Morphological Control

Applied Embodied Intelligence in Mechanical and Biological Systems Offering New Perspectives to Creativity Support Systems

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Zurich University of Applied Sciences

Content

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- **Drinking beer: You walk, because your body computes.**
- **Evolving self – assembling computers: Some Dos, some Don’t's.**
- **Chemically embodied intelligence: Much more than robots!**
- **Evolutionary engineering**
- **Morphological computation as a tool for creativity**

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Morphological Control:
Exploit the physical dynamics of the system for control purposes.

Embodied Intelligence

Technical Systems (Robocup 2013)

Pennsylvania Ballet's Valerie Amiss and Jonathon Stilesin the world premiere of Kirk Peterson's "Dancing With Monet (A Gathering at Argentuil)" Photo: Paul Kolnik

Biological Systems

Overview

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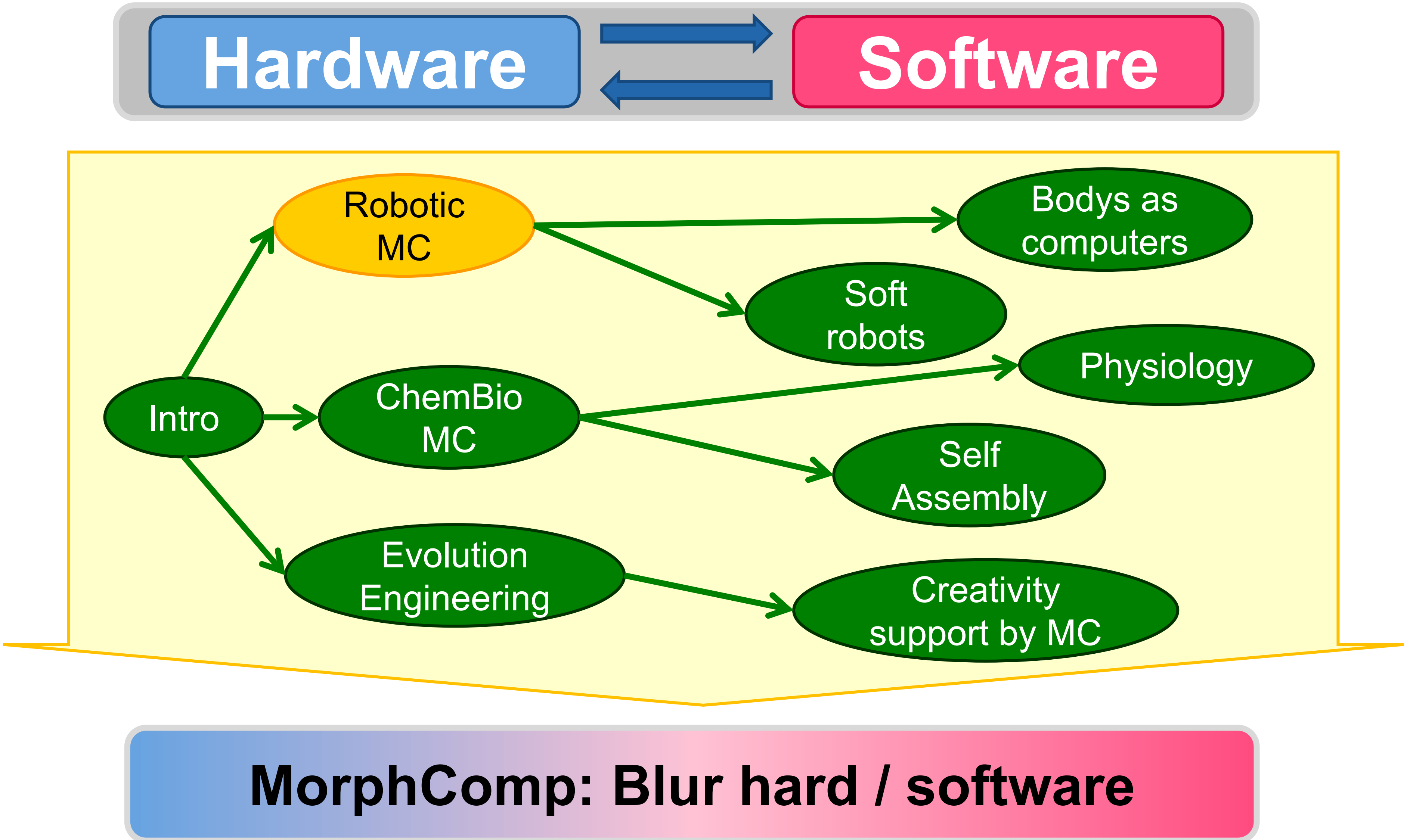
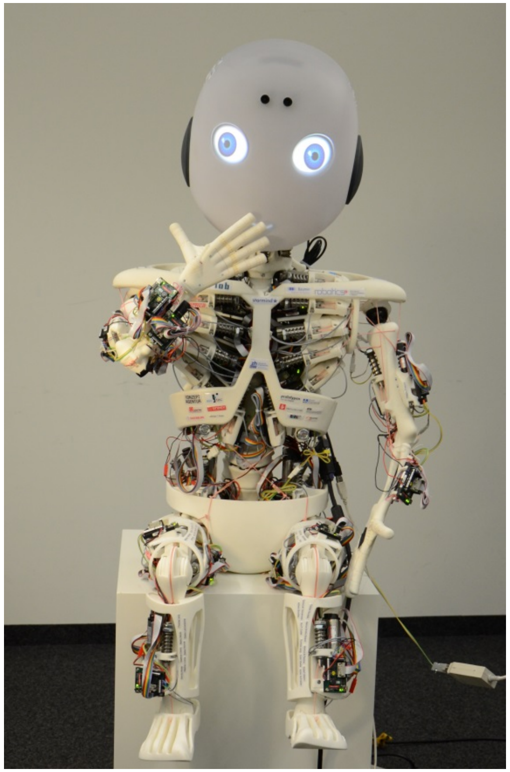
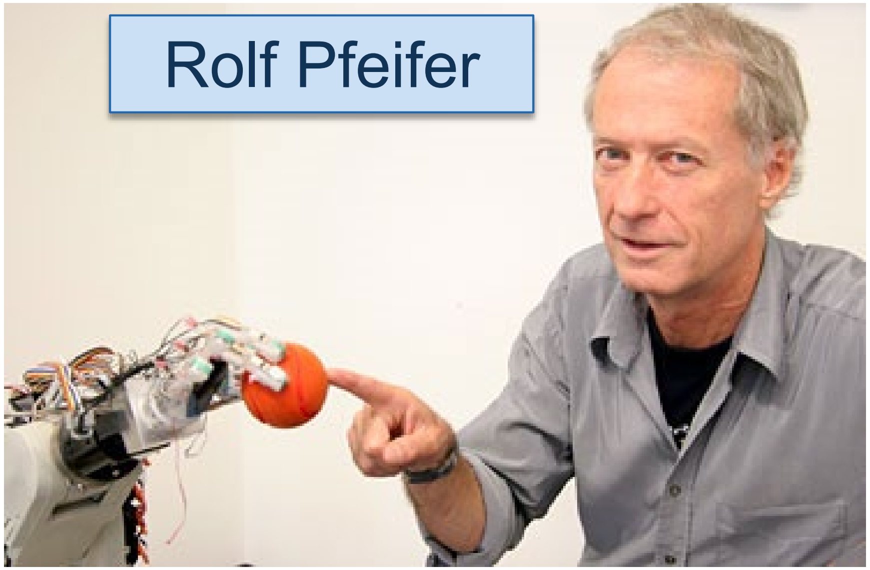


Embodiment: Control outsourced to body morphology.

