Body symmetry – studies in the Framsticks simulator

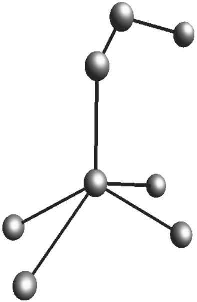
Wojciech Jaskowski Maciej Komosinski

www.framsticks.com

Details of this research are available in [JK06; JK08].

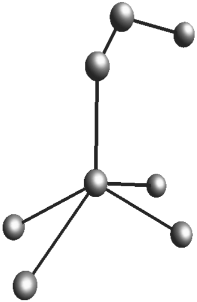
Model components

- Body
  - Parts (3D location & orientation)
  - Joints
- Brain
  - Neurons (embodied or not)
  - Connections



Model components

- Body
  - Parts (3D location & orientation)
  - Joints
- Brain
  - Neurons (embodied or not)
  - Connections



Properties

Physical and biological: lengths, sizes, masses, etc.

Model constraints

- at most one Joint can directly connect two Parts
- each Joint must be connected with two distinct Parts
- all Parts must be directly or indirectly connected with each other

Native simulation engine – *MechaStick*

- physics-based: create real-world feeling to intuitively understand behaviors
- not necessarily very accurate but fast – performance matters demo
- Parts: atomic physical objects
- Joints: description of internal forces and constraints, visualized as sticks

Native simulation engine – *MechaStick*

- physics-based: create real-world feeling to intuitively understand behaviors
- not necessarily very accurate but fast – performance matters demo
- Parts: atomic physical objects
- Joints: description of internal forces and constraints, visualized as sticks

—

- rigid bodies: no
- volume bodies: no
- collision detection within creatures: no

Symmetry

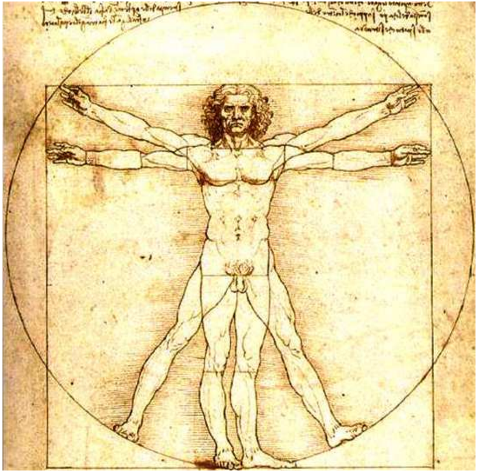


Figure: Vitruvian Man

Symmetry. What's that?

Definition

Symmetry is an intrinsic property of a mathematical object which causes it to remain *invariant* under certain classes of transformations (such as rotation, reflection, inversion, or more abstract operations).

Symmetry in various disciplines

Figure: The Taj Mahal, Agra, India, 1648 r.

- Physics
- Math
- Music
- Poetry
- Architecture

Symmetry in various disciplines

Figure: The Taj Mahal, Agra, India, 1648 r.

- Physics
- Math
- Music
- Poetry
- Architecture
- Moral symmetry (tit for tat)

Symmetry

Herman Weyl, "Symmetry"

Symmetry is an idea which has guided man through the centuries to the understanding and the creation of **order**, **beauty** and **perfection**.

Symmetry in biology

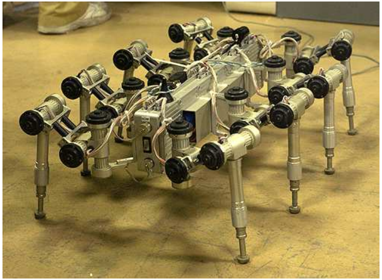


Figure: Symmetry – a popular evolutionary concept.

- Popular evolutionary concept
- Usually bilateral symmetry (the bilateria)
- Oldest known symmetrical organism: Vernanimalcula (600 mln years ago)
- Notable asymmetrical exceptions: sponges.

Sponges

Figure: Sponges

Symmetry everywhere?

- Animals are symmetrical only superficially and only in a macro scale
- Asymmetry in chemistry
- Alice's cat
- DNA is clockwise

What is on the other side of looking glass?

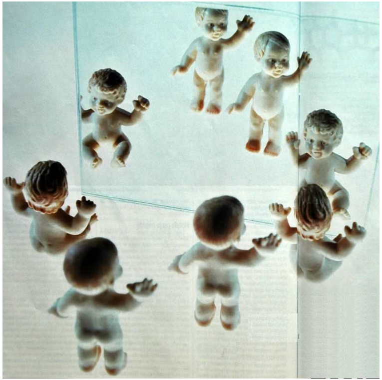


Figure: On the other side

- Is the reflected world possible?
- Let us reflect the whole universe. . . from stars till atoms. . .

What is on the other side of looking glass?

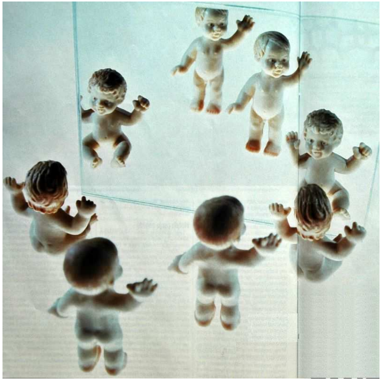


Figure: On the other side

- Is the reflected world possible?
- Let us reflect the whole universe. . . from stars till atoms. . .
- A reflection of neutrino is impossible → reflected world is impossible. . .

