# Evoling Embodied Intelligence

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Vrije Universiteit Amsterdam, Netherlands
University of York, United Kingdom

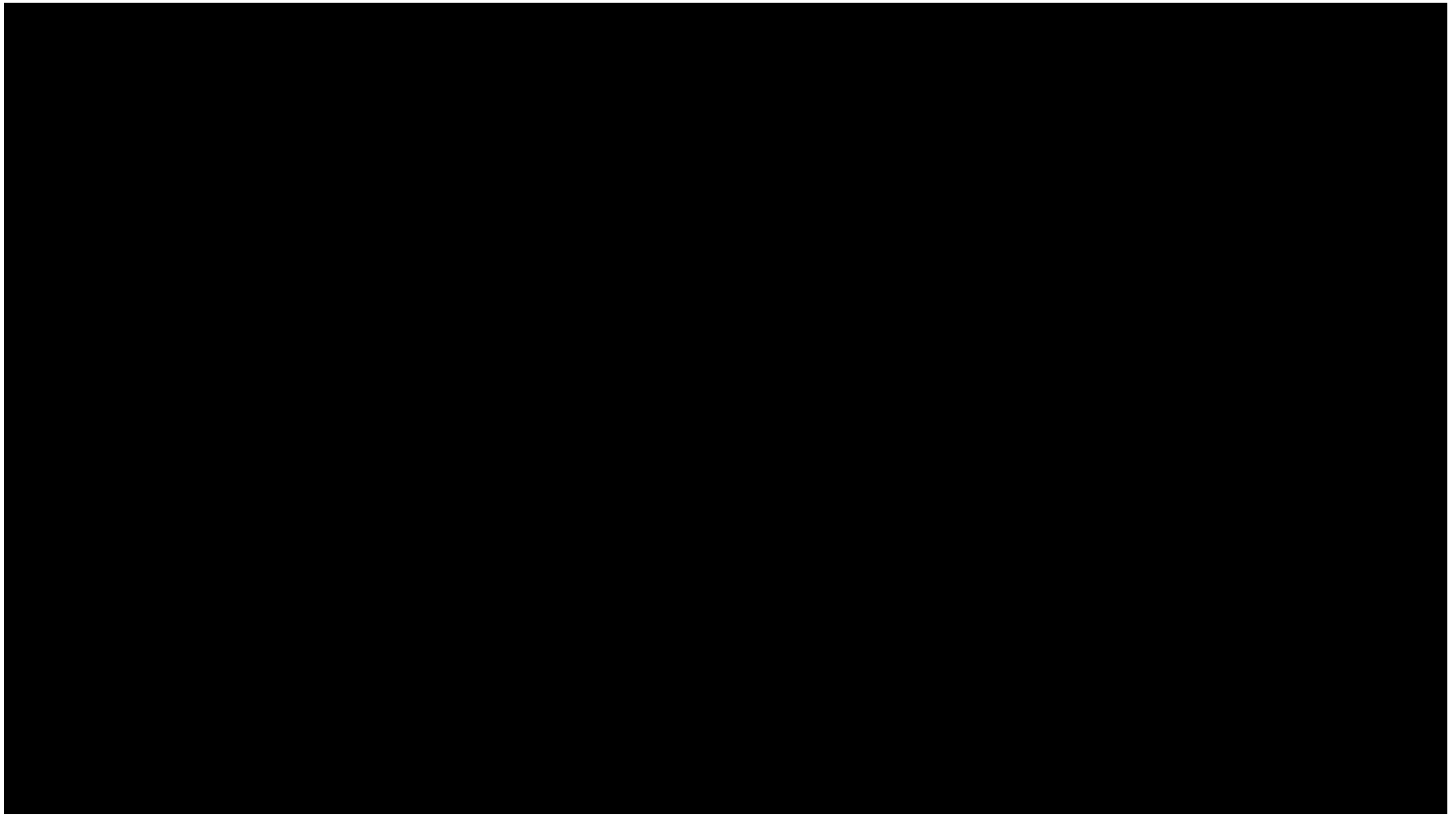
IJCCI, Malta, 24-10-2022


NOS
Primetime news on national television

Evolution can create intelligence

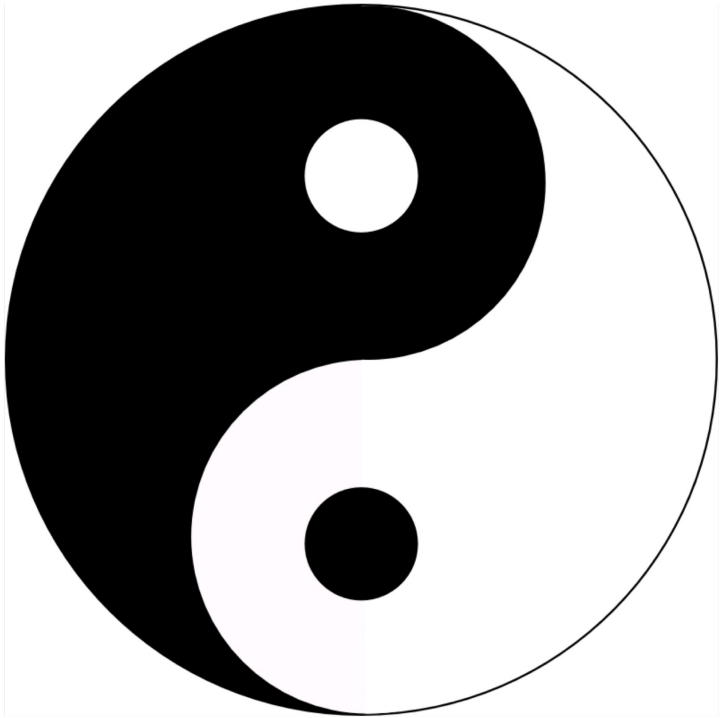
Artificial evolution can create
artificial intelligence

Jelisavcic, De Carlo, Hupkes, Eustratiadis, Orlowski, Haasdijk, Auerbach, Eiben, Real-World Evolution of Robot Morphologies: A Proof of Concept, ***Artificial Life 23(2),*** 2017.



Body

Hardware



Brain

Software

intelligence (narrow)

Environment + body + brain → behavior

intelligence (broad)

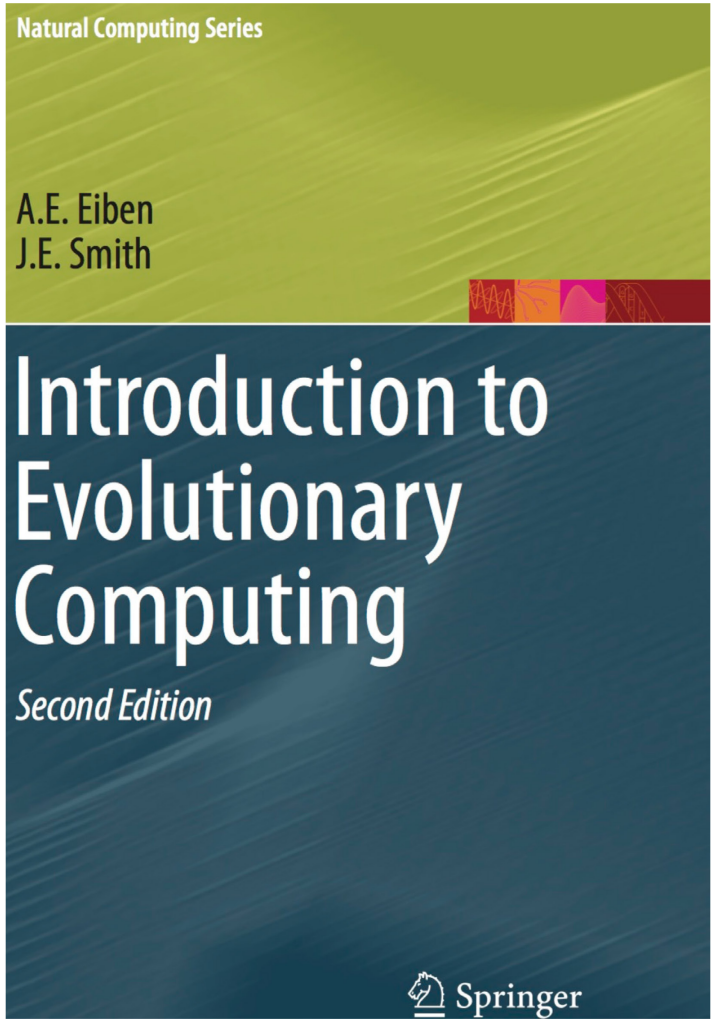
Optimal body = ?

Pragmatist

Antropo-chauvinist

Radicalist

Optimal brain = ?