In general: BLURR DISTINCTION BETWEEN HARD- AND SOFTWARE

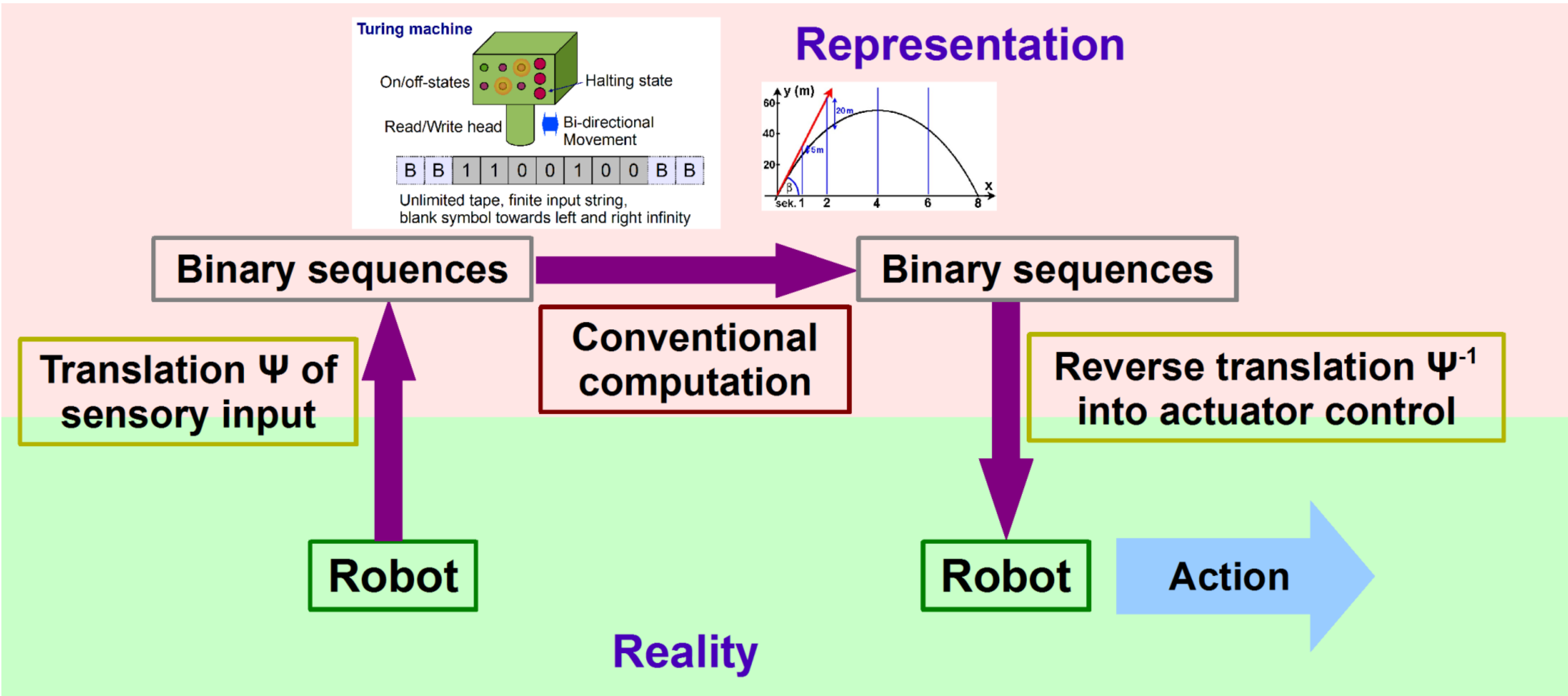




Rolf Pfeifer

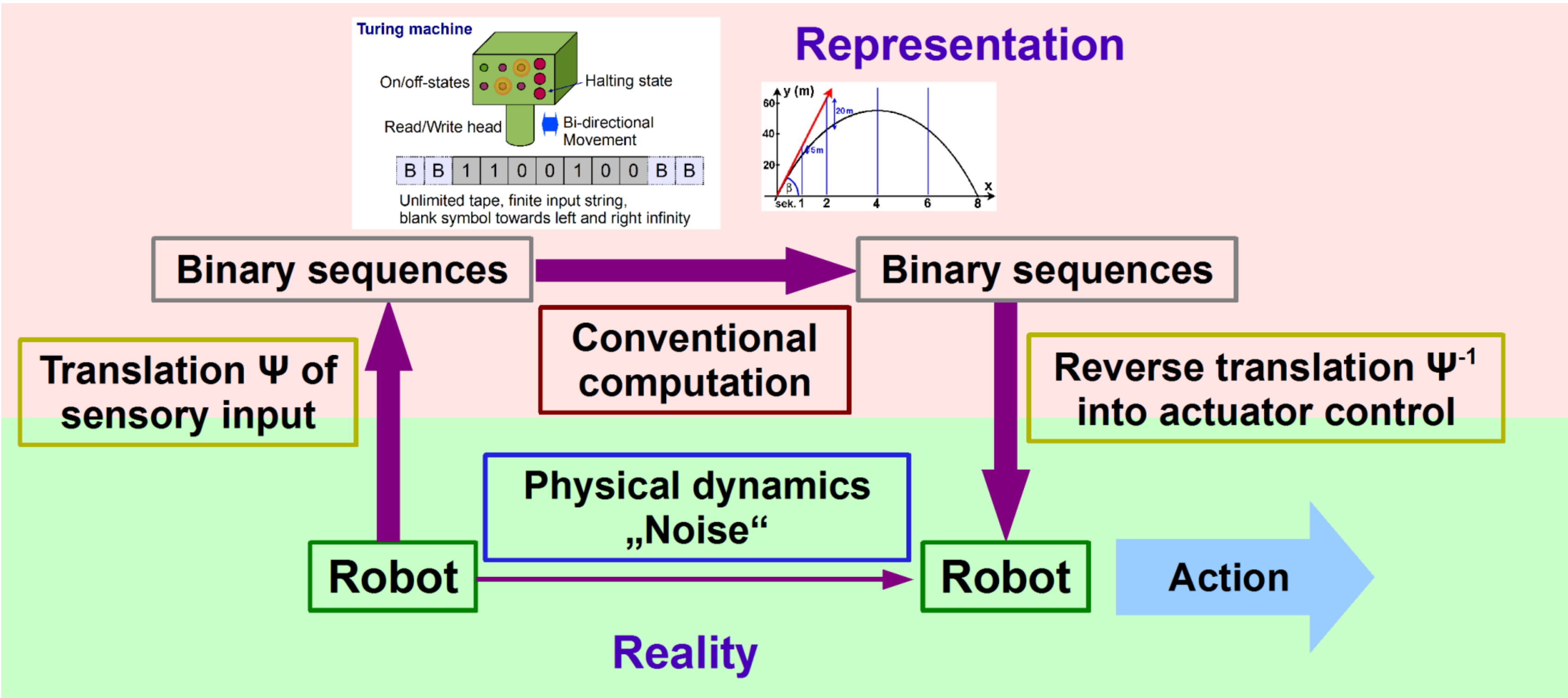
Morphology = Shape + material properties

Conventional Control: Ideal Situation



“Ideal” conventional control: complete abstraction of the control task.

Conventional Control: Real Situation



Real control: minimize the effects of the morphology.

Morphological Control

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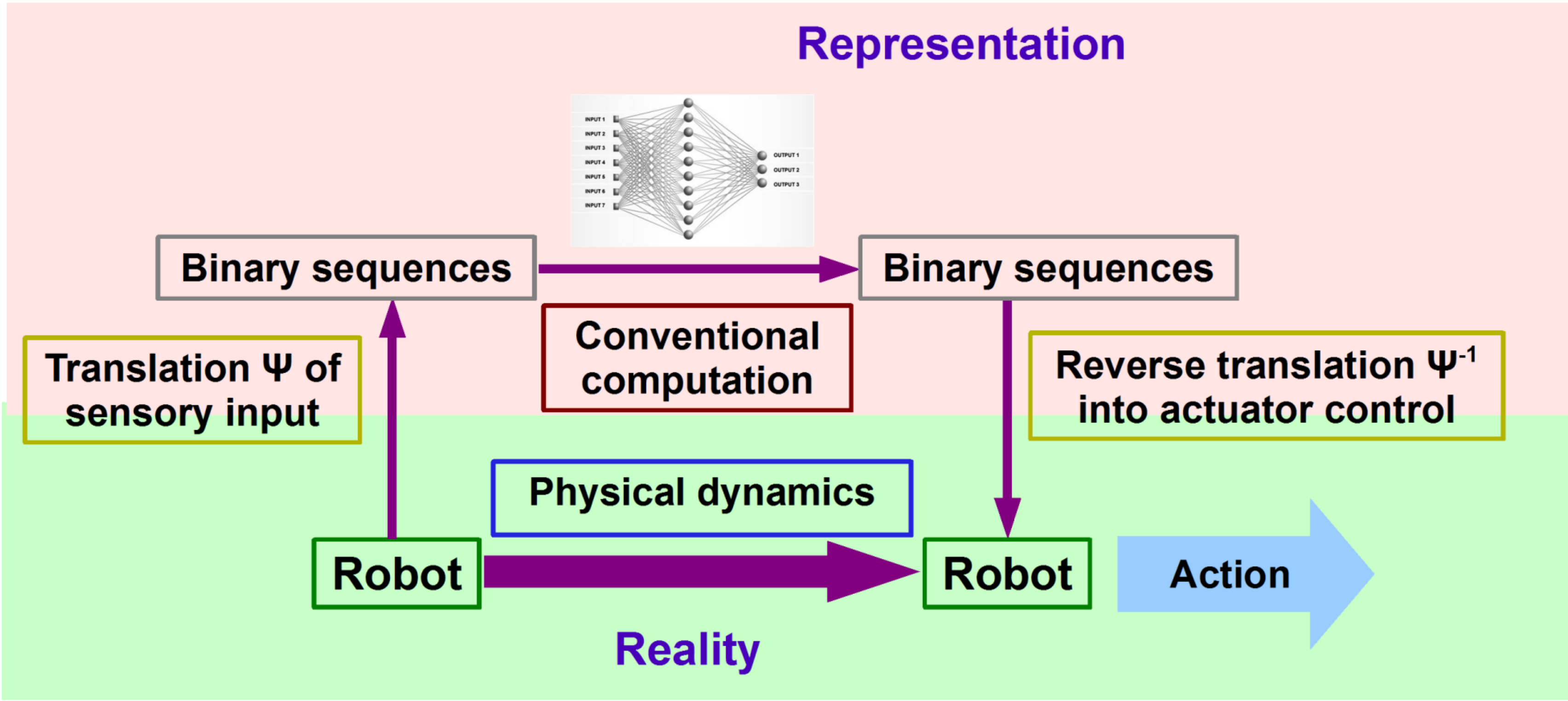
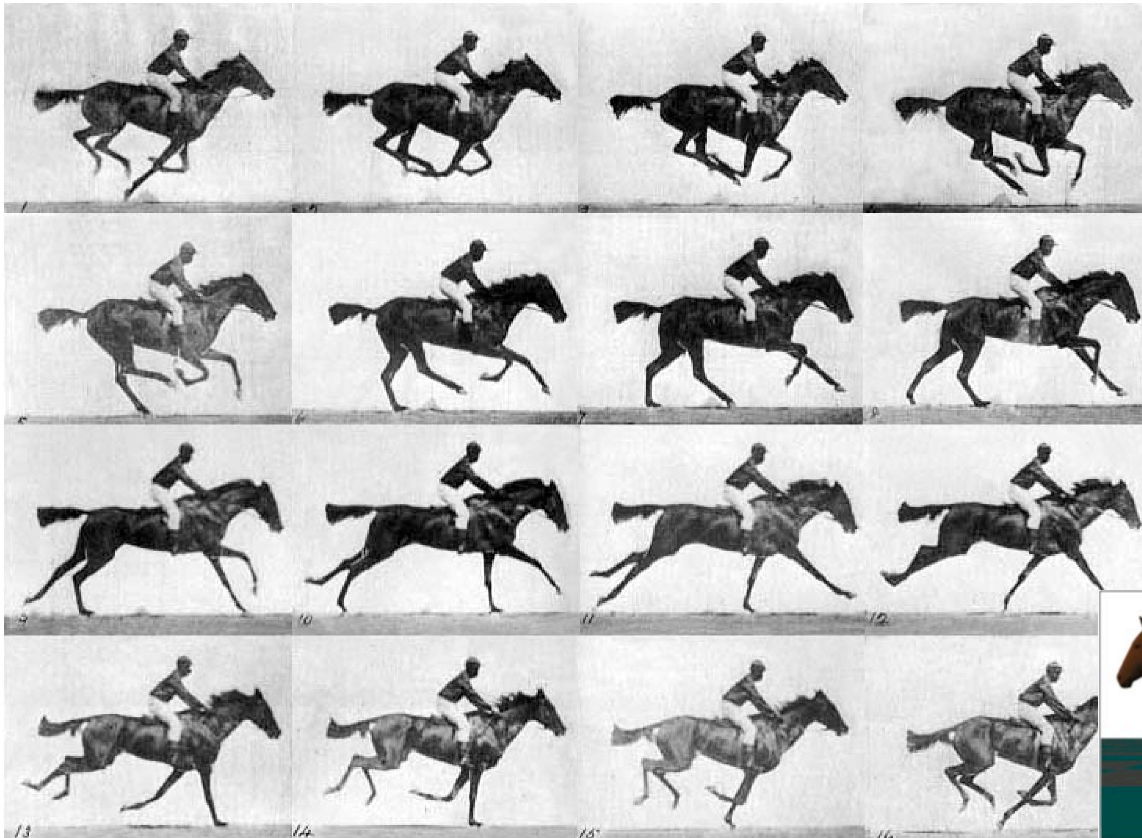
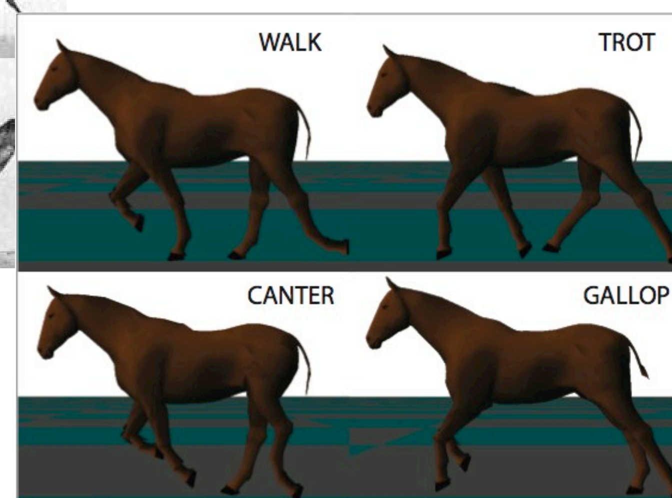