What is on the other side of looking glass?

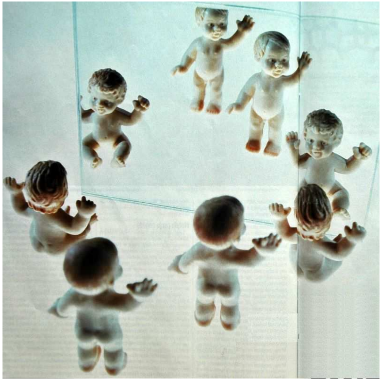


Figure: On the other side

- Is the reflected world possible?
- Let us reflect the whole universe. . . from stars till atoms. . .
- A reflection of neutrino is impossible → reflected world is impossible. . .
- unless we also reflect the arrow of time. . .

Why symmetry is such a popular evolutionary concept?

- An open problem.

Why symmetry is such a popular evolutionary concept?

- An open problem.
- Females of some species prefer males with the most symmetrical sexual ornaments.

Why symmetry is such a popular evolutionary concept?

- An open problem.
- Females of some species prefer males with the most symmetrical sexual ornaments.
- For humans, there are proved positive correlations between facial symmetry and health and
- between facial symmetry and perception of beauty

Why symmetry is such a popular evolutionary concept?

- An open problem.
- Females of some species prefer males with the most symmetrical sexual ornaments.
- For humans, there are proved positive correlations between facial symmetry and health and
- between facial symmetry and perception of beauty
- Intuition: bilateral symmetry resulted from the direction of movement of living creatures

Why symmetry is such a popular evolutionary concept?

- An open problem.
- Females of some species prefer males with the most symmetrical sexual ornaments.
- For humans, there are proved positive correlations between facial symmetry and health and
- between facial symmetry and perception of beauty
- Intuition: bilateral symmetry resulted from the direction of movement of living creatures
- Proof: positive correlations between locomotive efficiency and morphological symmetry

Why symmetry is such a popular evolutionary concept?

- An open problem.
- Females of some species prefer males with the most symmetrical sexual ornaments.
- For humans, there are proved positive correlations between facial symmetry and health and
- between facial symmetry and perception of beauty
- Intuition: bilateral symmetry resulted from the direction of movement of living creatures
- Proof: positive correlations between locomotive efficiency and morphological symmetry
- If so, why in the world of flowers symmetry (usually radical) is so common? Certainly not for locomotion.

Numerical measure of symmetry – motivations

- Common language is capable to express various degrees of symmetry, but no general numerical symmetry definition exists
- Natural, binary notion of symmetry is insufficient for research
- Numerical measure of symmetry could allow determining the extent to what an object is symmetrical, but also. . .
- if one object is more symmetrical than another.

Numerical measure of symmetry – motivations

- Common language is capable to express various degrees of symmetry, but no general numerical symmetry definition exists
- Natural, binary notion of symmetry is insufficient for research
- Numerical measure of symmetry could allow determining the extent to what an object is symmetrical, but also...
- if one object is more symmetrical than another.

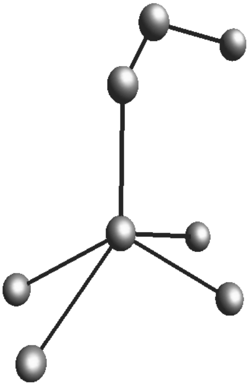
Symmetry is not such a popular concept in artificial worlds, so in order to study the phenomenon of symmetry and its implications, there is a need for defining a **numerical**, fully **automated** and **objective** measure of symmetry for creatures living in artificial environments

More motivations

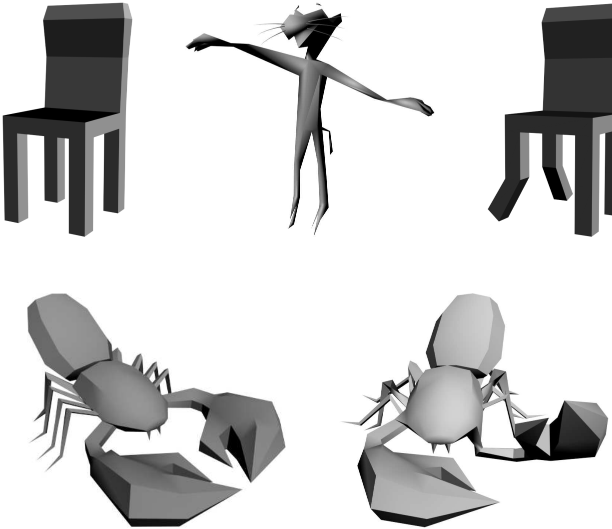
- A tool for researcher (earlier: "similarity" measure)
- Possible research applications:
  - Do symmetrical creatures move faster/further/more reliably?
  - Do symmetrical creatures perform better in environments they were not evolved in?
  - Does evolution produce more symmetrical creatures in worlds with difficult terrain/bigger/smaller gravitation?
  - . . . and more

Creature's model (framsticks)

Only skeleton is taken into account.



Solid 3D objects



Symmetry measure design (1)

- **The Symmetry Condition.** If c is perfectly bilaterally symmetrical, then $sym(c) = 1.0$.