Genetic algorithms

Evolution strategies

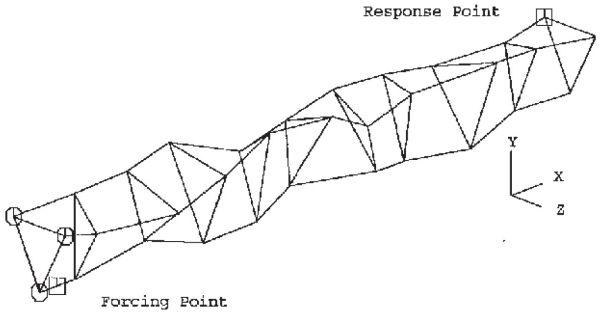
Evolutionary programming

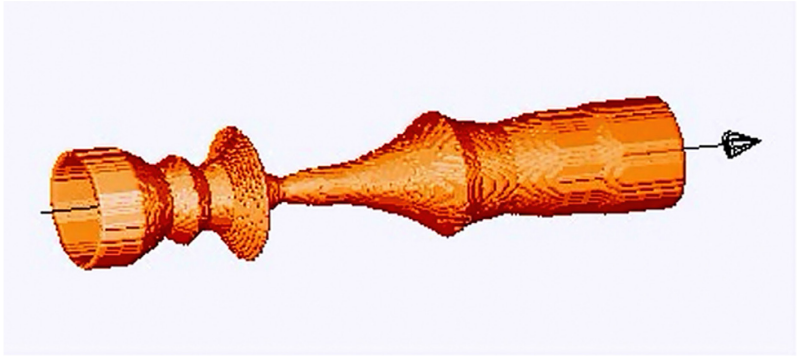
Genetic programming

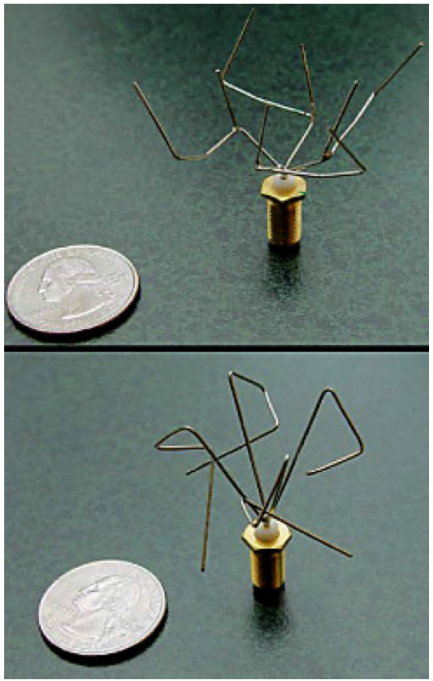
Differential evolution

…

# Evolutionary design





passive  active

agency
autonomy

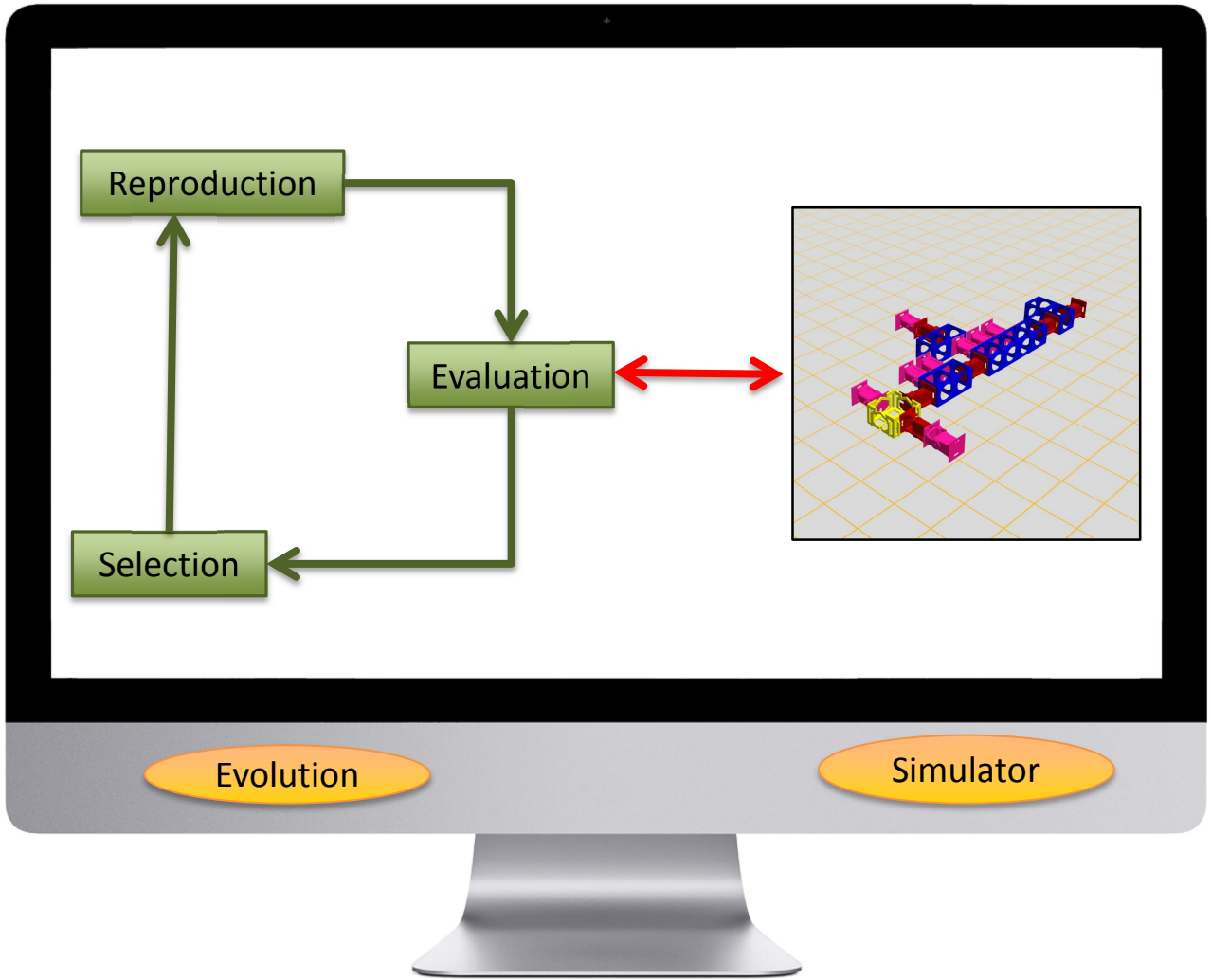
# Evolutionary Robotics

The Biology, Intelligence, and Technology of Self-Organizing Machines

Stefano Nolfi *and* Dario Floreano

2nd order engineering

“Aims to apply evolutionary computation techniques to evolve the overall design or controllers, or both, for real and simulated autonomous robots” (Vargas et al., 2014)”


Reproduction
Evaluation
Selection
Evolution
Simulator

Matter matters

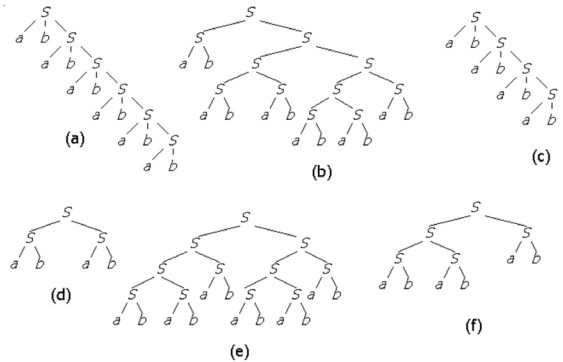
# REALITY GAP

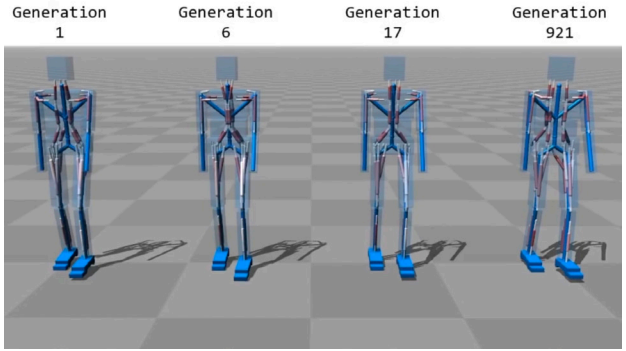
real

sweet spot

passive

active



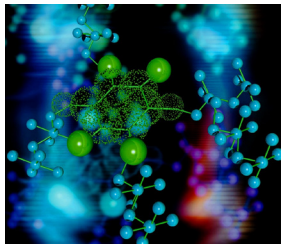




virtual

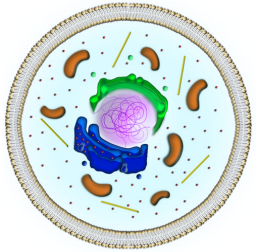
2011


Computing
Embodied Artificial Evolution
TEDx Danubia
x = independently organized TED event

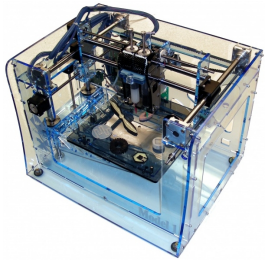
Eiben, Kernbach, Haasdijk, Embodied artificial evolution: Artificial evolutionary systems in the 21st Century, Evolutionary Intelligence, 5(4):261-272, 2012



Chemistry



Biology



Engineering

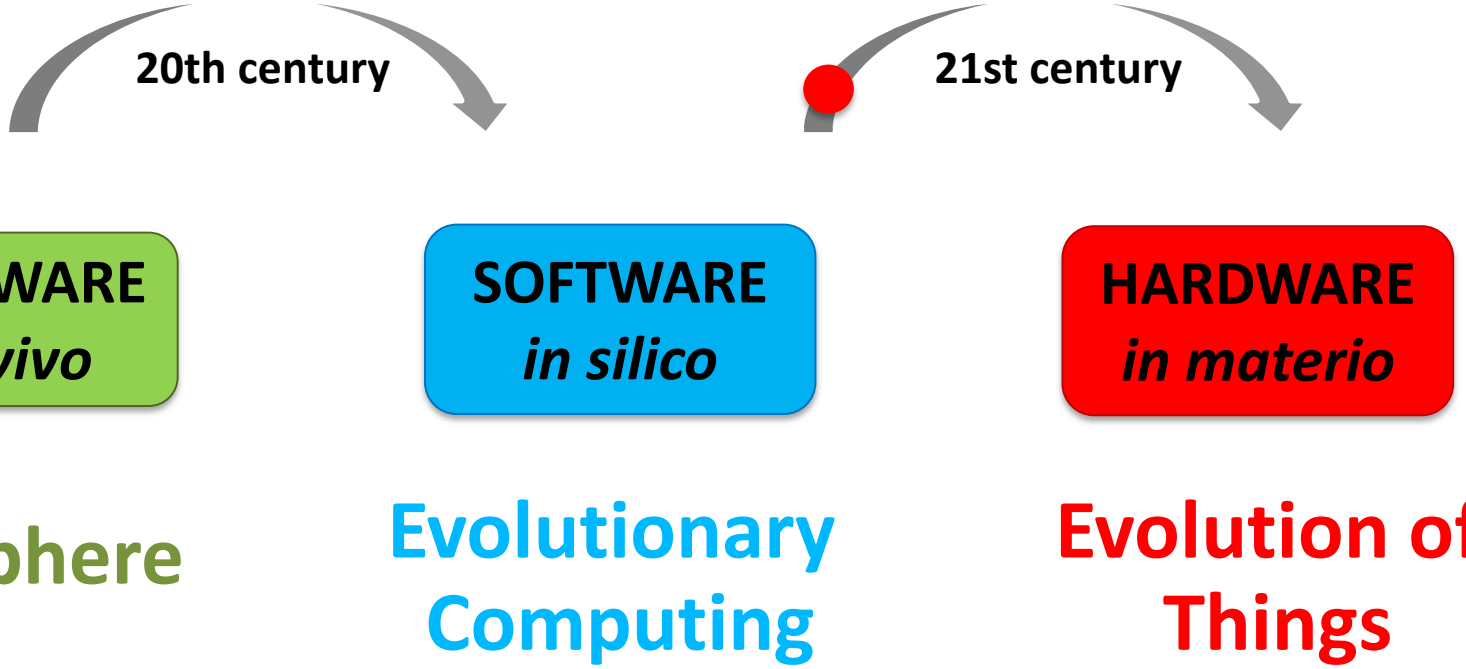
Eiben, Kernbach, Haasdijk, Embodied artificial evolution: Artificial evolutionary systems in the 21st Century, Evolutionary Intelligence, 5(4):261-272, 2012

## GRAND CHALLENGES

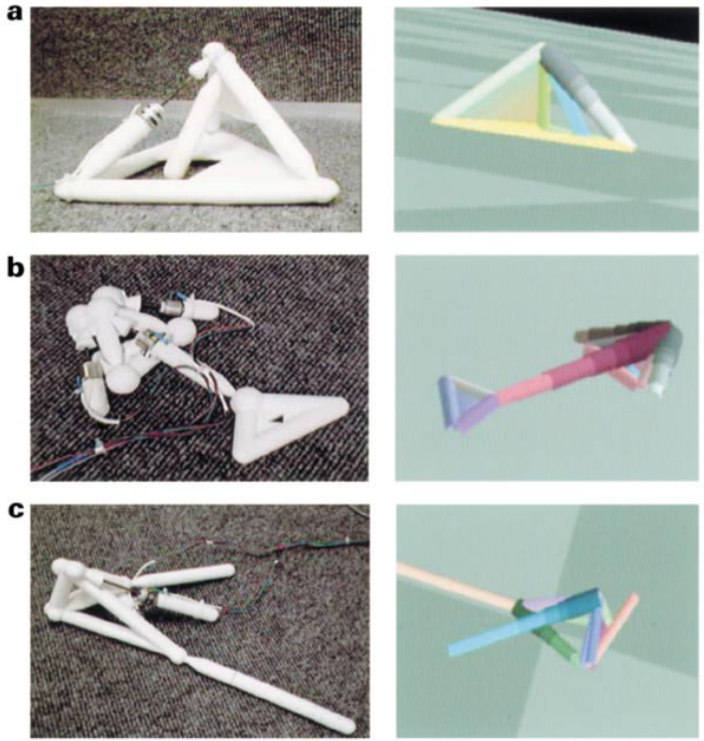
1. Body types
2. How to start (reproduction)
3. How to stop (kill switch)
4. Evolvability & speed
5. Process control & methodology
6. Body+brain evolution + learning