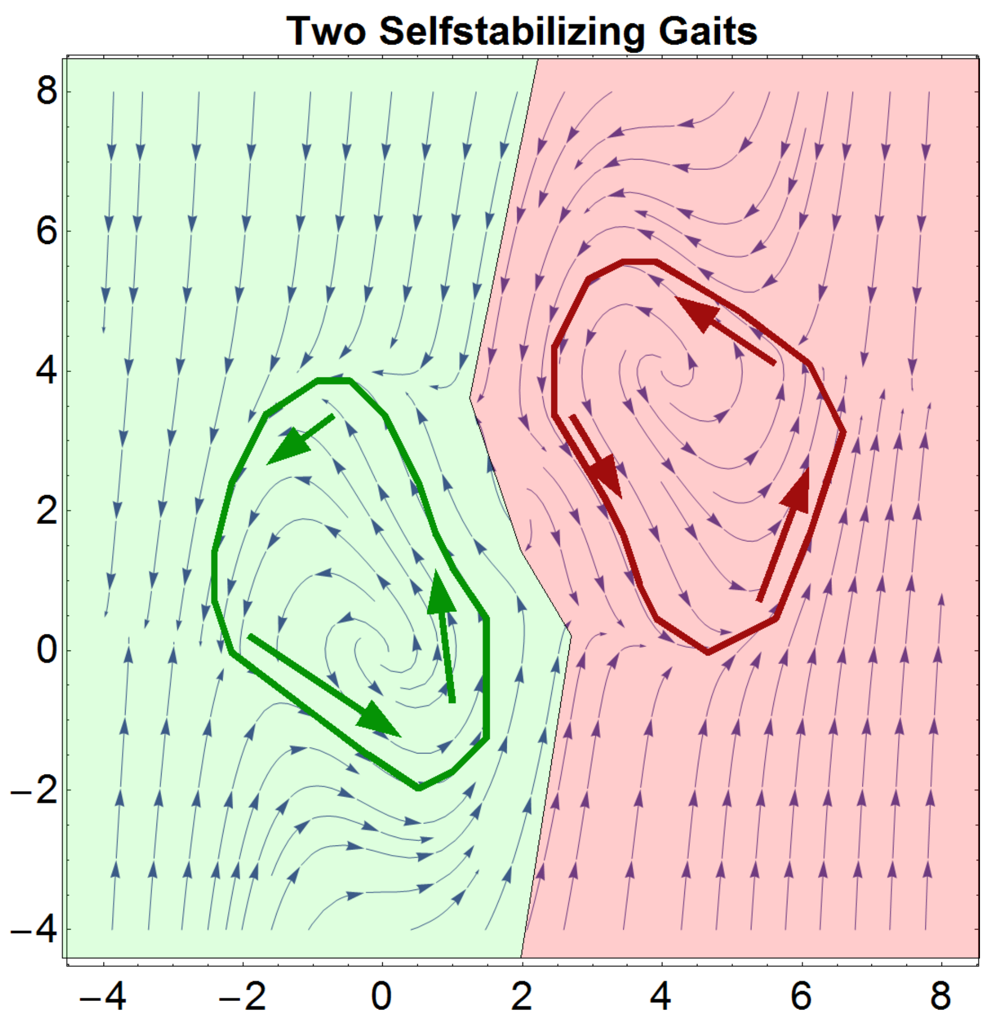
Morphological control exploits and optimizes the effects of morphology.

Gait Patterns





Gait Patterns



- **Brain** chooses red or green basin of attraction.
- **Body-dynamics** drives system into attractor (and keeps it there).

Gait Patterns: Picture incomplete

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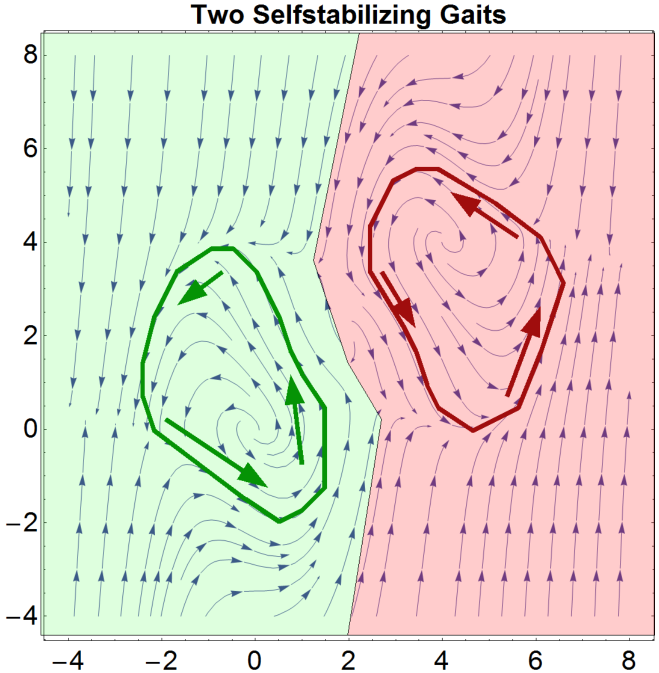

- **Transient time should be short.**
- **Fluctuations: Strong damping**
- **Attractor landscape can be changed.**

Morphological Control: Adapting Attractors

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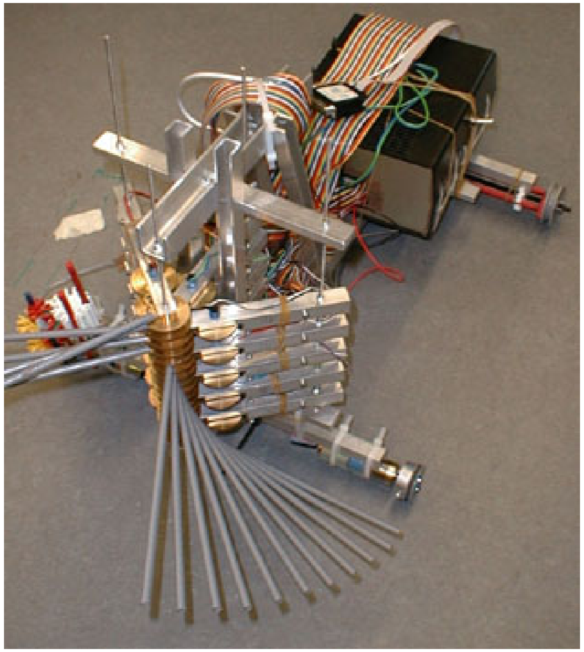
Training → Brains learns posture such that specific movements are optimally supported by morphology

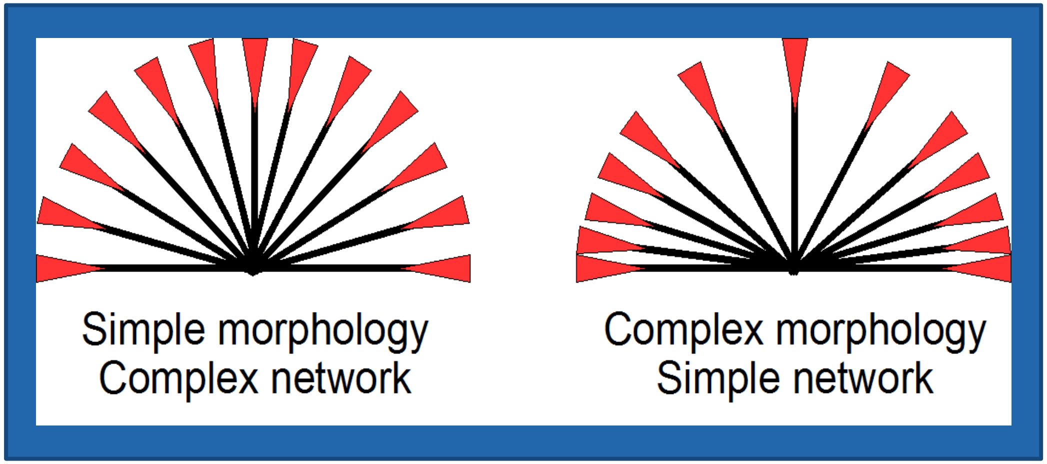
Experienced skiers: Posture is essential for precise reactions on unexpected bumps.

Schack, T., & Ritter, H (2009). .

Obstacle Avoidance: The Insect's Way



Eye bot



Lukas Lichtensteiger

Aging: Loss of Control over Movements

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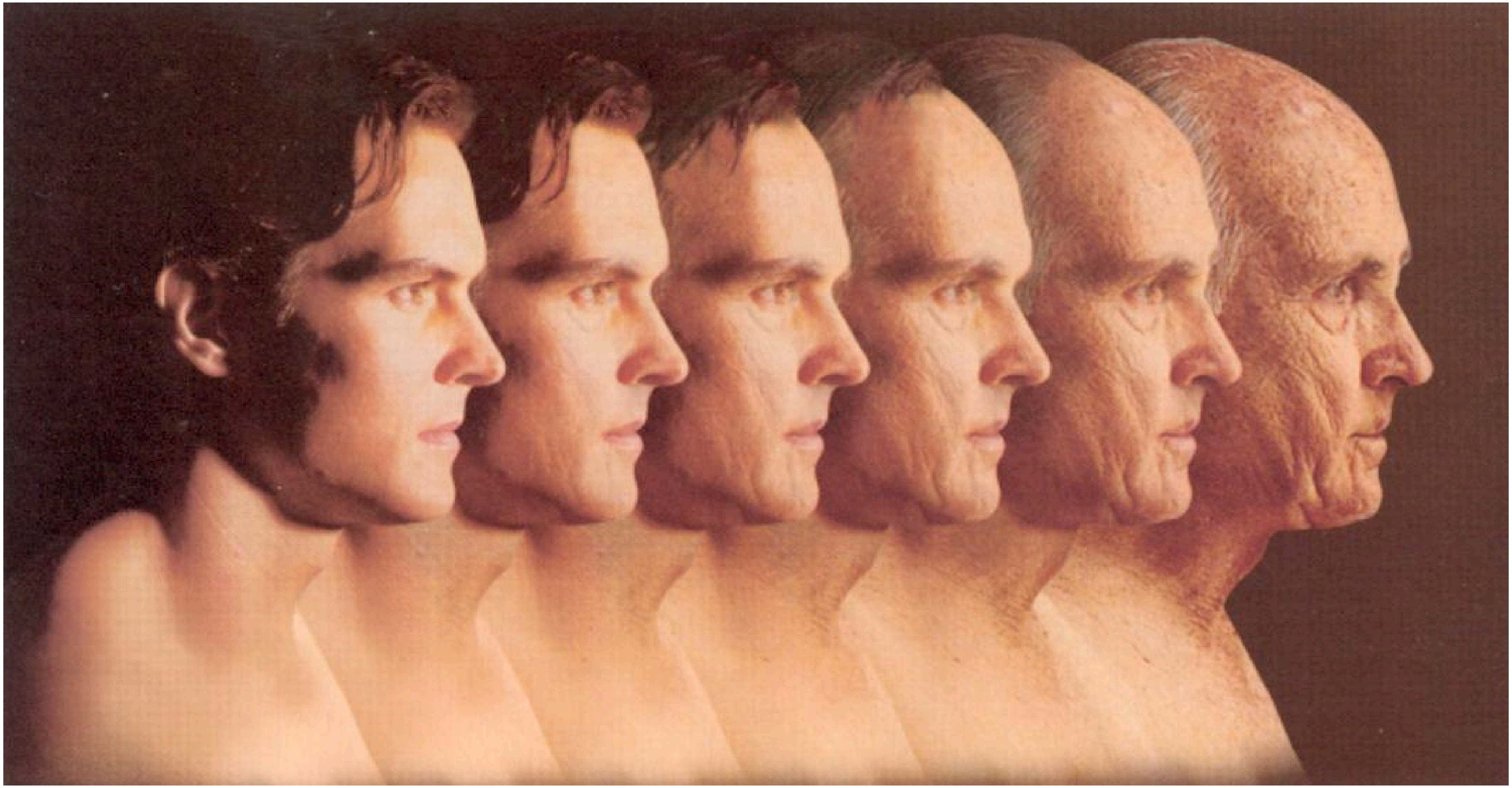

Good News from MorphControl

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We can't rejuvenate your body.
But maybe, we can rejuvenate your attractor landscape!