Symmetry measure design (1)

- **The Symmetry Condition.** If c is perfectly bilaterally symmetrical, then $sym(c) = 1.0$.
- **The Asymmetry Condition.** If c is completely asymmetrical then $sym(c) = 0.0$.

Symmetry measure design (1)

- **The Symmetry Condition.** If c is perfectly bilaterally symmetrical, then $sym(c) = 1.0$.
- **The Asymmetry Condition.** If c is completely asymmetrical then $sym(c) = 0.0$.
- **The Common Sense Condition.** If c_1 is more symmetrical than c_2, then $sym(c_1) > sym(c_2)$.

Symmetry measure design (1)

- **The Symmetry Condition.** If c is perfectly bilaterally symmetrical, then $sym(c) = 1.0$.
- **The Asymmetry Condition.** If c is completely asymmetrical then $sym(c) = 0.0$.
- **The Common Sense Condition.** If c_1 is more symmetrical than c_2, then $sym(c_1) > sym(c_2)$.
- **The Proportional Difference Condition.** The difference between $sym(c_1)$ and $sym(c_2)$ should correspond to the difference in anatomical symmetry between c_1 and c_2.

Symmetry measure design (1)

- **The Symmetry Condition.** If c is perfectly bilaterally symmetrical, then $sym(c) = 1.0$.
- **The Asymmetry Condition.** If c is completely asymmetrical then $sym(c) = 0.0$.
- **The Common Sense Condition.** If c_1 is more symmetrical than c_2, then $sym(c_1) > sym(c_2)$.
- **The Proportional Difference Condition.** The difference between $sym(c_1)$ and $sym(c_2)$ should correspond to the difference in anatomical symmetry between c_1 and c_2.
- **The Scalability Condition.** The proposed measure should be robust against scaling: for creature c_2 that is a scaled version of c_1 (body enlarged or diminished), we expect $sym(c_2) = sym(c_1)$.

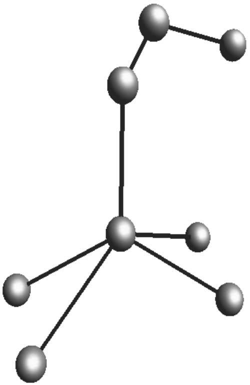
Symmetry measure design (2)

Let us denote symmetry of a creature c about plane p as $sym(c, p)$.
We say that "a creature is symmetrical" if it is symmetrical about **any plane**, therefore we are looking for a plane that yields the highest symmetry:

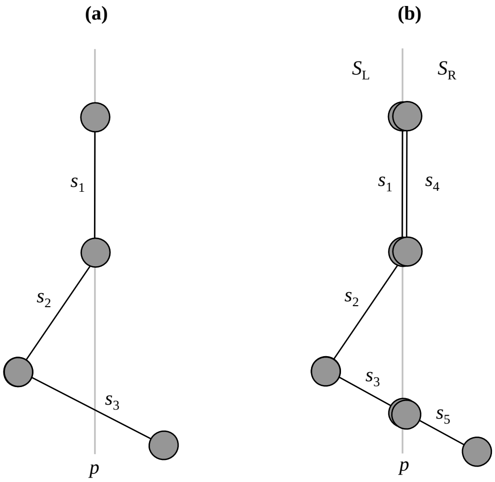
$$sym(c) = \max_{p}(sym(c, p)) \tag{1}$$

Creature's model

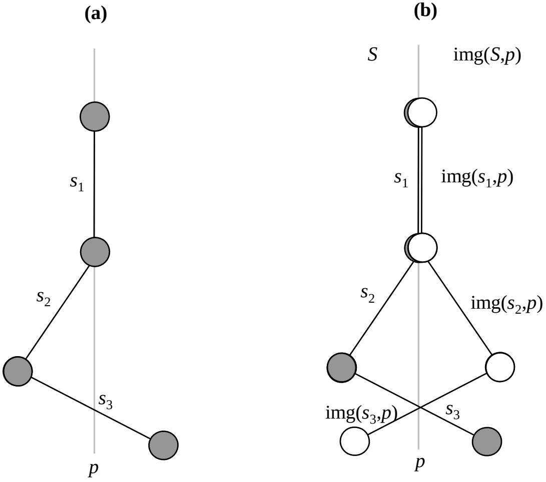
Looking for matching sticks. . .



How to compute $sym(c, p)$? (1)



How to compute $sym(c, p)$? (2)



How to compute $sym(c, p)$? (3)

$$sym(c, p) = \max_{\Pi} \left(\frac{\sum_{(s_1, s_2) \in \Pi} w_{s_1 s_2} sim(s_1, s_2)}{\sum_{(s_1, s_2) \in \Pi} w_{s_1 s_2}} \right) \qquad (2)$$

where

$$w_{s_1 s_2} = \begin{cases} len(s_1) + len(s_2) & \text{if} \quad s_1 \neq s_2 \\ len(s_1) & \text{if} \quad s_1 = s_2 \end{cases} \qquad (3)$$

$$sim(s_1, s_2) = \exp \frac{-dist^2(s_1, s_2)}{(\alpha \cdot s_f)^2} \qquad (4)$$

where α is a constant, and s_f is a creature scale factor.