# The Evolution of Things

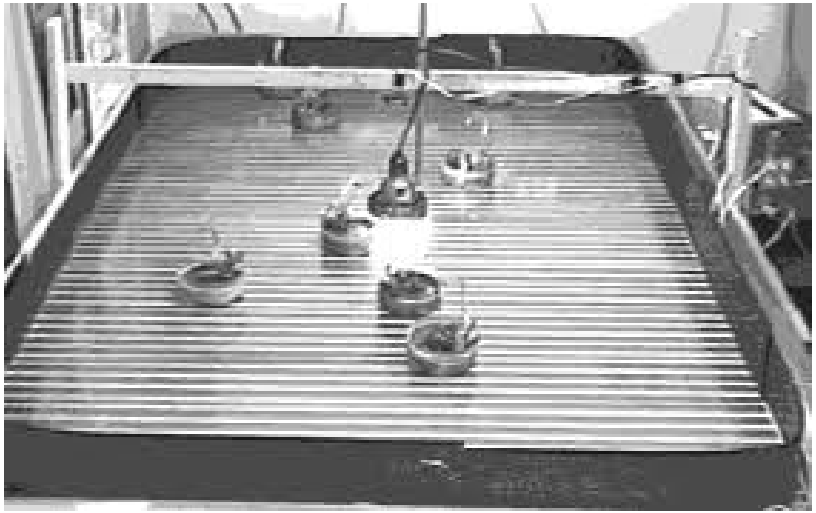
Eiben and Smith, From evolutionary computation to the evolution of things, ***Nature***, 2015



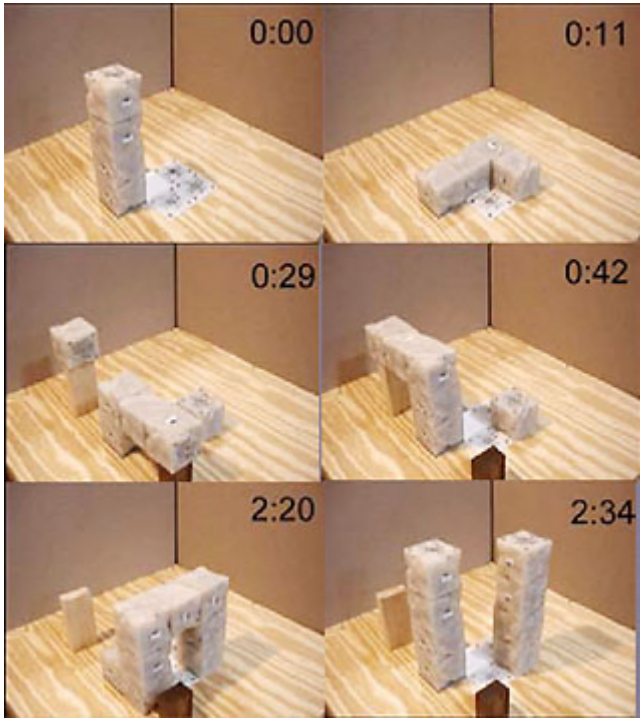
Lipson, Pollack, Automatic design and manufacture of robotic lifeforms, *Nature* 406, 2000



Watson, Ficici, Pollack, Embodied Evolution, *Robotics and Autonomous Systems* 39, 2002

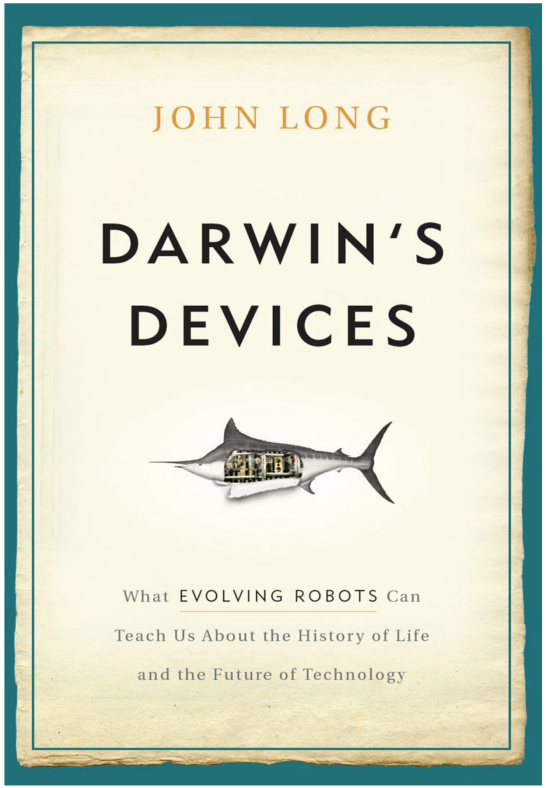


Zykov, Mytilinaios, Adams, Lipson, Self-reproducing machines, *Nature* 435, 2005



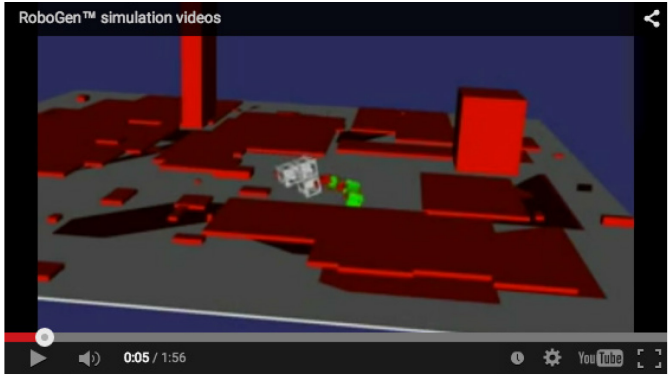
John Long, Darwin's Devices: What Evolving Robots Can Teach Us About the History of Life and the Future of Technology, *Basic Books* 2012

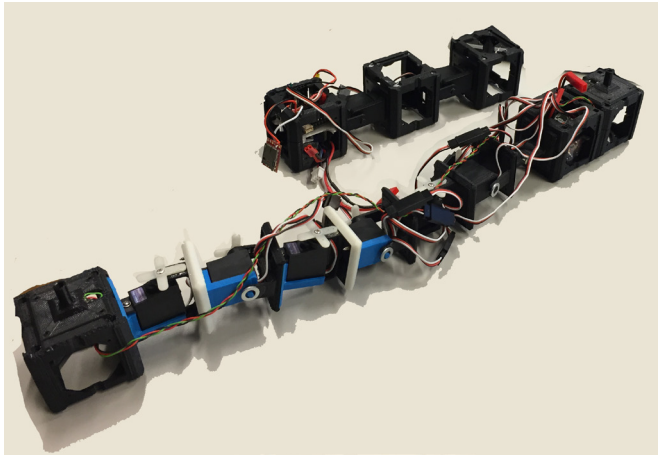
DARWIN'S DEVICES: WHAT EVOLVING ROBOTS CAN TEACH US ABOUT THE HISTOR...



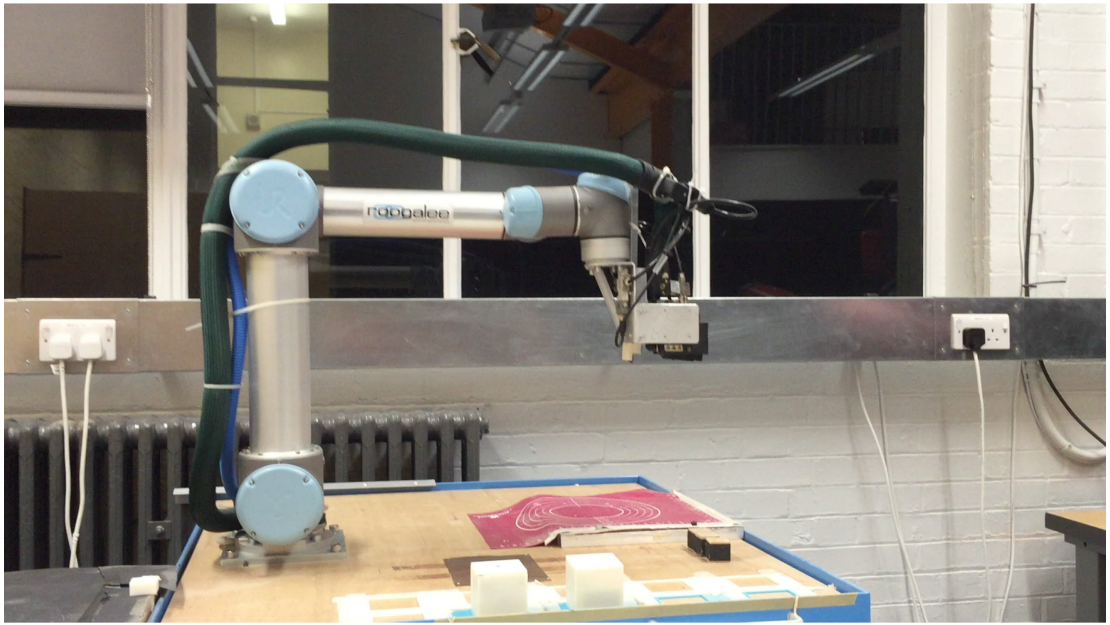

Learning reading speed 1%

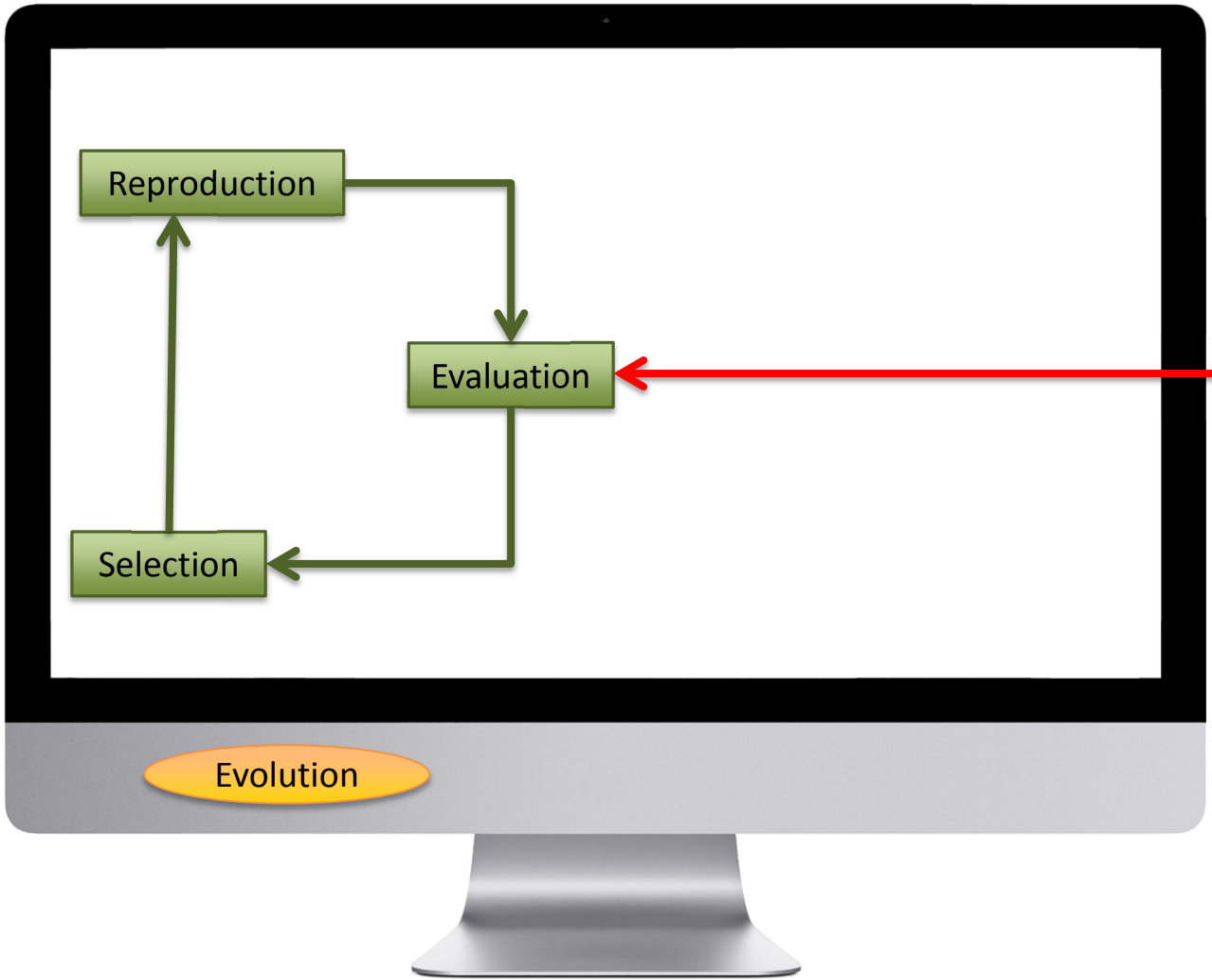
Auerbach *et al.*, RoboGen: Robot generation through artificial evolution, Proc. of Artificial Life 2014, MIT Press, 2014