First Steps Towards Support System

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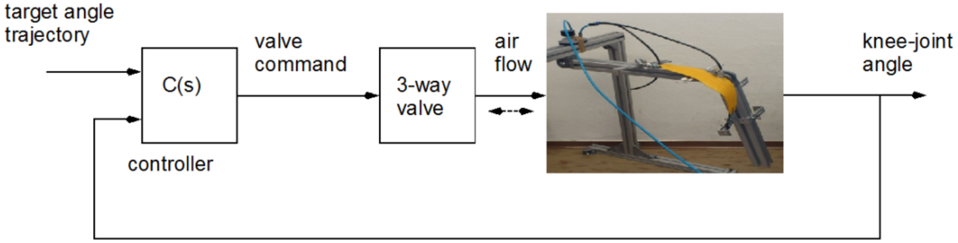
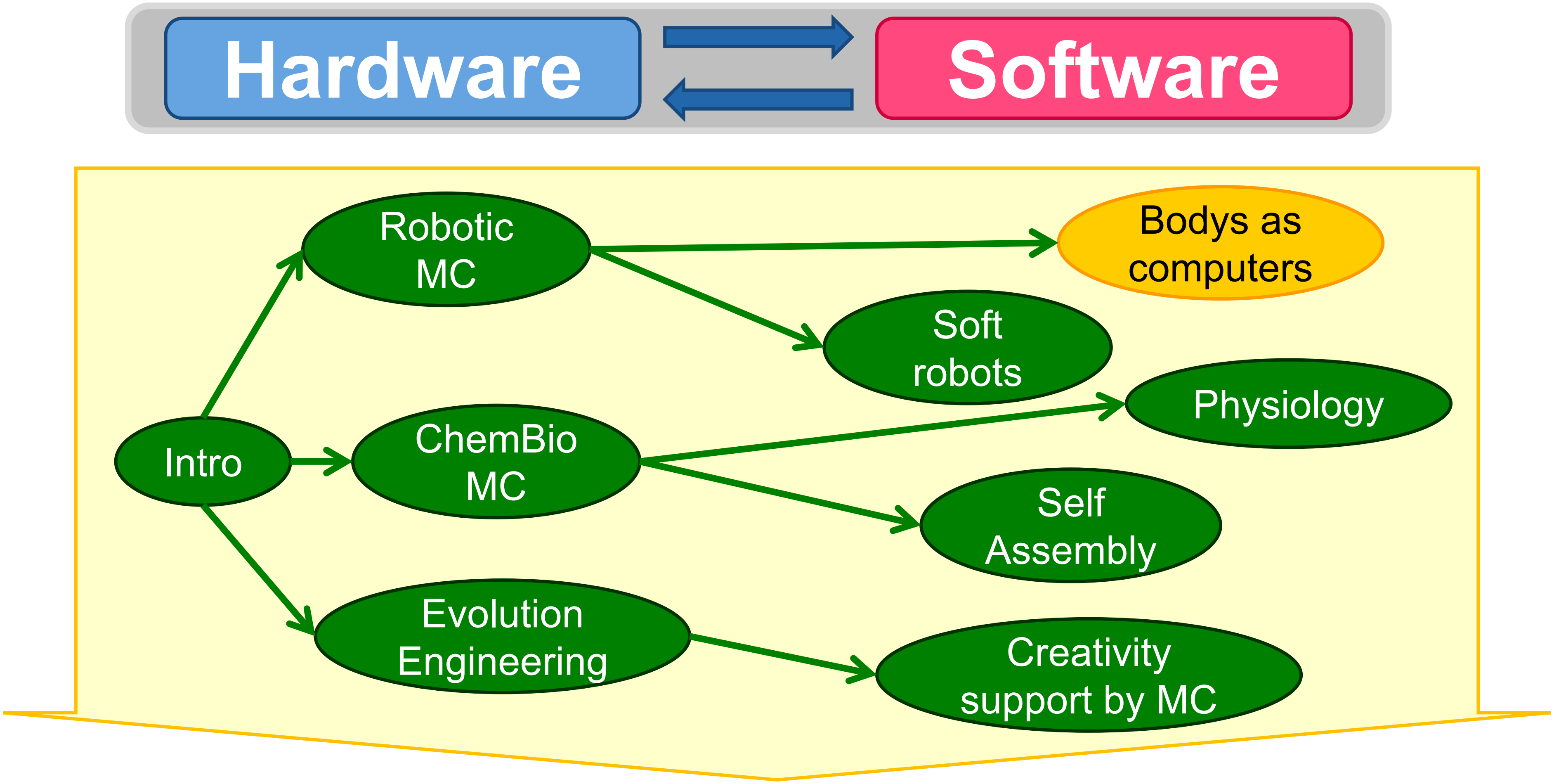
Berner Fachhochschule



Test system for supporting and stabilizing knee dynamics:
Not a servo!

A.Dzyakanchuk, Kenneth Hunt, R. Füchslin, R. Luchsinger, M. Muster

Overview



MorphComp: Blur hard / software

Brain & Body: A Result from Robotics

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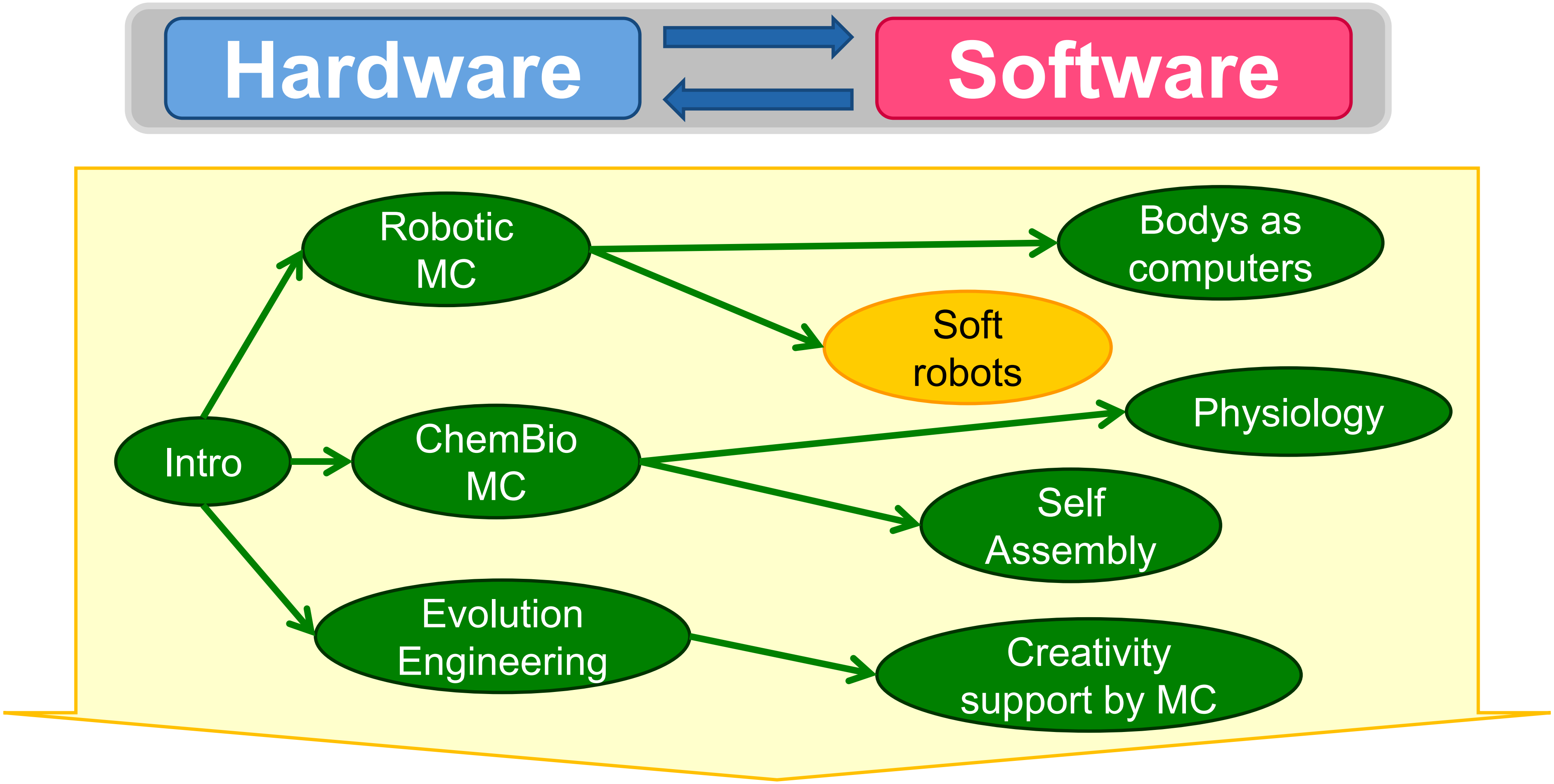
- **Feed-forward neural networks** have some but not universal computational power.
- **Mechanical mass-spring systems** can generate time-dependent signals.

Recent result: A properly interfaced hybrid system (mass-spring + feed forward neural network) can emulate/compute large classes of filters (functions onto functions).

Hauser, H.; Ijspeert, A.J.; Füchslin, R.M.; Pfeifer, R., Maass, W.„**Towards a theoretical foundation for morphological computation with compliant bodies**", Biological Cybernetics, 2011, Volume 105, Numbers 5-6, p 355-370.

Füchslin; R.M., Dzyakanchuk, A.; Flumini, D.; Hauser, H.; Hunt, K.J.; Luchsinger, R.H.; Reller, B.; Scheidegger,S.;Walker, R . "**Morphological Control Applications and Steps Towards a Formal Theory**". Artificial Life 19 9-34.

