
rules : (A → AB), (B → A)
```

which produces:

```
n = 0 : A
n = 1 : AB
n = 2 : ABA
n = 3 : ABAAB
n = 4 : ABAABABA
n = 5 : ABAABABAABA
n = 6 : ABAABABAABAABA
n = 7 : ABAABABAABAABAABAABA
```

Example 1: Algae, explained



Using A Formal Grammar To Evolve Robot Bodies and Brains

A = algae
B = bud (cannot reproduce)

A → AB is a model of growth:
algae 'spawns' a bud.

B → A models maturation:
bud becomes adult algae
capable of reproduction.

Hornby, G.S., Pollack, J. (2001)
Creating high-level components with a generative representation for body-brain evolution.
GECCO 2001.

Lindenmayer system =

A system in which ‘turtle graphics’ commands serve as the elements in a formal grammar.

Example: “Drawing” Cantor dust.

variables : A B

constants : none

start : A {starting character string}

rules : (A → ABA), (B → BBB)

Let A mean "draw forward" and B mean "move forward".



Using A Formal Grammar To Evolve Robot Bodies and Brains

Given the right L-system, one can produce structures that look like biological plants:

Example: Fractal plant

variables : X F

constants : + -

start : X

rules : (X → F-[X]+X)+F[+FX]-X),
(F → FF)

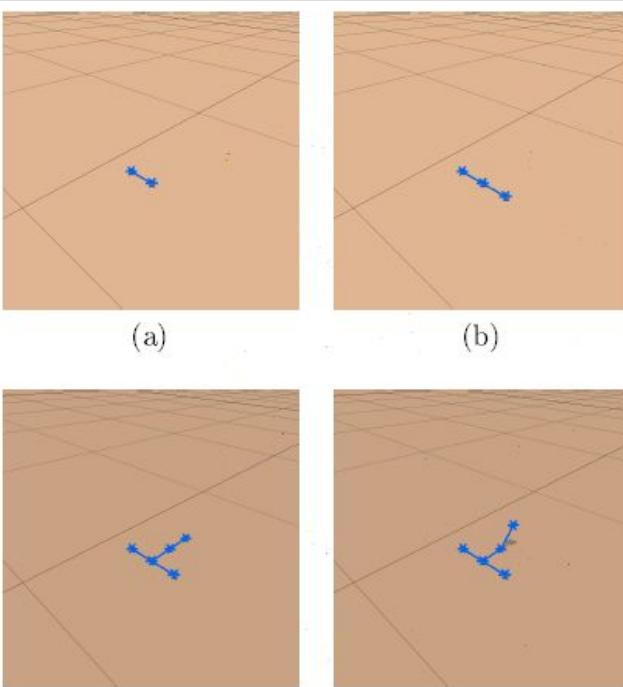
F means "draw forward",

- means "turn left 25°", and
+ means "turn right 25°".

X does not correspond to any drawing action.

[= 'push' position and angle
] = 'pop' position and angle

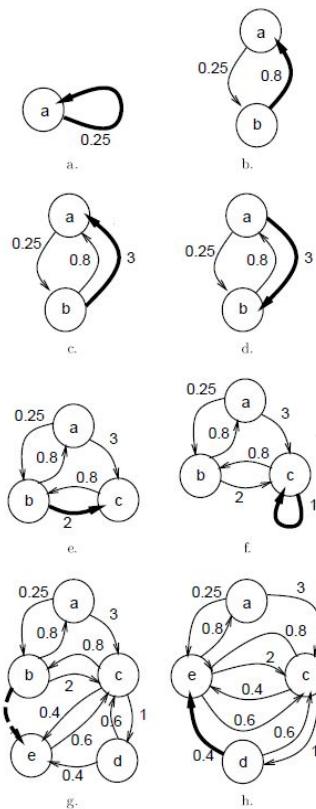




Building bodies with L-systems

[= push state
] = pop state
{block}(n) = repeat enclosed block n times.
forward: create bar forward
backward: move backward
Revolute-1(n): move forward, add joint around Z
Revolute-2(n): move forward, add joint around Y
up(n): rotate heading $+n^{\circ}$
down(n): rotate $-n^{\circ}$ around X
left/right(n): ... around Y
counter/clockwise(n): ... around Z
(n = rate of oscillation of motor)

Hornby, G.S., Pollack, J. (2001)
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with a generative representation
for body-brain evolution.
GECCO 2001.



Turtle 'lives' on synapses.

Building brains with L-systems

If turtle's 'home' link connects neuron A to neuron B...

[= push 'home' link
] = pop new 'home' link

decrease-weight(n): subtract n from weight of current link.

duplicate(n): Create new link from A to B with weight n .

loop(n): Create new link from B to itself with weight n .

merge(n): Merge neurons A and B into single neuron, C.
new 'home' link is n th input link to C.

parent(n): move to n th input link to A.

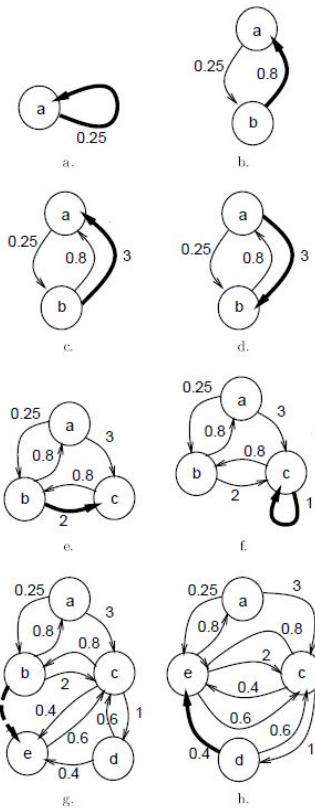
next(n): move to n th output link from B.

reverse: link changed to point from B to A.

output(n): neuron A sends commands to the closest joint.

split(n): create new neuron C; attach edge from A to C; and
create a new edge from C to B with weight n .
8

Connecting Body and Brain



In the formal grammar, throw ‘body’ and ‘brain’ elements together.

Turtle ‘points’ to both a body part and a synapse.

If a ‘joint’ element is called, output(1) is also called:

connects part of the neural network to the joint.

9

For example, the L-system,

$$\begin{aligned} a : & \rightarrow a \ b \\ b : & \rightarrow b \ a \end{aligned}$$

if started with the symbol *a*, produces the following strings,

a
ab
abba
abbabaab

A parametric L-system [Lindenmayer, 1974] is a class of L-systems in which production rules have parameters and algebraic expressions can be applied when parameter values to successors. Parameter values can also be used in determining which production rule to apply. For example, the P0L-system,

$$\begin{aligned} a(n) : (n > 1) & \rightarrow a(n-1) \ b(n) \\ a(n) : (n \leq 1) & \rightarrow a(0) \\ b(n) : (n > 2) & \rightarrow b(n/2) \ a(n-1) \\ b(n) : (n \leq 2) & \rightarrow b(0) \end{aligned}$$

When started with *a*(4), the P0L-system produces the following sequence of strings,

a(4)
a(3)*b*(4)
a(2)*b*(3)*b*(2)*a*(3)
a(1)*b*(2)*b*(1.5)*a*(2)*b*(0)*a*(2)*b*(3)
a(0)*b*(0)*b*(0)*a*(1)*b*(2)*b*(0)*a*(1)*b*(2)*b*(1.5)*a*(2)
a(0)*b*(0)*b*(0)*a*(0)*b*(0)*b*(0)*a*(0)*b*(0)*b*(0)*a*(1)*b*(2)
a(0)*b*(0)*b*(0)*a*(0)*b*(0)*b*(0)*a*(0)*b*(0)*b*(0)*a*(0)*b*(0)

L24

Parametric Lindenmayer systems

Hornby, G.S., Pollack, J. (2001)
 Creating high-level components
 with a generative representation
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GECCO 2001.

Parametric Lindenmayer systems

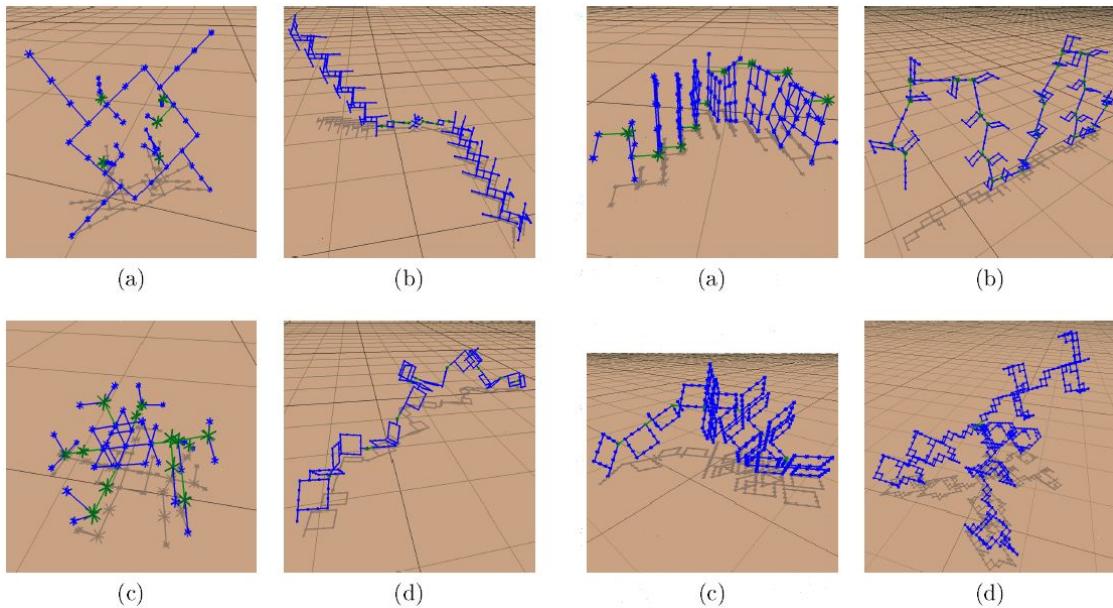
Advantages of a parametric L-system are a P0L-system can produce a family of structures, with the specific structure created being determined by the starting parameters. Similarly, parameters can be used so that repeating patterns of connections will have different weights. An example of a P0L-system for a network is,

$$\begin{aligned} P0(n0) : \\ n0 > 1.0 \rightarrow & P1(n0) P0(n0 - 1) \\ n0 > 0.0 \rightarrow & \text{loop}(1) P1(1) \text{parent}(1) \text{merge}(1) \end{aligned}$$

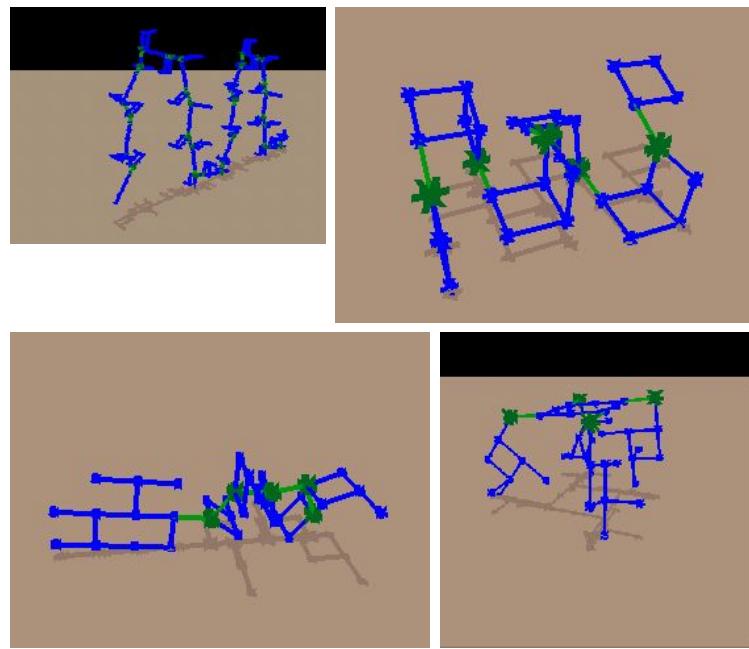
$$\begin{aligned} P1(n0) : \\ n0 > 1.0 \rightarrow & \text{split}(0.8) \text{duplicate}(n0) \text{reverse} \\ n0 > 0.0 \rightarrow & \{\text{split}(0.6) \text{duplicate}(0.4)\}(2) \text{reverse} \end{aligned}$$

This L-system consists of two productions, each containing two condition-successor pairs and when started with $P0(3)$ produces the sequence of four strings: *a*, $P1(3) P0(2)$; *b*, $\text{split}(0.8) \text{duplicate}(3) \text{reverse } P1(2) P0(1)$; *c*, $\text{split}(0.8) \text{duplicate}(3) \text{reverse split}(0.8) \text{duplicate}(2) \text{reverse loop}(1) P1(1) \text{parent}(1) \text{merge}(1)$; and *d*, $\text{split}(0.8) \text{duplicate}(3) \text{reverse split}(0.8) \text{duplicate}(2) \text{reverse loop}(1) \{\text{split}(0.6) \text{duplicate}(0.4)\} \text{reverse parent}(1) \text{merge}(1)$. This last is interpreted as: $\text{split}(0.8) \text{duplicate}(3) \text{reverse split}(0.8) \text{duplicate}(2) \text{reverse loop}(1) \text{split}(0.6) \text{duplicate}(0.4) \text{split}(0.6) \text{duplicate}(0.4) \text{reverse parent}(1) \text{merge}(1)$, and the network that it constructs is shown in figure 2.h.