Sample landscape

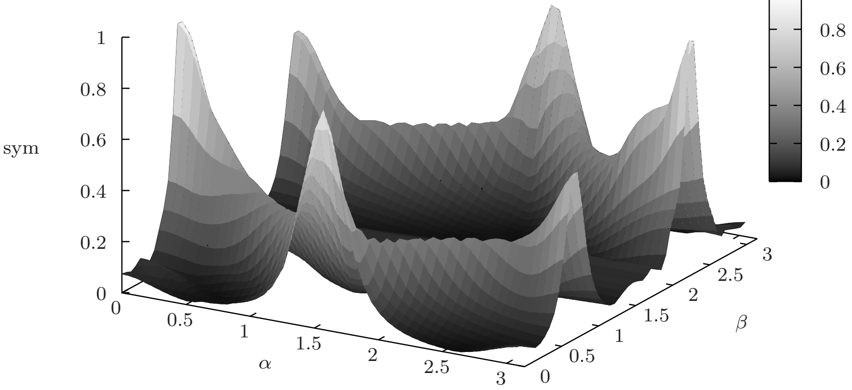


Figure: In order to find the plane of the highest symmetry, we sample the 3-dimensional (α, β, t) space for each creature stick and then perform a local search to further improve the best found plane.

Illustration of symmetry planes (1)

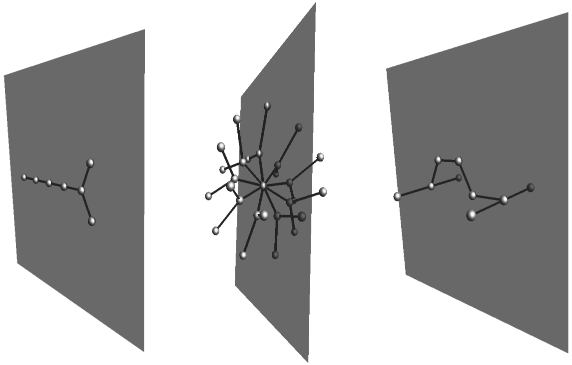


Figure: Sample creatures, estimation of their symmetry planes and symmetry values. Values of symmetry are: 1.0, 1.0, 0.99

Illustration of symmetry planes (2)

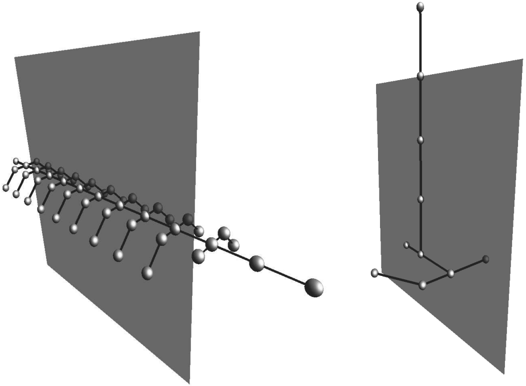


Figure: Values of symmetry are: 0.97, 0.82

Illustration of symmetry planes (3)

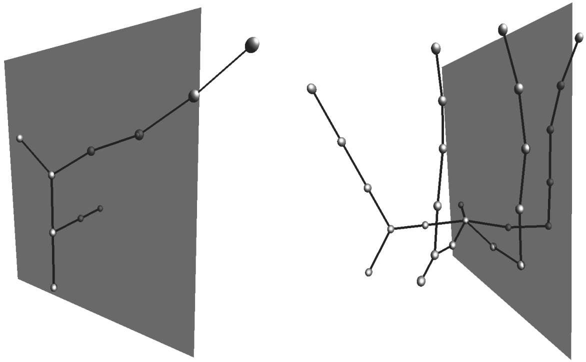
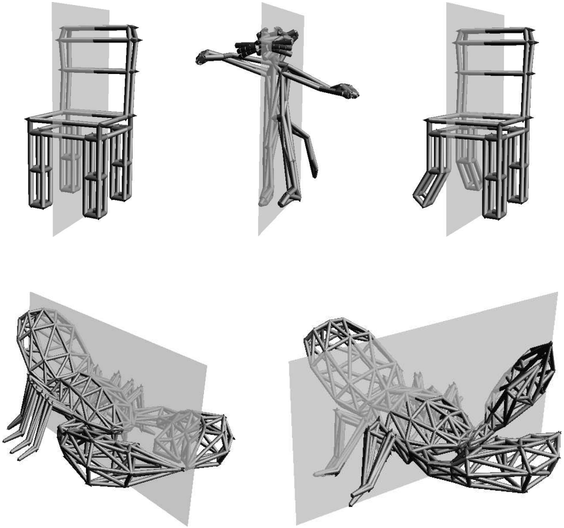


Figure: Values of symmetry are: 0.70, 0.39

Illustration of symmetry planes (4)