Overview



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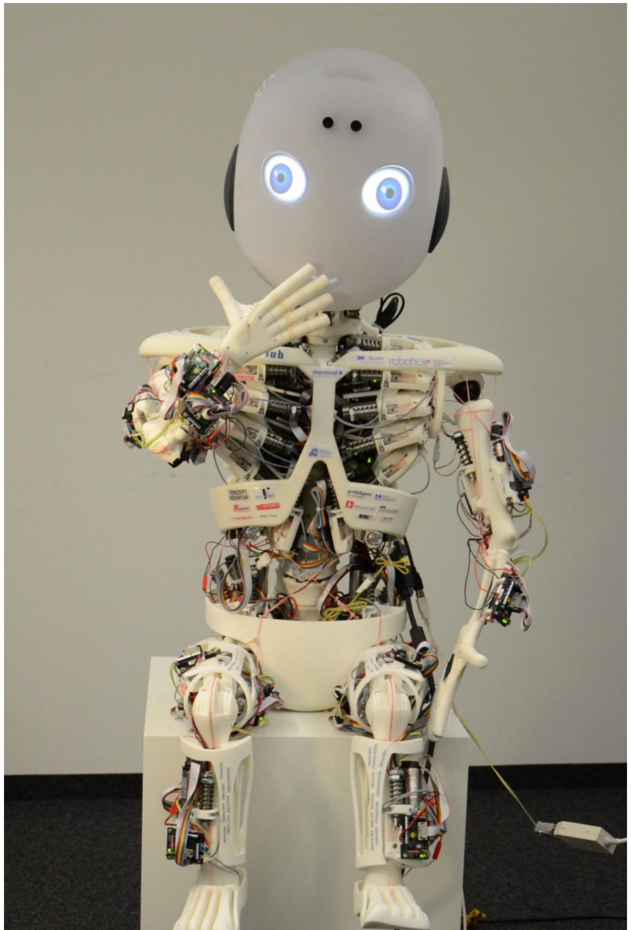
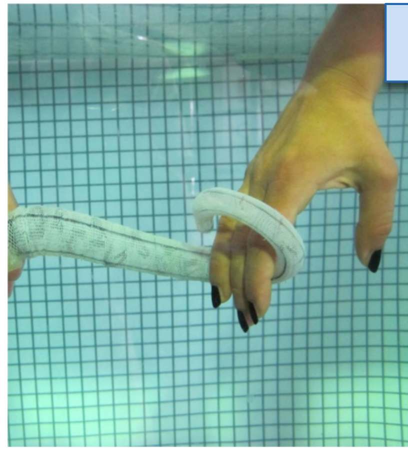
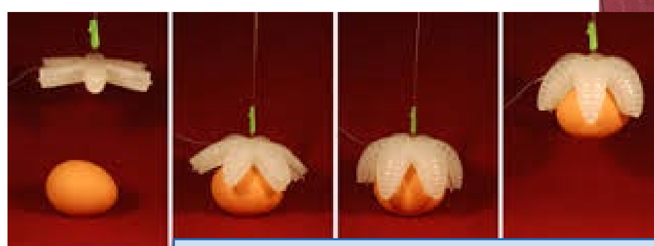
AILabs's Roboy and other Softies

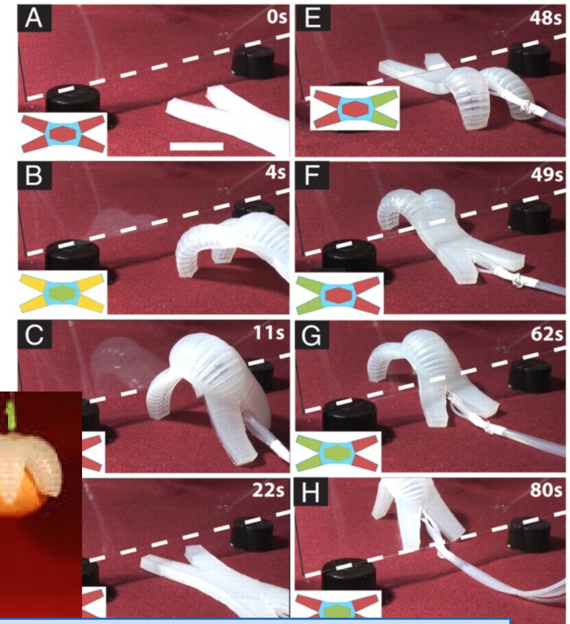


Tendon driven humanoid robot



Project Octopus





Soft robots at the lab of G. Whitesides

Soft robots are safe(r) robots!
(and cheaper and nicer and …)

Industrial robots

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Conventional Control: Real Situation

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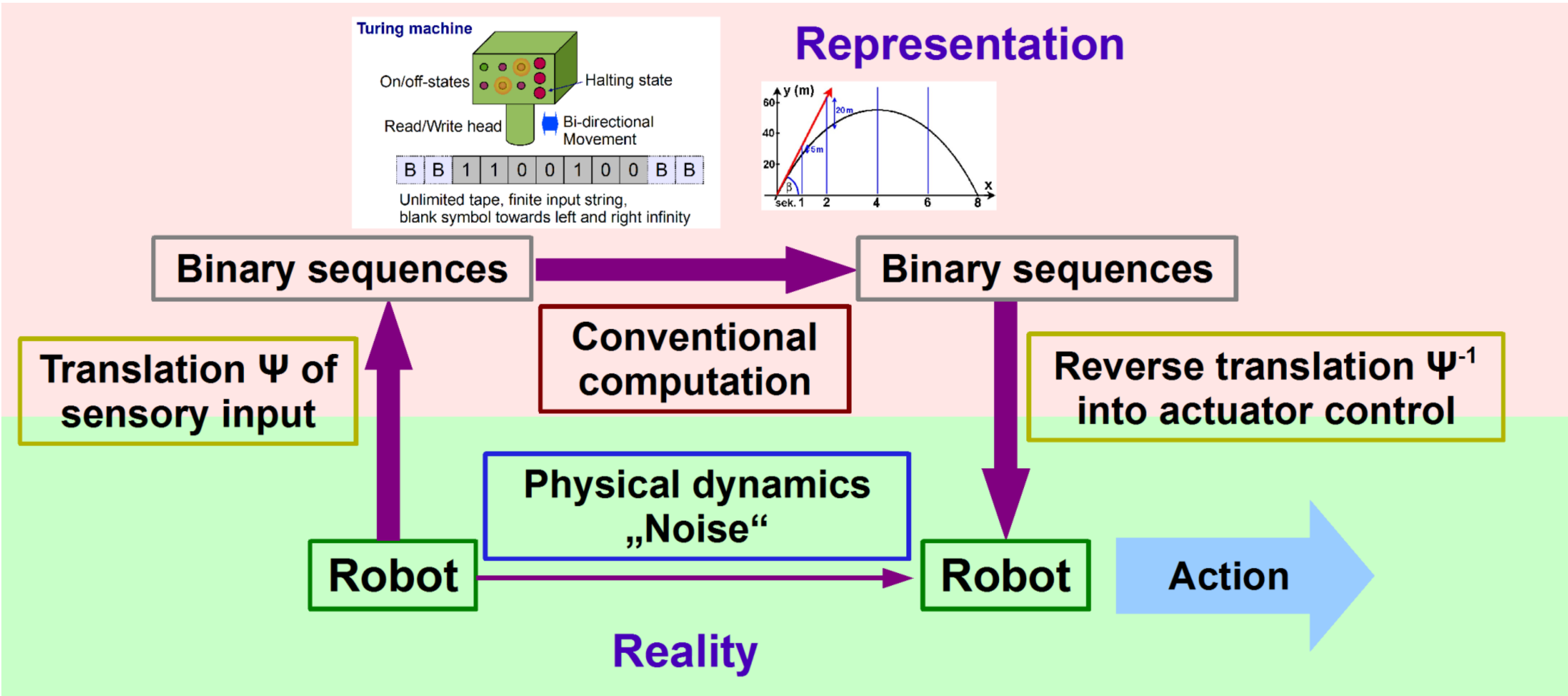

Real control: minimize the effects of the morphology.

Makes robots stiff (localization in real space) and heavy (localization in momentum space).

Why Soft Robots?

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Soft Robots Are Safe Robots

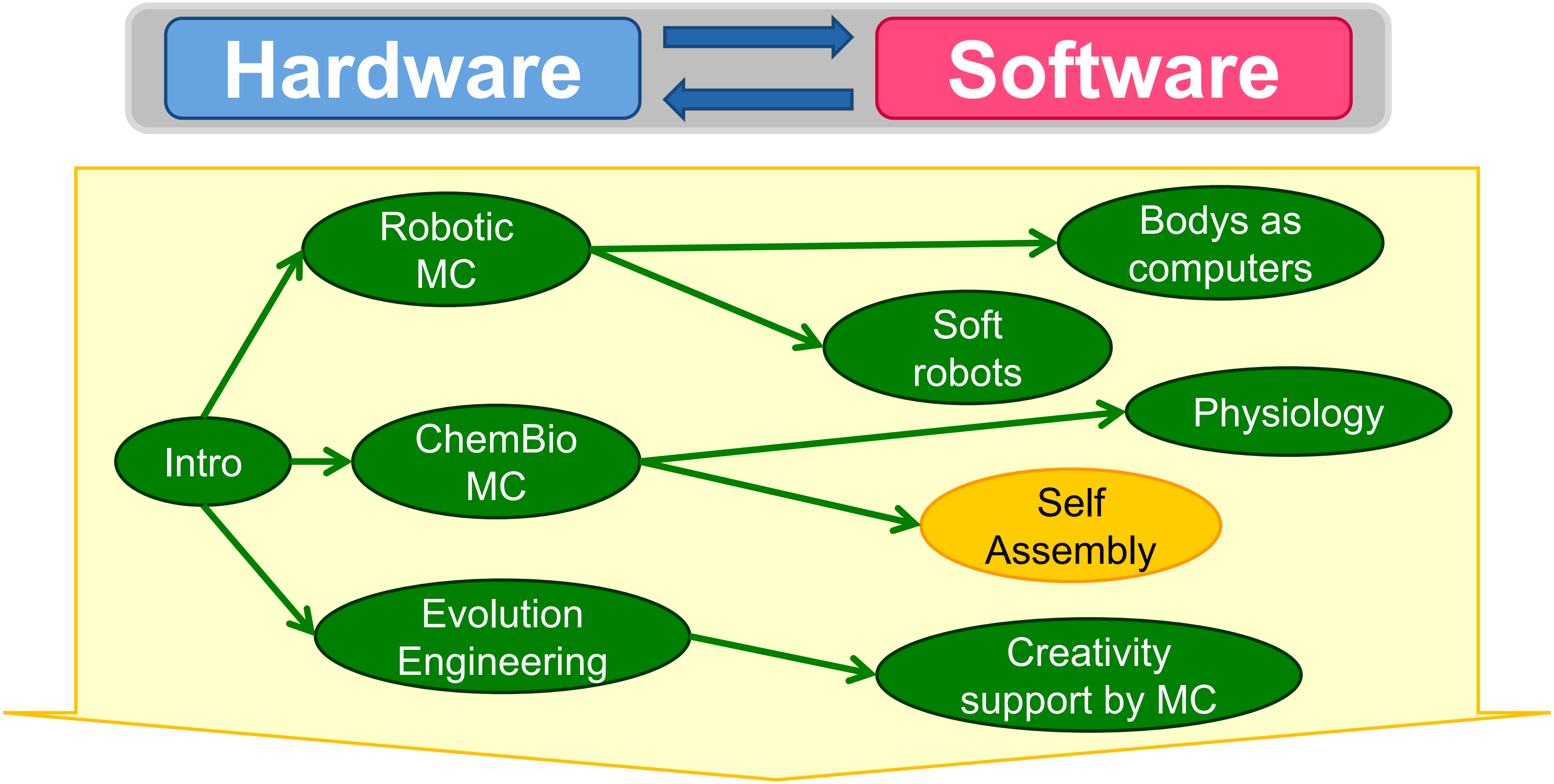
(and cheap and of low weight and …)