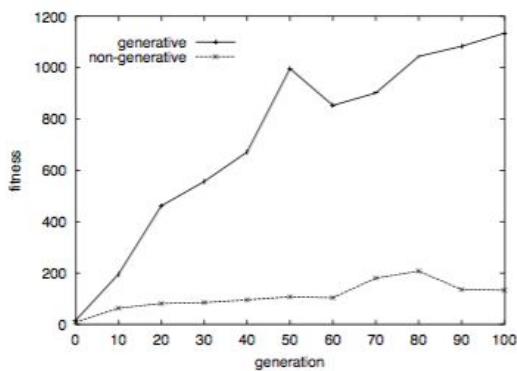
Hornby, G.S., Pollack, J. (2001)
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GECCO 2001.



Hornby, G.S., Pollack, J. (2001)
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 with a generative representation
 for body-brain evolution.
GECCO 2001.



L24
Generative vs.
Non-generative
Genotype to phenotype
Mappings

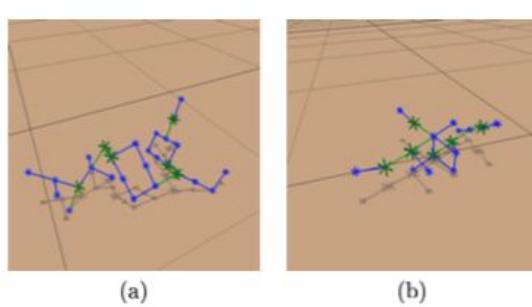
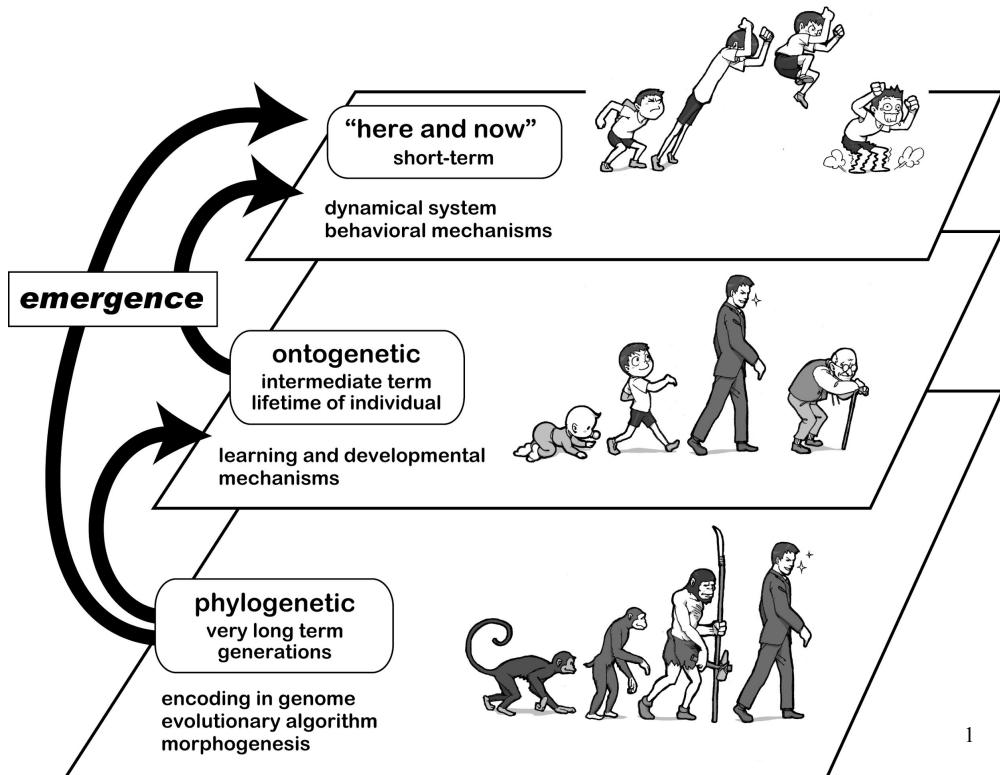
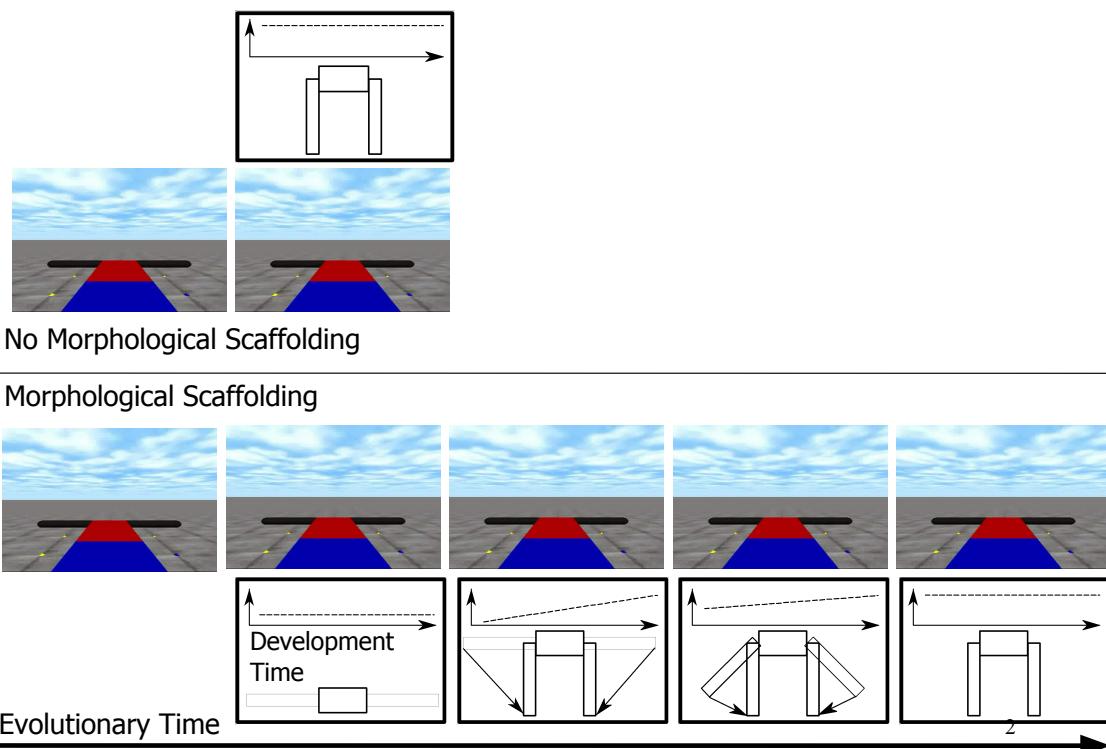


Figure 4: Results with Non-generative Encoding

Hornby, G.S., Pollack, J. (2001)
 Creating high-level components
 with a generative representation
 for body-brain evolution.
GECCO 2001.