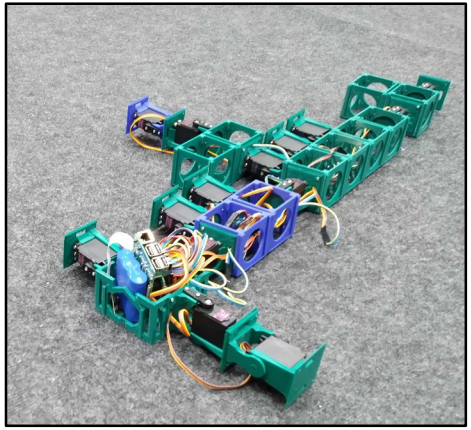


Brodbeck, Hauser, and Iida, Morphological evolution of physical robots through model-free phenotype development, PLoS One, 10(6) 2015.



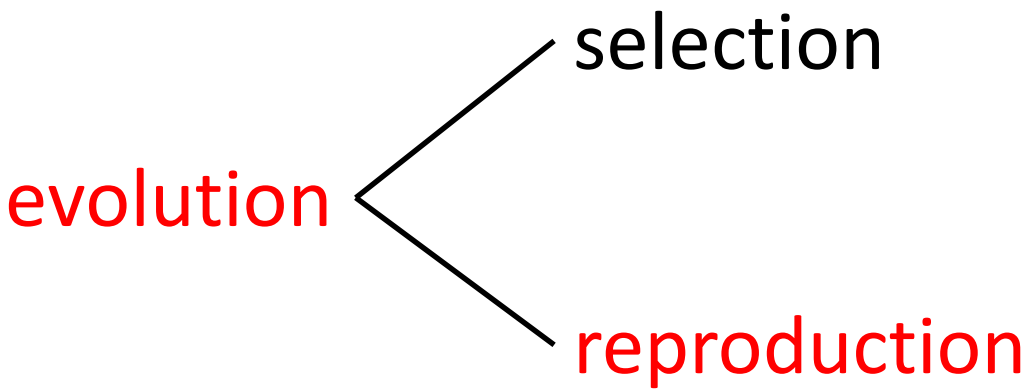


Real world

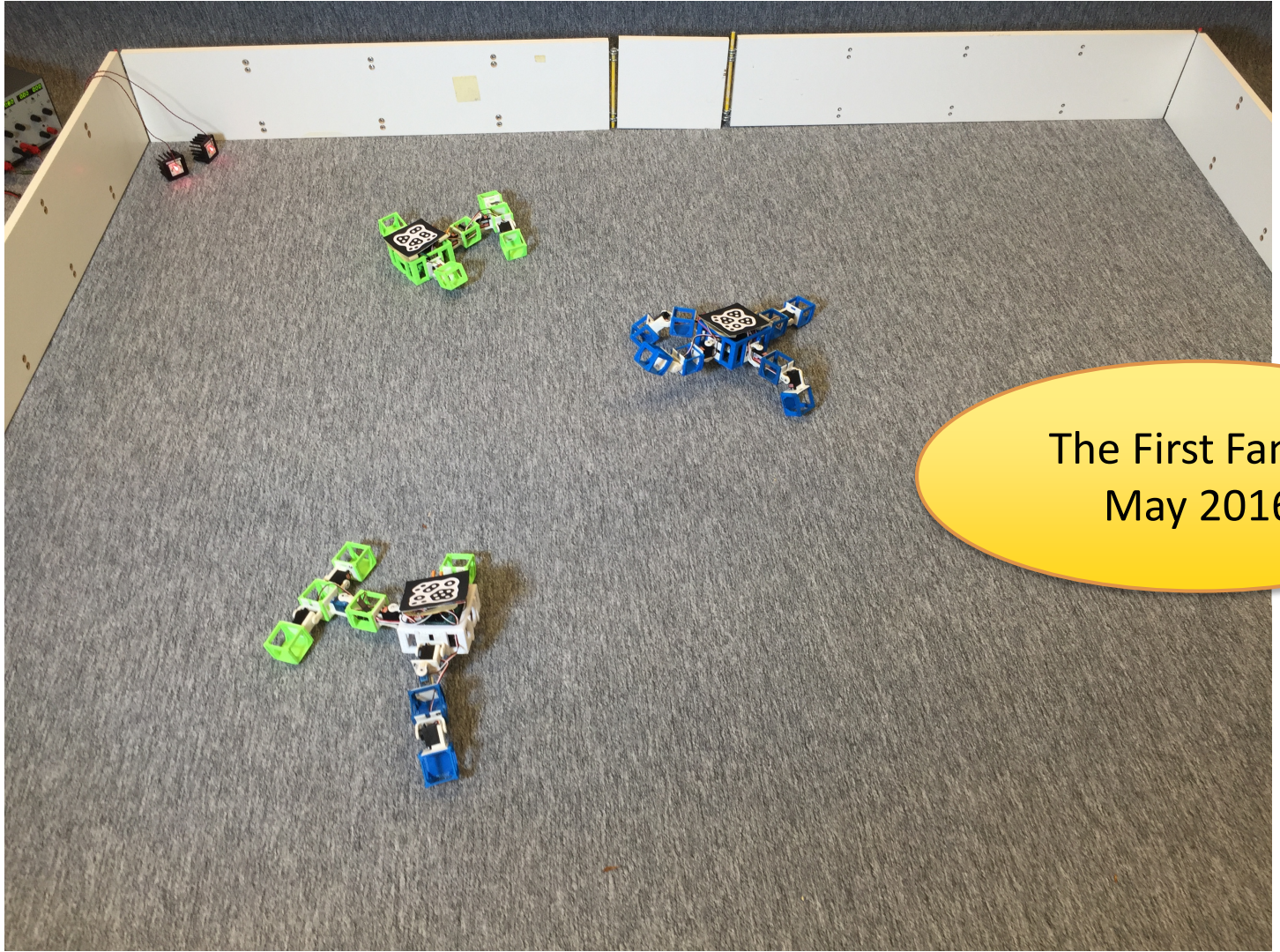
# how i met your mother

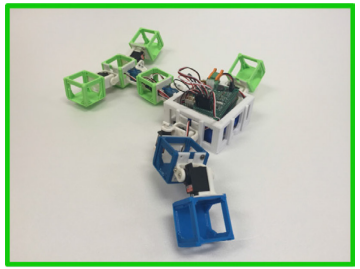
Jelisavcic, De Carlo, Hupkes, Eustratiadis, Orlowski, Haasdijk, Auerbach, Eiben, Real-World Evolution of Robot Morphologies: A Proof of Concept, ***Artificial Life 23(2),*** 2017.

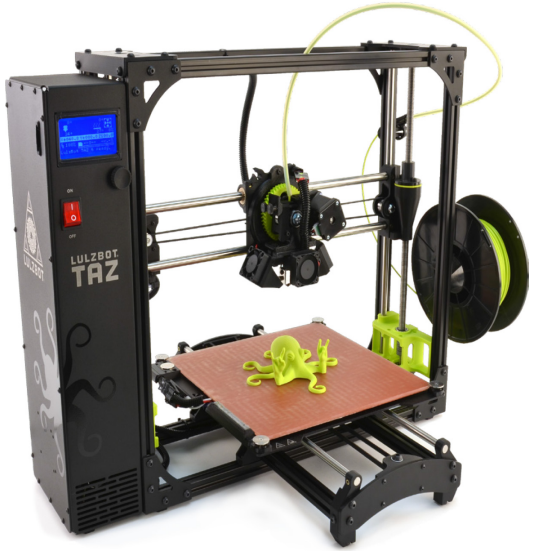



"easy"

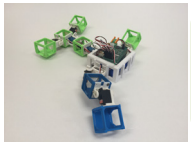
Can robots have children?


The First Family
May 2016




LULZBOT
TAZ

Eiben, Bredeche, Hoogendoorn, Stradner, Timmis, Tyrrell, Winfield, The Triangle of Life: Evolving Robots in Real-time and Real-space, ***ECAL***, 2013



**Delivery**

Phenotype
with inherited brain

Morphogenesis

Learning

Infancy

Genotype

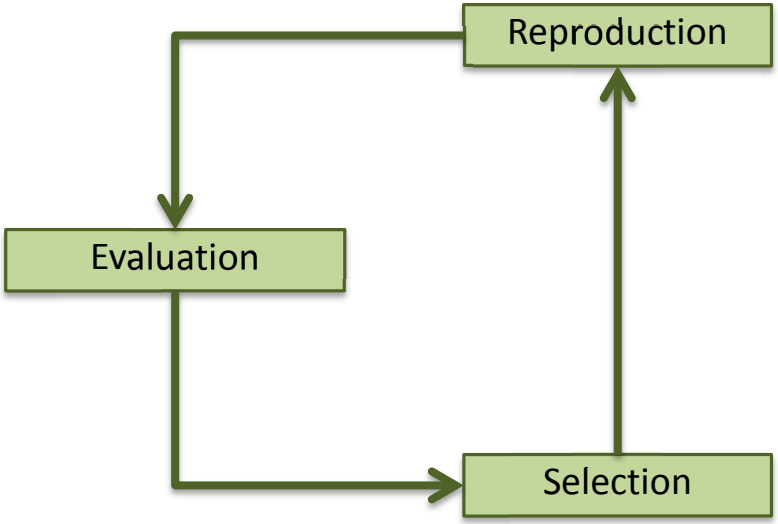
**Conception**

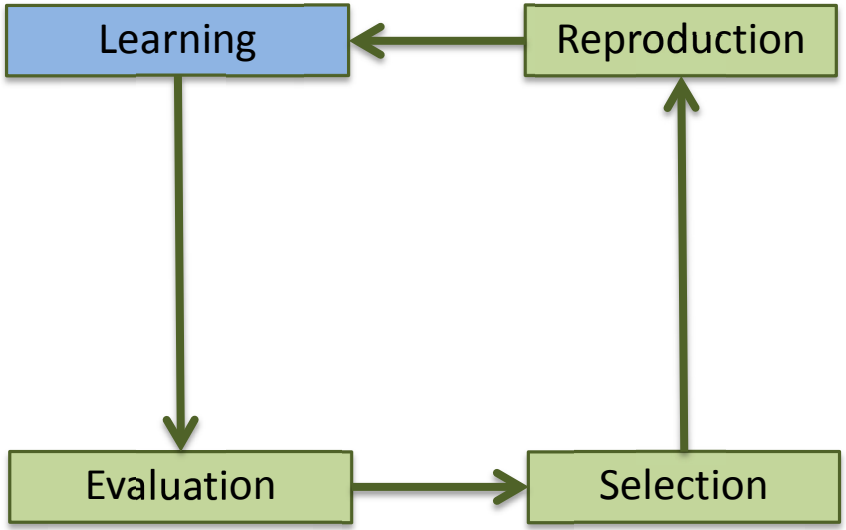
Phenotype
with learned brain

**Maturity test**

Mature life

# Eiben and Hart, If it evolves it needs to learn, ***GECCO workshop***, 2020



Cheney, Bongard, SunSpiral, Lipson, Scalable Cooptimization of Morphology and Control in Embodied Machines, J. R. Soc. Interf., 2018