Employing L-systems to Generate Mass-Spring Networks for Morphological Computing

R. Bernhardsgrütter†, C. W. Senn†, R. M. Füchslin†, C. Jaeger†, K. Nakajima‡ and H. Hauser♯

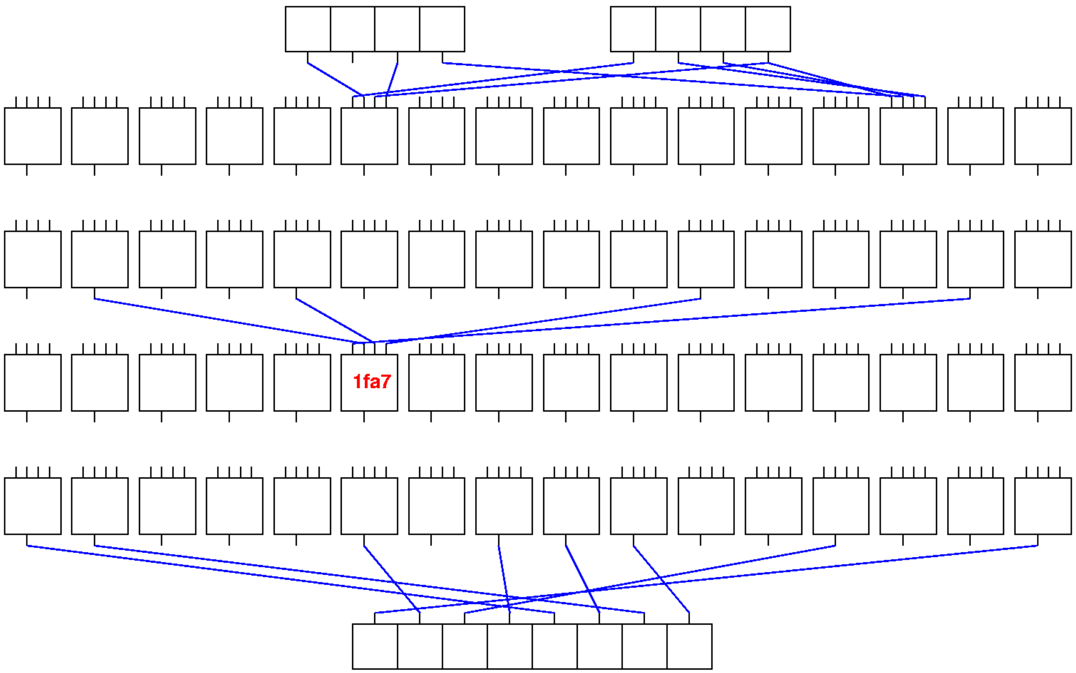
† Institute of Applied Mathematics and Physics, Zurich University of Applied Sciences, Winterthur, Switzerland
‡ Hakubi Center for Advanced Research, Kyoto University, Kyoto, Japan
‡ Nonequilibrium Physics and Theoretical Neuroscience, Department of Applied Analysis and Complex Dynamical Systems, Graduate School of Informatics, Kyoto University, Kyoto, Japan
♯ Artificial Intelligence Laboratory, University of Zurich, Zurich, Switzerland

Overview



MorphComp: Blur hard / software

Problem: Evolving a 4bit x 4bit Multiplier



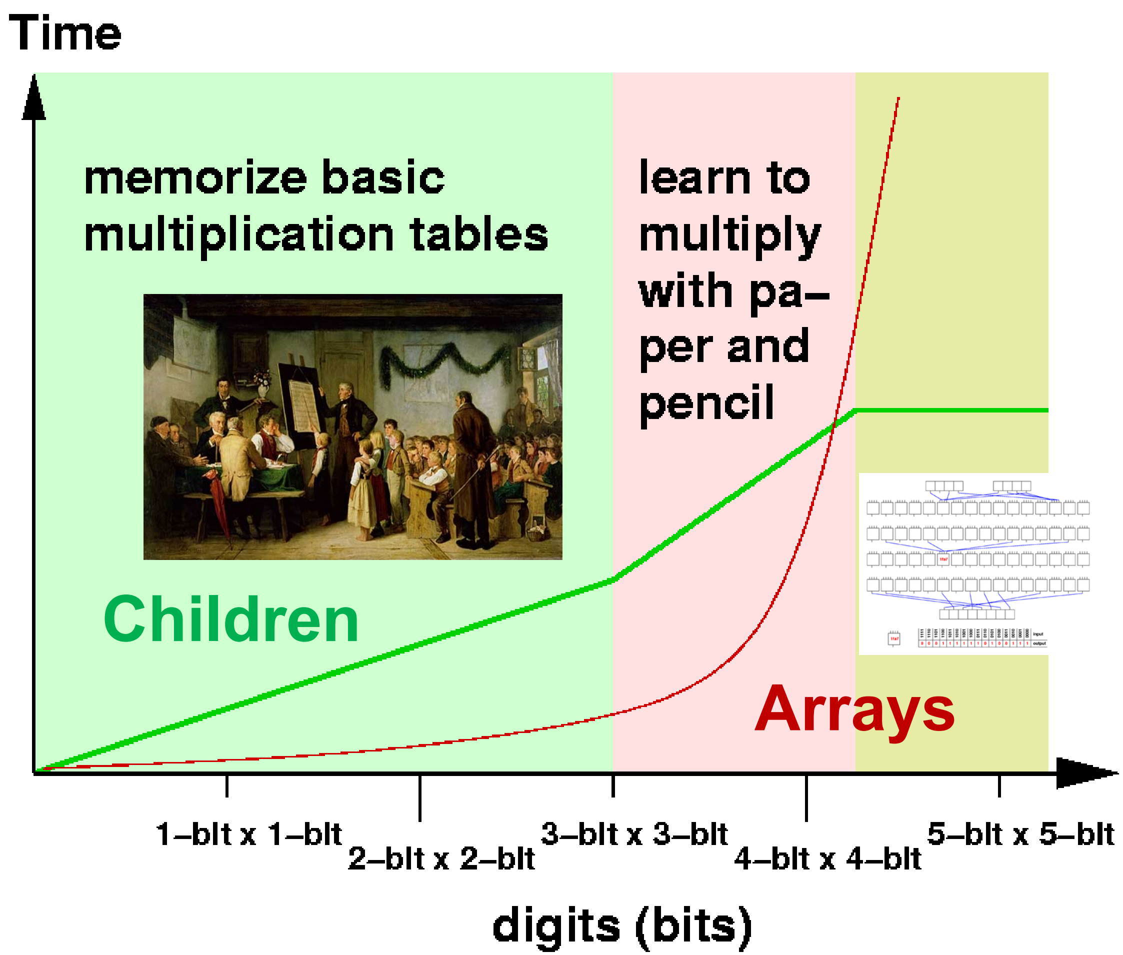
input	1111	1110	1101	1100	1011	1010	1001	1000	0111	0110	0101	0100	0011	0010	0001	0000
output	0	0	0	1	1	1	1	1	1	0	1	0	0	1	1	1

Each square represent a logical gate (4 input, one output).

The gates as well as the wiring is evolvable.

- Tangen Uwe.
- Miller, Julian.

Problem: Intelligent Learning

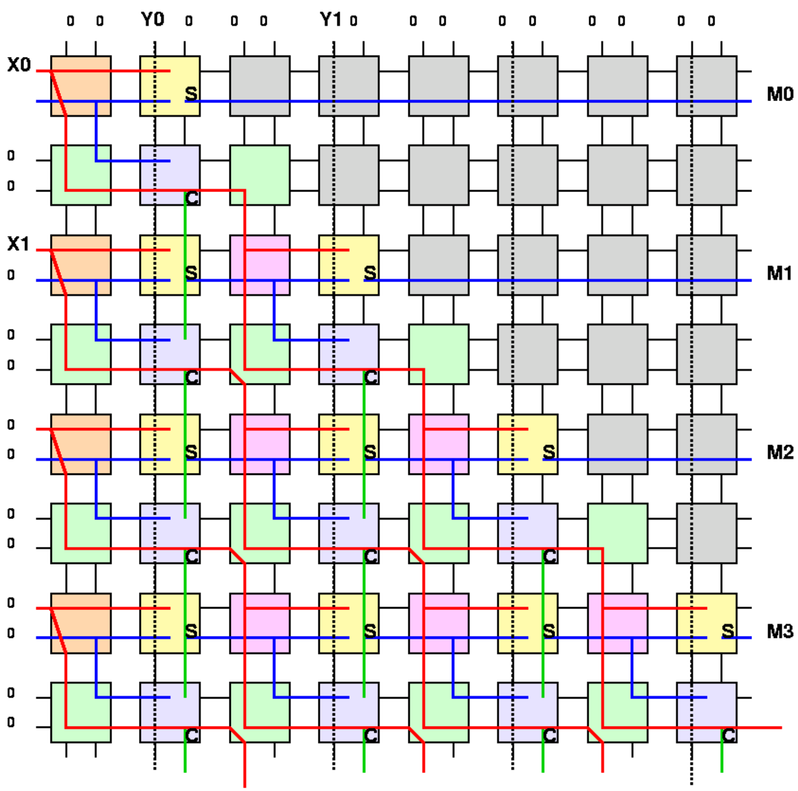


Such arrays of logical gates did not show good evolvability.

They never exhibited structure or could generalize results.

Patterned circuits

Many problems are solved by a regular arrangement of simple logical components.



X, Y: factors
M: Product
S: Sum
C: Carry

Rationally designed multplier

Patterned circuits

Global logic structure of a problem is transferred into the **geometry of the arrangement** of function generators.

Self assembly

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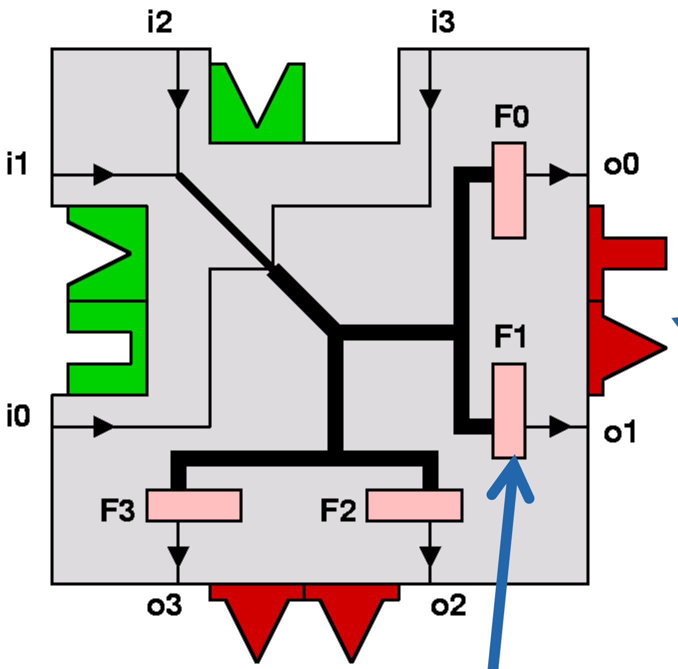
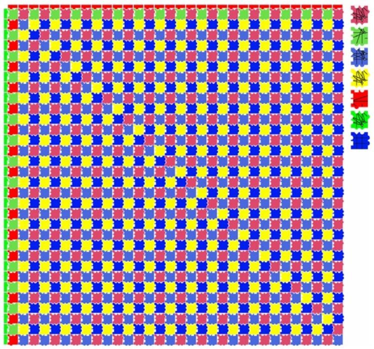
Scalable patterned structures can be obtained from self-assembling logical blocks (SLB).