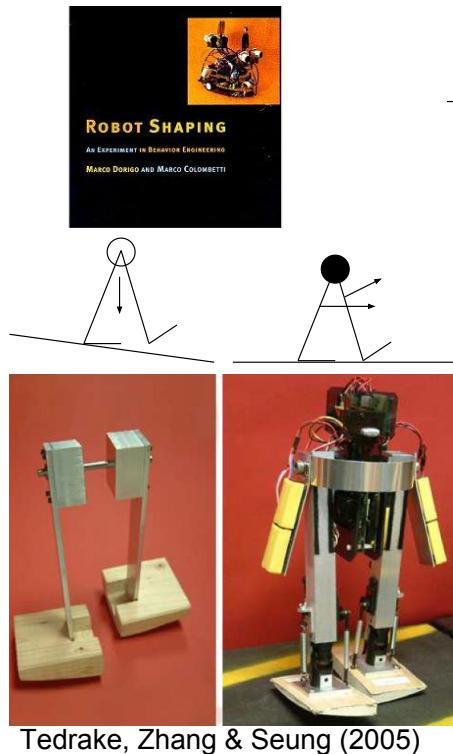


1



2

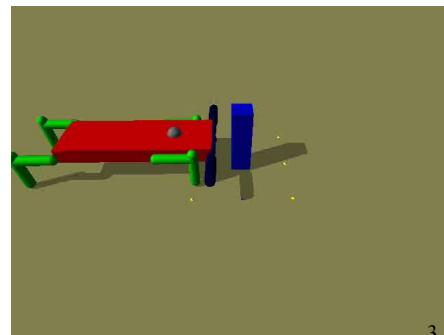
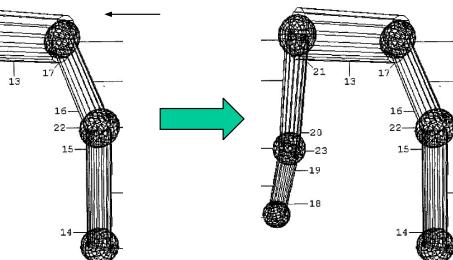
Robot Shaping
(Dorigo & Colombetti, 1997)



Tedrake, Zhang & Seung (2005)

Environmental Shaping

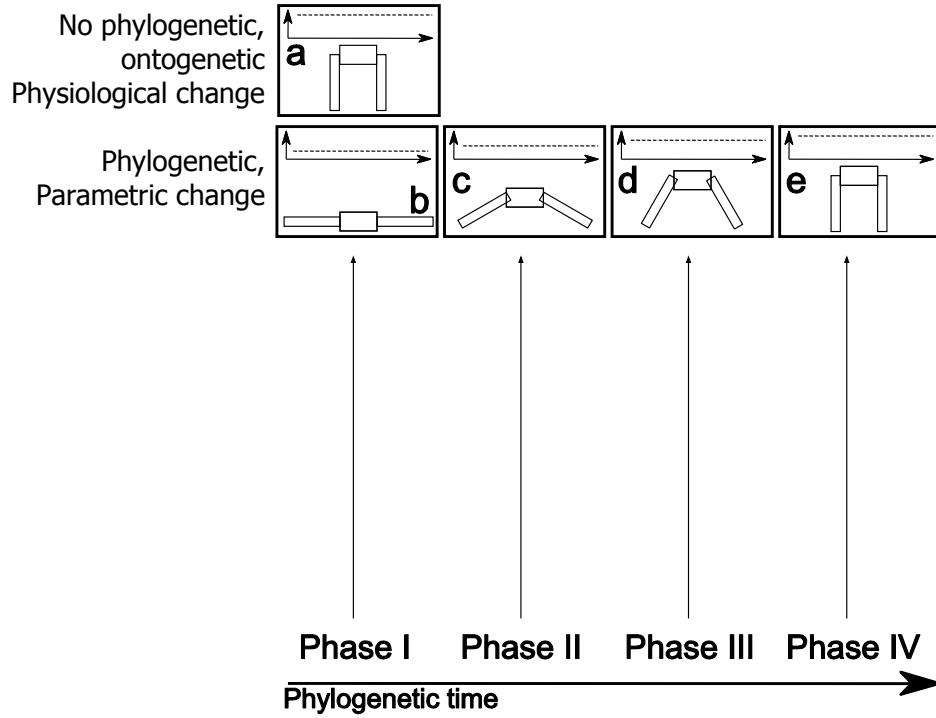
Reil & Husbands (2002)

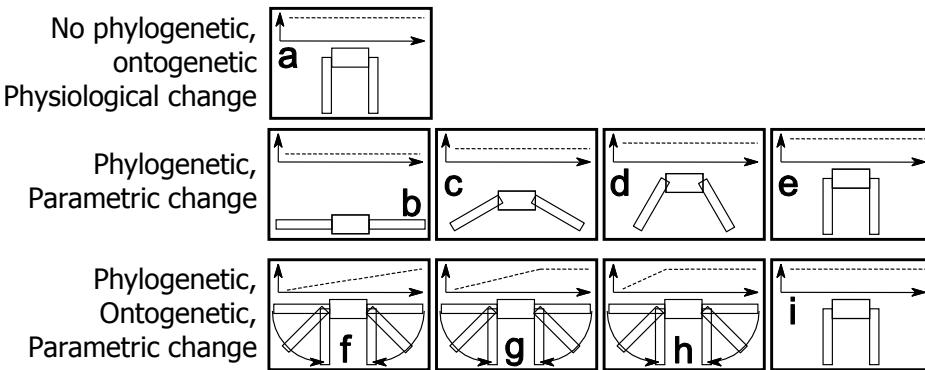


Bongard (2008)

Why Evolve Morphology?

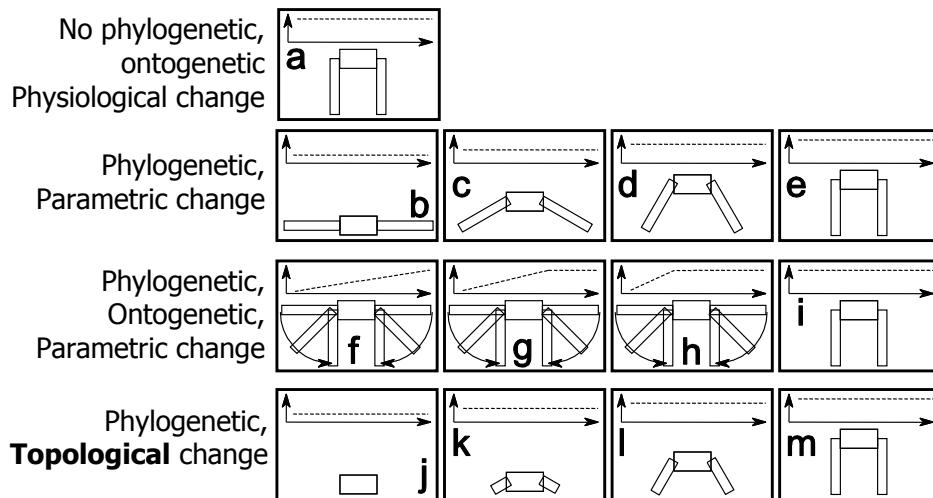
L25





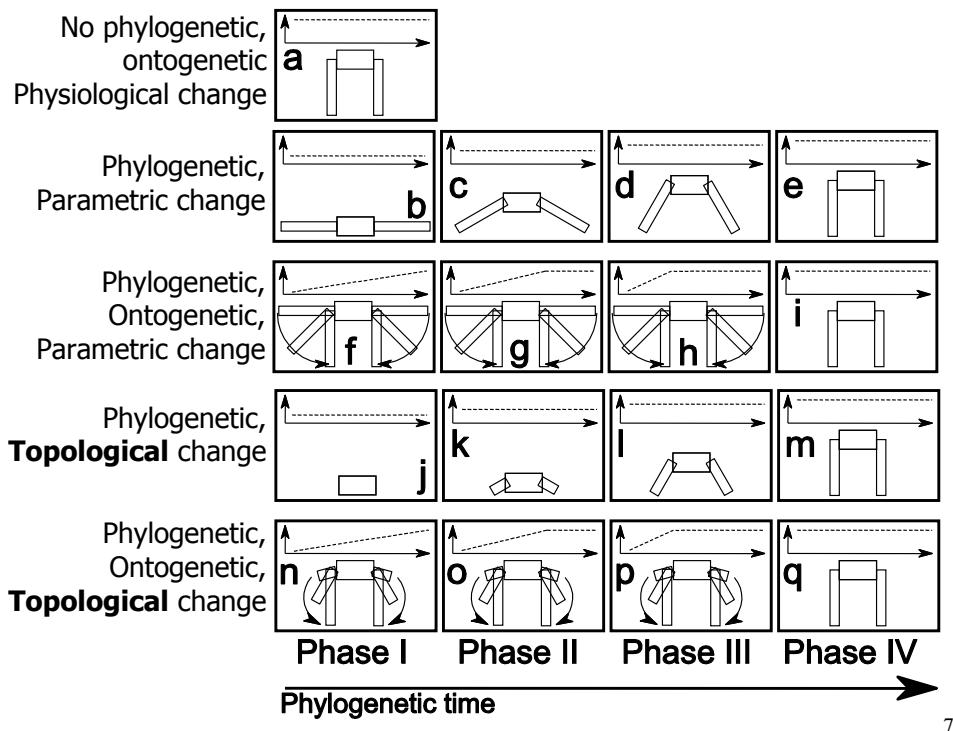
Phase I Phase II Phase III Phase IV
Phylogenetic time →

5

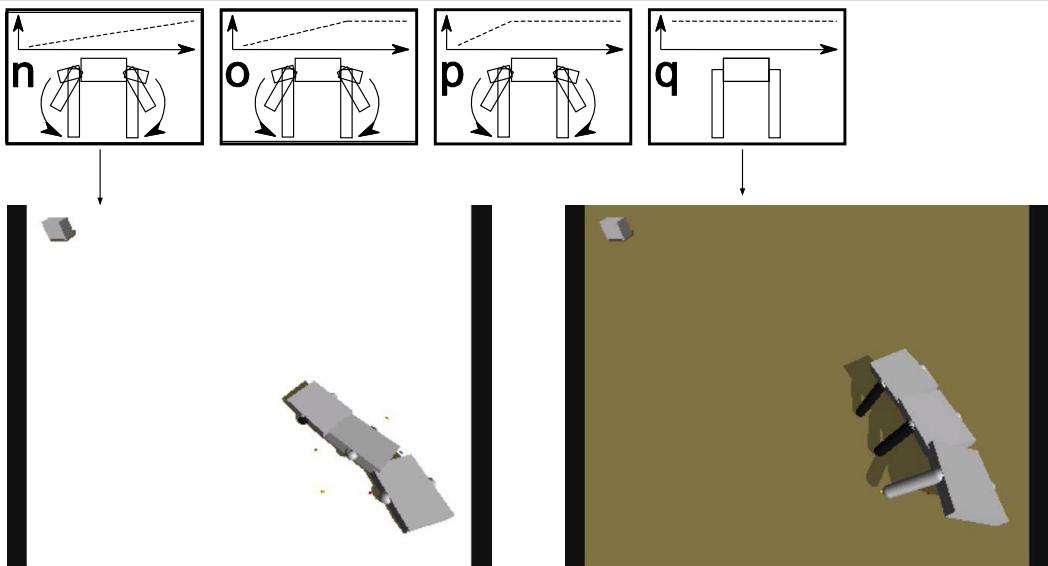


Phase I Phase II Phase III Phase IV
Phylogenetic time →