A random set of individuals

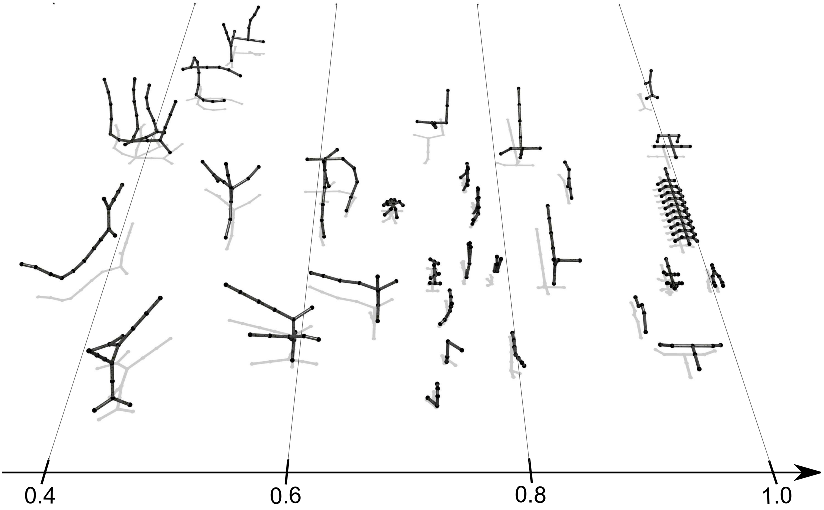


Figure: 30 diverse creatures arranged horizontally according to their values of symmetry (the most symmetrical on the right).

Symmetry in human design and evolution

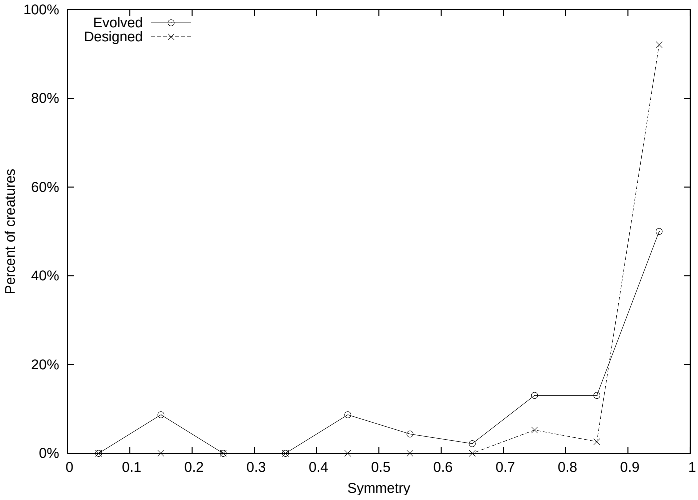


Figure: Distribution of symmetry values among 84 creatures (38 designed, 46 evolved).

Evolved creatures

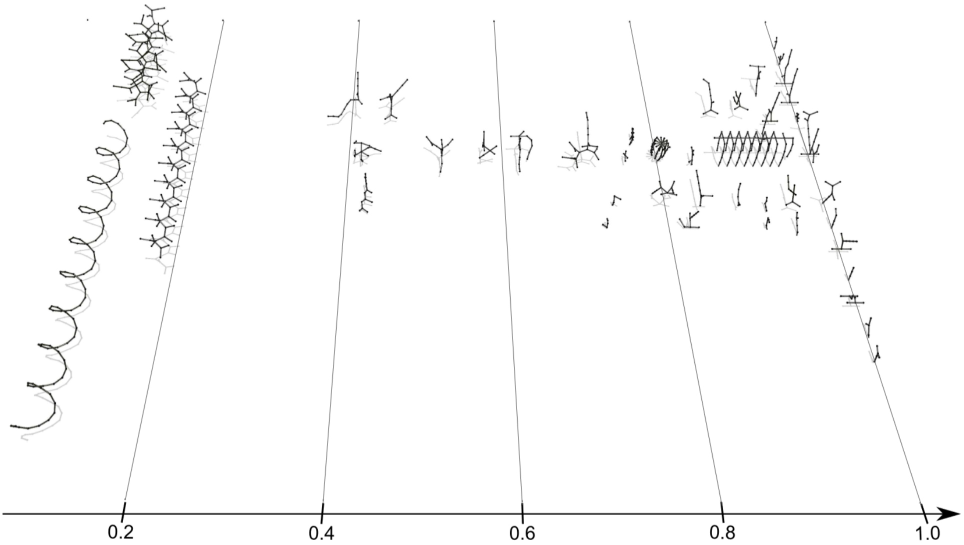


Figure: Evolved creatures. Constructs with the highest symmetry are usually simple.

Designed creatures

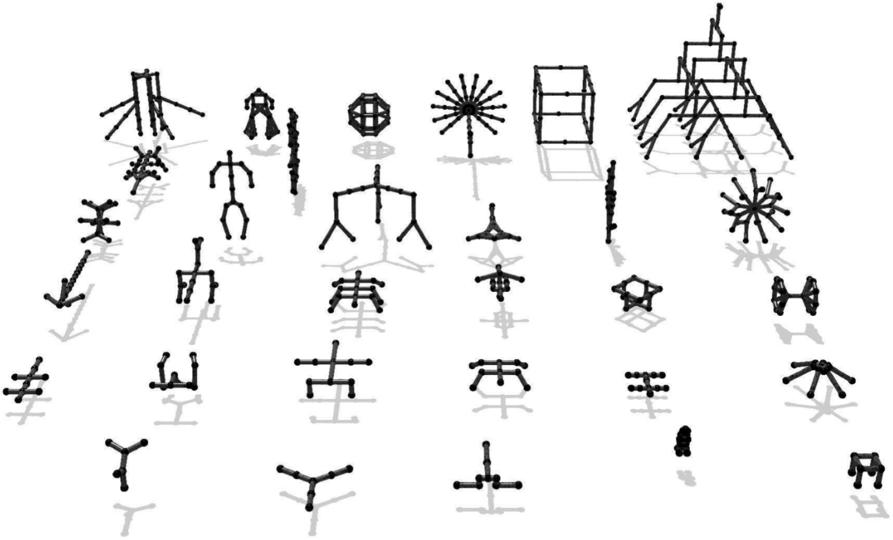
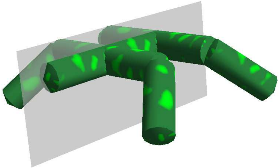


Figure: Designed creatures with symmetry of 1.0.