# Should the infant learner be fertile?

**Morphological innovation protection**

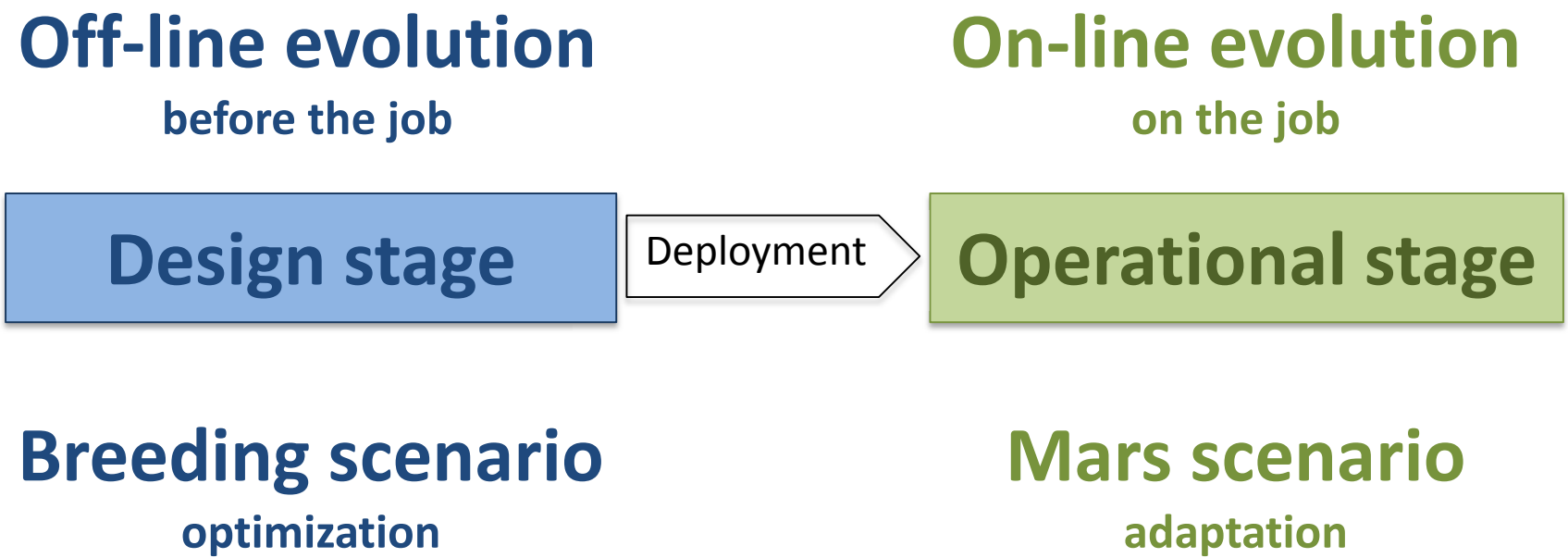
Newborn robot can reproduce during learning

To protect the newborn robot from too strong population members

**Infant learning in the Triangle of Life**

Newborn robot cannot reproduce during learning

To protect the population from inferior genes


Off-line evolution
before the job
On-line evolution
on the job
Design stage
Deployment
Operational stage
Breeding scenario
optimization
Mars scenario
adaptation


Ethics

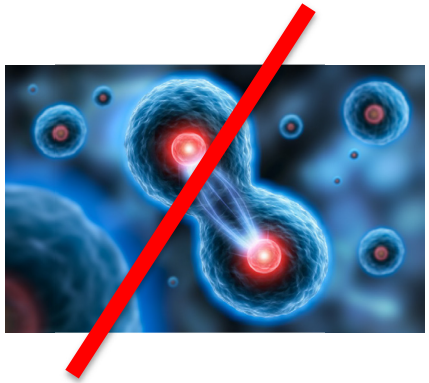

WARNING
RADIATION
HAZARD

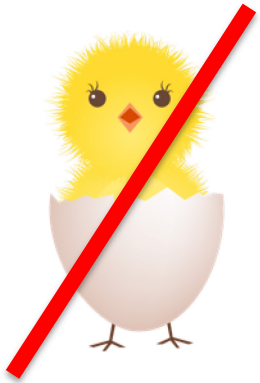

CAUTION
BIOHAZARD


CAUTION
ROBO HAZARD


STOP
EMERGENCY

KILL SWITCH

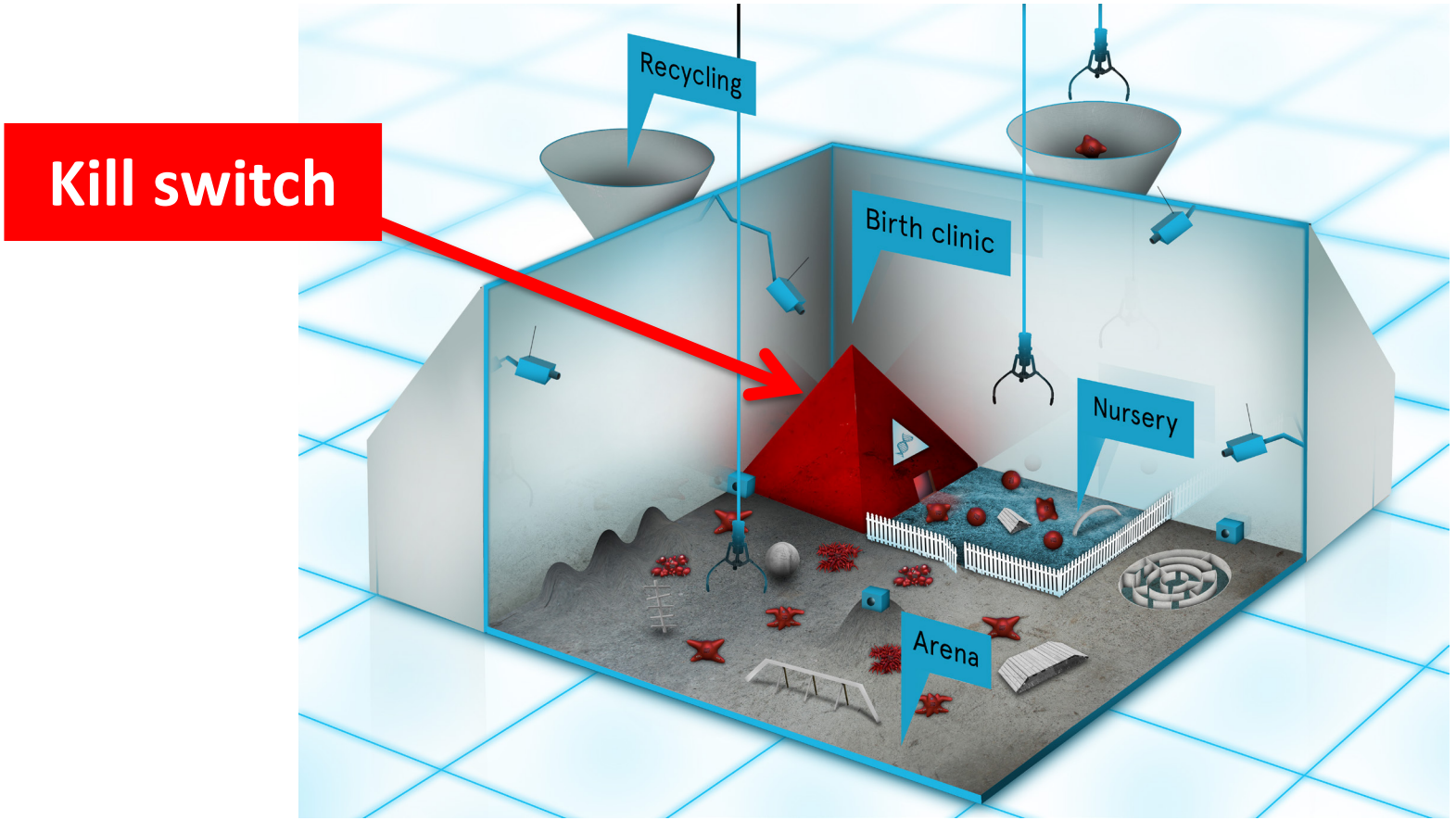


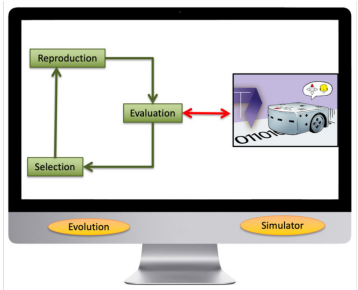


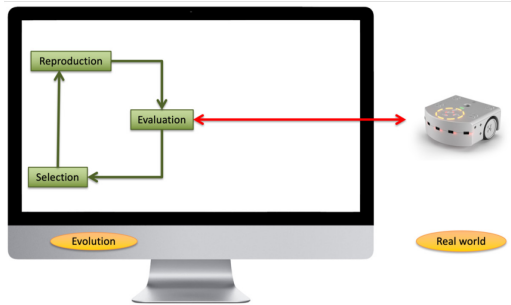
# Centralized, externalized reproduction

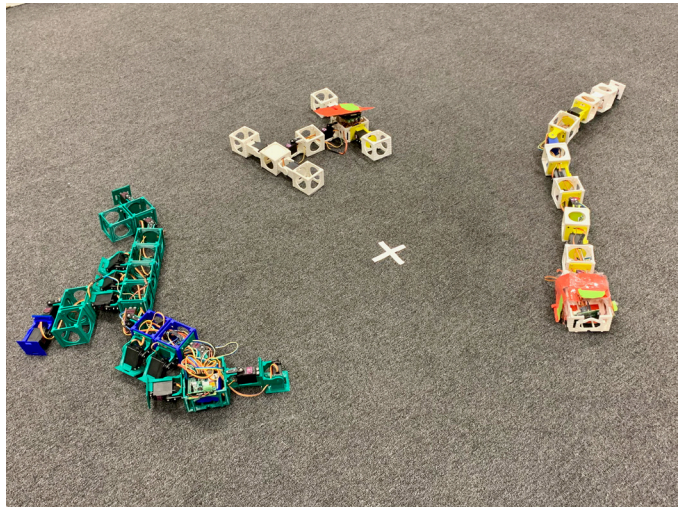
Does not invalidate the concept of evolution

Eiben, EvoSphere: the world of robot evolution, ***TPNC conference***, 2015.