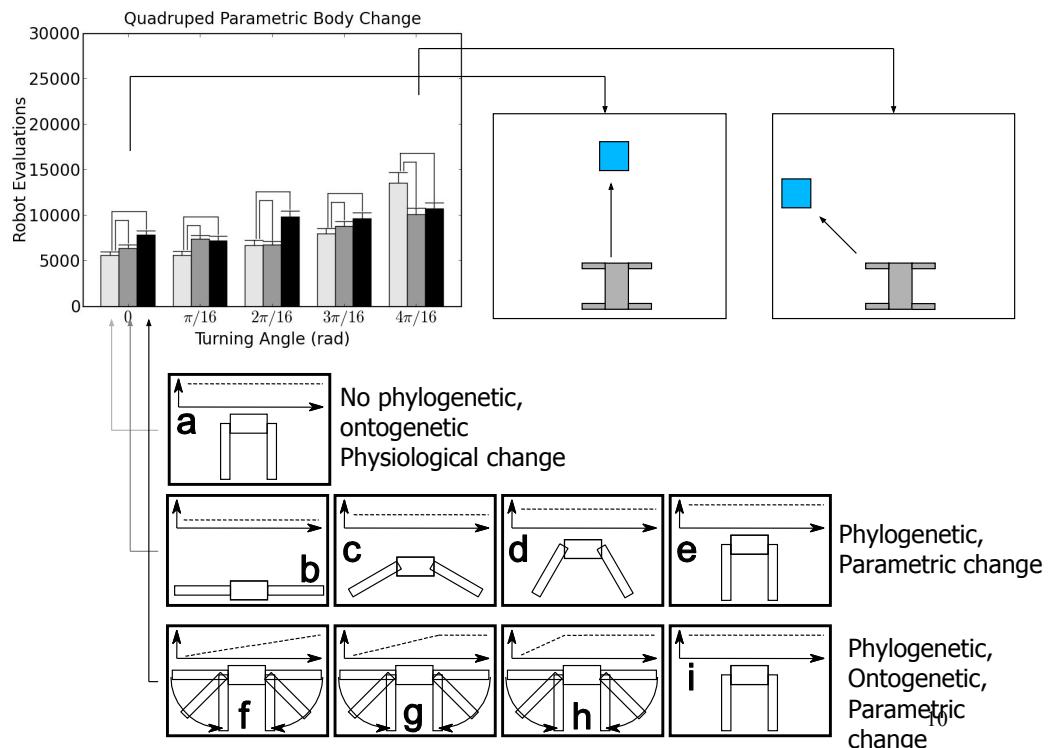
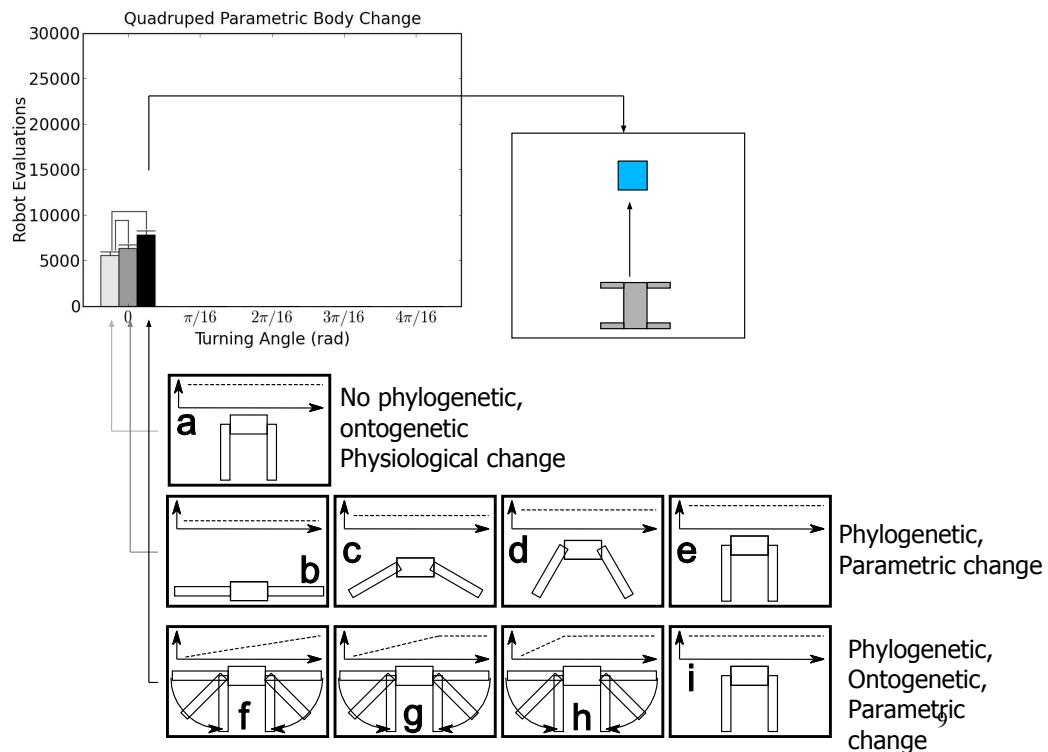
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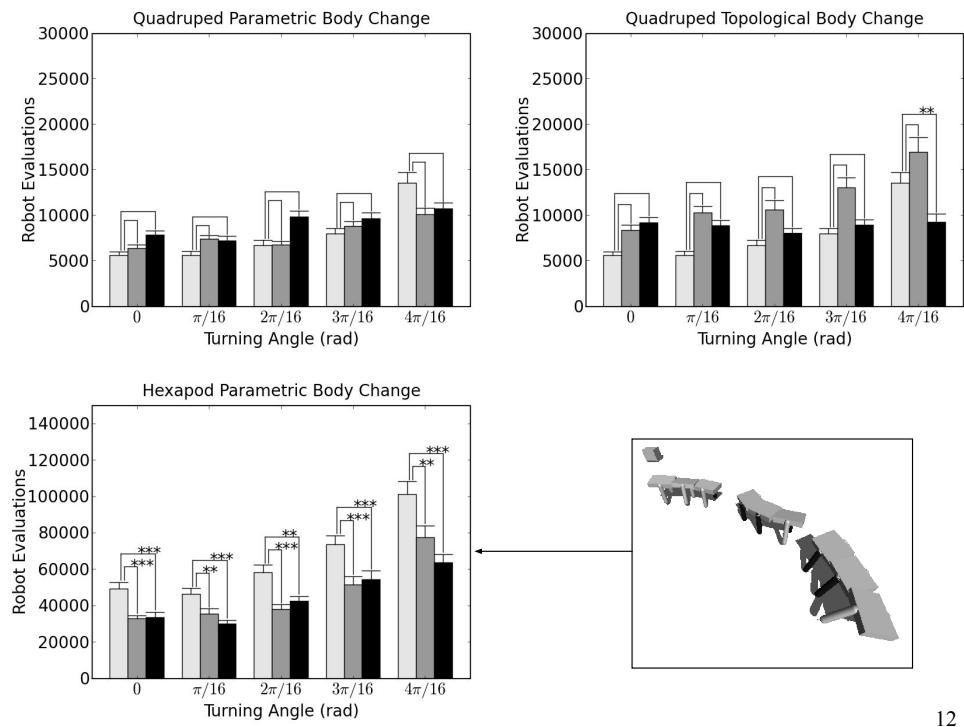
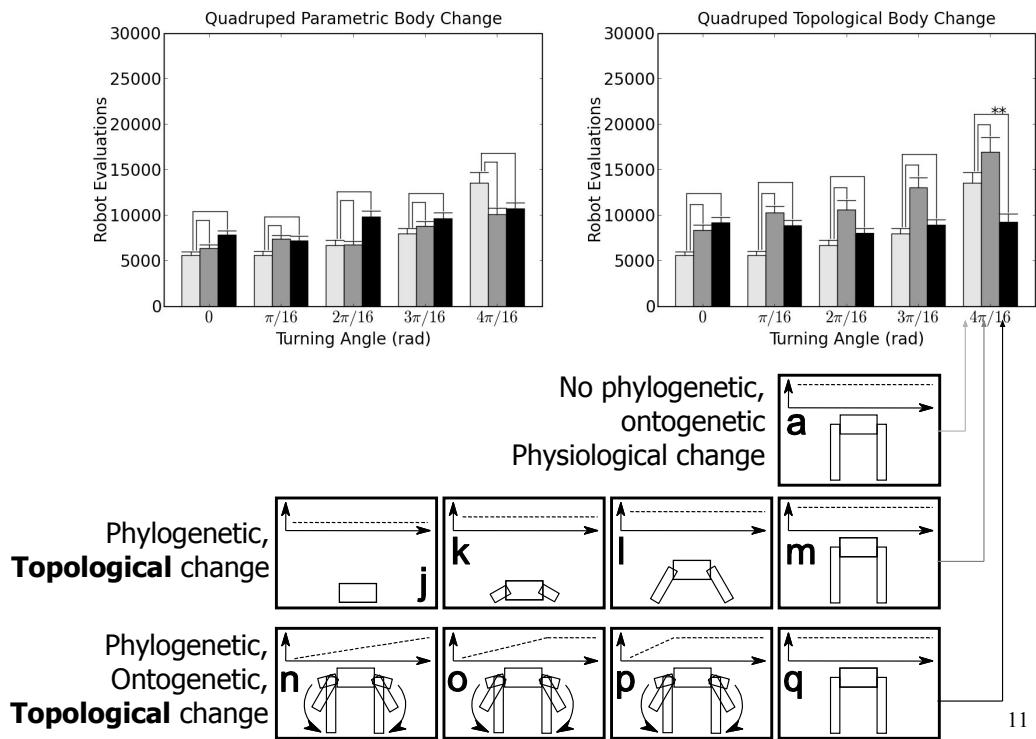


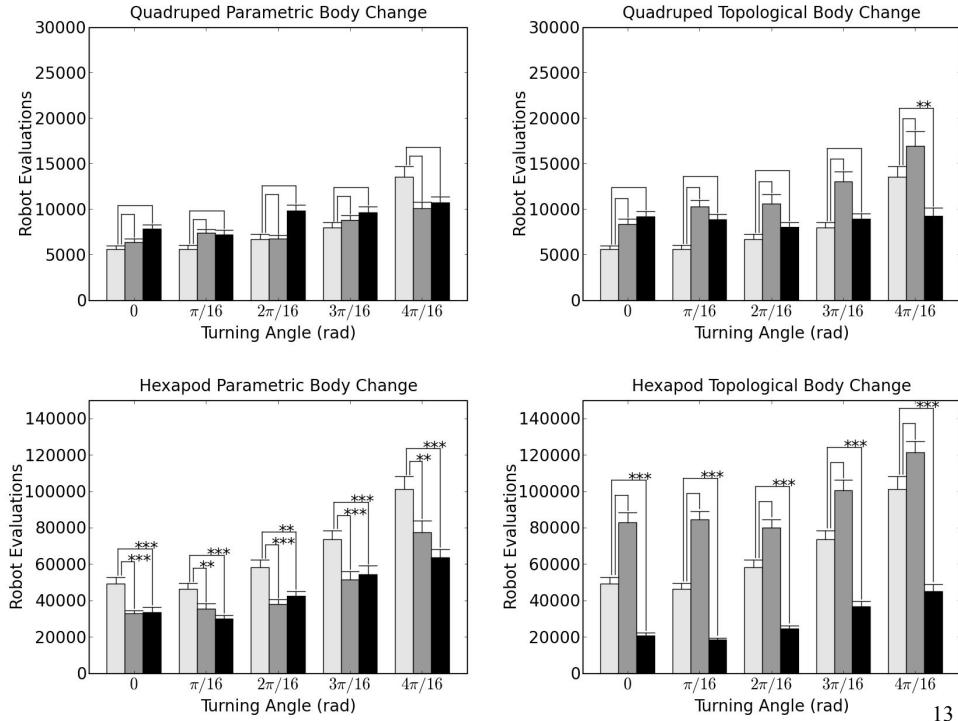
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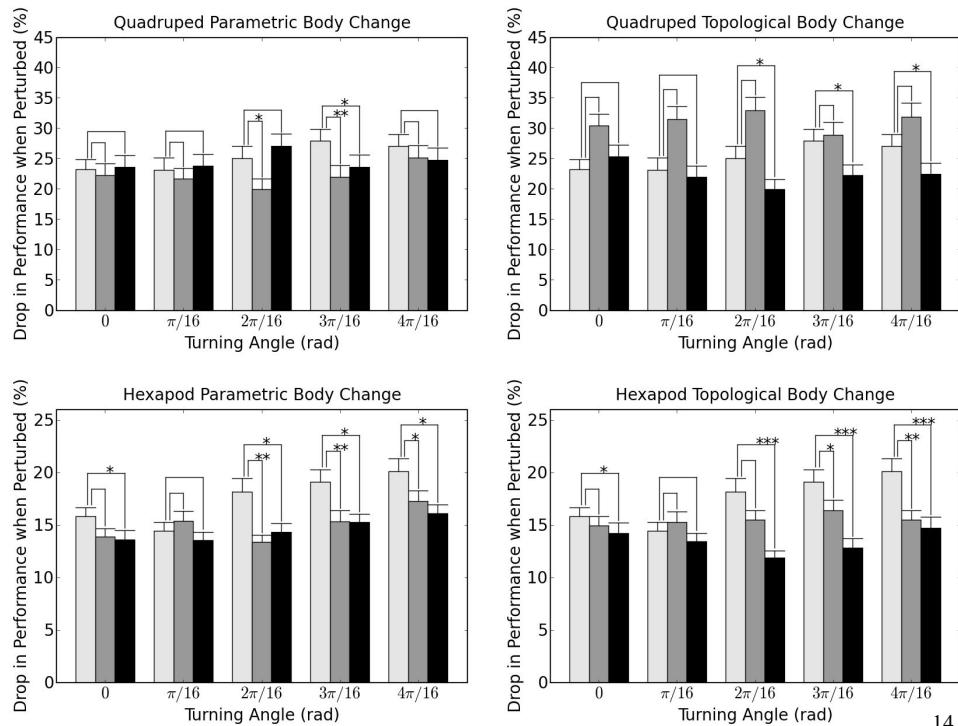
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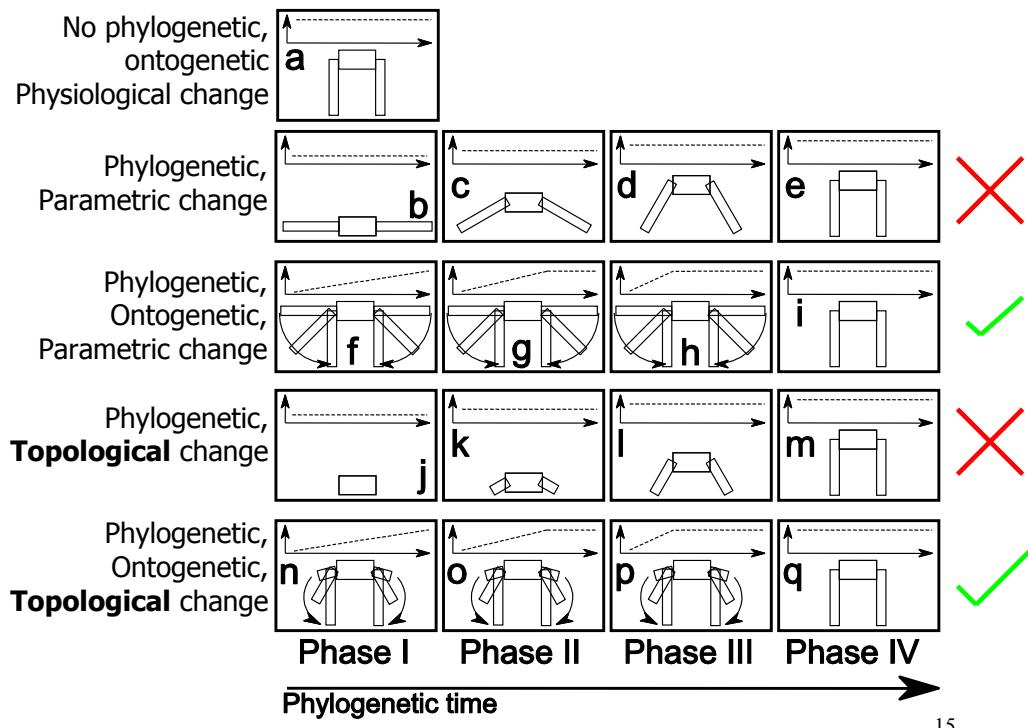




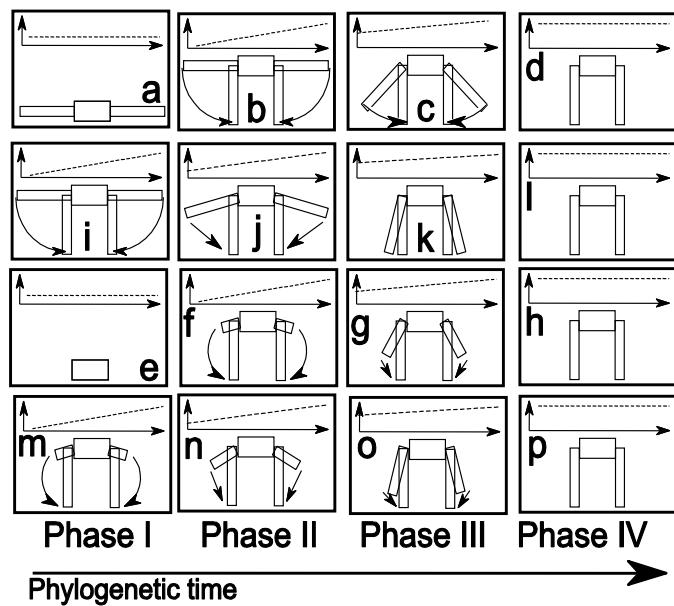
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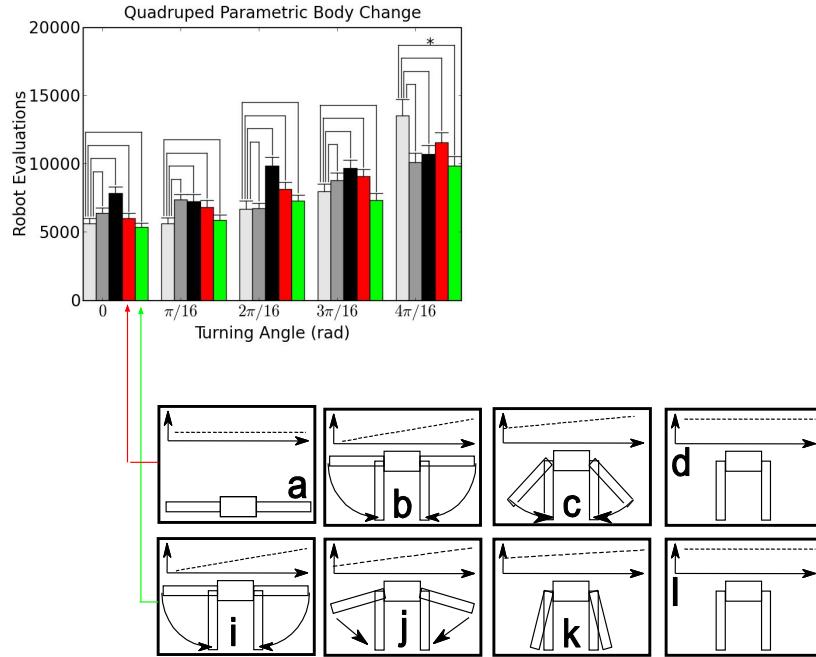
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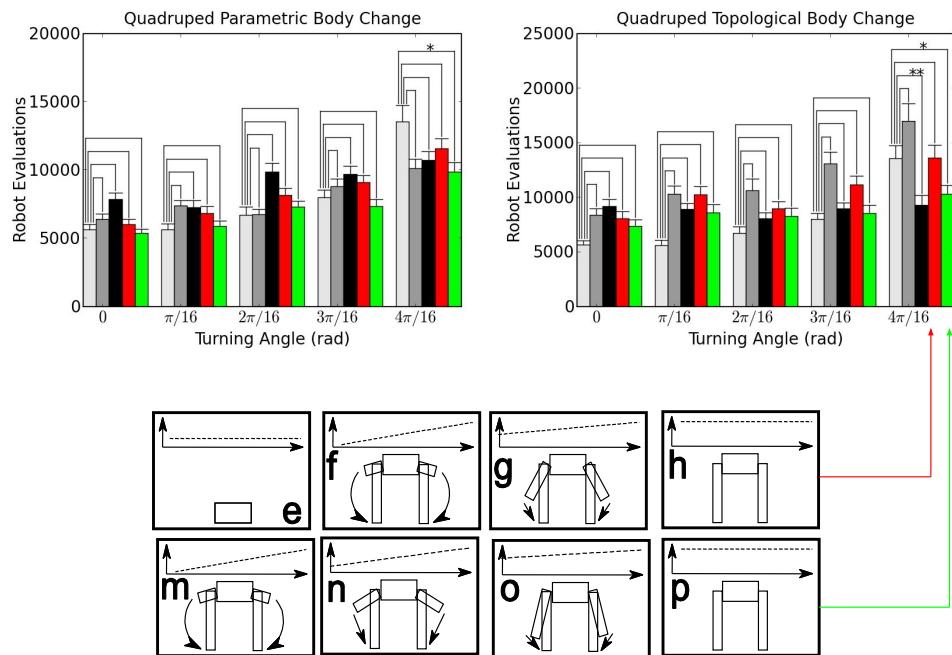