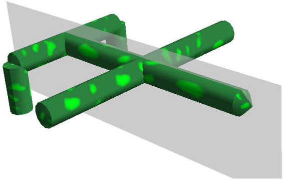
Motivations

- Operates on the phenotype in motion (opposed to: symmetry of genotype)
- Characterizes motion (a feature of the motion pattern).
- Other: whether (to what degree) the movement is periodic or chaotic, how dynamic, effective it is
- Implications:
  - understanding the evolution on Earth
  - methods of locomotion both in living animals and designed robots

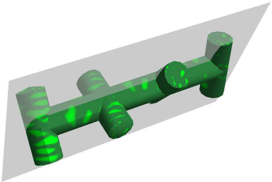
Static symmetries



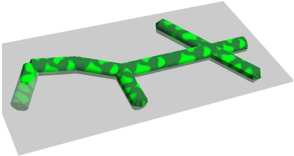
(a) Basic Quadruped (1.000)



(b) Bulldog (1.000)



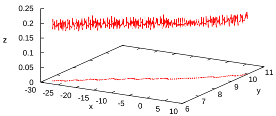
(c) Rototiller (0.850)



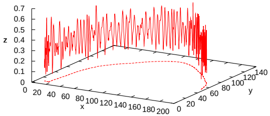
(d) Imunus Katehe (0.956)

Figure: Symmetry planes of the four considered creatures. Symmetry values are given in brackets.

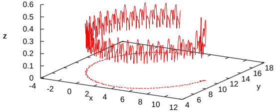
3D paths



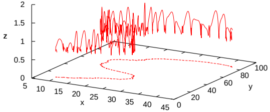
(a) Basic Quadruped



(b) Bulldog



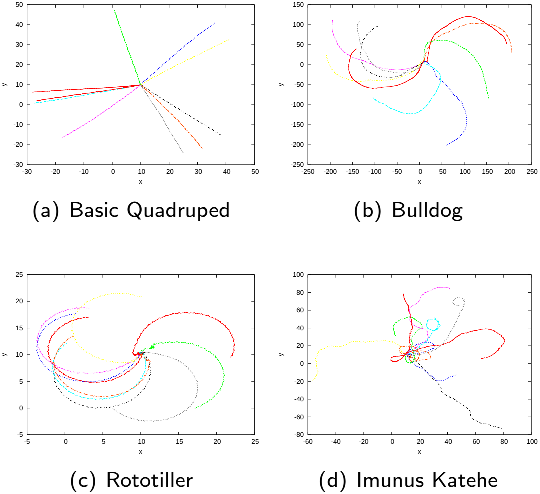
(c) Rototiller



(d) Imunus Katehe

Figure: Sample 3D paths for four creatures.

2D paths

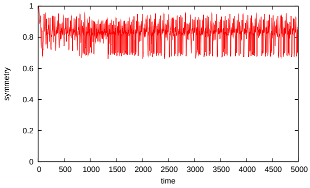


(a) Basic Quadruped (b) Bulldog

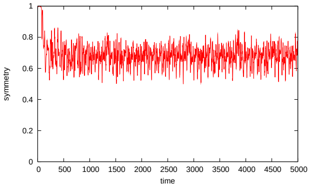
(c) Rototiller (d) Imunus Katehe

Figure: 10 paths for four considered creatures.

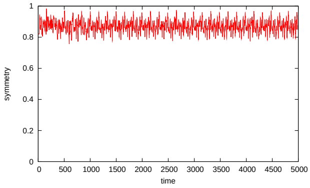
Symmetry (3df) over time



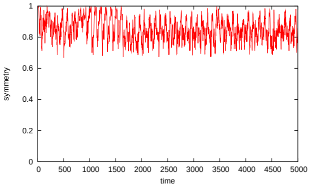
(a) Basic Quadruped



(b) Bulldog



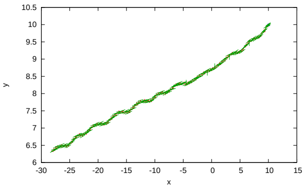
(c) Rototiller



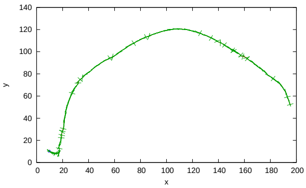
(d) Imunus Katehe

Figure: The values of symmetry over time.

