Evolutionary Developmental Soft Robotics

Towards adaptive and intelligent machines
following Nature's approach to design

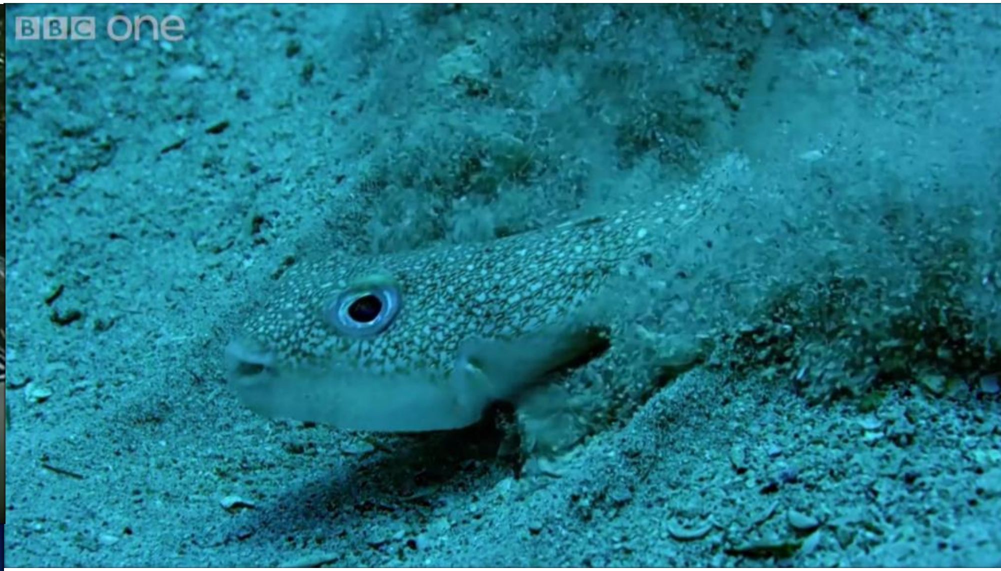
Francesco Corucci, PhD

Motivations: diversity, complexity, sophistication

Motivations: intelligent and adaptive behavior

Camouflage

Creativity



Skills

Reasoning, cognition

Motivations

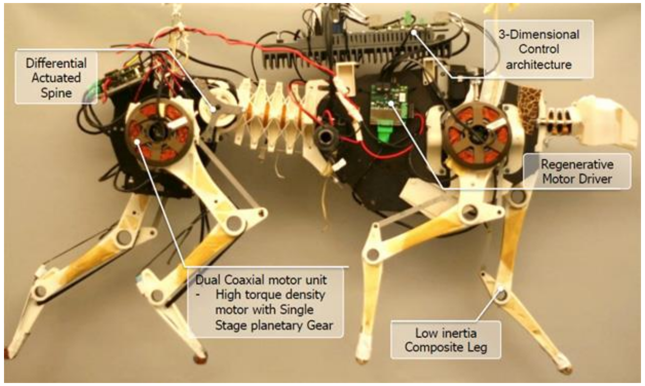
Can we *automatically* design a wealth of artificial systems that are as *sophisticated, adaptive, robust, intelligent*, for a wide variety of tasks and environments?

Adaptivity, robustness, intelligence

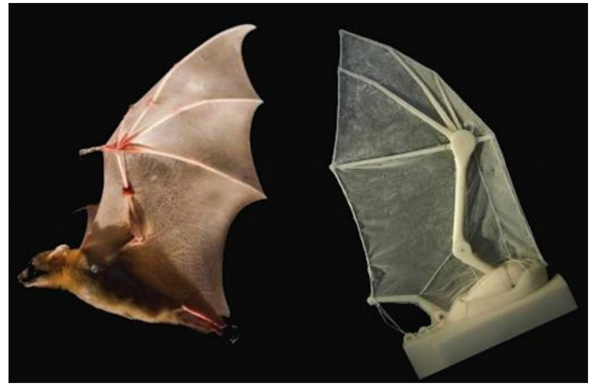
State of the art robots still lack many of these features
→ Keep failing outside controlled environments (where they are most needed)

DARPA Robotics Challenge Finals, 2015

Biologically inspired robotics (biorobotics)

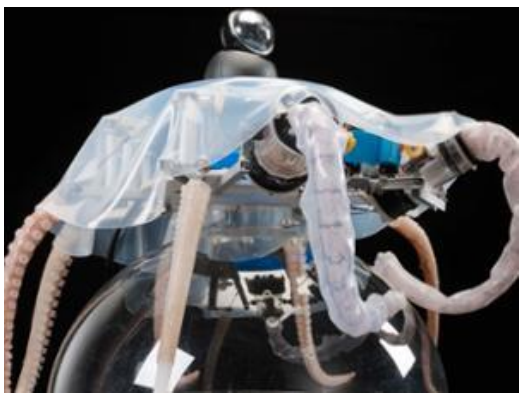


Cheetah robot, MIT

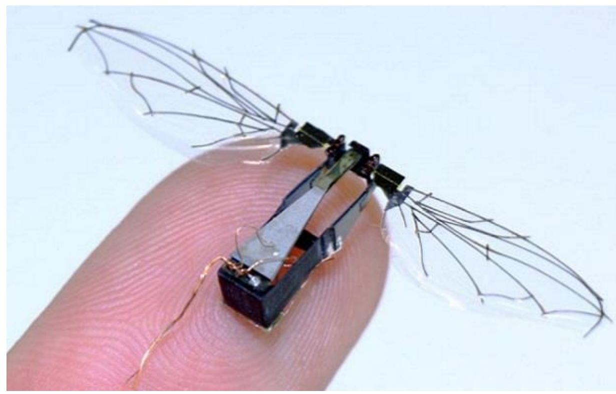


Bat robot, Brown

Soft fish, MIT



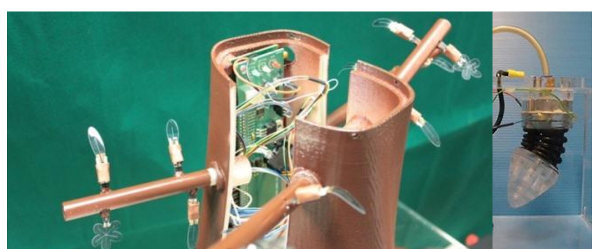
OCTOPUS, SSSA



RoboBees, Harvard

ECCE robot

Lampetra, SSSA



Plantoid robot, IIT

Biologically inspired robotics: Soft Robotics

Biologically inspired robotics: pros and cons

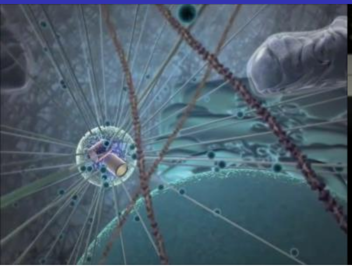
- **Pros:**
  - New technologies and design principles
  - New knowledge related to the biological model (sometimes)
  - Insights related to the intelligence of particular species (sometimes)

- **Cons:**
  - Requires a lot of human knowledge and careful engineering
  - Focuses on very specific organisms/behaviors
  - Does not necessarily:
    - Generalize to arbitrary tasks and environments
    - Help realizing general forms of artificial intelligence

What do all these things have in common?

They are the result of an **EVOLUTIONARY PROCESS**

A paradigm shift in bioinspiration




Instead of replicating some of the <u>solutions</u> found by Nature,
why not imitating <u>Nature's approach to design</u> instead? → <u>EVOLUTION</u>

From replicating natural <u>products</u>,
to replicating the natural <u>processes</u> which gave rise to them

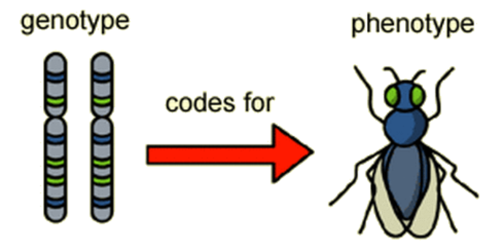
→ <u>Ultimate form of bioinspiration</u>



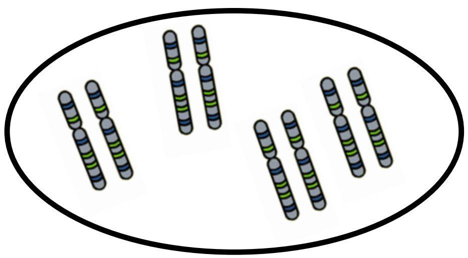

Evolution: Nature's approach to design

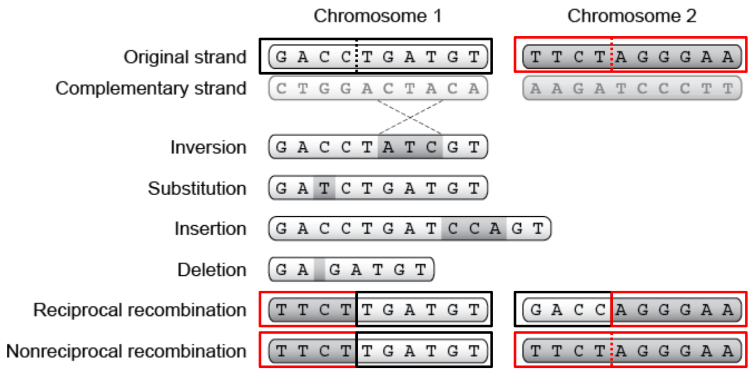
Ingredients:

- A way to *encode* the observable traits of an organism (*<u>phenotype</u>*) into a compact set of instructions (*<u>genotype</u>*, «blueprint» of an organism)
- A *<u>population</u>* of diverse individuals which can *<u>reproduce</u>* among themselves
- <u>Mechanisms to manipulate the genetic material</u> upon reproduction (*<u>genetic recombination</u>*, *<u>mutation</u>*)
    - <u>Error prone:</u>
      → <u>Random variation</u>
      → <u>Novel traits</u>



Population

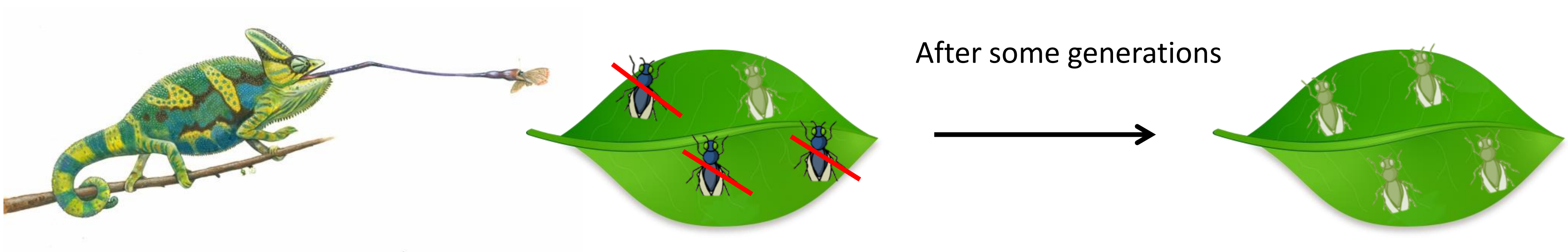




Evolution: Nature's approach to design

- A <u>*selection criterion*</u>:
  - At each <u>*generation*</u>, individuals that are <u>better adapted to the environment</u> (<u>*fitness*</u>) have higher chance of:
    - Surviving and reproducing
    - Propagating their genetic material (and, thus, their traits) to subsequent generations

Natural selection



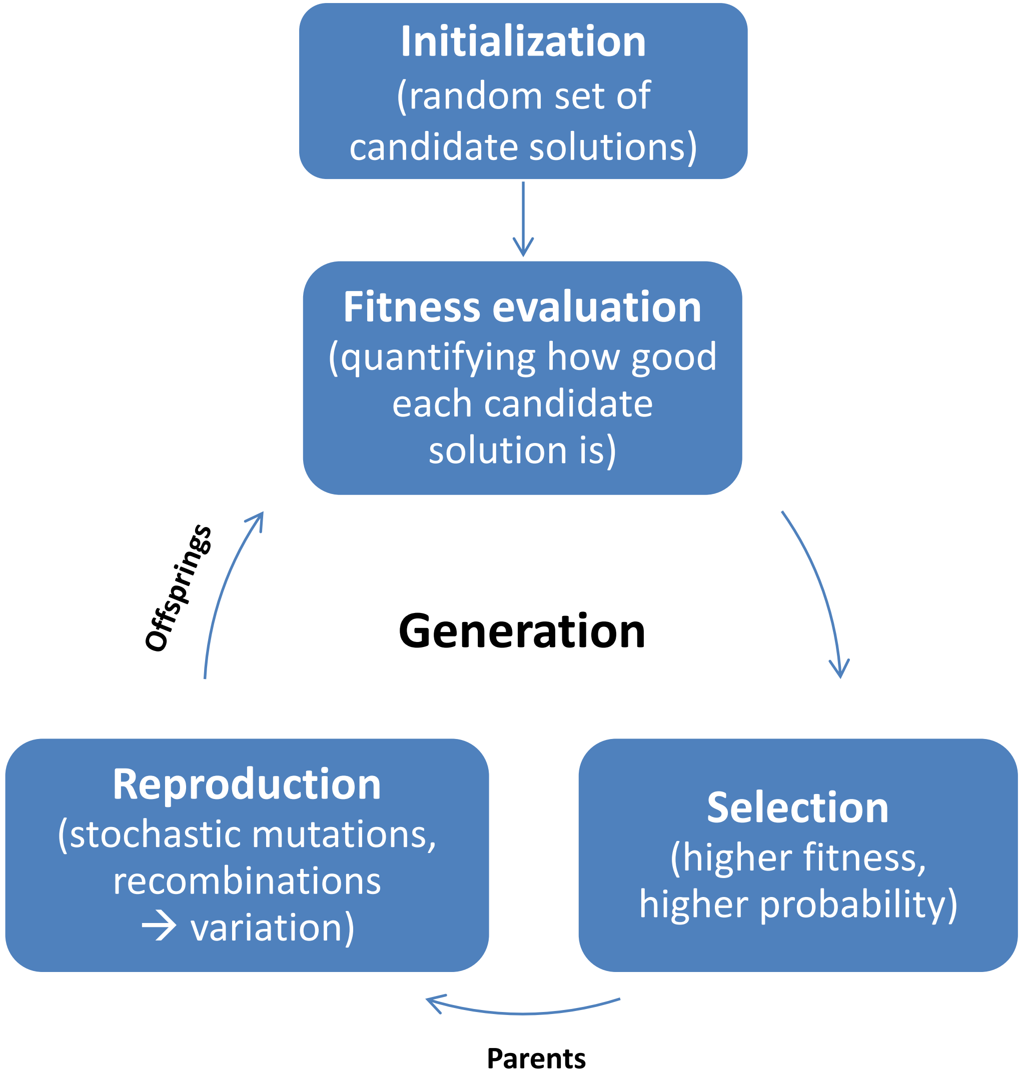
Evolution: basic algorithmic principle

Trial-and-error procedure in which innovation is driven by the non-random selection of random variations

Evolutionary Algorithms (EAs)

Class of population-based, iterative, stochastic ***optimization*** algorithms inspired by this algorithmic principle

- Fitness → A function (objective) to be maximized/minimized
- Individuals → Candidate solutions
- Encoding → Data structure (e.g. bitstring, network, …)
- Reproduction → Stochastic operators manipulating the candidate solutions (e.g. flip a bit with a given probability)