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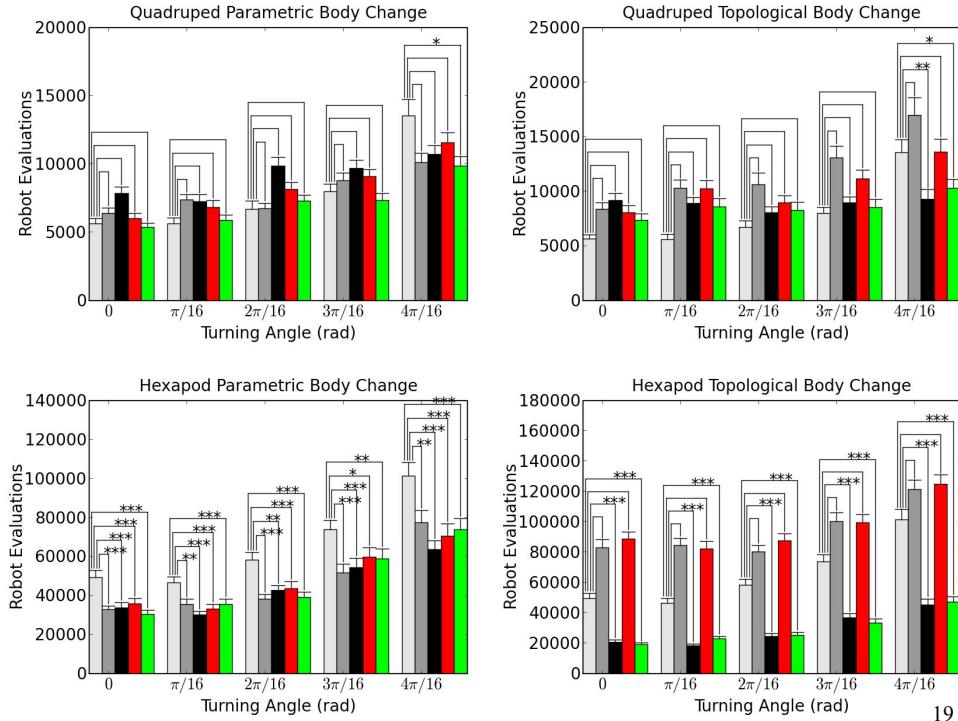
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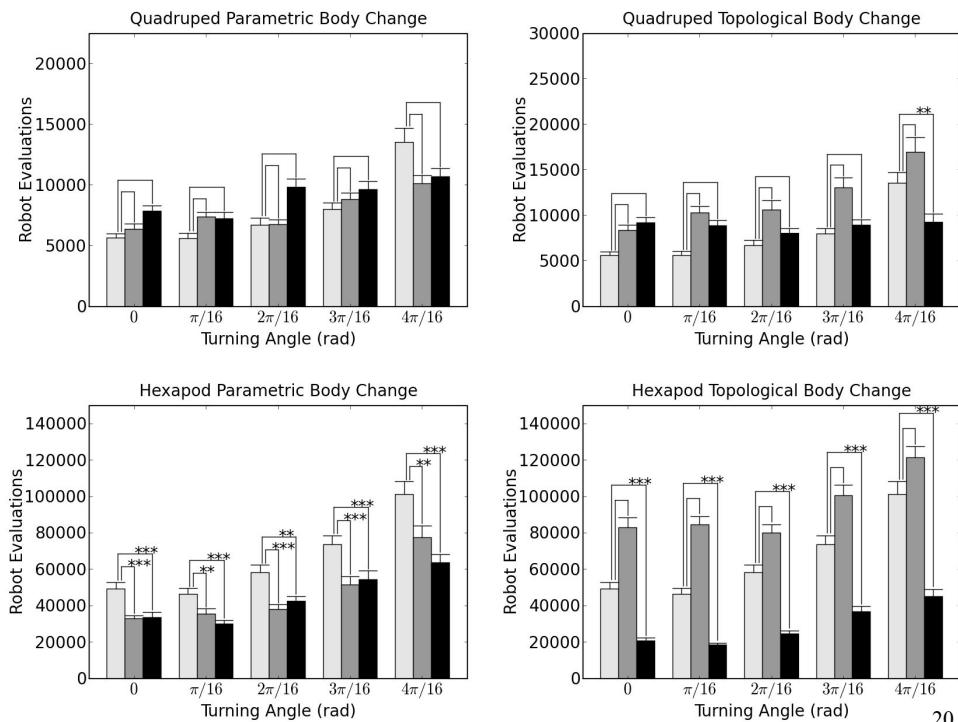
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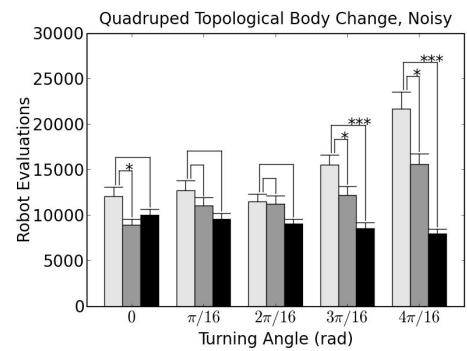
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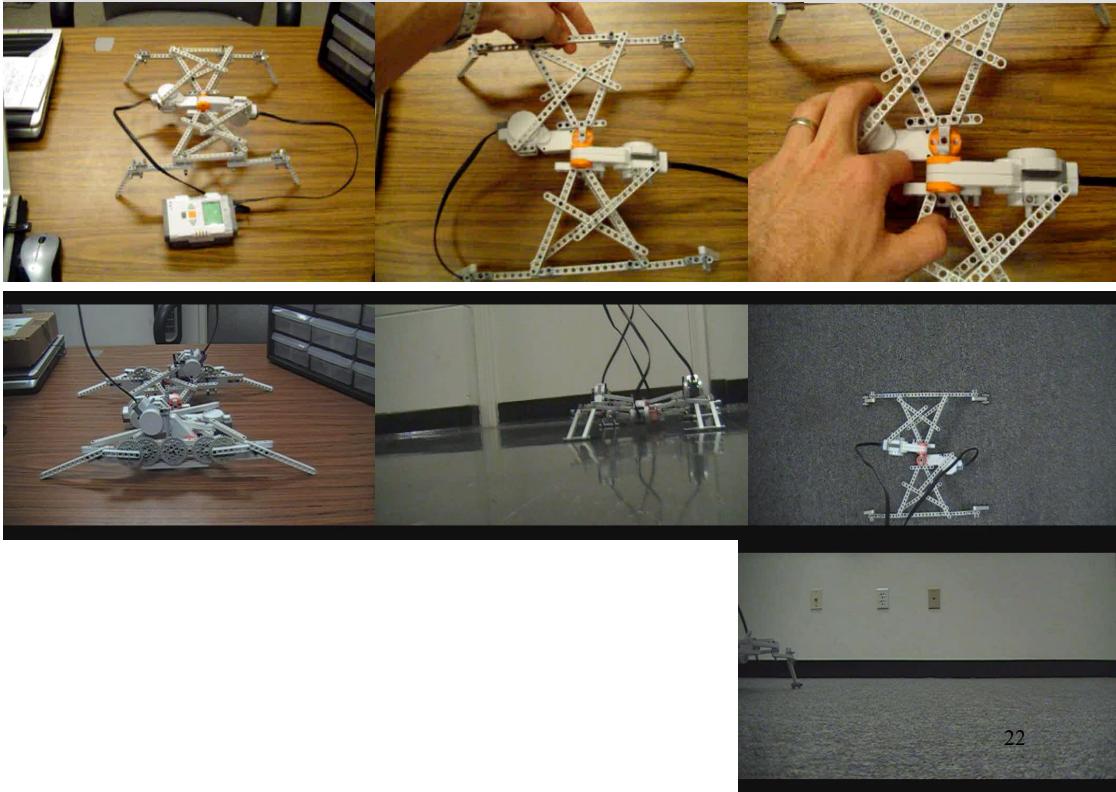
19



20



21



22

Robots that can adapt like animals.

Video Summary:

<http://youtu.be/T-c17RKh3uE>

Example gaits:

<http://youtu.be/lHQgnpSphEI>

A Cully *et al.* *Nature* **521**, 503-507 (2015) doi:10.1038/nature14422

nature¹