Reproduction
Evaluation
Selection
Evolution
Simulator

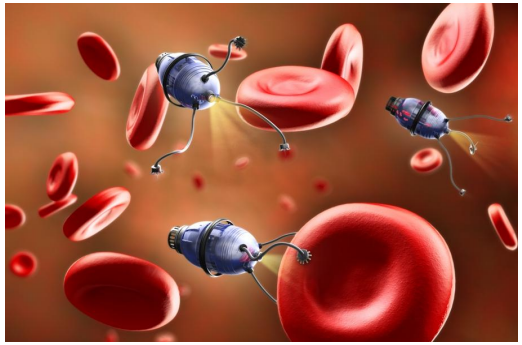

Reproduction
Evaluation
Selection
Evolution
Real world



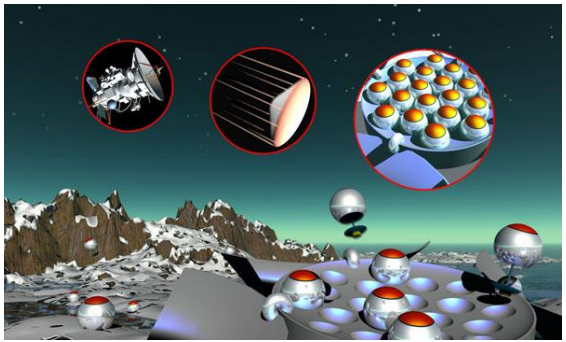
# Applications

Forresters (monitoring)

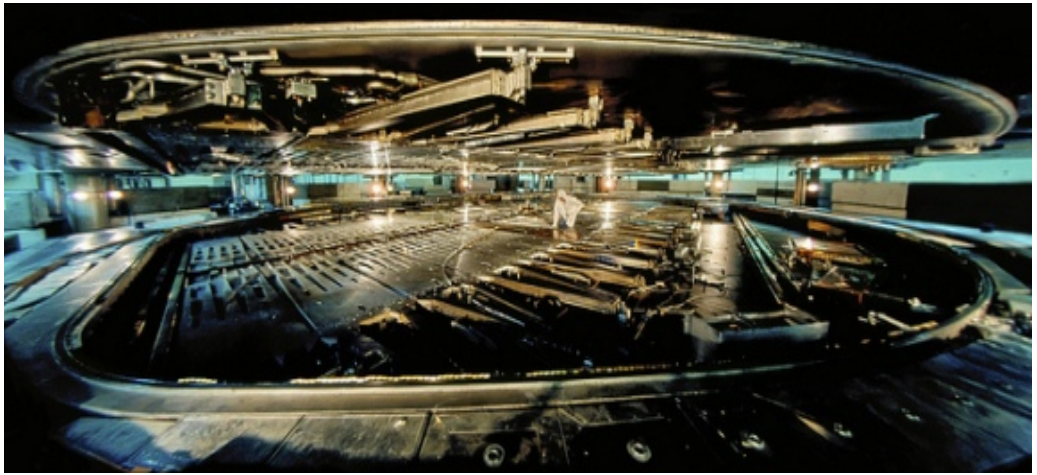
Seafloor mining



Medical nano robots



Terraforming



EvoSphere = novel research instrument

Stars → telescope
Particles → cyclotron
Evolution → EvoSphere

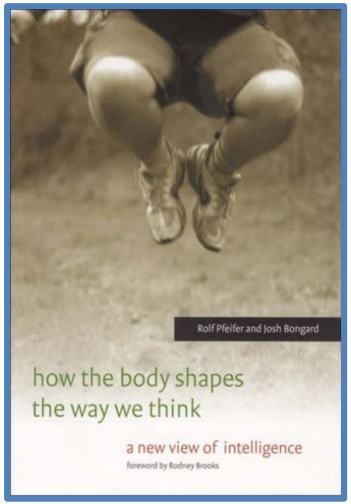
“So far, we have been able to study only one evolving system and we cannot wait for interstellar flight to provide us with a second. If we want to discover generalizations about evolving systems, we have to look at artificial ones.”

**Evolutionary biologist John Maynard Smith**

Karine Miras

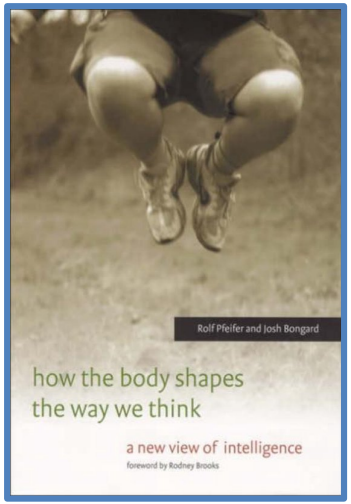
# Evolution of intelligence

preconditions, attractors, invariants



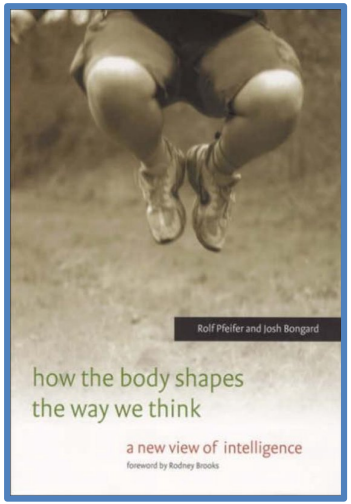

Brains

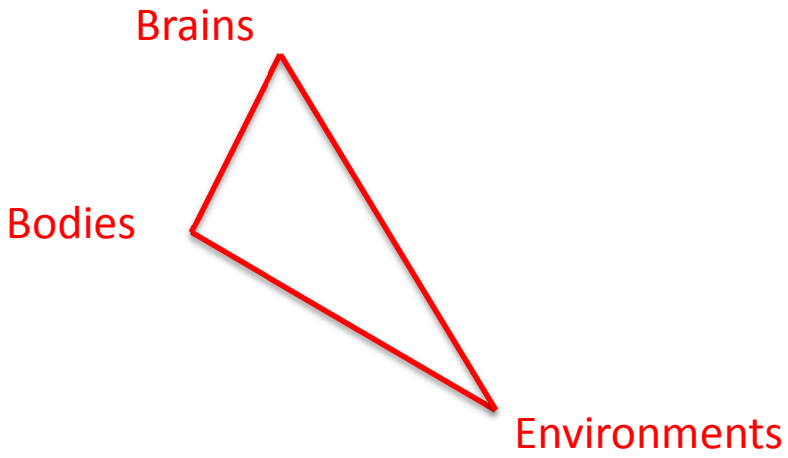
Bodies

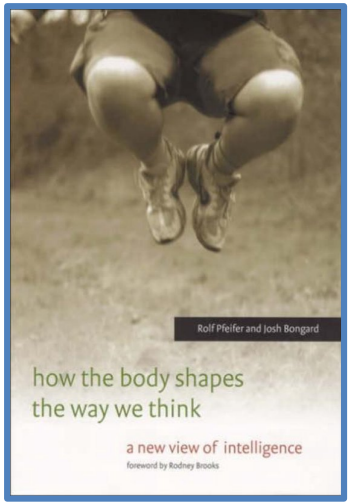



Brains

Bodies


Rolf Pfeifer and Josh Bongard
how the body shapes
the way we think
a new view of intelligence
foreword by Rodney Brooks


Brains
Bodies
Environments


Rolf Pfeifer and Josh Bongard
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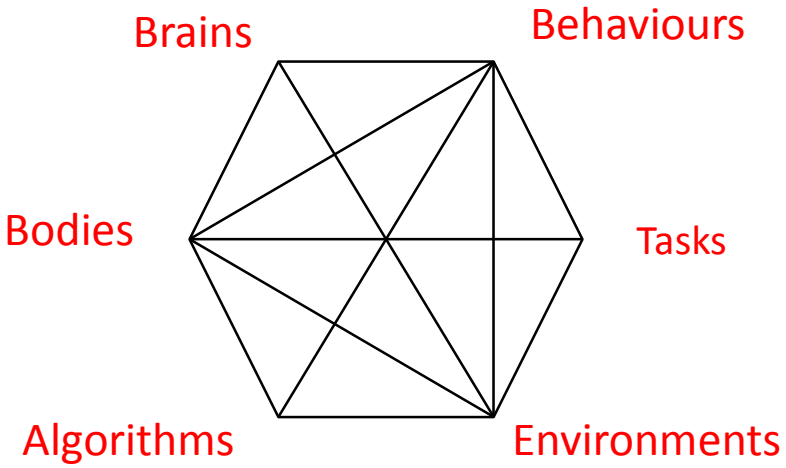

Brains
Behaviours
Bodies
Tasks
Algorithms
Environments

VU VRIJE UNIVERSITEIT AMSTERDAM

laying the groundwork

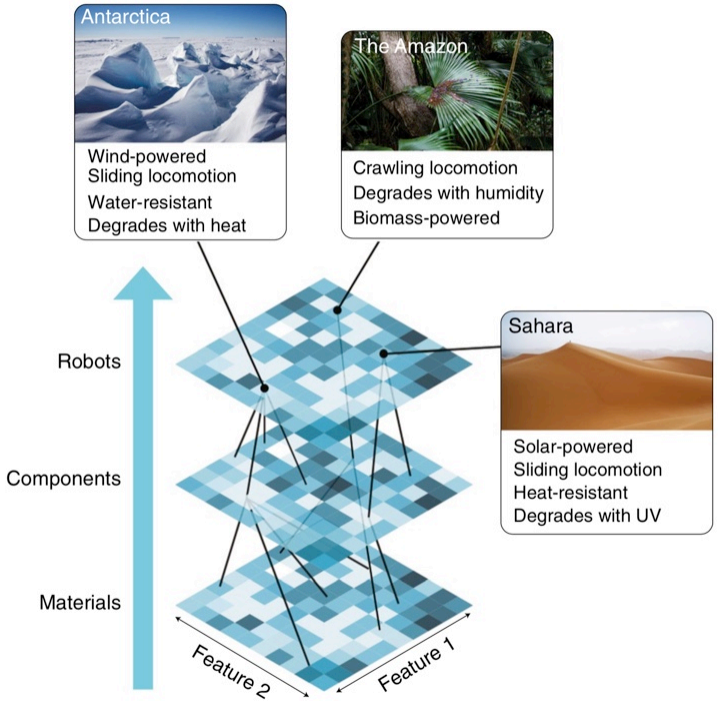
developing algorithms & know-how

seeking deeper understanding

(patterns, relationships, invariants)