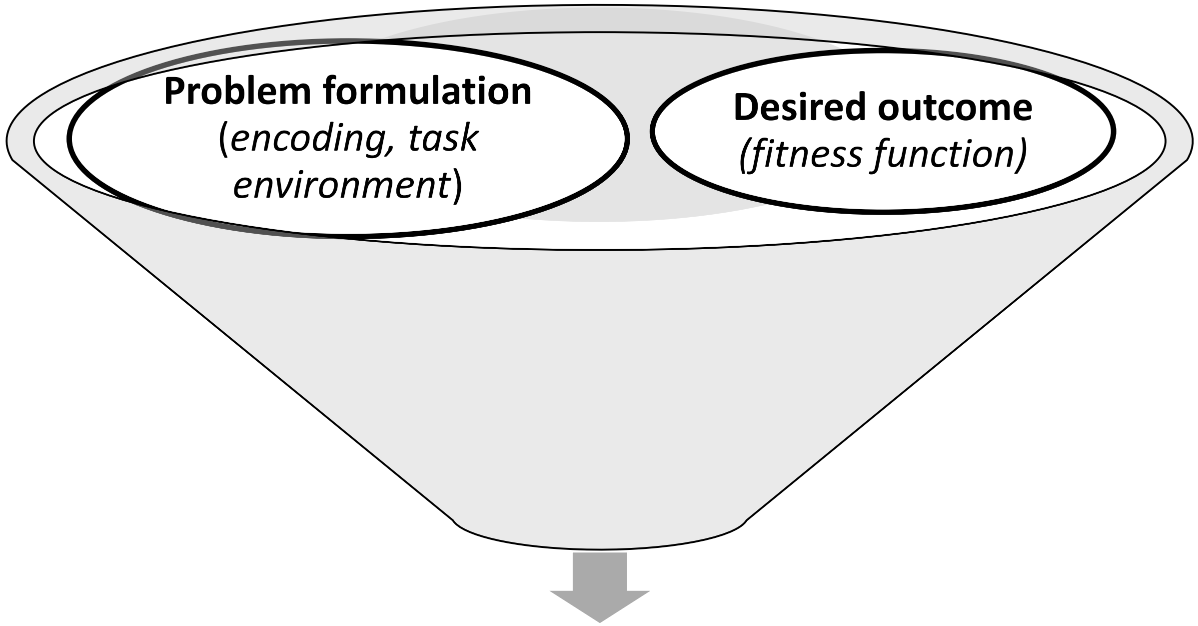
Evolutionary Robotics (evo-robo)

- **<u>Core idea</u>: to apply evolutionary algorithms in order to optimize robots**

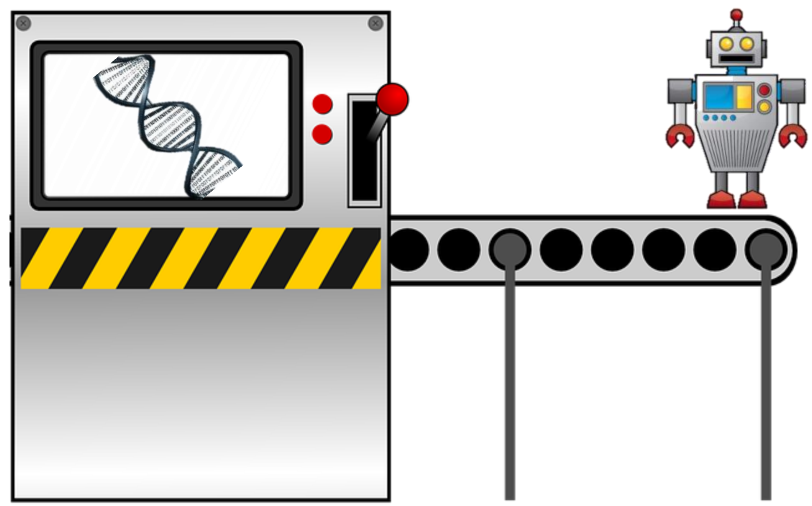
- **<u>Example:</u>**
  - Fixed morphology
  - A population of controllers is evolved
  - <u>Fitness</u>: traveled distance

From: YouTube (Arseniy Nikolaev, virtual spiders evolution)

Implications: design automation technique



- Evolutionary system
- Advanced fabrication techniques (e.g. 3D printing)



Complete, optimized robotic system, ready to be deployed

Implications: co-evolution

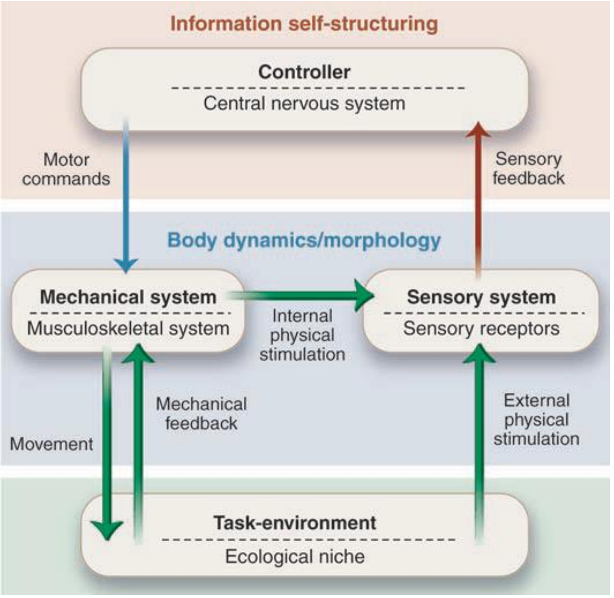
- In evo-robo, EAs are usually coupled with *powerful encodings*, which allow to efficiently represent (and thus co-evolve/co-optimize) complex characteristics such as:
    - Morphology
    - Controller
    - Sensory system
    - …

Implications: Embodied Cognition

The possibility to co-optimize all of these aspects (and the body in particular) is very appealing in light of recent trends in AI (*Embodied Cognition*)

Intelligent and adaptive behavior starts within the body, and its dynamic interplay with brain and environment (*embodiment*)

A suitable morphology can greatly simplify control by performing implicit/explicit computation (*morphological computation*)



Pfeifer et al. *Self-Organization, Embodiment, and Biologically Inspired Robotics*, Science (2007)

Mc Geer 1990, Passive Dynamic Walker
Pfeifer and Bongard, *How the body shapes the way we think (2006)*

Implications: Embodied Cognition, Soft Robotics

A **soft** body, in particular, is thought to facilitate the emergence of these phenomena:

- Better mean of interaction between brain and environment (richer proprioceptive and exteroceptive stimulation)
- Greater computational power (Hauser et al. 2011, Nakajima et al. 2013)

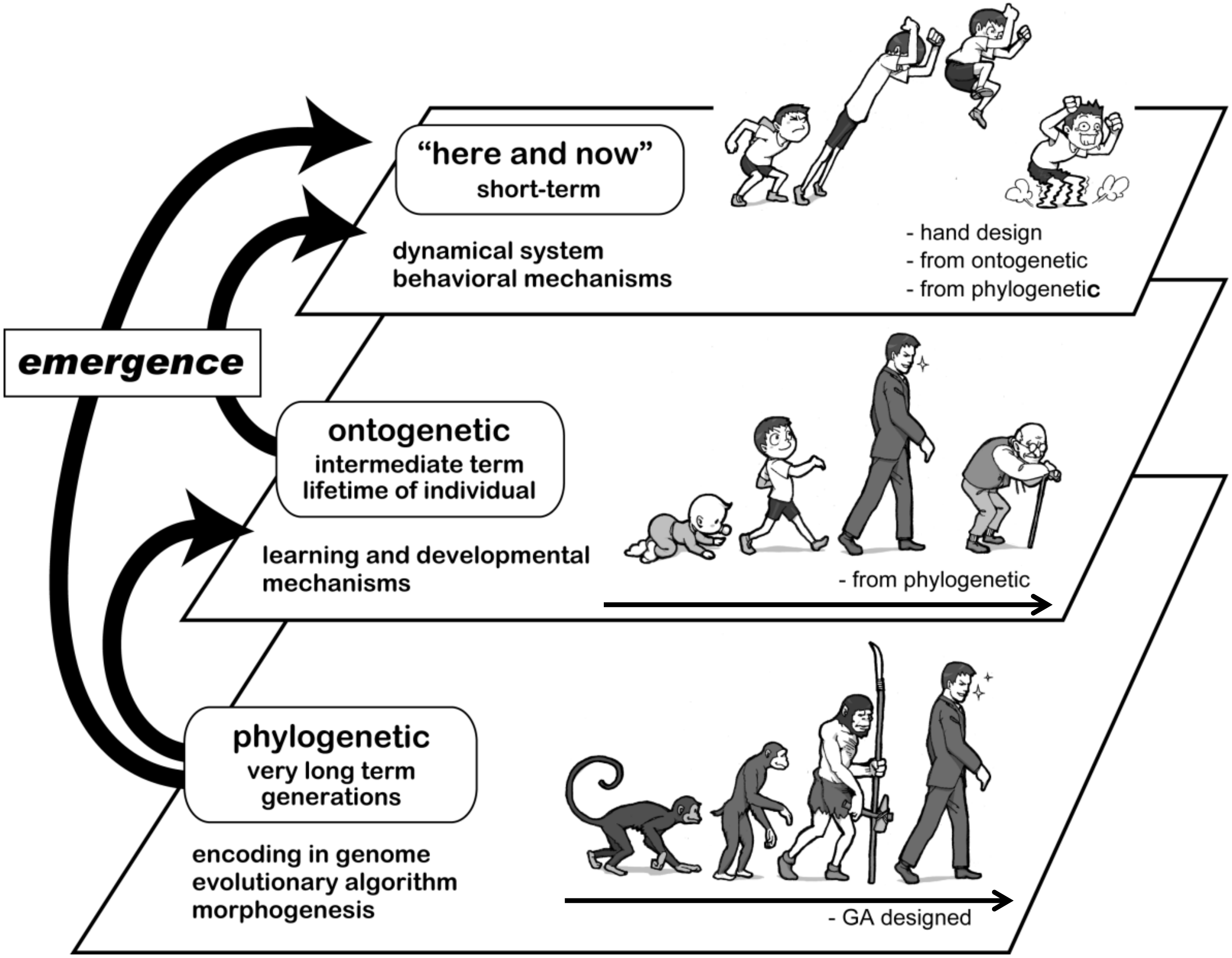
→ **We are going to evolve soft robots (*evo-SoRo*)**

Rolf Pfeifer, Hugo Gravato Marques, and Fumiya Iida. Soft robotics: the next generation of intelligent machines. In Proceedings of the Twenty-Third international joint conference on Artificial Intelligence,pages 5{11. AAAI Press, 2013.

Helmut Hauser, Auke J Ijspeert, Rudolf M Fuchslin, Rolf Pfeifer, and Wolfgang Maass. *Towards a theoretical foundation for morphological computation with compliant bodies*. Biological cybernetics, 105(5-6):355-370, 2011.

Kohei Nakajima, Helmut Hauser, Rongjie Kang, Emanuele Guglielmino, Darwin G Caldwell, and Rolf Pfeifer. *A soft body as a reservoir: case studies in a dynamic model of octopus-inspired soft robotic arm*. Front. Comput. Neurosci, 7(10.3389), 2013.

A comprehensive bottom-up approach



SENSORIMOTOR DYNAMICS

DEVELOPMENT

Can be modeled as well
→ evo-devo

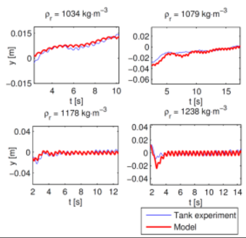
EVOLUTION

From: Pfeifer, Bongard, *How the body shapes the way we think, MIT press*

Evo-devo-soro: some case studies

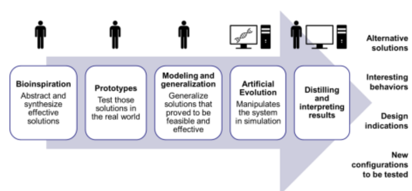
SOLVING COMPLEX OPTIMIZATION PROBLEMS

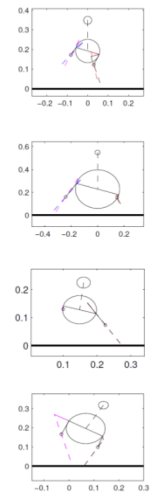
Genetic parameters estimation and locomotion of an aquatic soft robot



EXPLORING THE DESIGN SPACE OF A BIOINSPIRED ROBOT

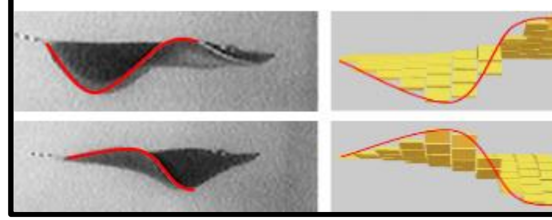
Novelty-based evolutionary design of an aquatic soft robot





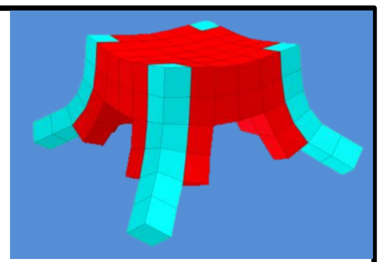
STUDYING ANIMALS

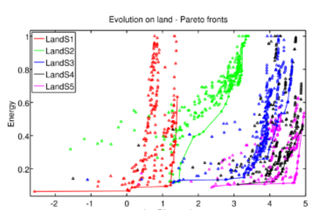
Evolution and adaptation of a batoid-inspired wing in different fluids

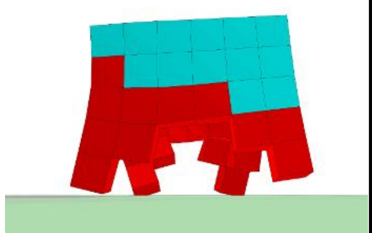


STUDYING THE EVOLUTION OF SOFT LOCOMOTION

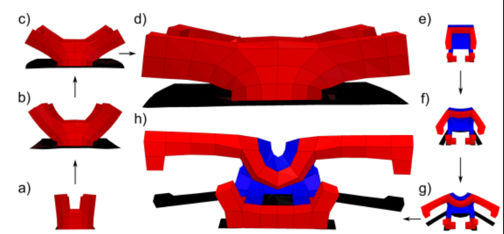
Free-form evolution: effects of material properties and environmental transitions

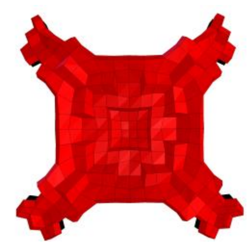


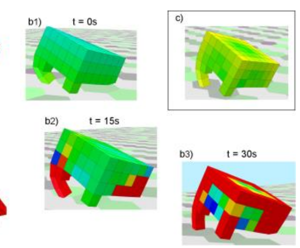




STUDYING THE EVOLUTION OF DEVELOPMENT AND MORPHOLOGICAL COMPUTATION







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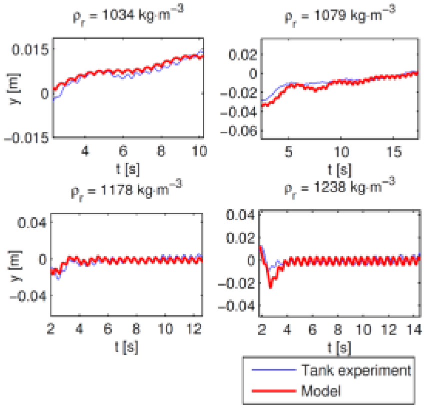


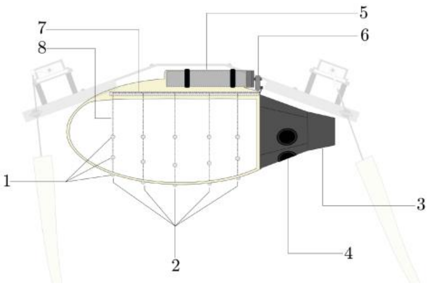
PoseiDRONE robot

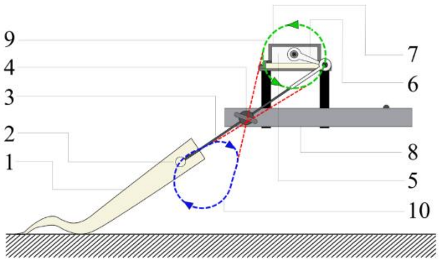
A. Arienti et al. "Poseidrone: design of a soft-bodied ROV with crawling, swimming and manipulation ability." OCEANS, 2013. IEEE, 2013.