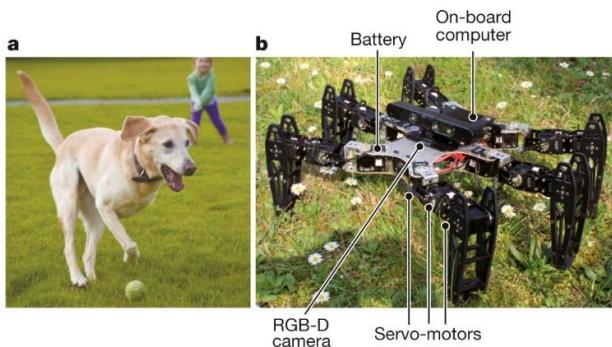
Using the Intelligent Trial and Error (IT&E) algorithm, robots, like animals, can quickly adapt to recover from damage.



A Cully *et al.* *Nature* **521**, 503-507 (2015) doi:10.1038/nature14422

nature²

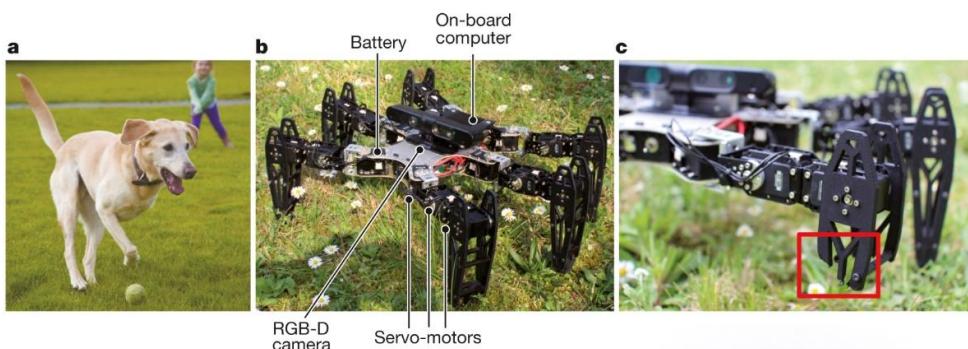
Using the Intelligent Trial and Error (IT&E) algorithm, robots, like animals, can quickly adapt to recover from damage.



A Cully *et al.* *Nature* **521**, 503-507 (2015) doi:10.1038/nature14422

nature³

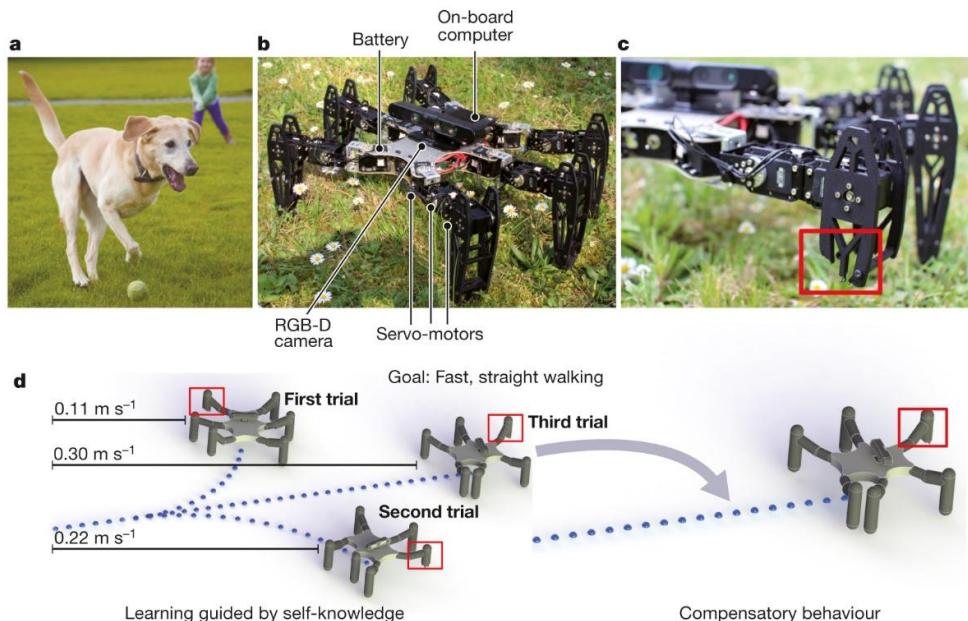
Using the Intelligent Trial and Error (IT&E) algorithm, robots, like animals, can quickly adapt to recover from damage.