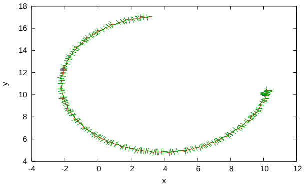
2D paths with symmetries



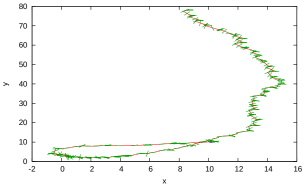
(a) Basic Quadruped



(b) Bulldog



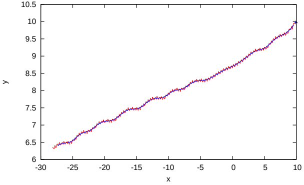
(c) Rototiller



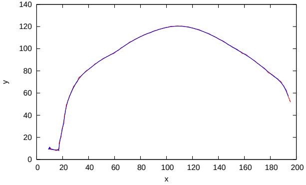
(d) Imunus Katehe

Figure: The creature 2D paths (red) with vertical planes shown (green).

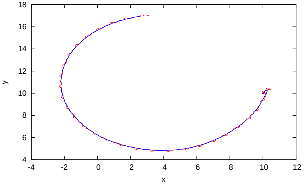
Smoothed paths



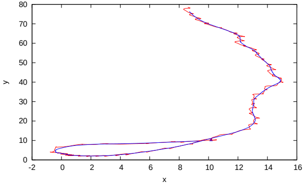
(a) Basic Quadruped



(b) Bulldog



(c) Rototiller



(d) Imunus Katehe

Figure: The original paths (red) and the ones smoothed using a low pass filter (blue).

Movement directions

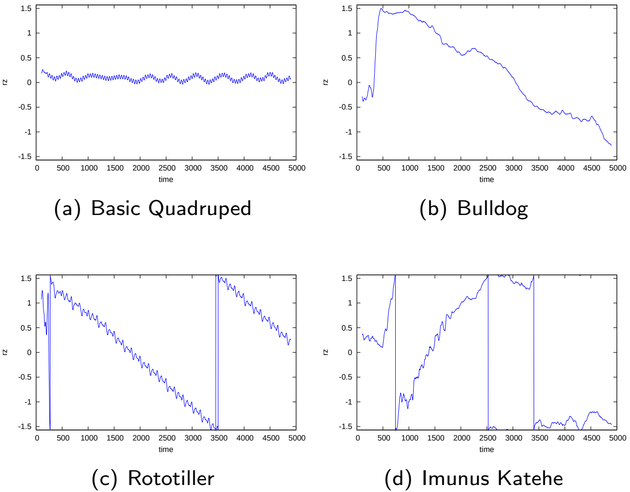
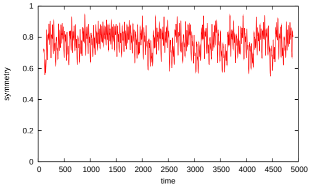


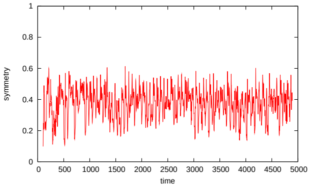
Figure: Movement directions based on the smoothed paths over time.

Framsticks
Reminder of the creature model
Symmetry itself
Static symmetry
Motivations
Approach
Experiments
Motion symmetry
Motivations
Approach
Further research
References

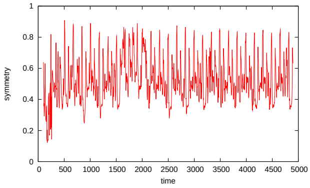
Vertical (1df) symmetry over time



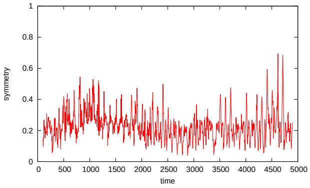
(a) Basic Quadruped



(b) Bulldog



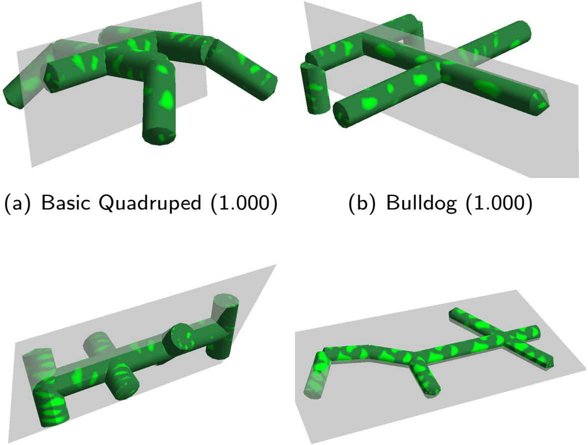
(c) Rototiller



(d) Imunus Katehe

Figure: The values of vertical (1df) symmetry over time.

Static symmetries



(a) Basic Quadruped (1.000) (b) Bulldog (1.000)

(c) Rototiller (0.850) (d) Imunus Katehe (0.956)

Figure: Symmetry planes of the four considered creatures. Symmetry values are given in brackets.