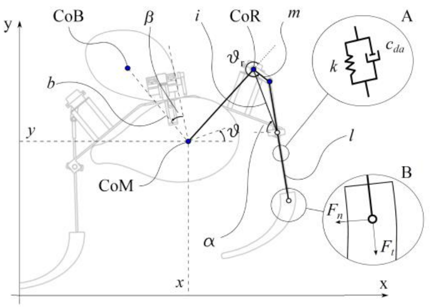
- Soft, octopus-inspired, underwater drone
- Dynamics model of its locomotion was available
- **Goal**: use the model to identify faster gaits

- **Problem:**
  - The model struggled to describe the behavior of the robot due to many unknown model parameters

→ Evolutionary Algorithms were applied to «ground» the model into physical reality through parameters estimation

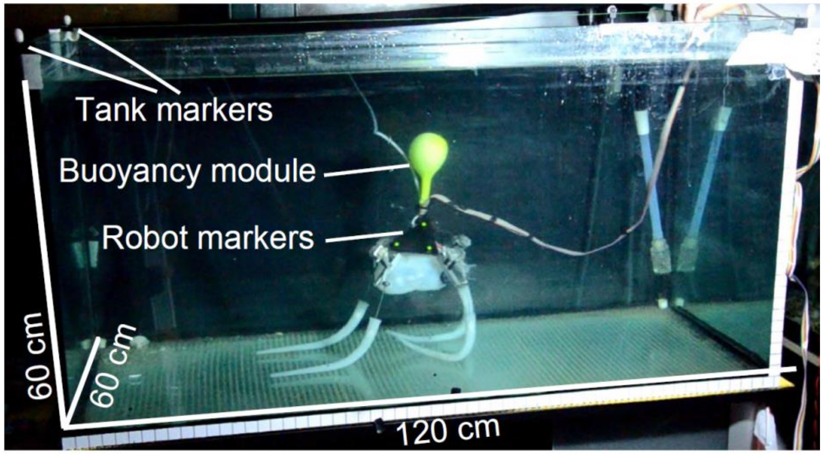






Genetic parameters estimation

- **Genetic parameters estimation:**
  Find the set of unknown model parameters that minimize the model-robot discrepancies through Genetic Algorithms



$$\boldsymbol{G} = (k, dr, \mu_s, \mu_d, m_{a_c}, J, \Lambda_t, \Lambda_r, \lambda_t, \lambda_n)$$

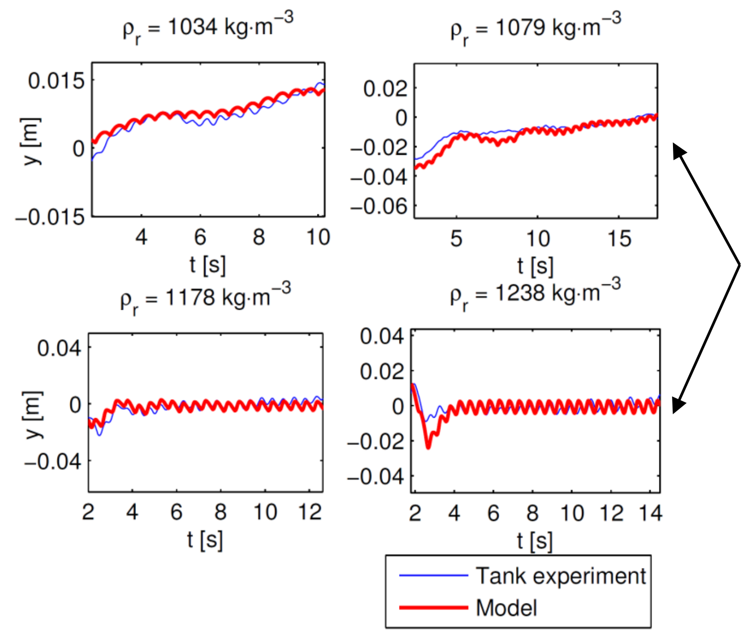
$$f(\boldsymbol{G}) = \begin{cases} P_{fall} \text{ if robot fell,} \\ \sum_{i=1}^{4} \left(\frac{f_T - f_G}{f_T}\right)^2 \text{ otherwise,} \end{cases}$$

- F. Giorgio-Serchi, A. Arienti, F. Corucci, M. Giorelli, C. Laschi, "Hybrid parameter identication of a multi-modal underwater soft robot", Bioinspiration & Biomimetics 12.2 (2017): 025007.
- M. Calisti, F. Corucci, A. Arienti, C. Laschi, "Dynamics of underwater legged locomotion: modeling and experiments on an octopus-inspired robot", Bioinspiration & Biomimetics 10.4 (2015): 046012
- M. Calisti, F. Corucci, A. Arienti, C. Laschi, "Bipedal walking of an octopus-inspired robot", Biomimetic and Biohybrid Systems - Living Machines 2014, Springer Lectures Notes in Articial Intelligence, 2014

Genetic parameters estimation: results

- After this procedure, the model faithfully represents the overall dynamics of the robot in various operative conditions
- Can be used for several purposes (mission planning, model-based controllers, etc.)

	Bound	Value
$k\ [N/m]$	$[25, 400]$	205.8
dr	$[0,\ 1.5]$	1.1
μ_s	$[0.6, 0.9]$	0.77
μ_d	$[0.6, 0.9]$	0.61
$m_{a_c}\ [kg]$	$[0.755, 7.55]$	6.65
$J\ [kg\ m^2]$	$[0.0003, 0.018]$	0.018
$\Lambda_t\ [kg/m]$	$[0.11, 145]$	63.6
$\Lambda_r\ [kg/m]$	$[0.0001, 1]$	0.068
$\lambda_t\ [kg/m]$	$[0, 0.08]$	0.026
$\lambda_n\ [kg/m]$	$[0, 0.3]$	0.033



Comparing model and robot trajectories in space

- F. Giorgio-Serchi, A. Arienti, F. Corucci, M. Giorelli, C. Laschi, "Hybrid parameter identication of a multi-modal underwater soft robot", Bioinspiration & Biomimetics 12.2 (2017): 025007.
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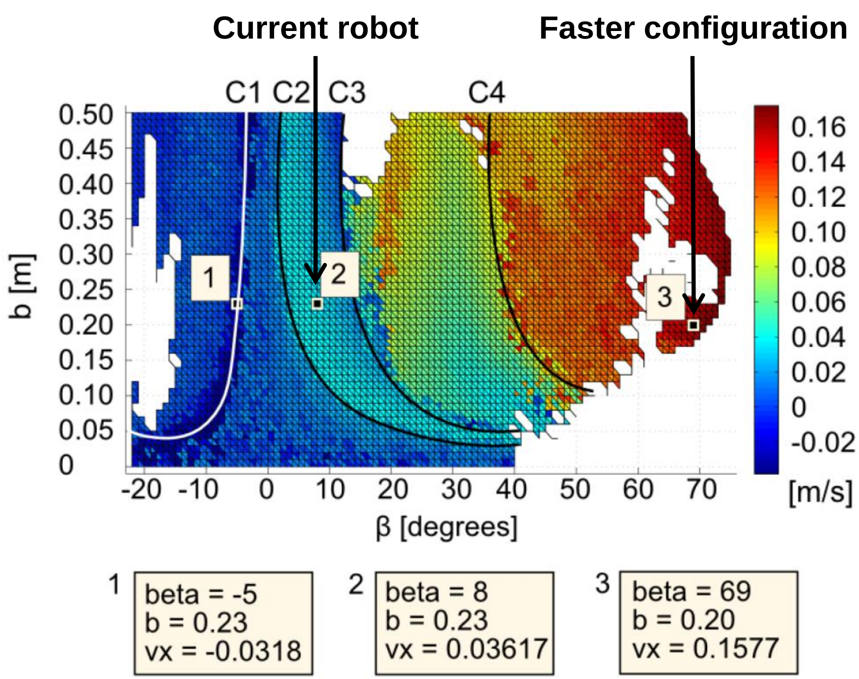
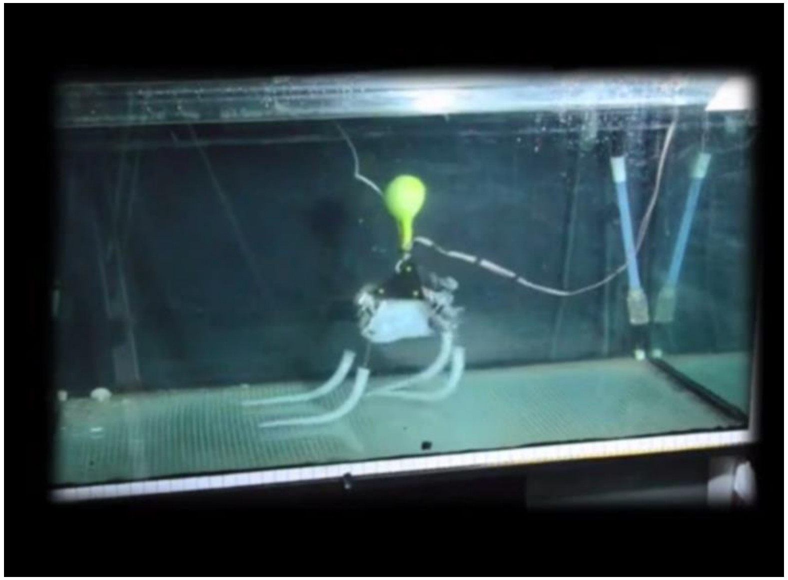
Model exploitation: examples

So far the it has been used to:

- Identify faster morphological configurations: some correctly transferred to the real world → Considerable performance increase (almost four times faster)
- Explore the viability of paradigms of adaptive morphology (*morphosis/morphing*)





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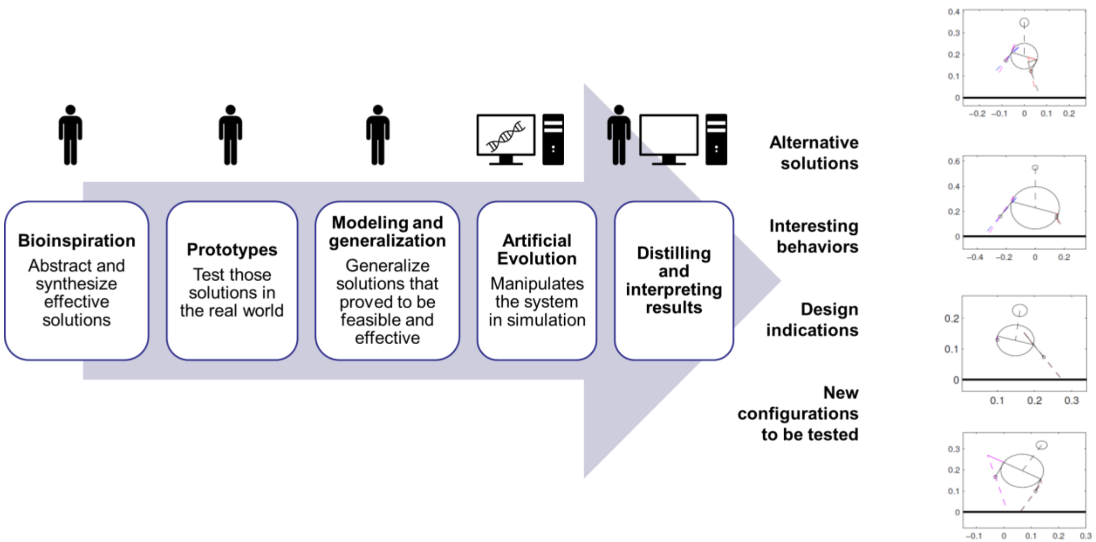


Exploring the design space of a bioinspired robot

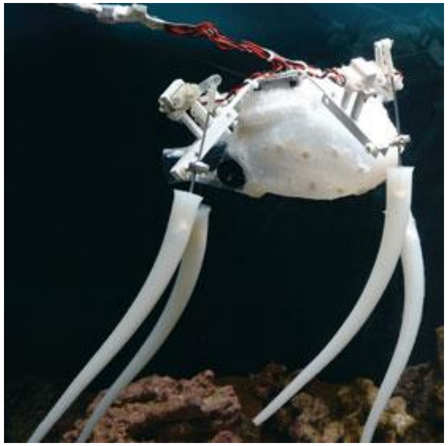
Goals:

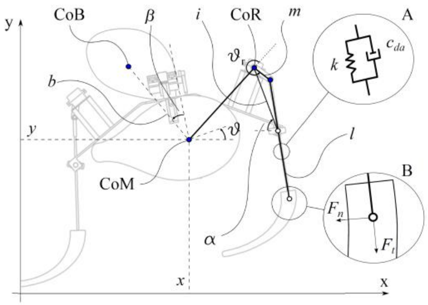
- Perform a more <u>extensive exploration of the design space</u> of the PoseiDRONE robot

Setup:

- <u>Model was generalized</u> and fed into an <u>evolutionary system</u>
- <u>Novelty-based</u> algorithm was used to explore the design space

→ Instead of rewarding individuals performing *better,* rewards individuals performing <u>*differently*</u>





<u>Corucci, F.</u>, Calisti, M., Hauser, H., & Laschi, C. (2015, July). Novelty-based evolutionary design of morphing underwater robots. In *Proceedings of the 2015 annual conference on Genetic and Evolutionary Computation* (pp. 145-152). ACM.

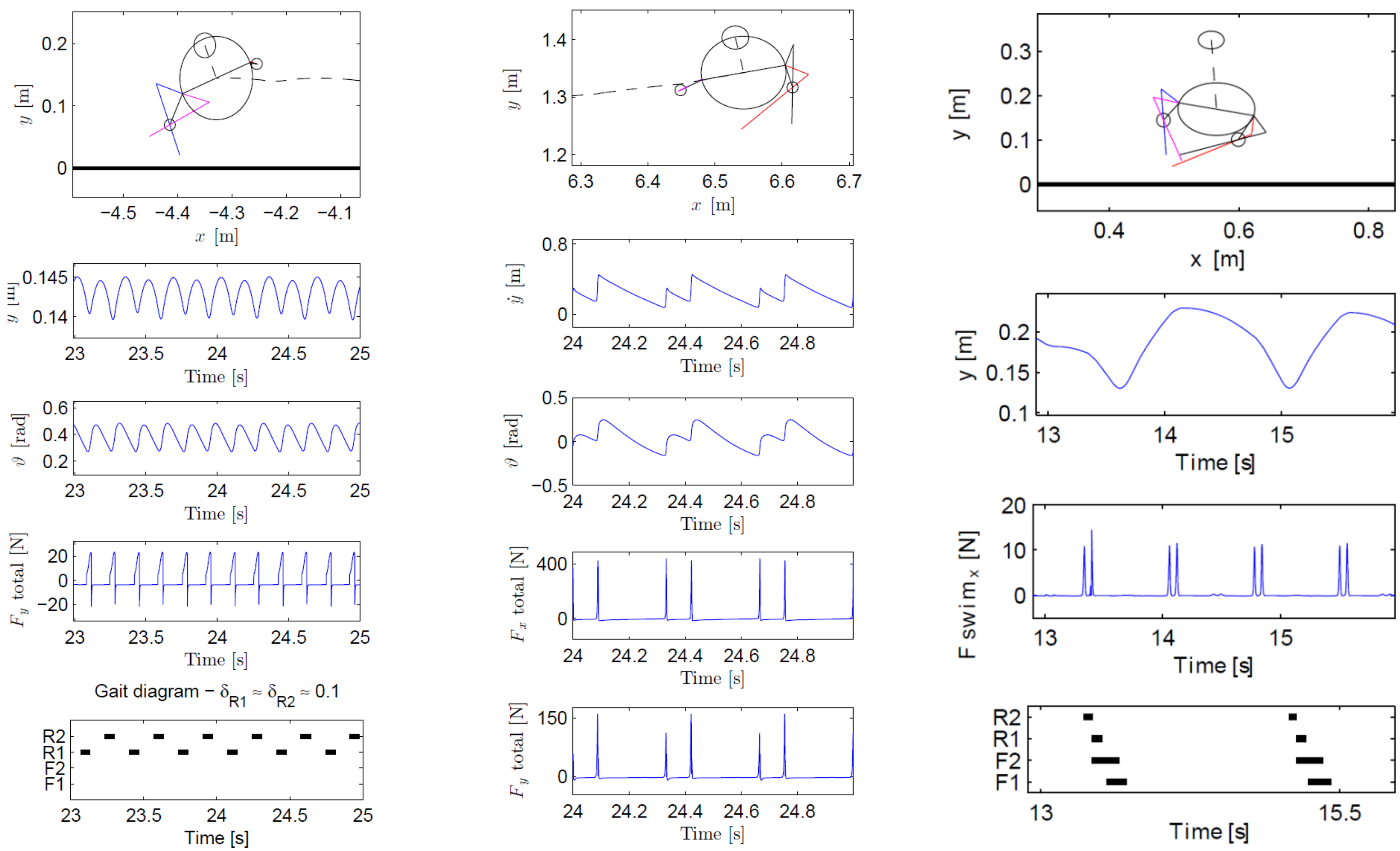
<u>Corucci, F.</u>, Calisti, M., Hauser, H., & Laschi, C. (2015, July). Evolutionary discovery of self-stabilized dynamic gaits for a soft underwater legged robot. In *Advanced Robotics (ICAR), 2015 International Conference on* (pp. 337-344). IEEE.