A Cully *et al.* *Nature* **521**, 503-507 (2015) doi:10.1038/nature14422

nature⁴

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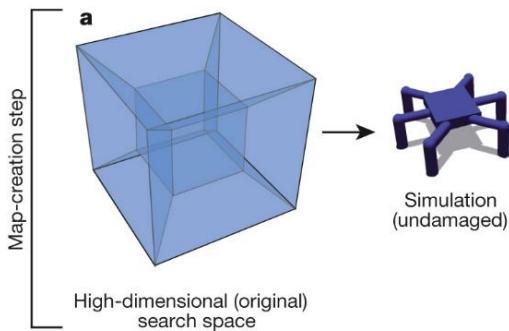


A Cully *et al.* *Nature* **521**, 503-507 (2015) doi:10.1038/nature14422

nature⁵

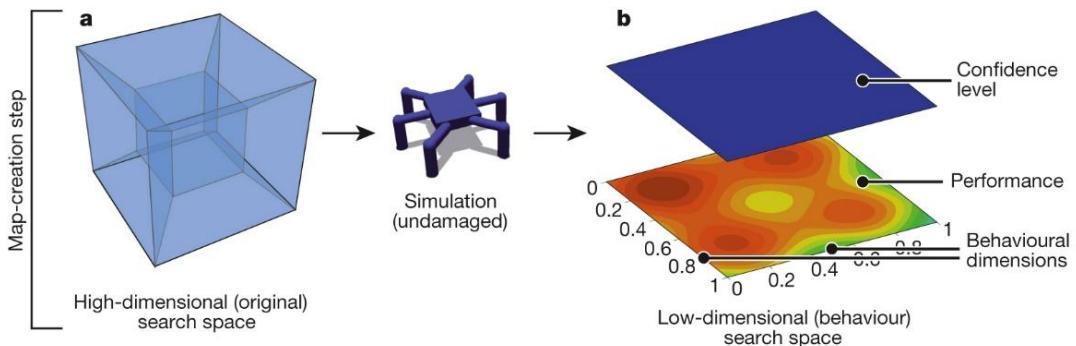
The two steps of IT&E.

L26



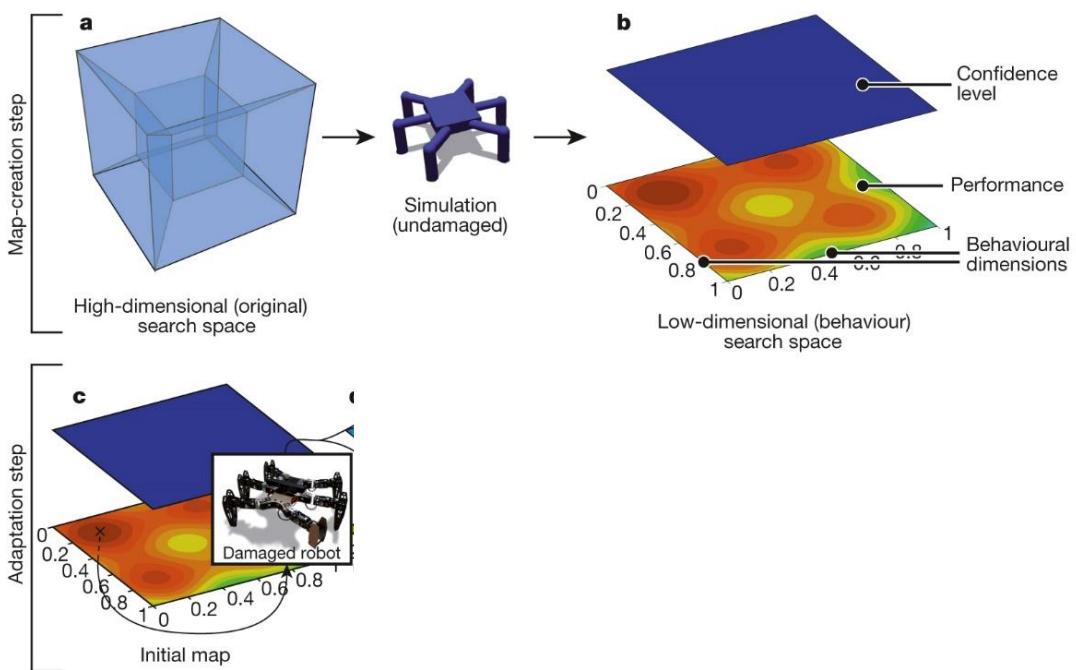
A Cully *et al.* *Nature* **521**, 503-507 (2015) doi:10.1038/nature14422

nature⁶



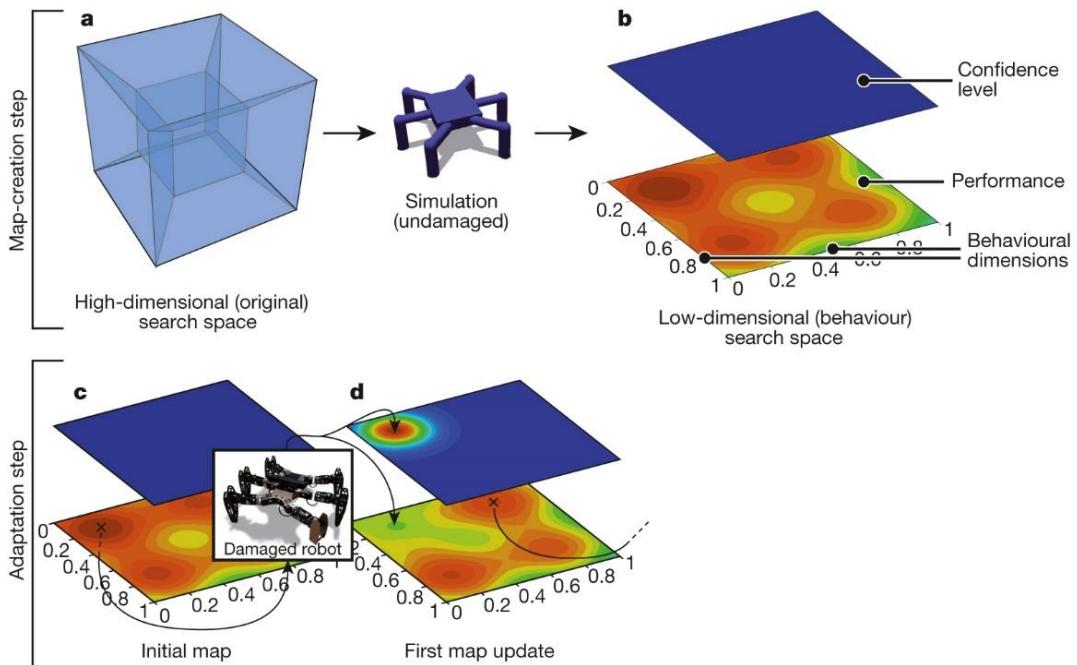
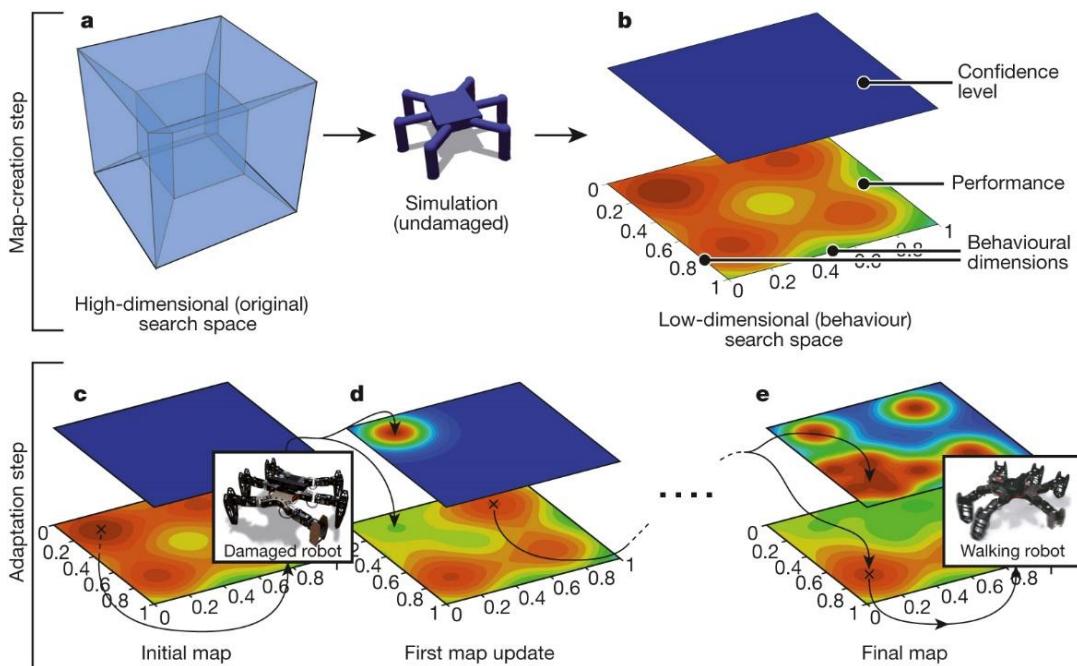
A Cully *et al.* *Nature* 521, 503-507 (2015) doi:10.1038/nature14422

nature⁷



A Cully *et al.* *Nature* 521, 503-507 (2015) doi:10.1038/nature14422

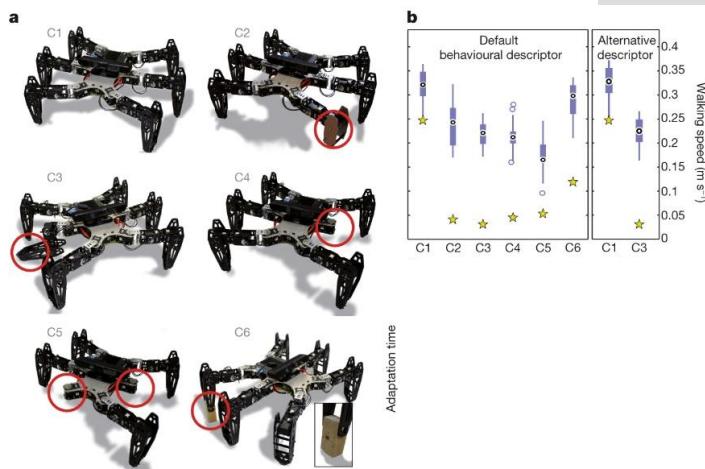
nature⁸

A Cully et al. *Nature* 521, 503-507 (2015) doi:10.1038/nature14422nature⁹A Cully et al. *Nature* 521, 503-507 (2015) doi:10.1038/nature14422nature¹⁰