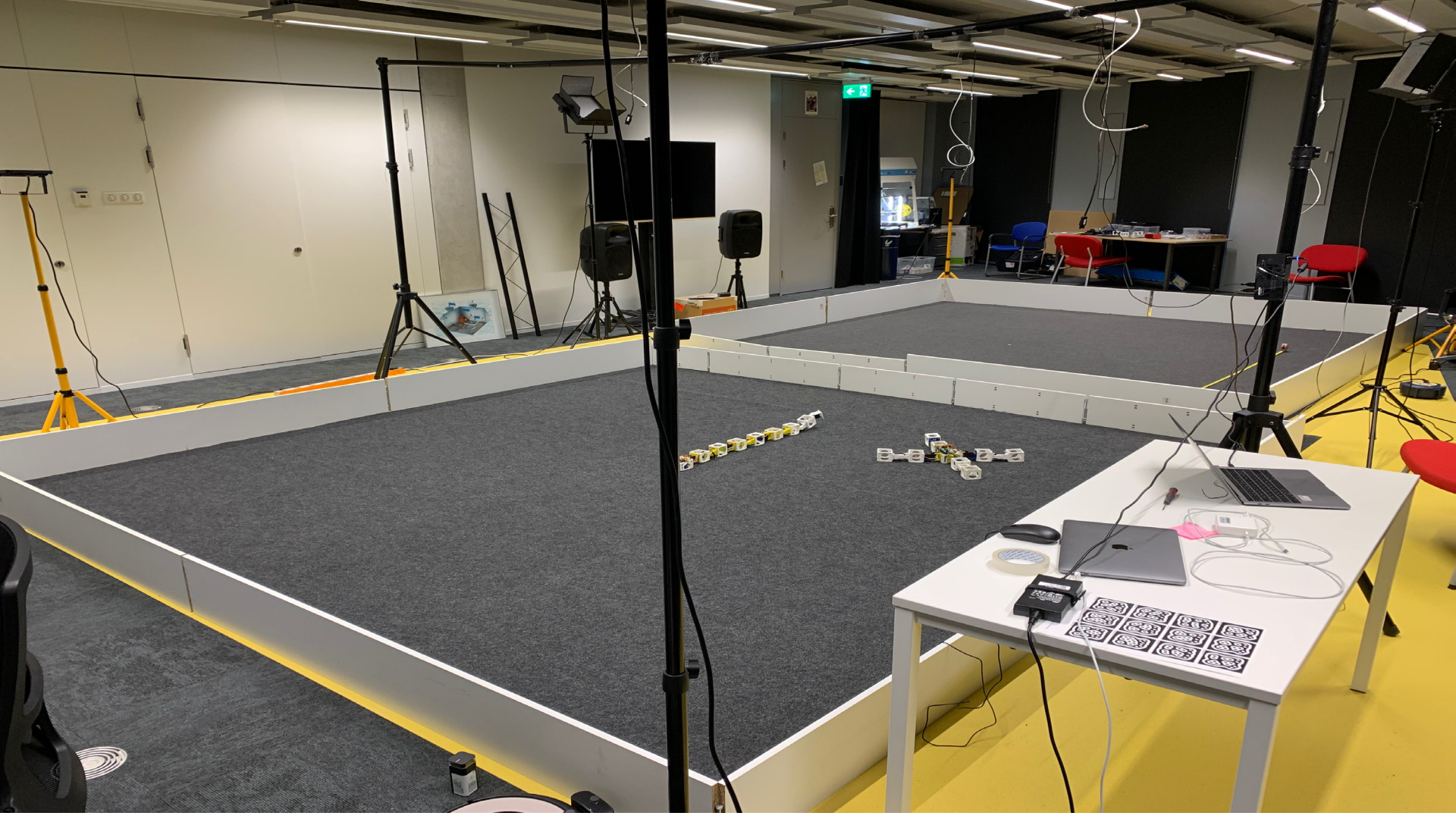
Howard, Eiben, Kennedy, Mouret, Valencia, Winkler, Evolving embodied intelligence from materials to machines, Nature Machine Intelligence 1(1), 2019

## Multi-Level Evolution




## Hybrid Evolution

- Real robot population evolves simultaneously with virtual robot population
- Same genetic language in both
  - Cross-fertilization: virtual father, real mother
  - Twin creation (digital twin or physical twin)
- Two populations – one species
- Virtual population explores good regions in search space quickly
- Real population keeps everything in check
- Best of both worlds



**effect of the environment**

(curse of the snakes)

GECCO, 2019
PloS ONE 2020

**fit for environment vs. fit for purpose**

(how to combine)

PLOS One, 2014

**interaction between body and brain**

(which one is “more important”)

ALife conf. 2018

**learning and evolution**

(Lamarck rules)

Frontiers in Robotics and AI, 2019, 2022

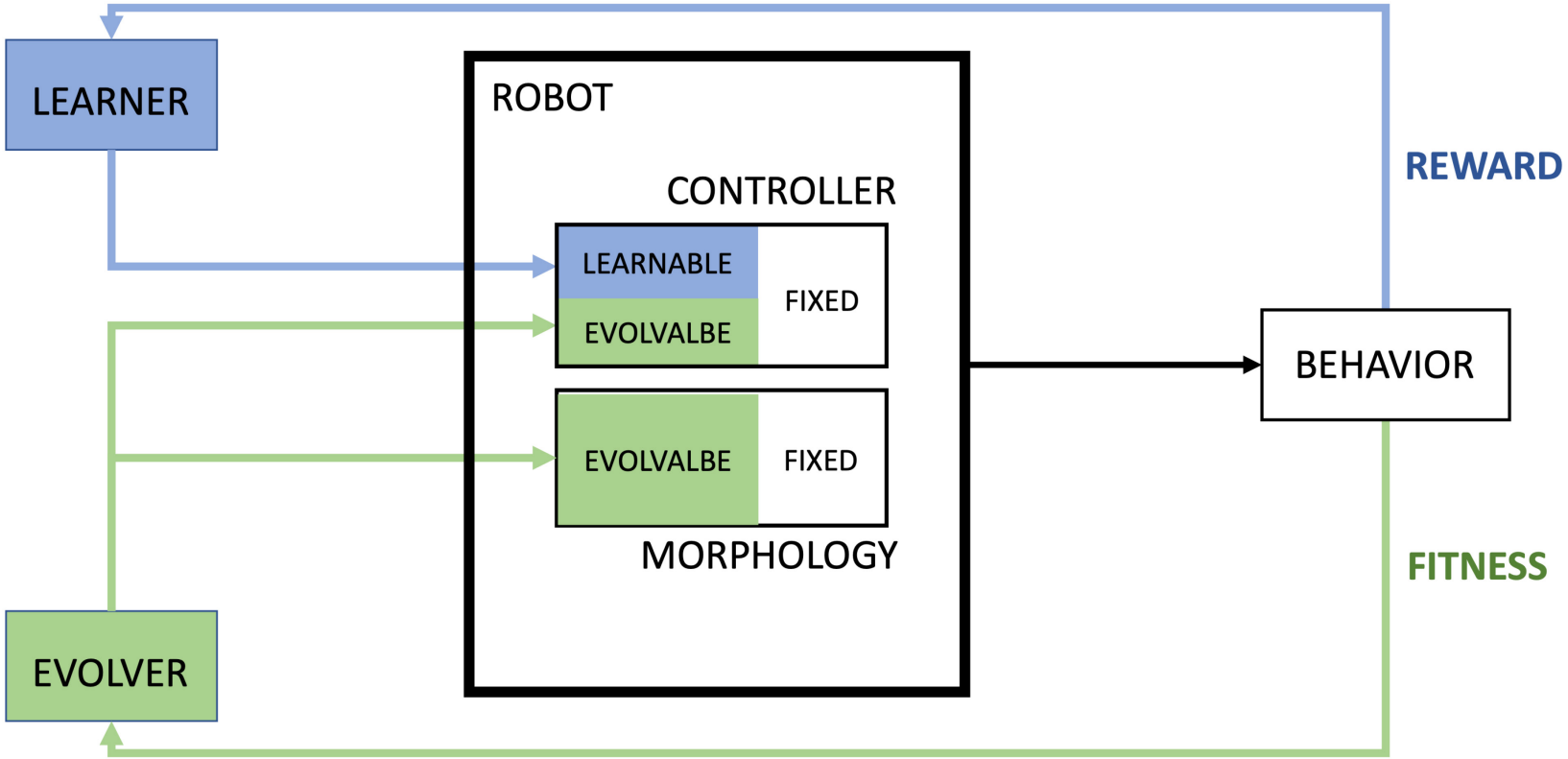
Jelisavcic, Roijers, Eiben, Robot Brains and Bodies: Which One is More Important?, ALife, 2018

Rationale: standard deviation lower → role / impact / relevance higher
Precondition: swappable brains
Conclusion: **morphology is more relevant than controller**

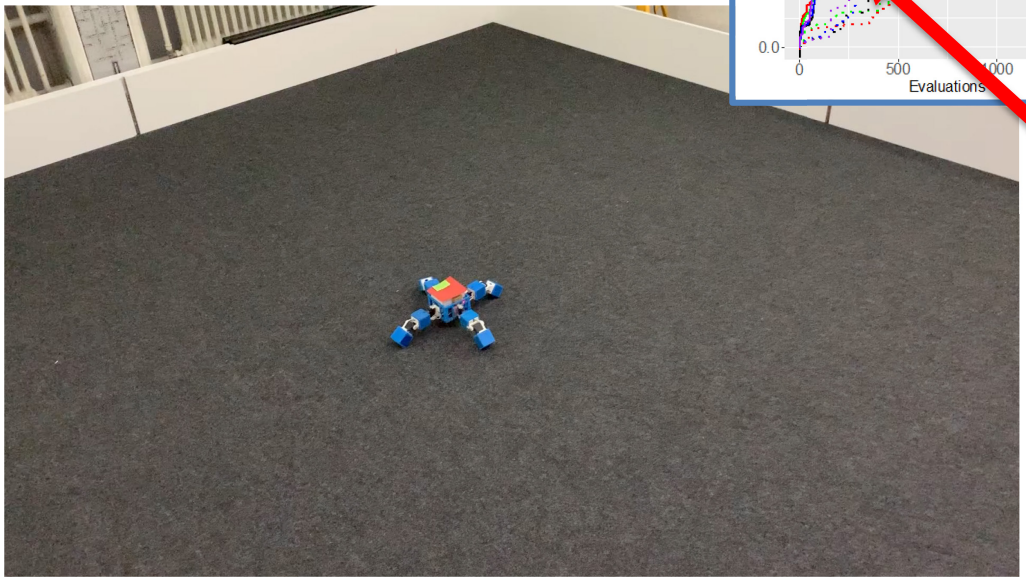
∑ = 682

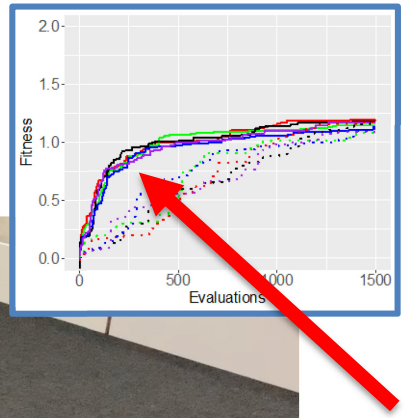
| | brain1 | … | brain_i | … | brain_100 | St. dev over row |
|---|---|---|---|---|---|---|
| body_1 | | | | | | |
| … | | | | | | |
| body_j | | | 7,14 m/s | | | |
| … | | | | | | |
| body_100 | | | | | | |
| St. dev over column | | | | | | |

∑ = 1099


LEARNER
ROBOT
CONTROLLER
LEARNABLE
FIXED
EVOLVALBE
EVOLVALBE
FIXED
MORPHOLOGY
BEHAVIOR
REWARD
FITNESS
EVOLVER

Lan, van Hooft, De Carlo, Tomczak, Eiben, Learning Locomotion Skills in Evolvable Robots, **Neurocomputing**, 2021





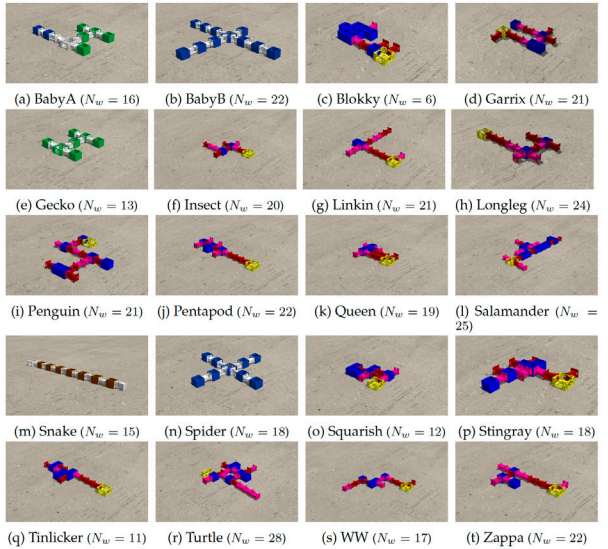
Van Diggelen, Ferrante, Eiben, Comparing lifetime learning methods for morphologically evolving robots, to appear

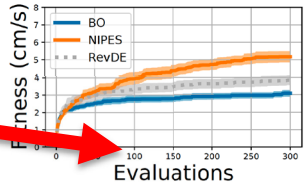
**New methodology:**

- Learning machines (1 morphology = 1 database)
- Speed & quality criteria extended by
- Consistency: variance on one morphology
- Robustness: variance on different morphologies