Exploring the design space of a bioinspired robot

Results – Embodiment:

An in-depth analysis of evolved morphologies and behaviors revealed that <u>artificial evolution was able to systematically discover and exploit *embodiment*</u>

A carefully tuned dynamic interplay between morphology, control, environment was often observed



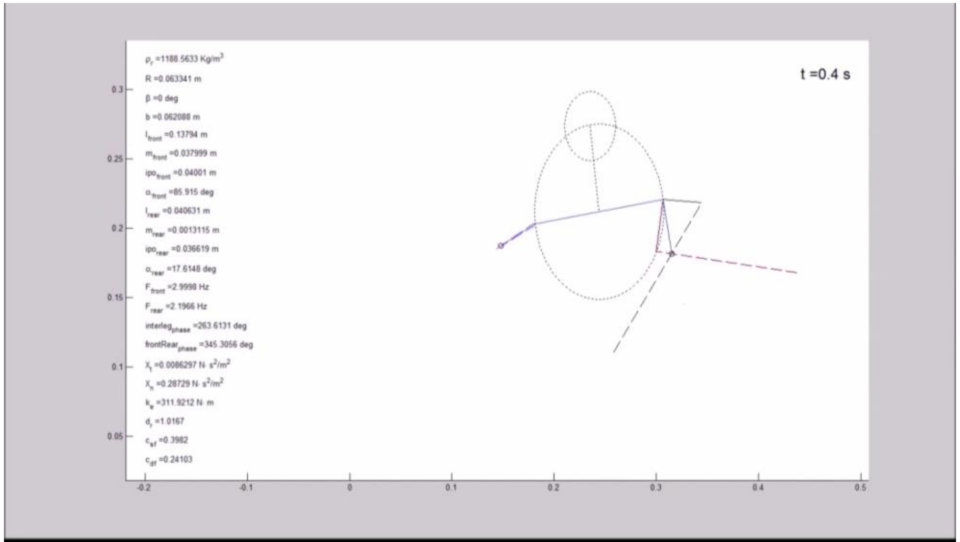
Exploring the design space of a bioinspired robot

Results – Design indications:

- Basic robot morphology was designed to crawl on the sea bed, but…
- … Artificial Evolution suggested a different locomotion modality that turned out to be much more effective (fast strokes → sculling-based swimming)
- It did so by reinterpreting (*exapting*) a human-devised leg mechanism originally conceived for crawling to a new purpose

→ **Evolutionary creativity**

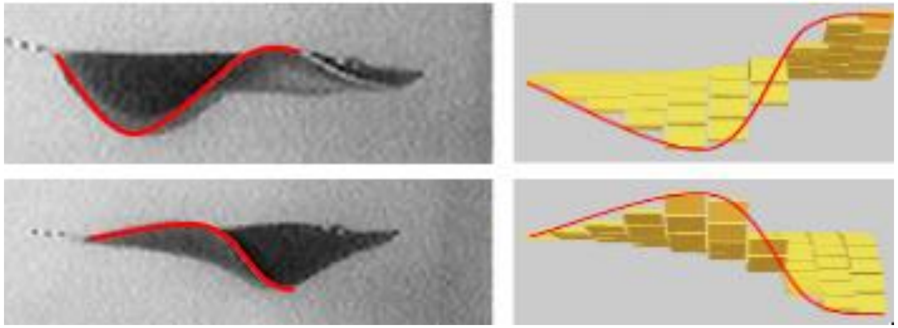
- Evolved designs exhibited several other symmetries and regularities which informed human designers



Fast sculling-based swimmer

STUDYING ANIMALS

Evolution and adaptation of a batoid-inspired wing in different fluids



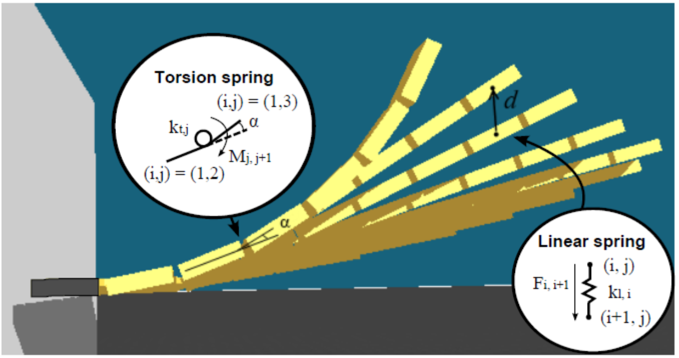
Evolution and adaptation of a soft fin

Goal:

- Study the <u>embodied intelligence of fishes</u> such as the manta ray, as a <u>paradigm for underwater soft robotics</u>
- Study the <u>relevant factors for the adaptation of a manta-inspired fin to different fluids</u>

Approach:

- Developing a <u>simplified simulated model</u>
- <u>Co-evolving morphology and control</u> in different fluids
- **<u>Fitness:</u>** fluid dynamics metric associated with swimming efficiency

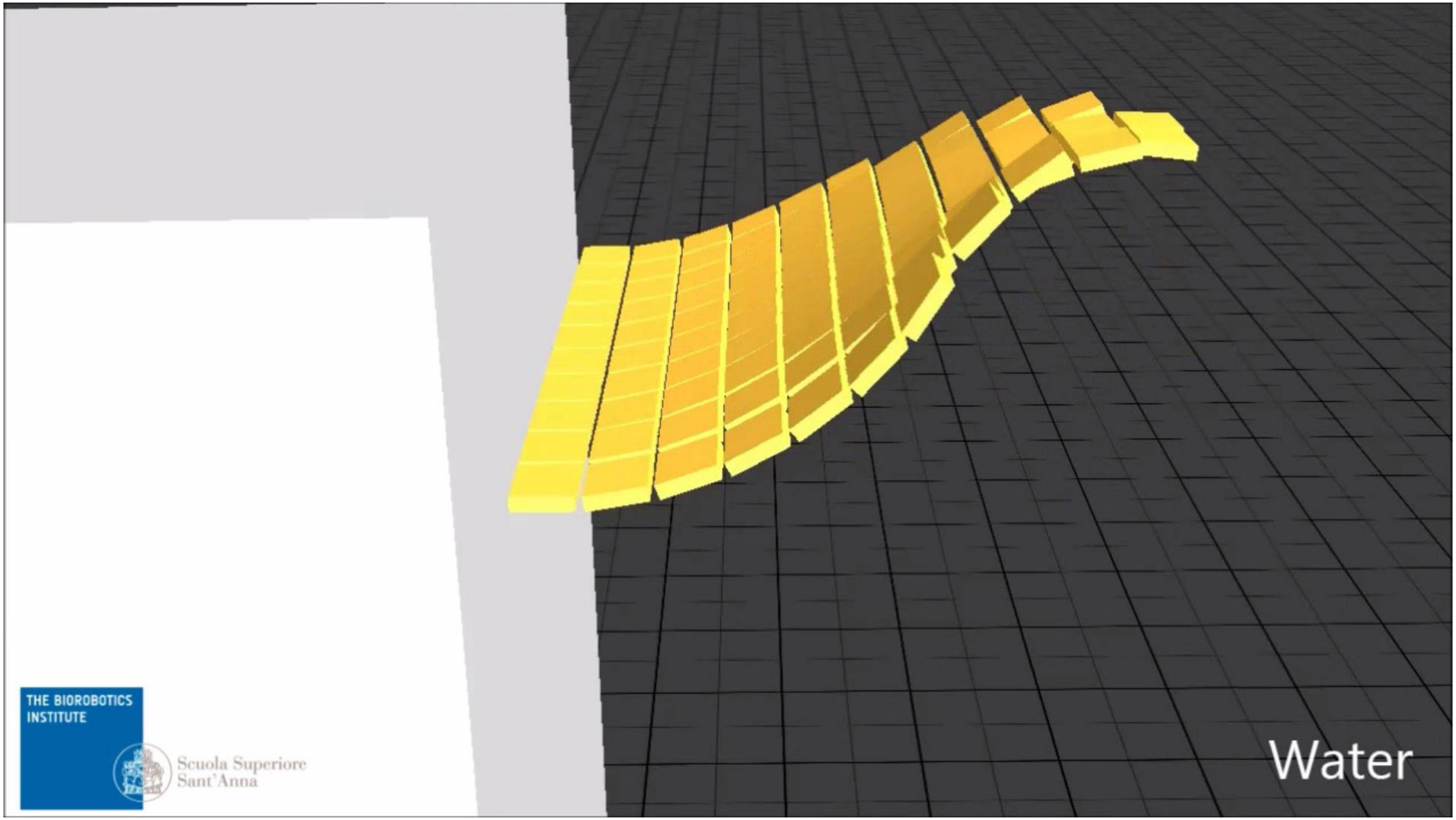


Cacucciolo, V.*, <u>Corucci, F.</u>*, Cianchetti, M., & Laschi, C. (2014, July). Evolving optimal swimming in different fluids: a study inspired by batoid fishes. In *Conference on Biomimetic and Biohybrid Systems* (pp. 23-34). Springer International Publishing. (*<u>equal contribution</u>)

Evolution and adaptation of a soft fin

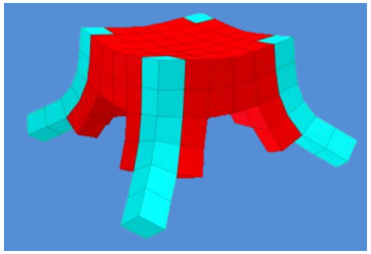
The ShanghAI Lectures 人工智能 上海授课 2014

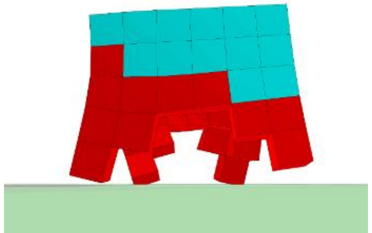
Cyberbotics ***Webots*** *simulator*

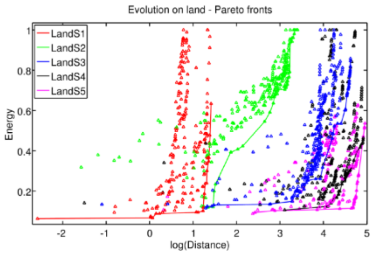


Cacucciolo, V.*, Corucci, F.*, Cianchetti, M., & Laschi, C. (2014, July). Evolving optimal swimming in different fluids: a study inspired by batoid fishes. In *Conference on Biomimetic and Biohybrid Systems* (pp. 23-34). Springer International Publishing. (*equal contribution)

STUDYING THE EVOLUTION OF SOFT LOCOMOTION







Evolving soft robots in aquatic and terrestrial environments

Goals:

- Investigate the free-form evolution of soft locomotion in both aquatic and terrestrial environments

- Investigate the effects of different material properties on:
  - Evolved morphologies and behaviors
  - Energy-performance trade-offs

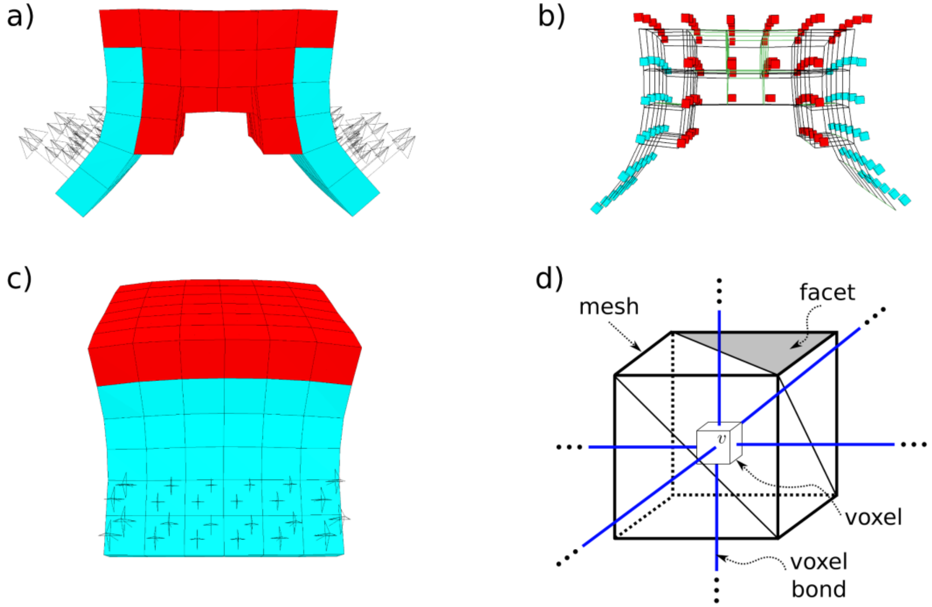
- Investigate the effects of environmental transitions water ↔ land:
  - Benefits of evolving swimming for walking?
  - Benefits of evolving walking for swimming?

- Corucci, F., Cheney, N., Giorgio-Serchi, F., Bongard, J., & Laschi, C. (2017). Evolving soft robots in aquatic and terrestrial environments: effects of material properties and environmental transitions (under review, arXiv preprint arXiv:1711.06605. ISO 690, 2017)
- Corucci, F., Cheney, N., Lipson, H., Laschi, C., & Bongard, J. (2016). Evolving swimming soft-bodied creatures. In ALIFE XV, The Fifteenth International Conference on the Synthesis and Simulation of Living Systems, Late Breaking Proceedings (p. 6-7).