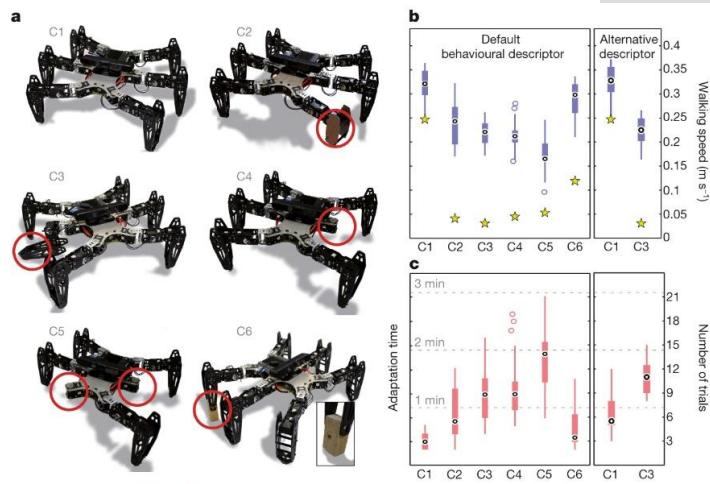
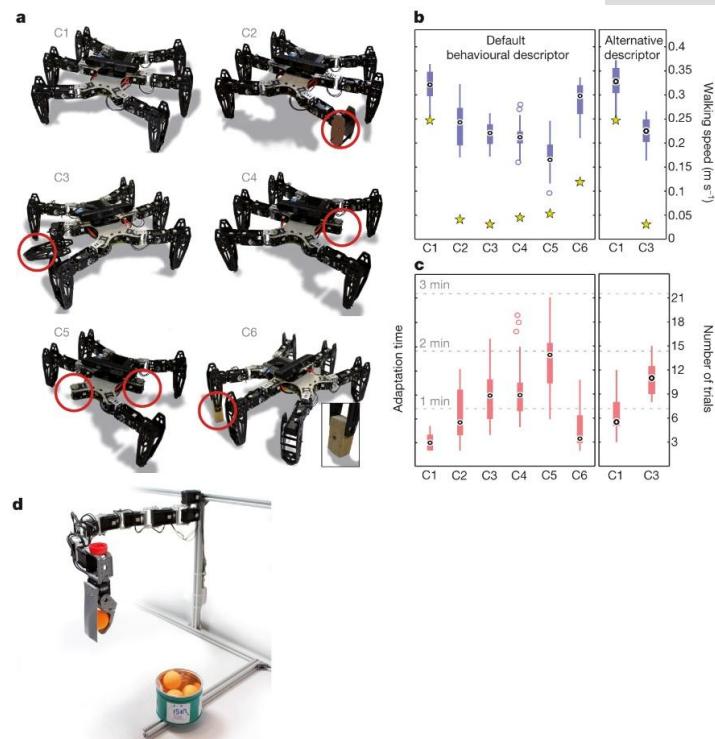
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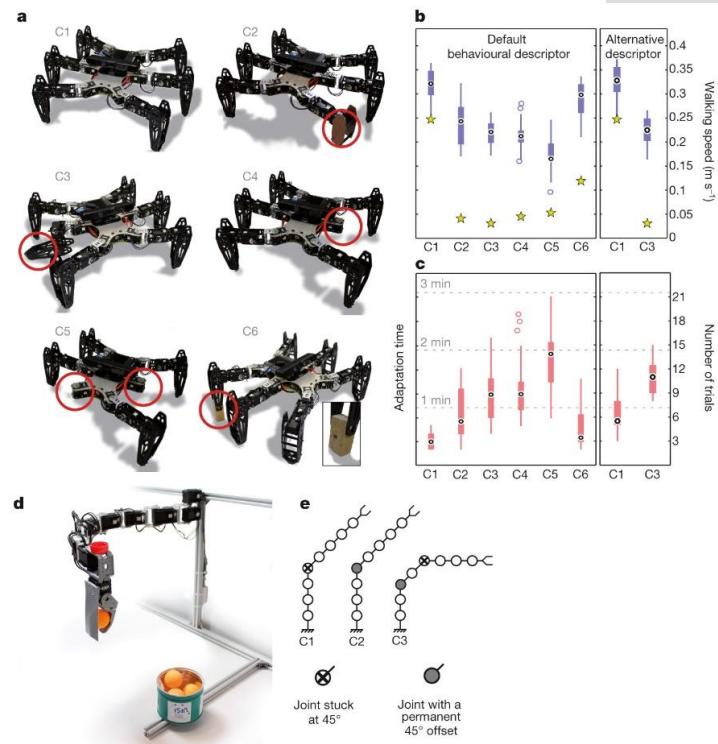
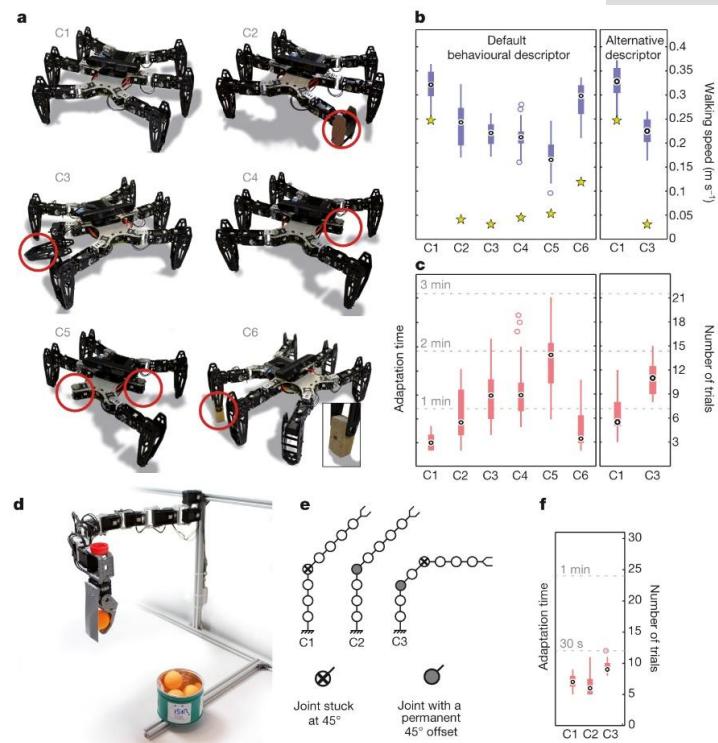
nature¹¹

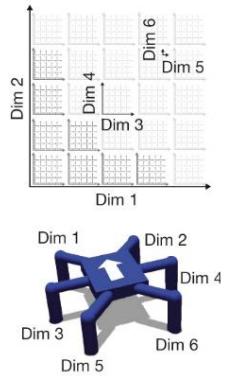


A Cully *et al.* *Nature* **521**, 503-507 (2015) doi:10.1038/nature14422

nature¹²

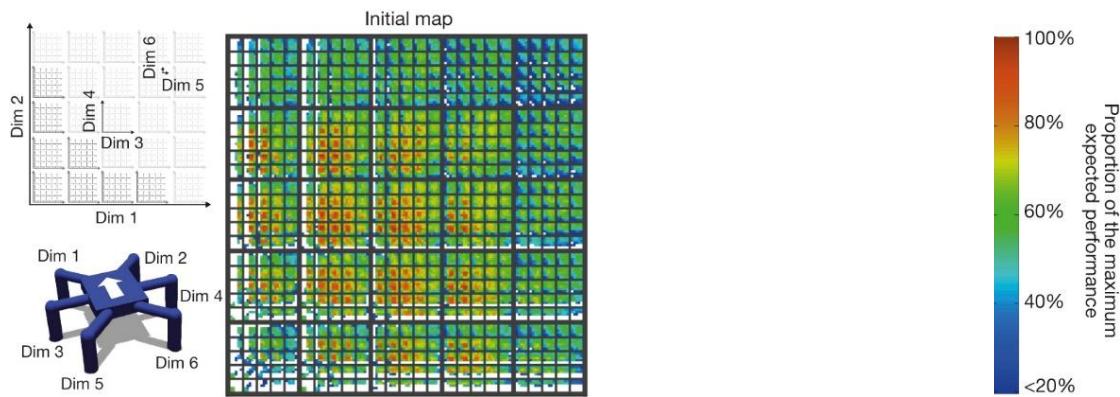
A Cully et al. *Nature* 521, 503-507 (2015) doi:10.1038/nature14422¹³natureA Cully et al. *Nature* 521, 503-507 (2015) doi:10.1038/nature14422¹⁴nature

A Cully et al. *Nature* 521, 503-507 (2015) doi:10.1038/nature14422nature¹⁵A Cully et al. *Nature* 521, 503-507 (2015) doi:10.1038/nature14422nature¹⁶



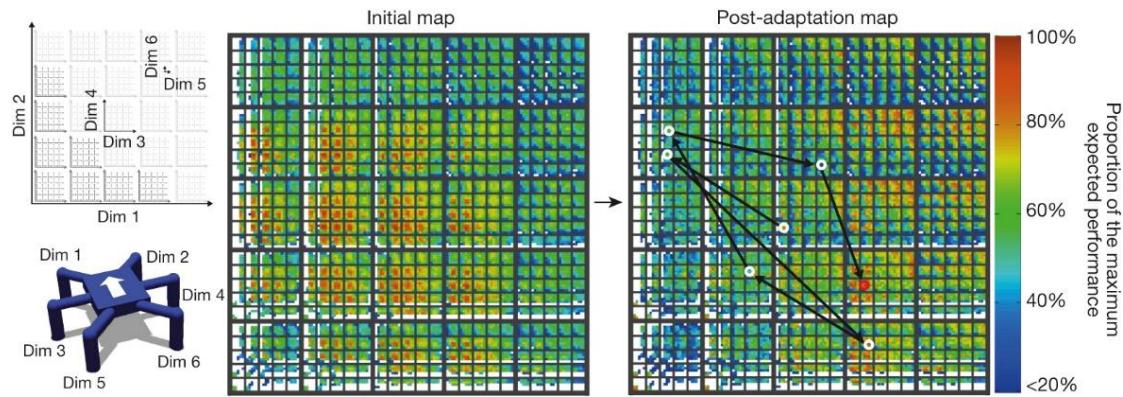
A Cully *et al.* *Nature* **521**, 503-507 (2015) doi:10.1038/nature14422

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