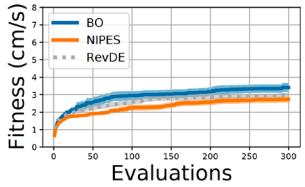
**New insights:**

- ES wins on quality (MBF, not signif.)
- BO wins on speed (AES, signif.)
- BO wins on consistency (signif.)
- BO and DE win on robustness (not signif.)
- 100 - 150 trials can be sufficient




(q) Tinlicker



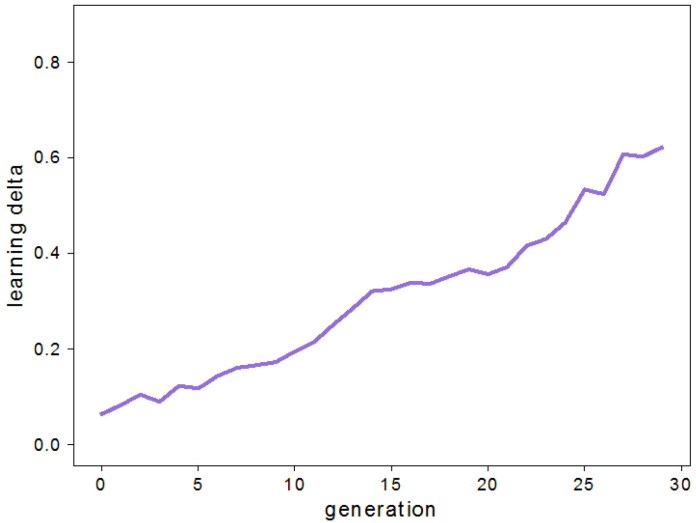

(r) Turtle

# The Learning Delta

Miras, De Carlo, Akhatou, Eiben, Evolving-Controllers Versus Learning-Controllers for Morphologically Evolvable Robots, EVOSTAR 2020, LNCS 12104, Springer, 2020

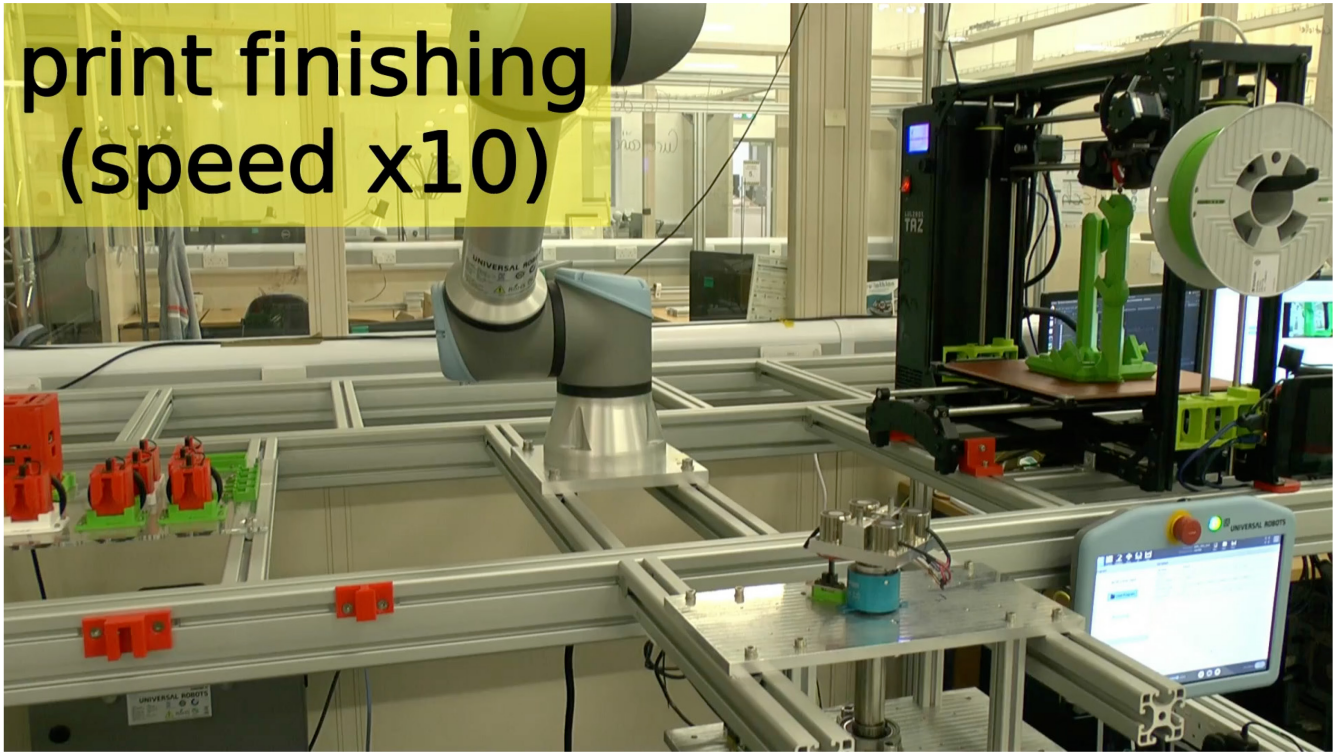
Le Goff et al., Morpho-evolution with learning using a controller archive as an inheritance mechanism, IEEE TCDS, 2021

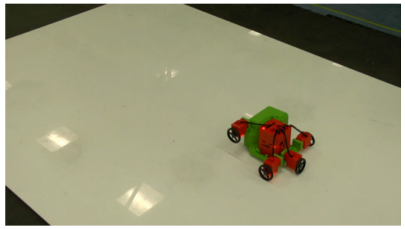
Luo, Stuurman, Tomczak, Ellers, Eiben, The Effects of Learning in Morphologically Evolving Robot Systems, Frontiers in Robotics and AI, 2022

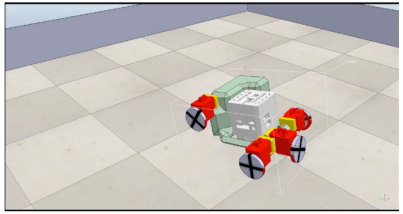



**Emergence of “morphological intelligence”**

# Autonomous Robot Evolution project (EPSRC, 2018-2022)





# Where to?

- Sensors !
- Multiple skills, complex tasks, missions
- Complex environments
- Longer lifetimes (hours, days) – charging battery, MOEA
- Interacting population members co-existing in the same space
- Utility + viability (open ended evolution) – Plos One paper
- Autonomous selection, birth & death detached – pop. size !
- Lamarckian evolution
- Soft materials, evolvable materials as per Howard et al. (2020)
- Tools & methods for scientific analysis

## < 5 years

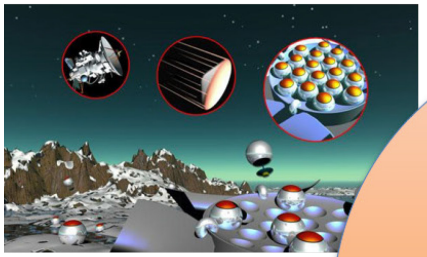
First real EvoSphere, robot breeding farms, strongly rely on humans

## 5 – 15 years

Semi-autonomous EvoSpheres, reproduction, selection w/o humans

## 15+ years

Evolving robot colonies for exploration, mining, terraforming, entertainment, …



**ENGINEERING**

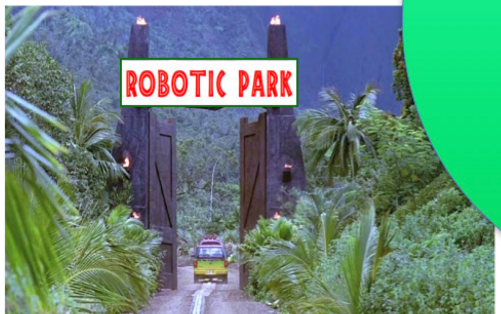
better robots

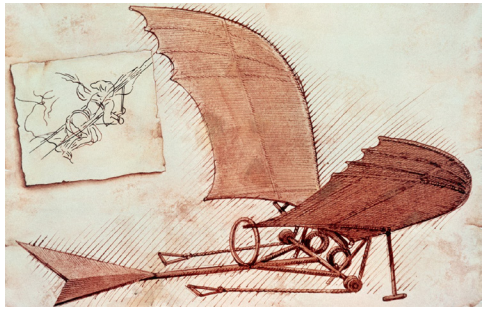
**SCIENCE**

fundamental research

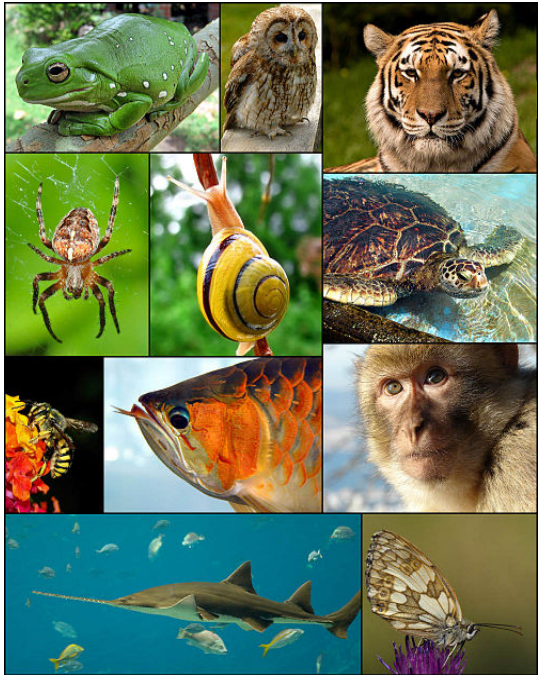
**OUTREACH**

robot zoo

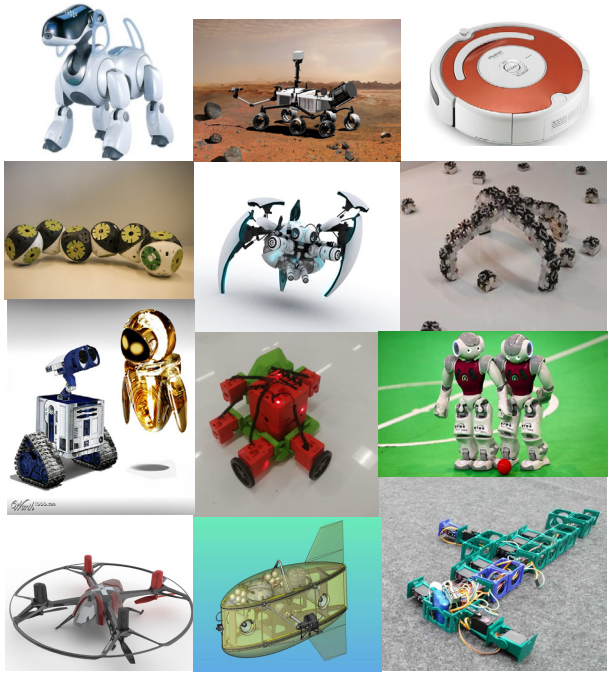




## Biosphere



## Robosphere



# IT’S LIFE JIM

# BUT NOT AS WE KNOW IT

Thanks to J. Auerbach, N. Bredeche, E. Buchanan, M. D'Angelo, M. De Carlo, F. van Diggelen, S. Doncieux , P. Eustratiadis, L. Le Goff, K. Glette, E. Haasdijk, M. Hale, E. Hart, J. Heinerman, E. Hupkes, M. Hoogendoorn, D. Howard, M. Jelisavcic, S. Kernbach, R. Kiesel, G. Lan, W. Li, J. Luo, K. Miras, J.-B. Mouret , G. Nietschke, J. Orlowski, B. Paechter, C. Rossi, J. Smith, J. Stradner, J. Timmis, A. Tyrrell, B. Weel, A. Winfield