Evolving soft robots in aquatic and terrestrial environments

Setup:

- Powerful soft robot simulator (VoxCAD, Hiller et al. 2014)
- Multi-objective evolutionary algorithm
- Powerful developmental encoding (*Compositional Pattern Producing Networks, CPPNs*) (Stanley, 2007)



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Evolving soft robots in aquatic and terrestrial environments

Optimization: (multi-objective)

- Maximize traveled distance
- Minimize actuated tissue
- Minimize employed material

Experiments:

- Evolution on Land for five different material stiffnesses (S1 – softest, …, S5 – stiffest)
- Evolution in Water (S1, …, S5)
- Land → Water (switching halfway during evolution, stiffness S3)
- Water → Land (switching halfway during evolution, stiffness S3)

- Corucci, F., Cheney, N., Giorgio-Serchi, F., Bongard, J., & Laschi, C. (2017). Evolving soft robots in aquatic and terrestrial environments: effects of material properties and environmental transitions (under review, arXiv preprint arXiv:1711.06605. ISO 690, 2017)
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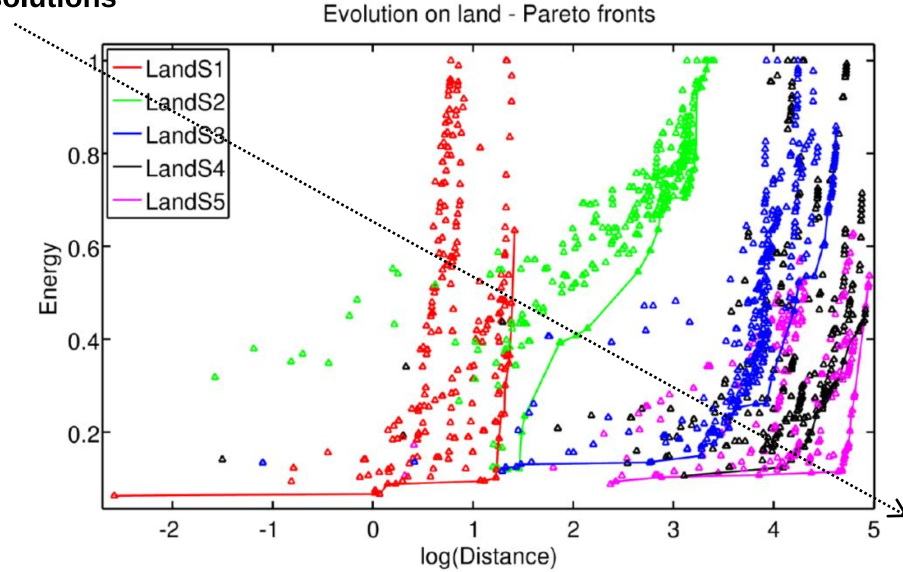
Evolving soft robots in aquatic and terrestrial environments

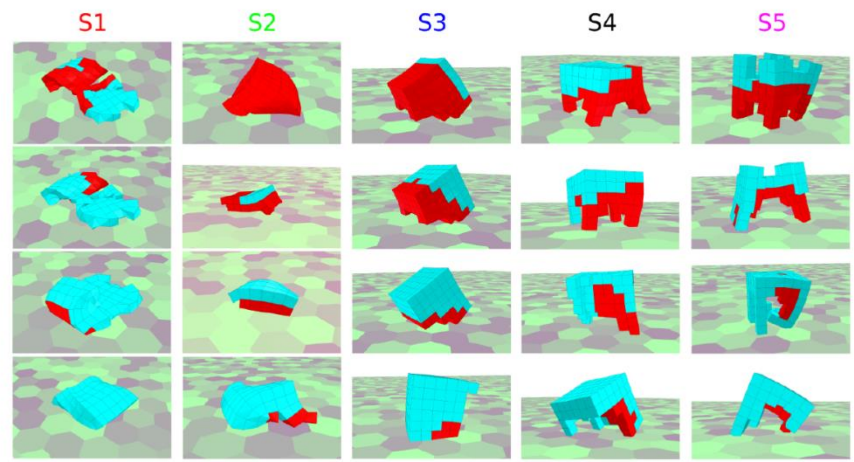
Better solutions



Evolution on land – Results:

- Terrestrial locomotion cannot evolve if the provided material is too soft (S1)
- Stiffer robots (S2 → … → S5):
  - → Better performances and lower energy consumption
  - → Increase in morphological and behavioral complexity
    - → Simpler robots, inching, crawling
    - → More complex morphologies and coordinated gaits

Pareto fronts sampling (rows order: decreasing energy usage):



Morphological and behavioral complexity increase

- Corucci, F., Cheney, N., Giorgio-Serchi, F., Bongard, J., & Laschi, C. (2017). Evolving soft robots in aquatic and terrestrial environments: effects of material properties and environmental transitions, (under review, arXiv preprint arXiv:1711.06605. ISO 690, 2017)
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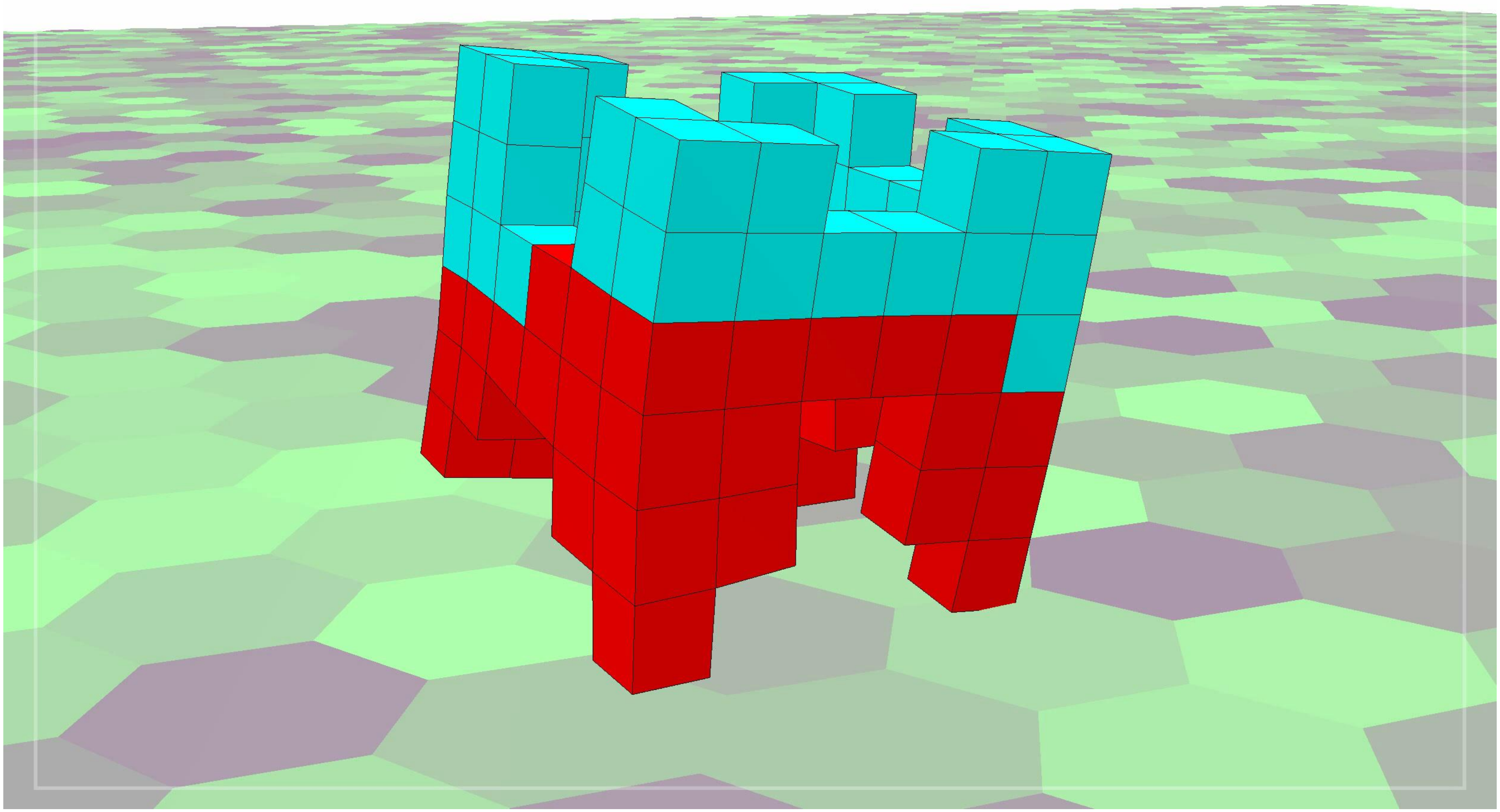
Evolving soft robots in aquatic and terrestrial environments

→ Both morphology and control are evolved from scratch
→ Stiffness is beneficial on land

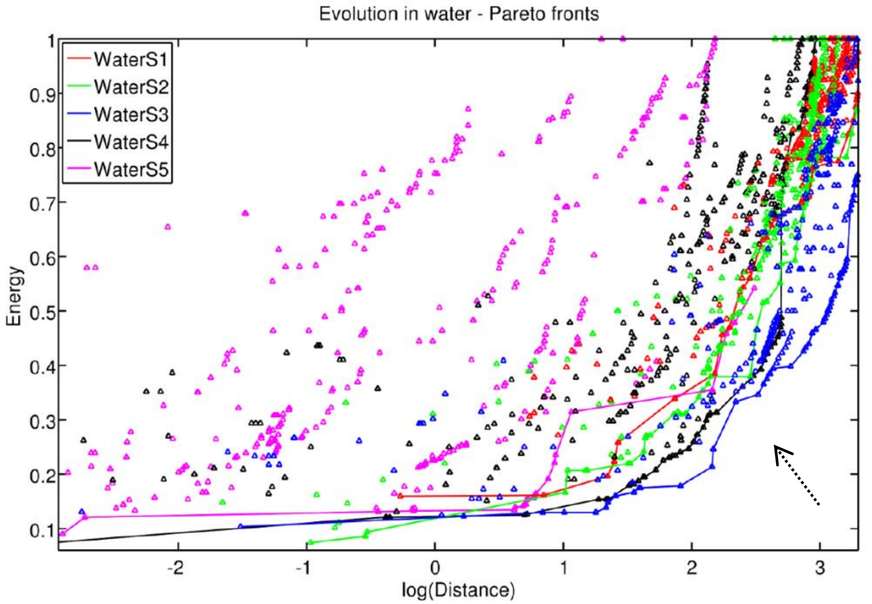


Evolving soft robots in aquatic and terrestrial environments

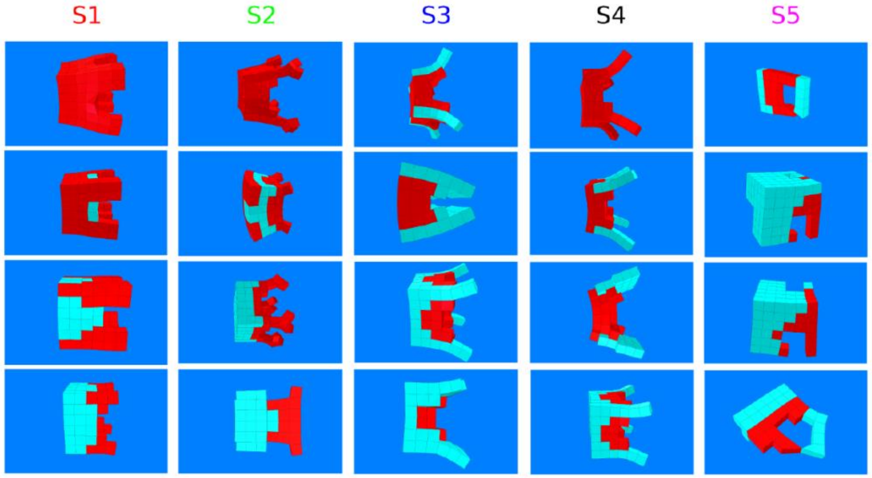
Evolution in water – Results:

- More complex energy-performance tradeoffs
- <u>Best energy-performance tradeoffs</u> are achieved for an <u>intermediate stiffness value (S3)</u>

→ <u>In water softness appears to be more useful</u>



<u>Pareto fronts sampling</u> (rows order: decreasing energy usage):



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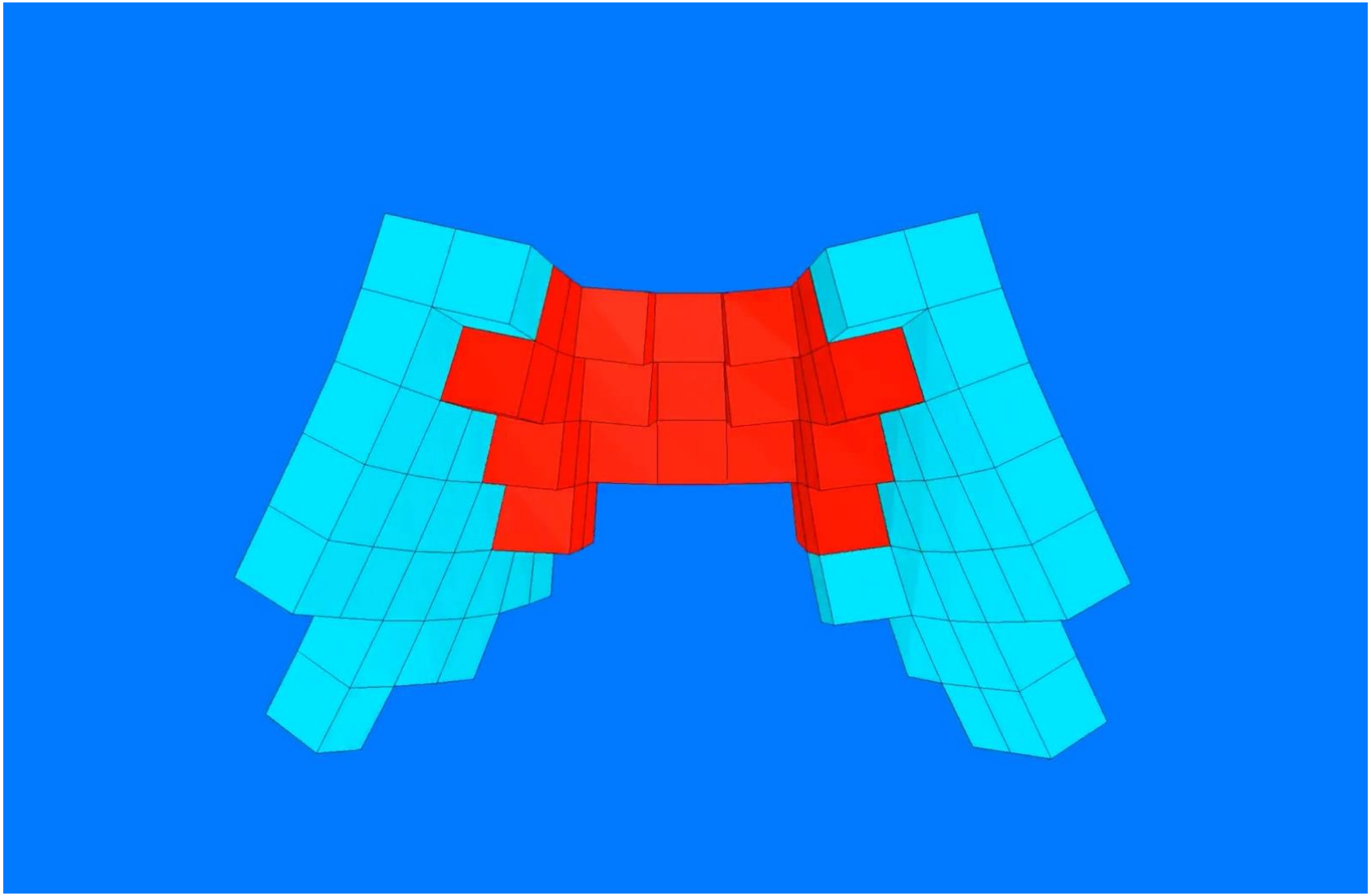
Evolving soft robots in aquatic and terrestrial environments