Final symmetry values (soft 1df symmetry)

Table: Soft dynamic 1df symmetries (soft 1df), their standard deviations and maximal and minimal values.

creature	soft 1df	std.dev.	min	max
Basic Quadruped	0.777	0.063	0.588	0.950
Bulldog	0.475	0.062	0.162	0.768
Rototiller	0.688	0.109	0.154	0.932
Imunus Katehe	0.327	0.119	0.090	0.737

Evolving movement

- MechaStick
    - experiments in 2001: diverse ways of movement evolved

Evolving movement

- MechaStick
  - experiments in 2001: diverse ways of movement evolved
  - were they really diverse?
  - mostly simple creatures (a few sticks... large constructs are inefficient)

Evolving movement

- MechaStick
  - experiments in 2001: diverse ways of movement evolved
  - were they really diverse?
  - mostly simple creatures (a few sticks. . . large constructs are inefficient)
  - most interesting ones were designed by hand and NNs were evolved

Evolving movement

- MechaStick
  - experiments in 2001: diverse ways of movement evolved
  - were they really diverse?
  - mostly simple creatures (a few sticks. . . large constructs are inefficient)
  - most interesting ones were designed by hand and NNs were evolved
  - new discovery: unexpected numerical instability

Evolving movement

- MechaStick
  - experiments in 2001: diverse ways of movement evolved
  - were they really diverse?
  - mostly simple creatures (a few sticks... large constructs are inefficient)
  - most interesting ones were designed by hand and NNs were evolved
  - new discovery: unexpected numerical instability
- ODE
  - high expectations (accuracy, volume bodies, self-collisions)

Evolving movement

- MechaStick
  - experiments in 2001: diverse ways of movement evolved
  - were they really diverse?
  - mostly simple creatures (a few sticks. . . large constructs are inefficient)
  - most interesting ones were designed by hand and NNs were evolved
  - new discovery: unexpected numerical instability
- ODE
  - high expectations (accuracy, volume bodies, self-collisions)
  - evolving movement turned out to be even more difficult! :o
  - elasticity of MechaStick was **so** important!

Evolving movement

- MechaStick
  - experiments in 2001: diverse ways of movement evolved
  - were they really diverse?
  - mostly simple creatures (a few sticks… large constructs are inefficient)
  - most interesting ones were designed by hand and NNs were evolved
  - new discovery: unexpected numerical instability
- ODE
  - high expectations (accuracy, volume bodies, self-collisions)
  - evolving movement turned out to be even more difficult! :o
  - elasticity of MechaStick was **so** important!
  - sticks as cylinders: rolling ("passive")… and stability phase does not help

Evolving movement

- MechaStick
  - experiments in 2001: diverse ways of movement evolved
  - were they really diverse?
  - mostly simple creatures (a few sticks. . . large constructs are inefficient)
  - most interesting ones were designed by hand and NNs were evolved
  - new discovery: unexpected numerical instability
- ODE
  - high expectations (accuracy, volume bodies, self-collisions)
  - evolving movement turned out to be even more difficult! :o
  - elasticity of MechaStick was **so** important!
  - sticks as cylinders: rolling ("passive"). . . and stability phase does not help
  - sticks as cuboids: instability of simulation, oscillations, and. . . rolling ("active")

Evolving movement

- MechaStick
  - experiments in 2001: diverse ways of movement evolved
  - were they really diverse?
  - mostly simple creatures (a few sticks. . . large constructs are inefficient)
  - most interesting ones were designed by hand and NNs were evolved
  - new discovery: unexpected numerical instability
- ODE
  - high expectations (accuracy, volume bodies, self-collisions)
  - evolving movement turned out to be even more difficult! :o
  - elasticity of MechaStick was **so** important!
  - sticks as cylinders: rolling ("passive"). . . and stability phase does not help
  - sticks as cuboids: instability of simulation, oscillations, and. . . rolling ("active")
  - many simulation parameters, each of them is important
  - interdependence between mass, gravity, collision parameters, muscle strength and speed

Evolving movement

- MechaStick
  - experiments in 2001: diverse ways of movement evolved
  - were they really diverse?
  - mostly simple creatures (a few sticks... large constructs are inefficient)
  - most interesting ones were designed by hand and NNs were evolved
  - new discovery: unexpected numerical instability
- ODE
  - high expectations (accuracy, volume bodies, self-collisions)
  - evolving movement turned out to be even more difficult! :o
  - elasticity of MechaStick was **so** important!
  - sticks as cylinders: rolling ("passive")... and stability phase does not help
  - sticks as cuboids: instability of simulation, oscillations, and... rolling ("active")
  - many simulation parameters, each of them is important
  - interdependence between mass, gravity, collision parameters, muscle strength and speed
  - rolling is a local optimum (so far) demo
- lots of lessons learned... and weeks of simulation.

Further research

- For which objectives (speed and locomotion, predation, height, etc.) evolution promotes symmetrical creatures?
- Is symmetry beneficial for creatures evolved spontaneously?
- Does symmetry emerge for creatures evolved spontaneously? (evolve, observe, surprise!)
- Which genetical encodings promote symmetry?
- Symmetry as a component of fitness formula.
- Encoding that preserves symmetry. Comparison with other encodings.

References I

[JK06] Wojciech Jaskowski and Maciej Komosinski. *Measuring symmetry of moving stick creatures*. Research report RA–20/06. Poznan University of Technology, Institute of Computing Science, 2006.

[JK08] Wojciech Jaskowski and Maciej Komosinski. "The Numerical Measure of Symmetry for 3D Stick Creatures". In: *Artificial Life Journal* 14.4 (Fall 2008), pp. 425–443. DOI: 10.1162/artl.2008.14.4.14402. URL: http://www.framsticks.com/files/common/NumericalMeasureSymmetry3DCreatures.pdf.