Morphology = geometry

Recognition sites for self-assembly

Function generator

R. M. Füchslin, T. Maeke, U. Tangen, and J. S. McCaskill. **Evolving inductive generalization via genetic self-assembly**. Adv. in Compl. Systems 9: 1-29 (2006).

Patterned circuits

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Self – assembly enables patterned, scalable circuitry.

New genetic algorithm is needed to enforce it.

Co-Evolving Test-Vectors

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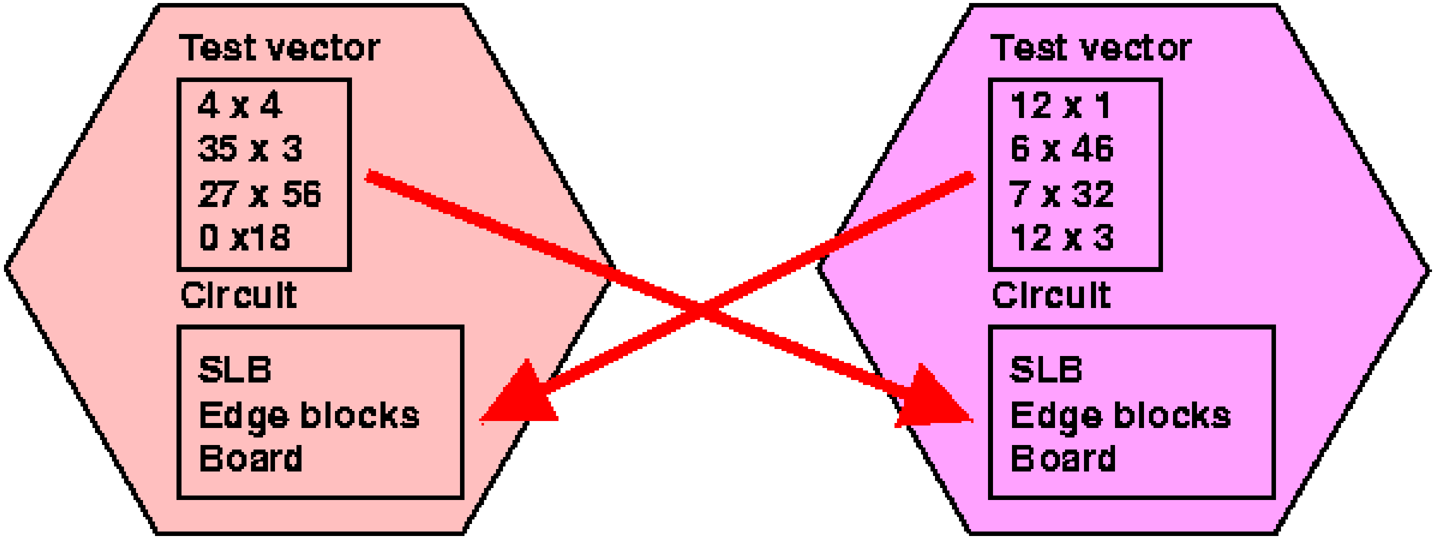

Each individual carries a construction scheme and a test vector, both evolvable

Tournament by mutual exchange of problems

Inductive Generalization: 8x8 bit multiplier

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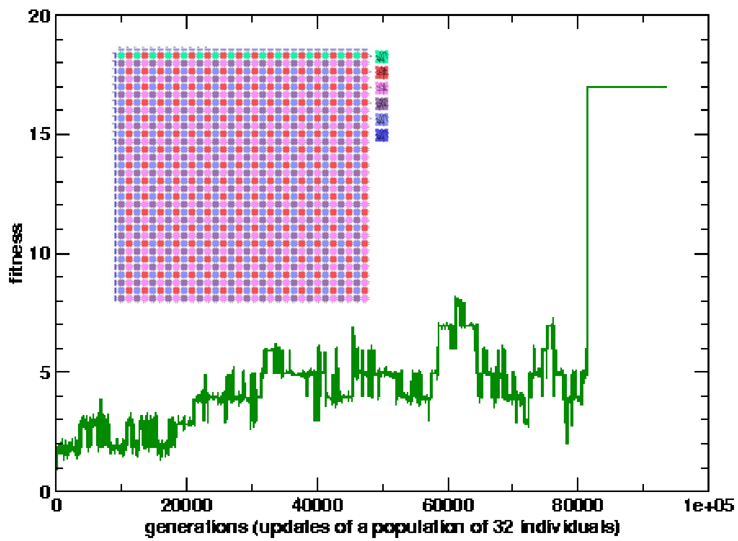
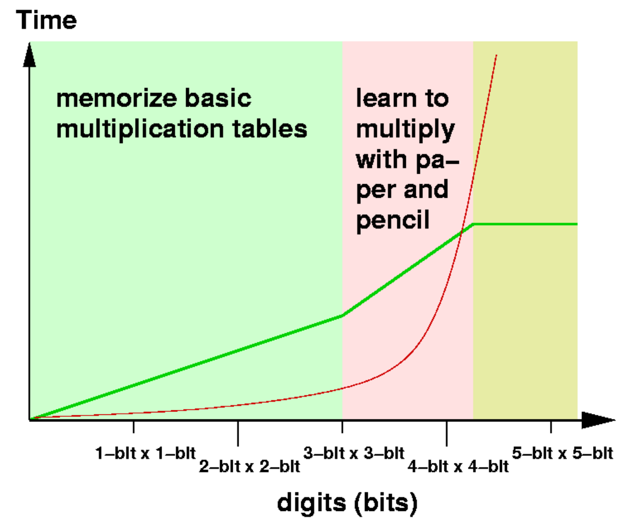
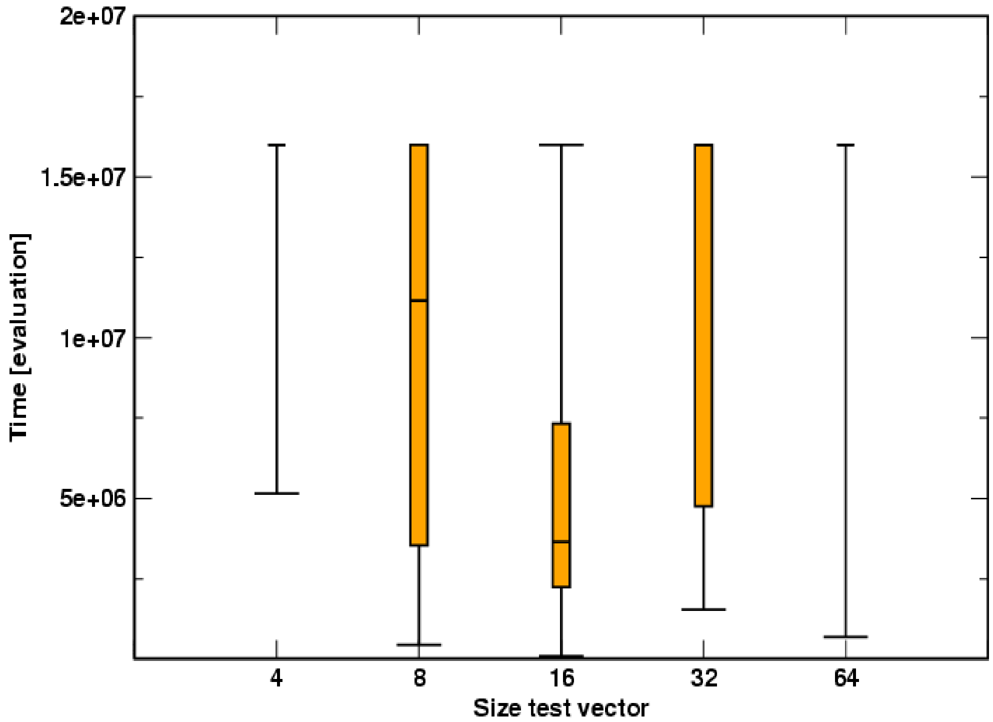




As soon as the circuit masters 4bit x 4bit („Das kleine Einmaleins“) multiplication, it can be scaled up to arbitrary size ➔ **inductive generalization.**

Size of Test-Vectors



32 runs for each testvector size, quartile box plots.

EITHER successful evolution of multiplier OR stop after 16 million generations.

For test vectors of size 4 or 64, more than three quarters of the runs didn‘t succeed.

Structural Subtask

1.

```
1101  x  0000
-------------
         0000
        0000
       0000
      0000
-------------
      0000000
-------------
```

mult. with zero

2.

```
0110  x  0001
-------------
         0110
        0000
       0000
      0000
-------------
      0000110
-------------
```

mult. with one

3.

```
1010  x  0100
-------------
         0000
        0000
       0100
      0000
-------------
      0010000
-------------
```

mult. with 2^n

4.

```
1010  x  1001
-------------
         0000
        1001
       0000
      1001
-------------
      1011010
-------------
```

carryless addition

5.

```
1001  x  1011
-------------
         1011
        0000
       0000
      1011
-------------
      1100011
-------------
```

full addition

Key Point of Test Vectors

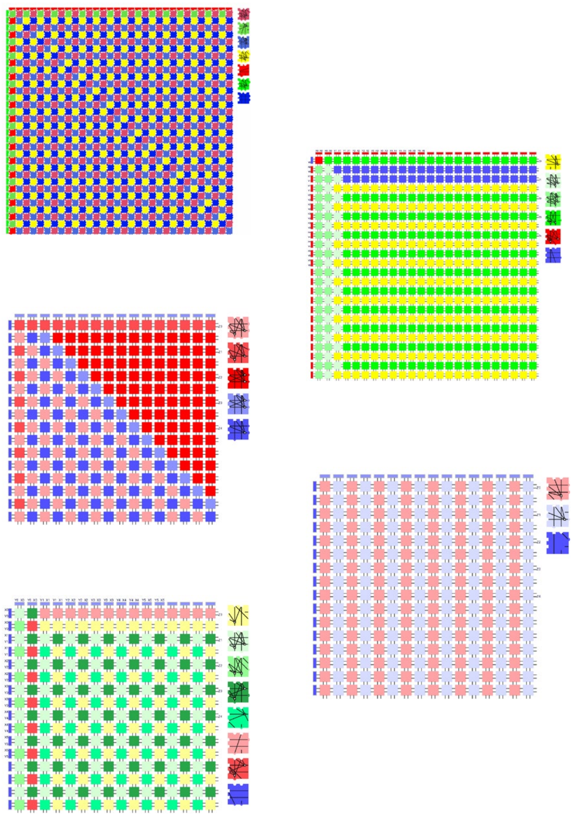
- Information is only **preserved** when **regularly tested**
- **“Learning”** the solution of a **specific** problem is of limited value; it will be forgotten in the **drifting population of test problems**
- **“Understanding”** how to handle a **whole class of problems** can be maintained.

Key Point of Test Vectors

If a circuit „stores“ the result of 13*2, the benefit is temporary, if it implements diagonal shifts for the multiplication with powers of two, a permanent gain results.