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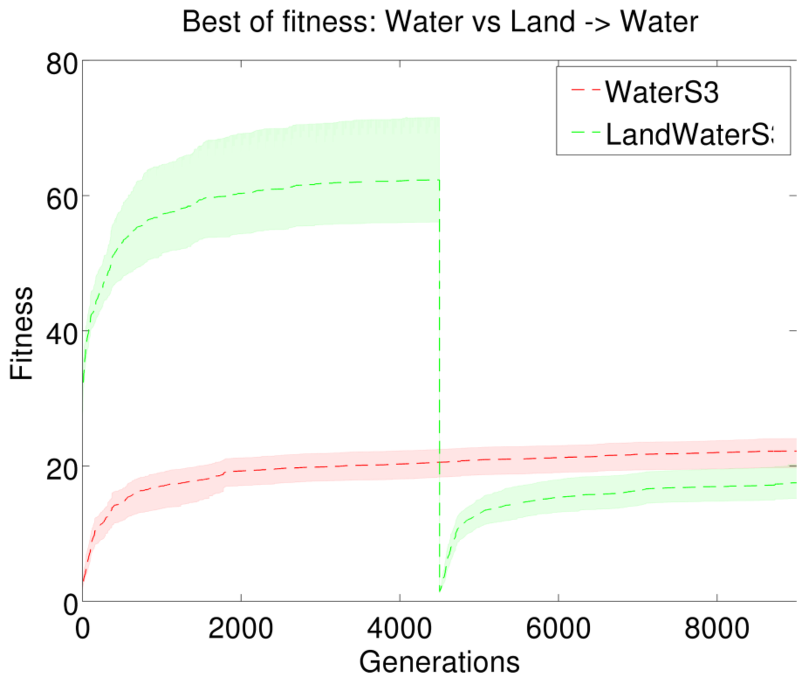
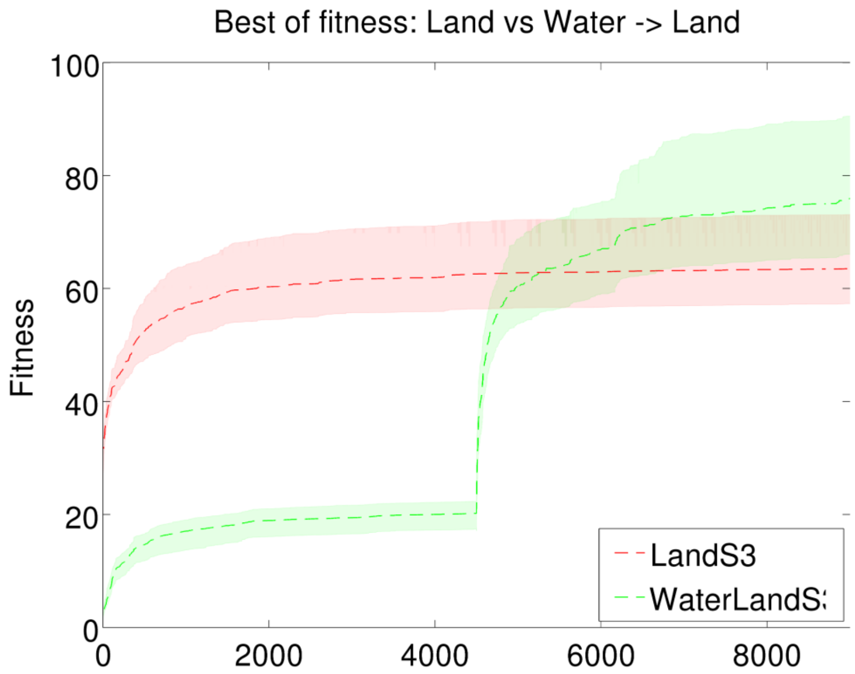
Evolving soft robots in aquatic and terrestrial environments

<u>Transition experiments - Results:</u> an <u>asymmetry</u> is observed

Evolving terrestrial locomotion <u>first does not help</u> to later evolve swimming



Evolving aquatic locomotion first <u>seems to help</u> later evolving walking



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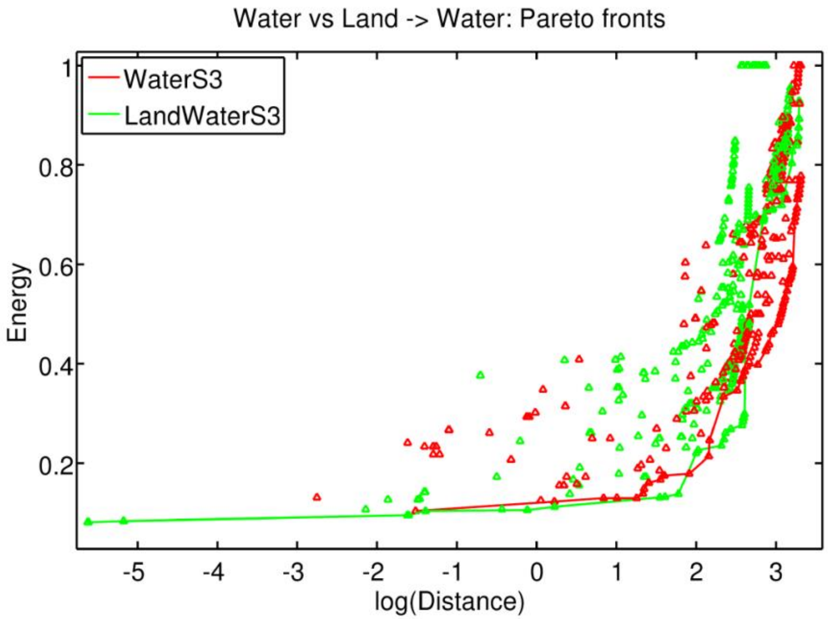
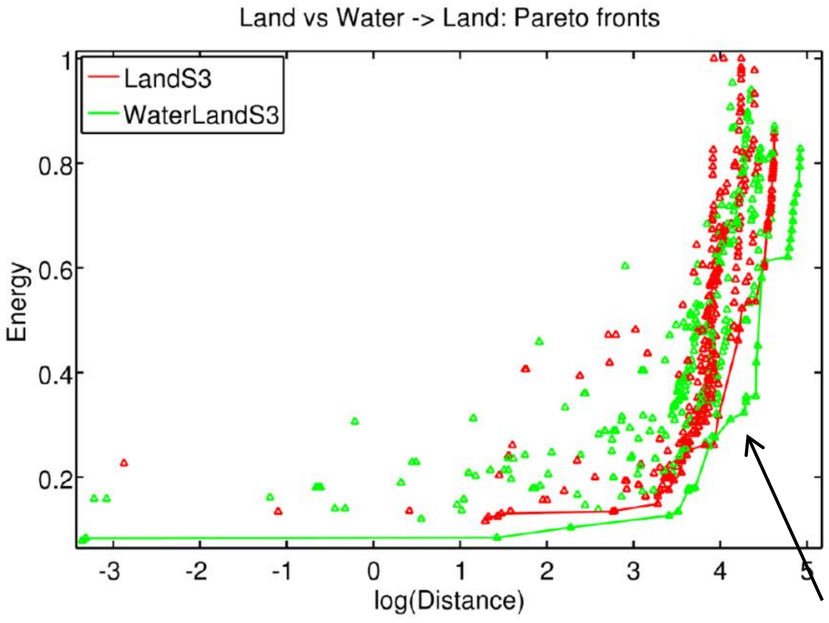
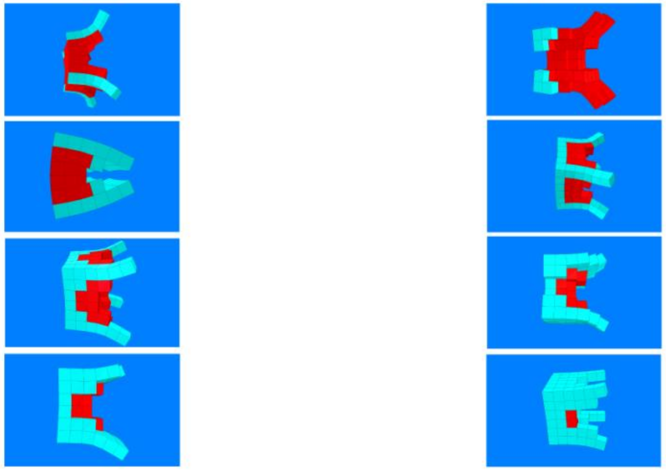
Evolving soft robots in aquatic and terrestrial environments





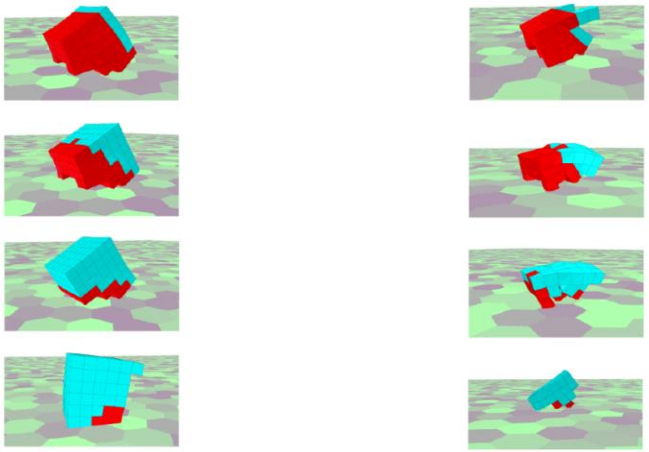
Pareto fronts sampling (rows order: decreasing energy usage):

Water | Land->Water

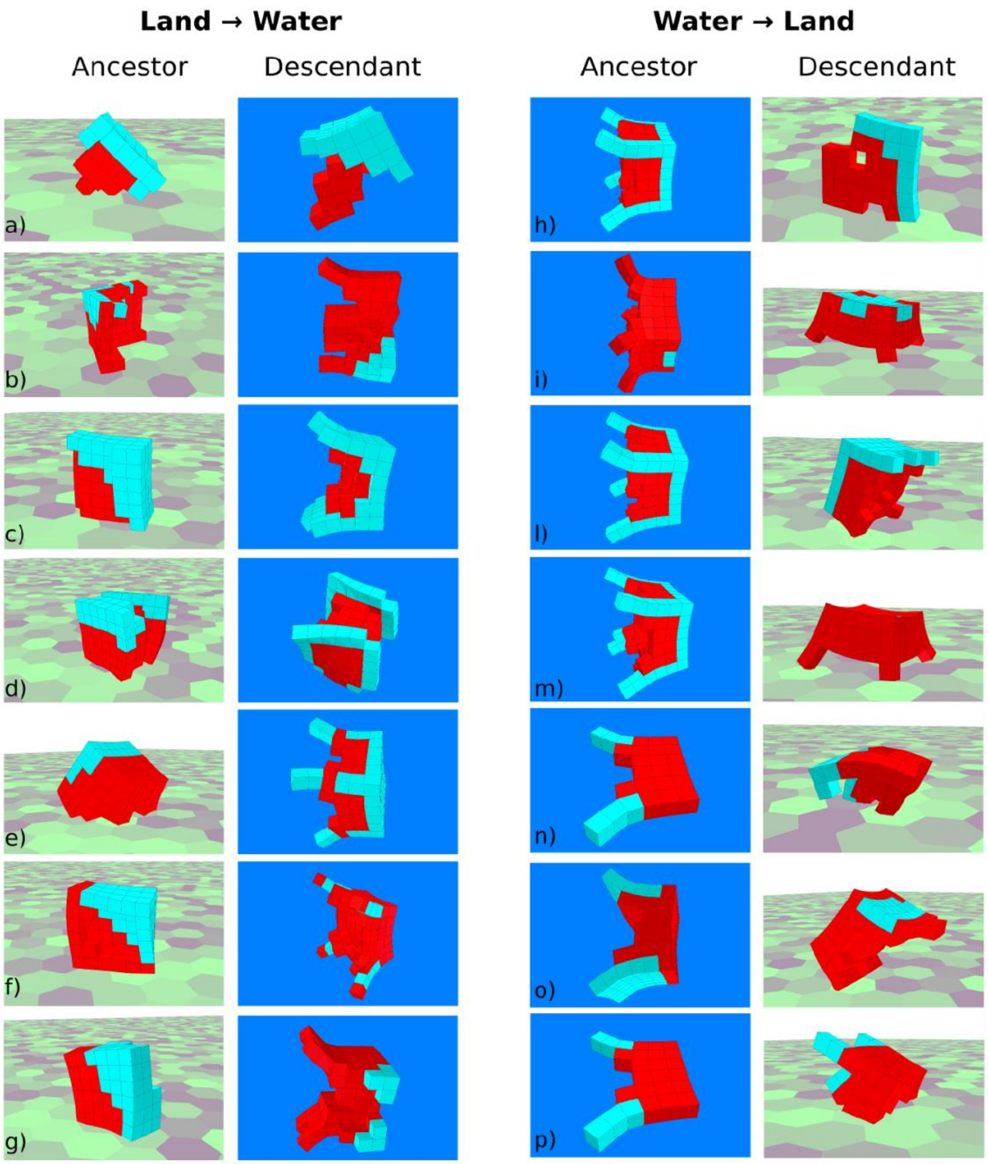


Pareto fronts sampling (rows order: decreasing energy usage):

Land | Water->Land



Evolving soft robots in aquatic and terrestrial environments



Various examples of spontaneous <u>exaptation</u> could be observed, e.g.:

Land → Water

- Robots develop flapping appendages for swimming

Water → Land

- Flapping appendages are shortened and become legs, arms

- <u>Corucci, F.</u>, Cheney, N., Giorgio-Serchi, F., Bongard, J., & Laschi, C. (2017). Evolving soft robots in aquatic and terrestrial environments: effects of material properties and environmental transitions (under review, arXiv preprint arXiv:1711.06605. ISO 690, 2017)
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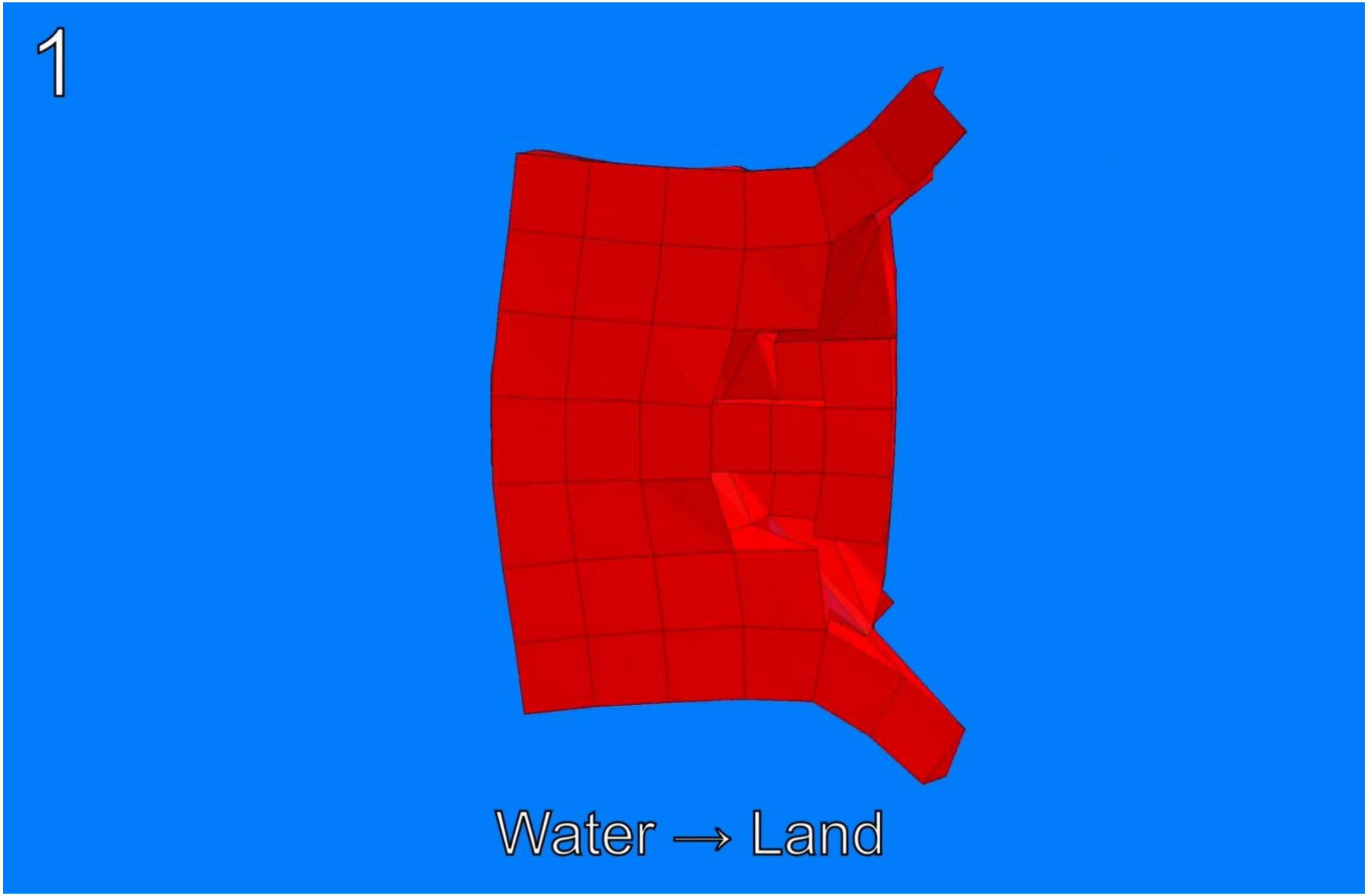
Evolving soft robots in aquatic and terrestrial environments



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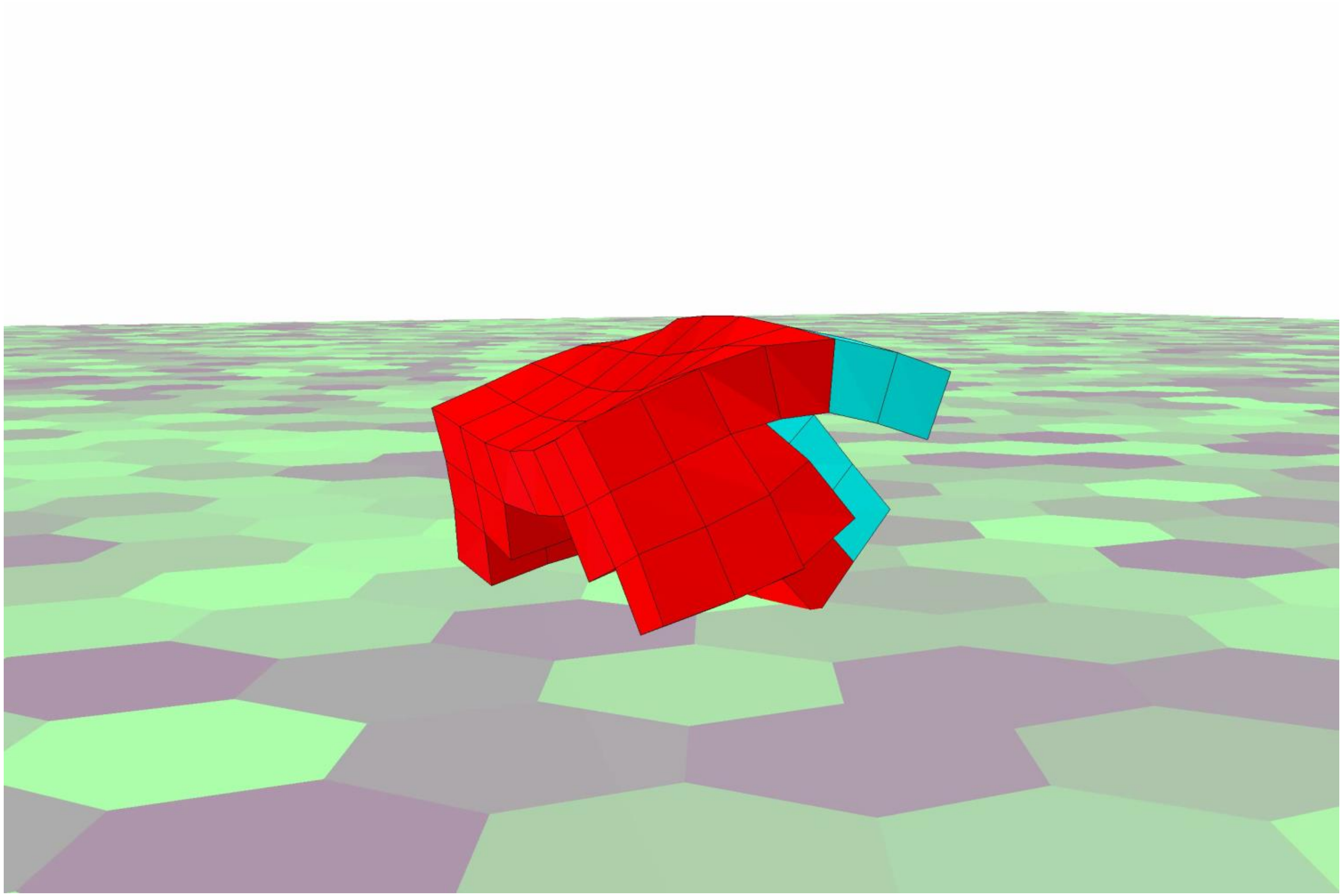
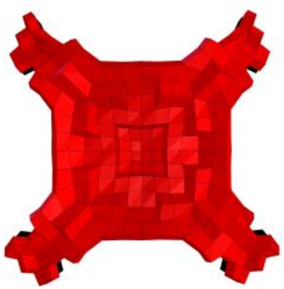
Evolving soft robots in aquatic and terrestrial environments

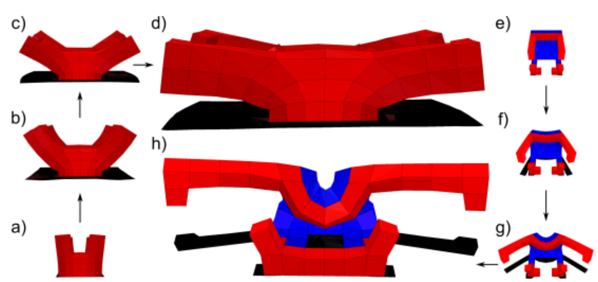
(Slow-motion)

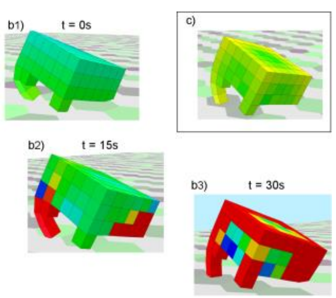


The <u>fastest terrestrial runner</u> was evolved in Water→Land experiments:
it shows <u>traces of ancestral tentacles once used to swim</u>, now used to balance

STUDYING THE EVOLUTION OF DEVELOPMENT AND MORPHOLOGICAL COMPUTATION





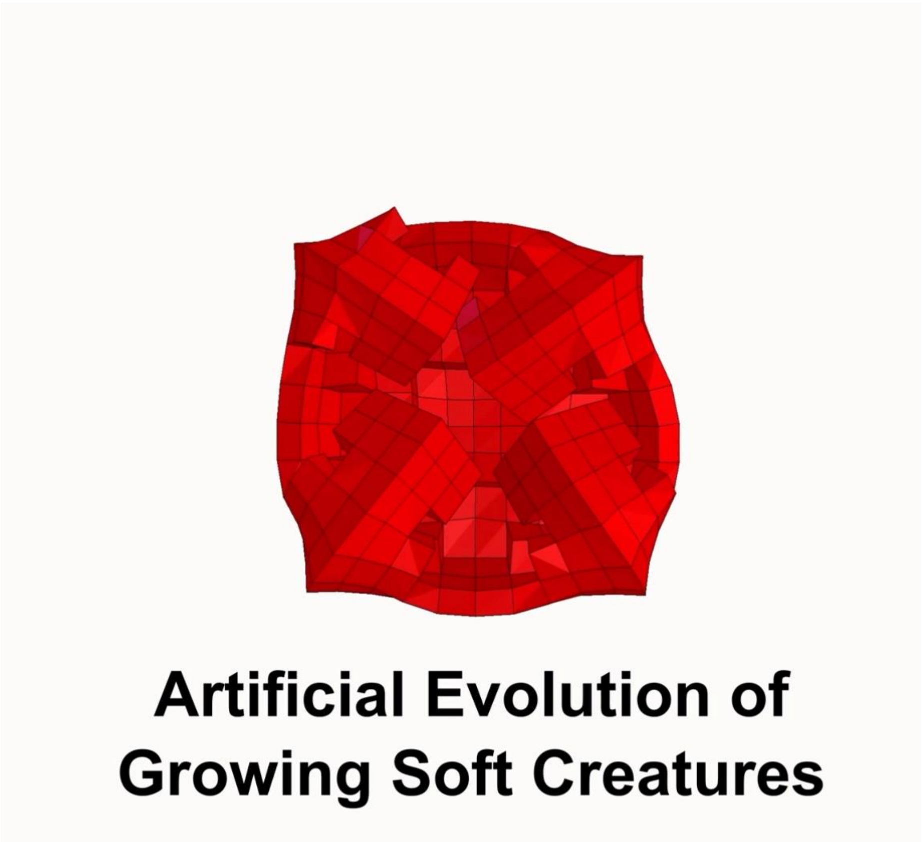


Morphological development

- Pervasive in Nature
- Soft robots have a <u>largely unexplored potential in this respect</u>

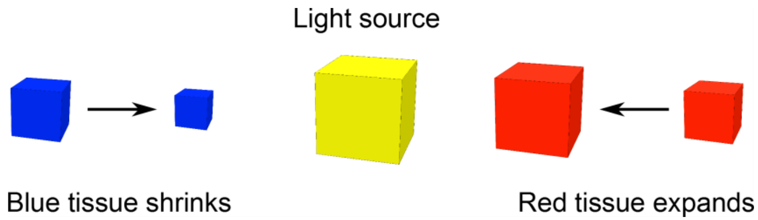
→ <u>Simulation studies can help understanding these new abilities</u>

Evolving morphological development in robots



Setup:

- Phototropism, growing towards light sources
- Time-dependent environment-mediated development: volumetric change in response to light (grow/shrink)

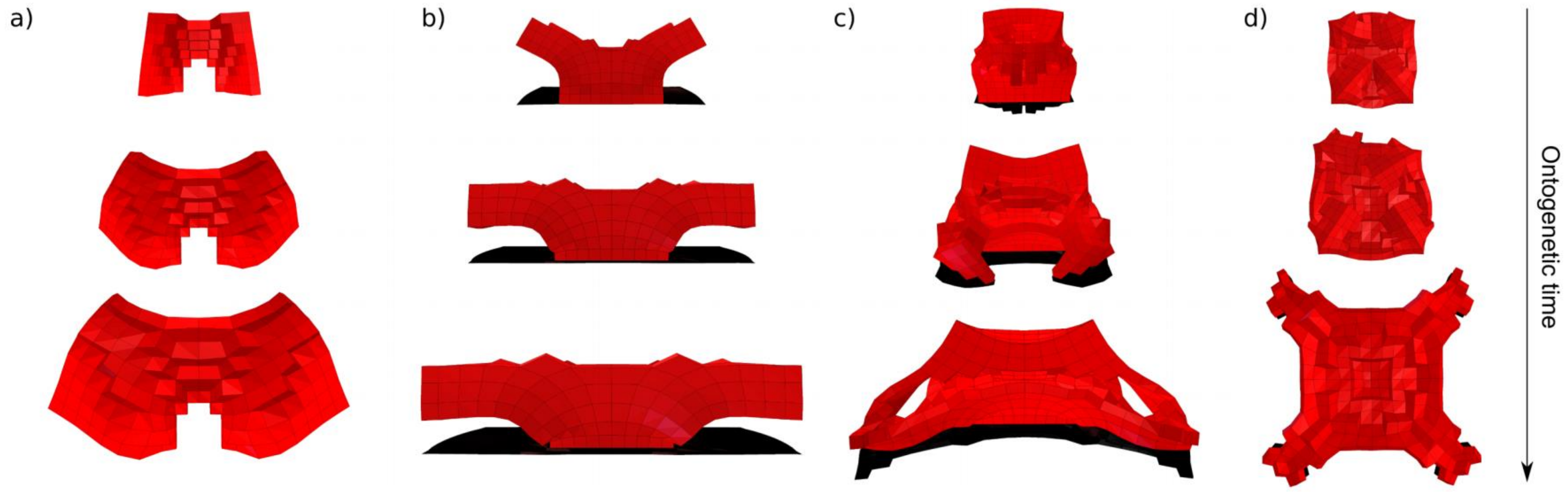


Evolution optimizes:

- Morphology and developmental parameters (grow/shrink, rate…)

Corucci, F., Cheney, N., Lipson, H., Laschi, C., & Bongard, J. (2016). Material properties affect evolution's ability to exploit morphological computation in growing soft-bodied creatures. In *ALIFE XV, The Fifteenth International Conference on the Synthesis and Simulation of Living Systems* (pp. 234-241).

Evolved growing soft robots



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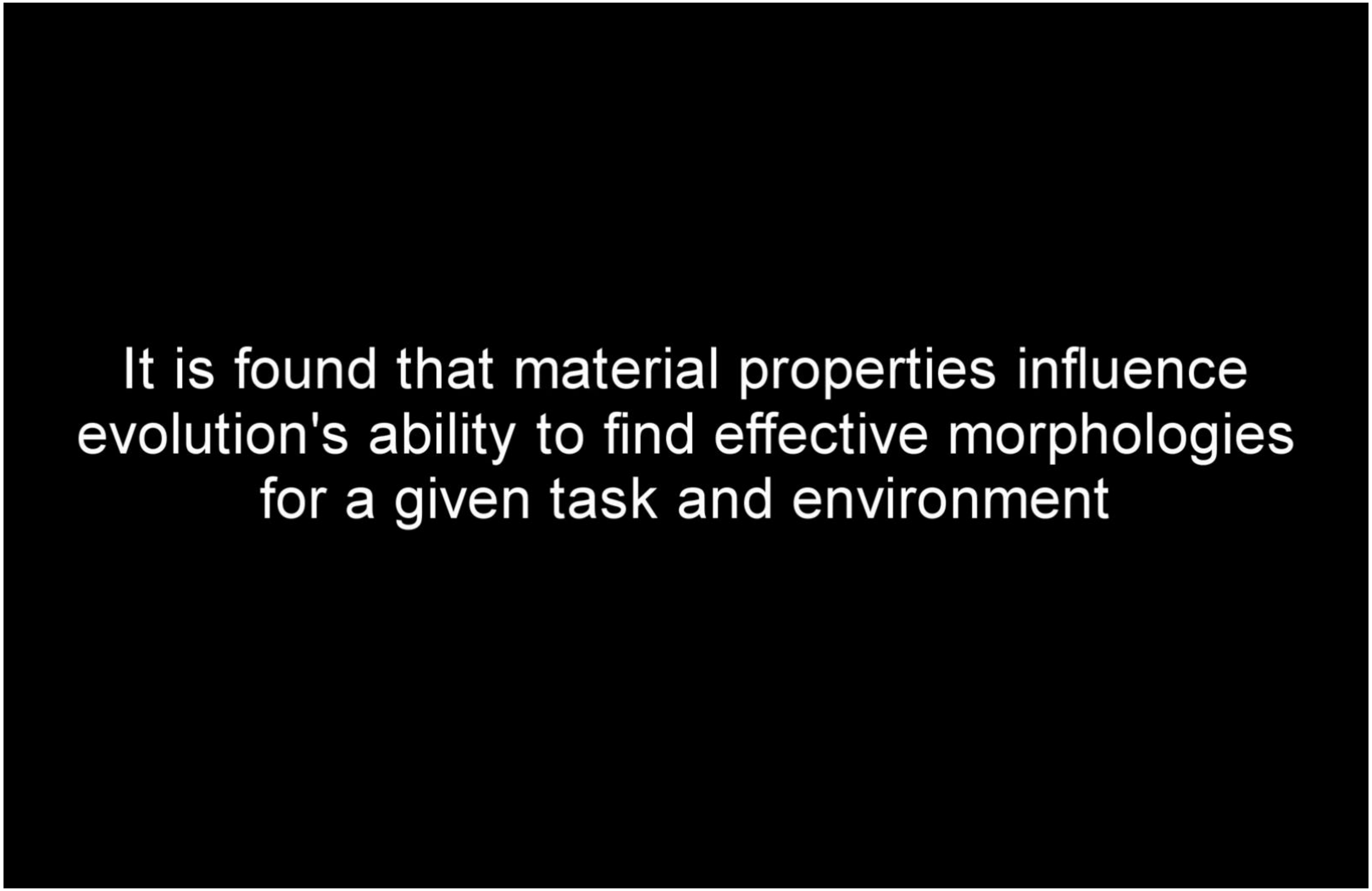
Evolving morphological computation

Under which conditions does morphological computation evolve in these growing soft-bodied creatures?

Evolving morphological computation



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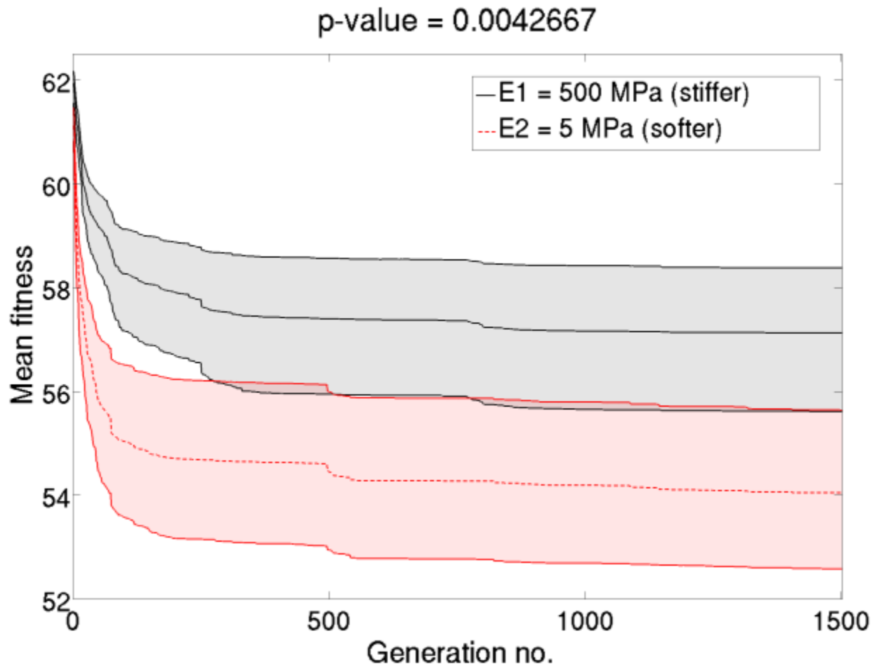
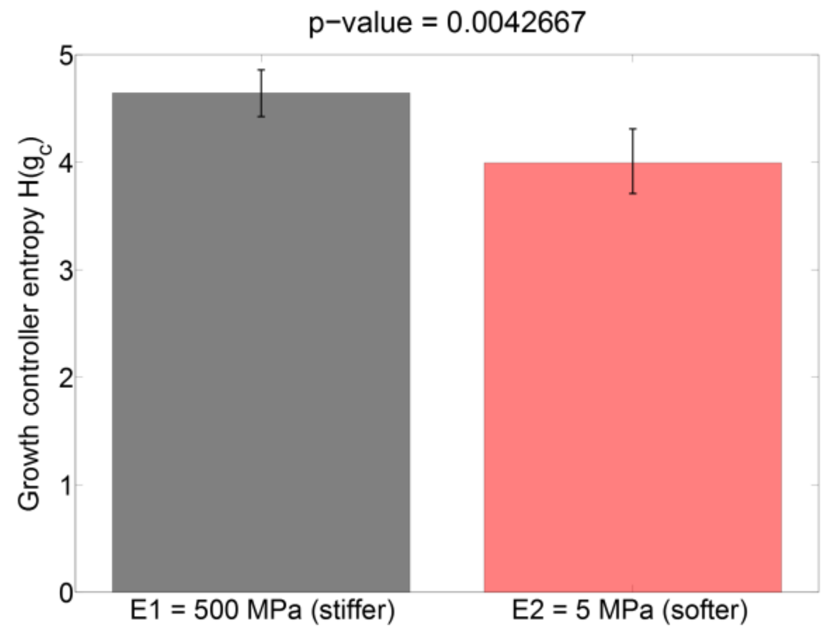
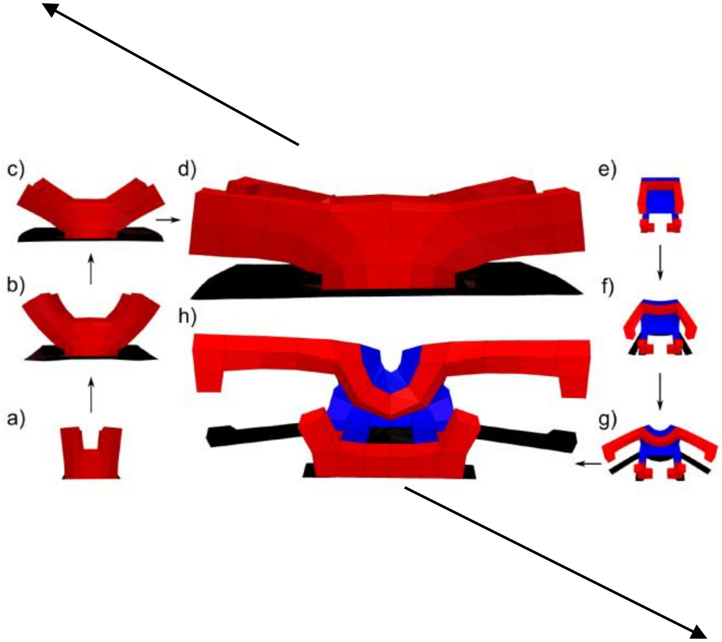
Evolving morphological computation





- → In this task, softer robots **perform better** despite using **simpler growth** controllers **→ Morphological computation**
- → **When morphological computation cannot be evolved** (stiff robots), evolution tries to automatically compensate for it by **«complexifying» the control**

Evolving morphological computation



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Evolving adaptation laws for soft robots

When, how, and in response to which stimuli should a soft-bodied creature adapt?

Can evolving morphological development result in increased adaptivity and robustness?

Corucci, F., Cheney, N., Kriegman, S., Laschi, C., Bongard, J., (2017). Evolutionary developmental soft robotics as a framework to study intelligence and adaptive behavior in animals and plants, Frontiers in Robotics and AI

Evolving adaptation laws for soft robots

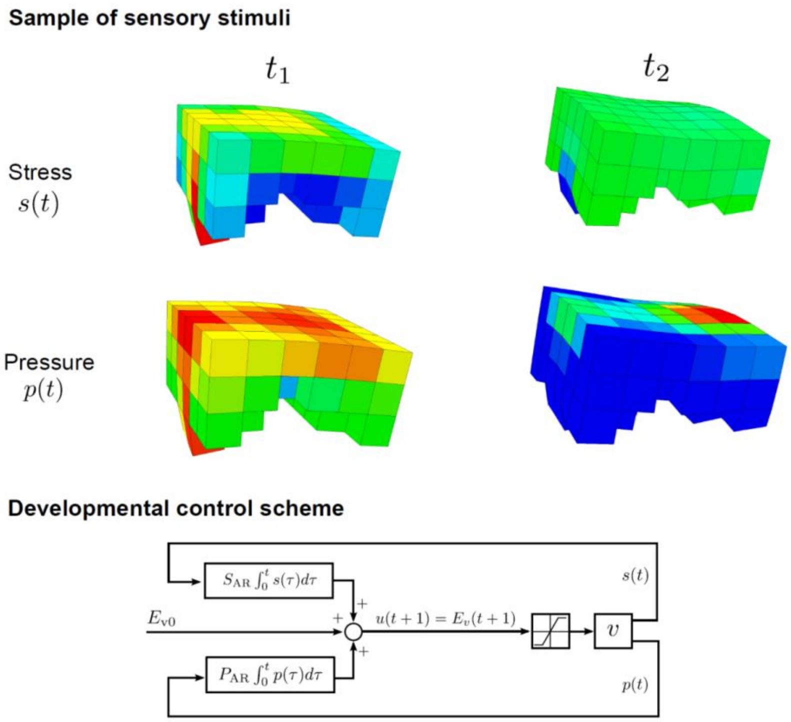
Task:

- Locomotion

Artificial Evolution dictates:

- The initial stiffness of each voxel
- Whether a voxel should soften or stiffen in response to mechanical stimulation

  → Biological inspiration: Wolff's law of bones remodeling
- The sensory stimuli driving the adaptive change (internal stress/pressure)



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Evolving adaptation laws for soft robots

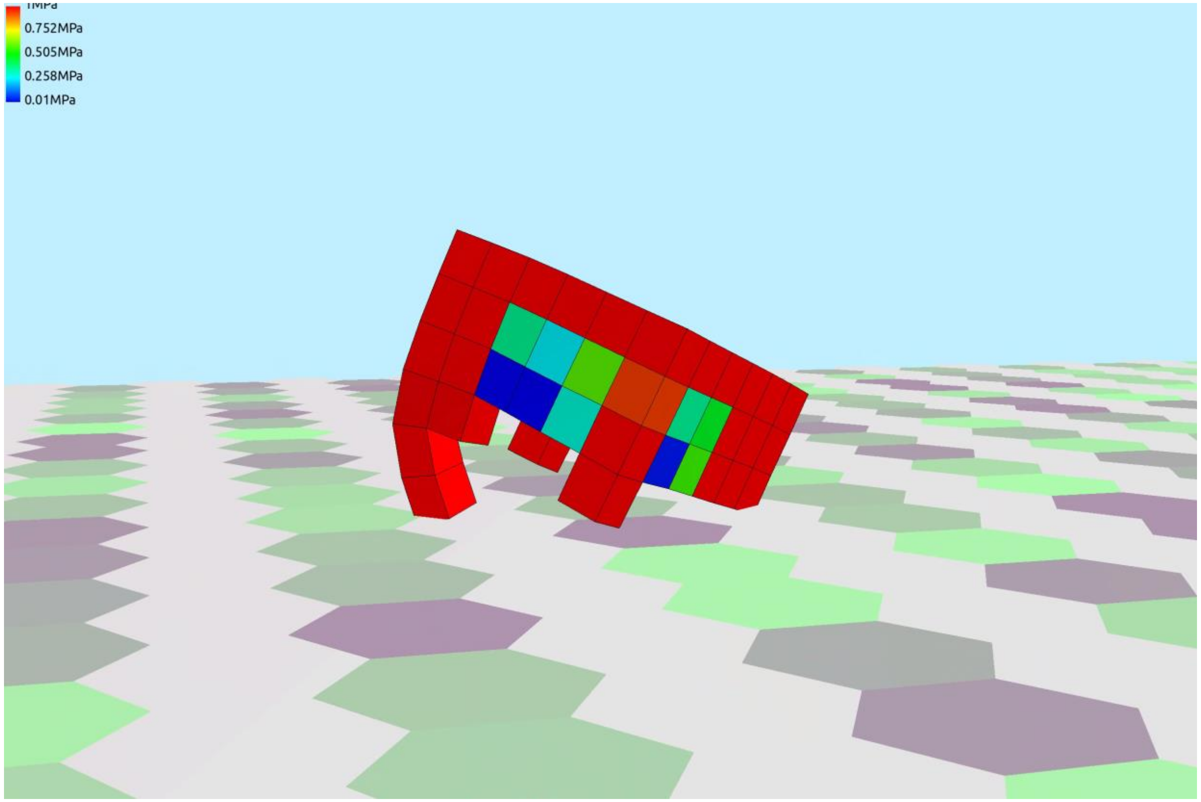
Best robot:

- Has evolved to stiffen in response to repeated mechanical stimulation (pressure is selected)
- Will now be exposed to a new environment (gravity x2) → Performances will drop, but…

  → Environmental change → Different sensory stimulation → Different adaptation

Color codes current stiffness:

Red: stiffer
Blue: softer



→ **A stiff skeleton (red) grows all around the robot in order to better withstand the increased load**

→ **This allows the robot to retains ~40% of its original fitness**

Corucci, F., Cheney, N., Kriegman, S., Laschi, C., Bongard, J., (2017). Evolutionary developmental soft robotics as a framework to study intelligence and adaptive behavior in animals and plants, Frontiers in Robotics and AI

Evolving adaptation laws for soft robots

→ **The evolved adaptive law appears to be <u>general</u>**

→ **Resulted in <u>increased adaptivity and robustness</u>**

Corucci, F., Cheney, N., Kriegman, S., Laschi, C., Bongard, J., (2017). Evolutionary developmental soft robotics as a framework to study intelligence and adaptive behavior in animals and plants, Frontiers in Robotics and AI

Conclusions

Artificial evolutionary and developmental approaches:

- Can solve complex engineering problems
- Can represent a general and comprehensive framework to automatically design adaptive robots for arbitrary tasks and environments
  - → With progresses in soft fabrication and 3D printing, a fully automated design-fabrication-deployment pipeline will soon become possible
- Can inform soft robotics, and help unleashing its full potential, especially in terms of adaptivity
- Can help understanding the conditions under which adaptive and intelligent behavior emerges in biological and artificial systems

Conclusions

- **EVOLUTIONARY CREATIVITY:** Artificial Evolution «thinks» outside the box, can suggest effective and counterintuitive solutions
- **EMBODIMENT**: Artificial Evolution can systematically produce embodiment and morphological computation
- **IMPORTANCE OF THE BODY:** Material properties dramatically affect the emergence of different morphologies and behaviors, as well as that of morphological computation
- **EVO-DEVO:** Artificial Evolution is able to discover general adaptation laws for soft robots that can result in increased robustness and adaptivity

References

- F. Corucci, N. Cheney, S. Kriegman, J. Bongard, C. Laschi, "*Evolutionary developmental soft robotics as a framework to study intelligence and adaptive behavior in animals and plants*", Frontiers in Robotics and AI
- F. Corucci, "*Evolutionary Developmental Soft Robotics: towards adaptive and intelligent soft machines following nature's approach to design*", In Soft Robotics: Trends, Applications and Challenges, Springer, 2017, 111-116
- F. Corucci, N. Cheney, H. Lipson, C. Laschi, and J. Bongard, "*Material properties affect evolution's ability to exploit morphological computation in growing soft-bodied creatures*", In: Proceedings of ALIFE XV, The Fifteenth International Conference on the Synthesis and Simulation of Living Systems, 2016
- S. Kriegman, N. Cheney, F. Corucci, J. Bongard, "*A Minimal Developmental Model Can Increase Evolvability in Soft Robots*", In: Proceedings of the Genetic and Evolutionary Computation Conference (GECCO), 2017
- F. Corucci, N. Cheney, F. Giorgio-Serchi, J. Bongard, C. Laschi, "*Evolving soft locomotion in aquatic and terrestrial environments: effects of material properties and environmental transitions*", (under review, arXiv preprint arXiv:1711.06605. ISO 690)
- F. Corucci, M. Calisti, H. Hauser, C. Laschi, "*Novelty-based evolutionary design of morphing underwater robots*", In: Proceedings of the Genetic and Evolutionary Computation Conference (GECCO), 2015
- F. Corucci, M. Calisti, H. Hauser, C. Laschi, "*Evolutionary discovery of self-stabilized dynamic gaits for a soft underwater legged robot*", In: Proceedings of the 17th IEEE International Conference on Advanced Robotics (ICAR2015), 2015
- V. Cacucciolo*, F. Corucci*, M. Cianchetti, C. Laschi, "*Evolving optimal swimming in different fluids: a study inspired by batoid fishes*", In: Biomimetic and Biohybrid Systems - Living Machines 2014, Springer Lectures Notes in Articial Intelligence, 2014 (* equal contribution)
- F. Giorgio-Serchi, A. Arienti, F. Corucci, M. Giorelli, C. Laschi, "*Hybrid parameter identication of a multi-modal underwater soft robot*", Bioinspiration & Biomimetics 12.2 (2017): 025007.