Is Self-Assembly Versatile?

- multiplier
- ALU
- binary to Gray-code
- Gray-code to binary
- binary in, add, Gray code out



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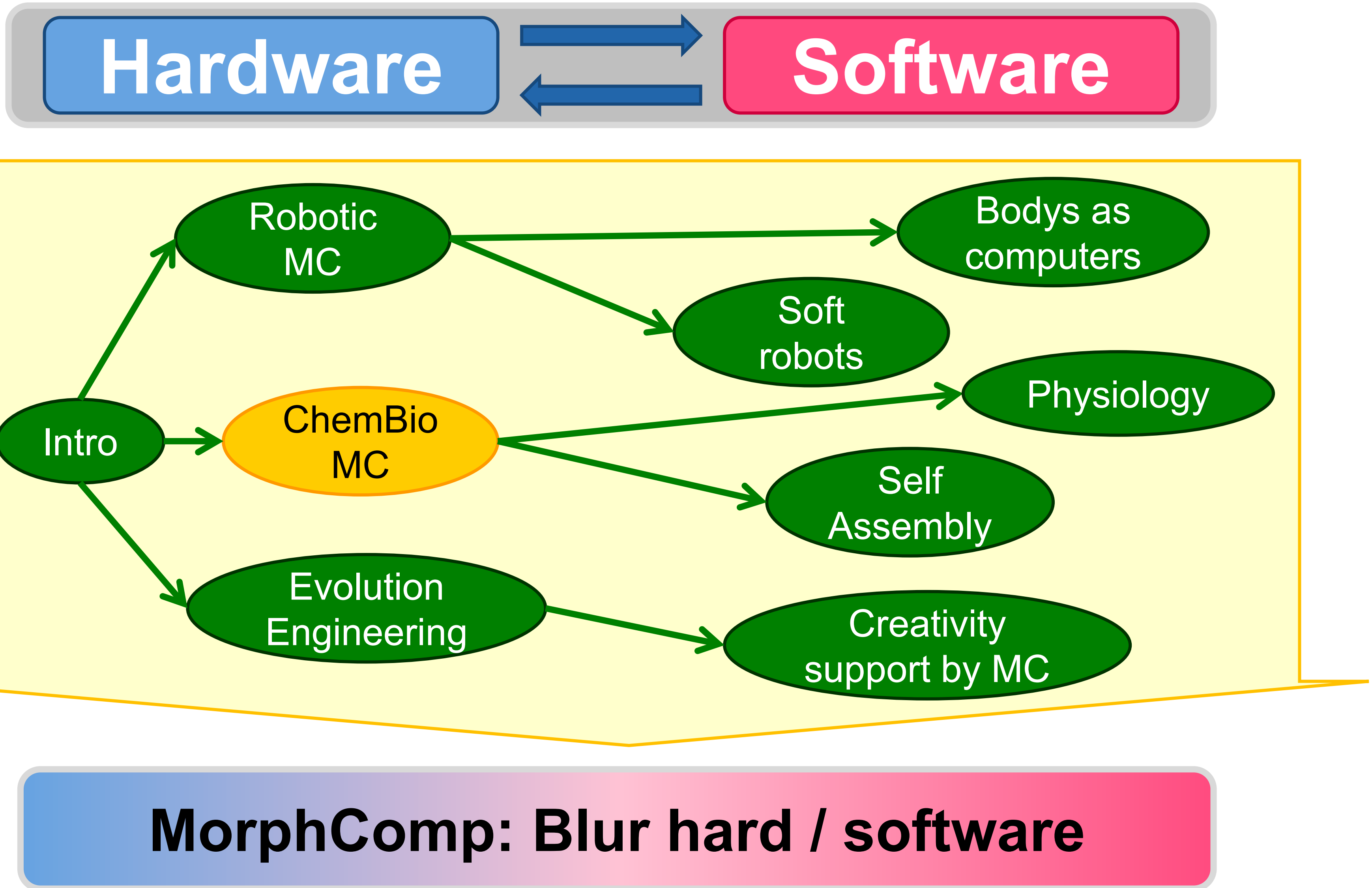

Embodied Process Control

$$\frac{\text{Embodied Intelligence in Robotics}}{\text{Classical Mechanics}} = \frac{\text{Embodied Process Management in Chemistry}}{\text{Statistical Mechanics}}$$

Morphology

=

Chemistry + supramolecular compounds + membranes + …

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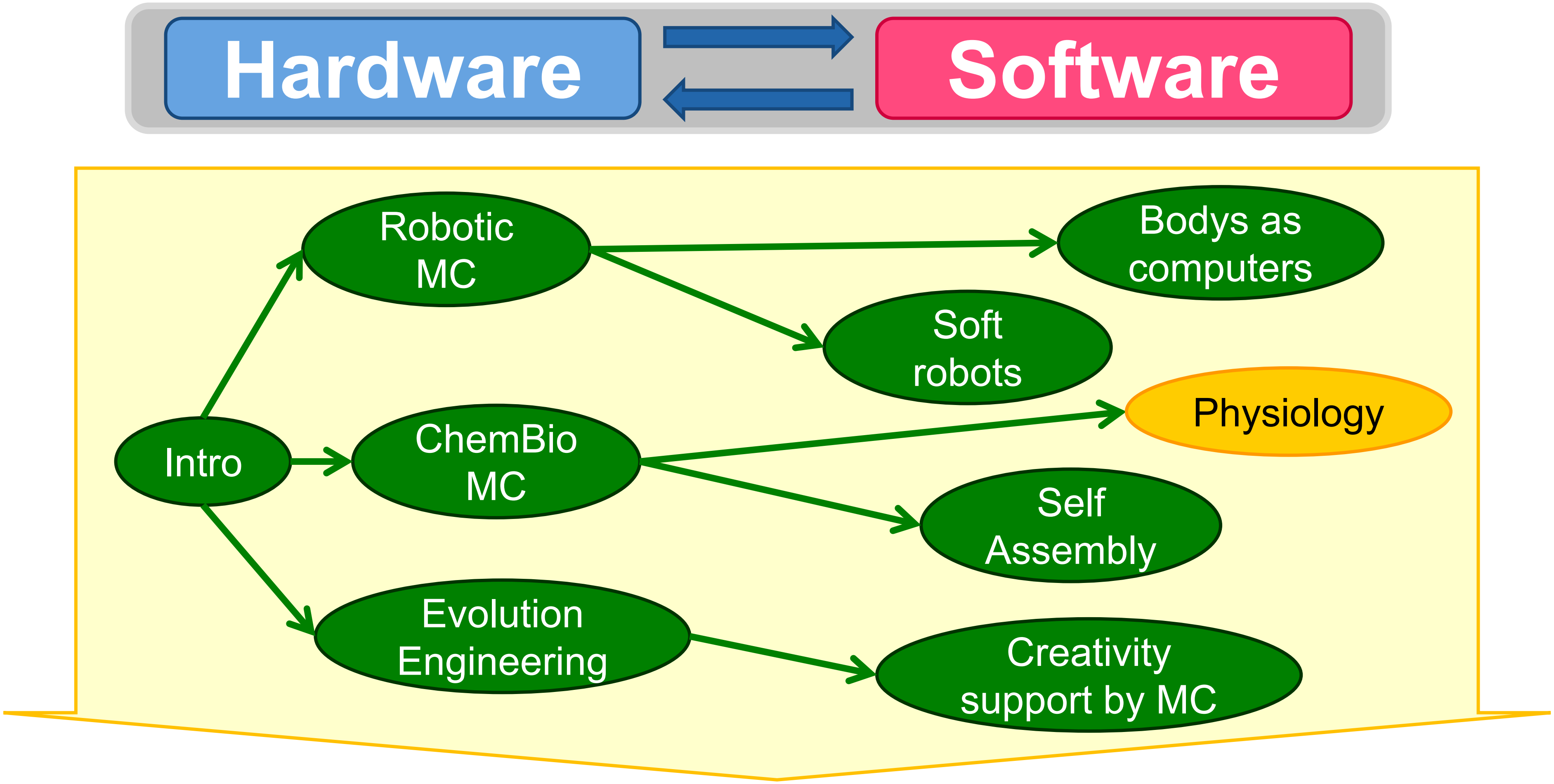

MorphComp: Blur hard / software

Cells: The Network Picture

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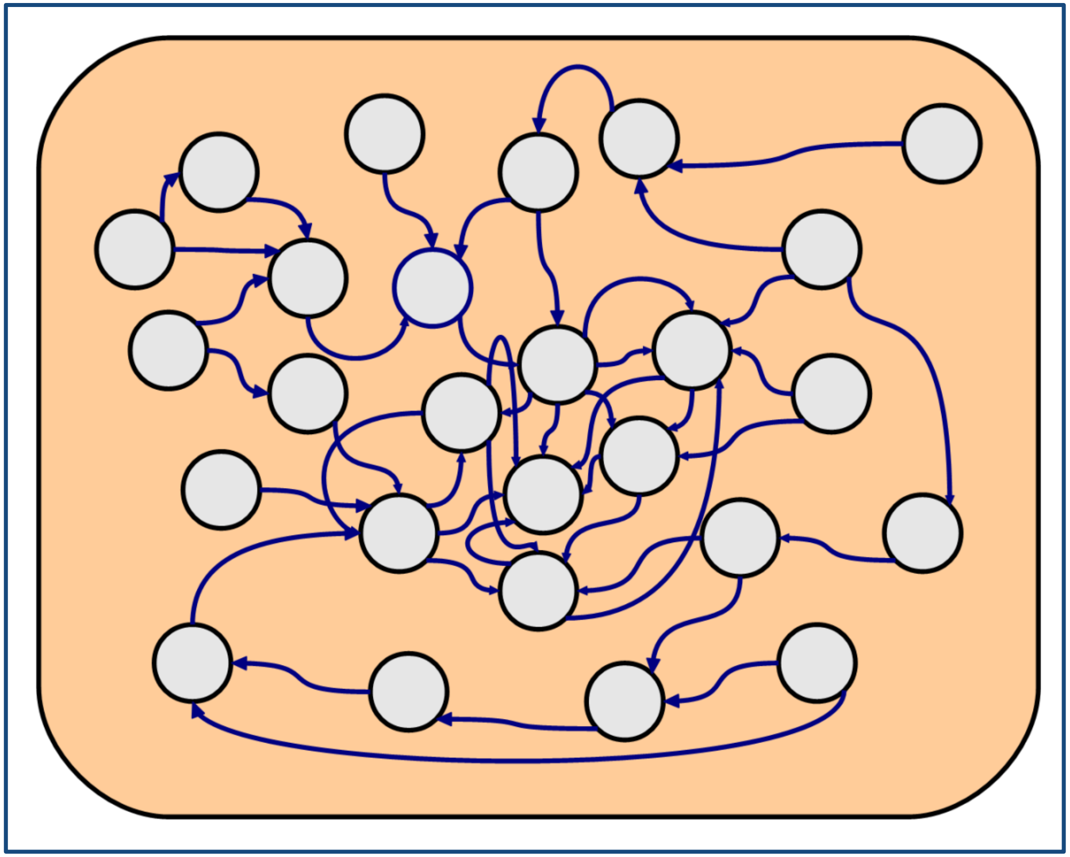
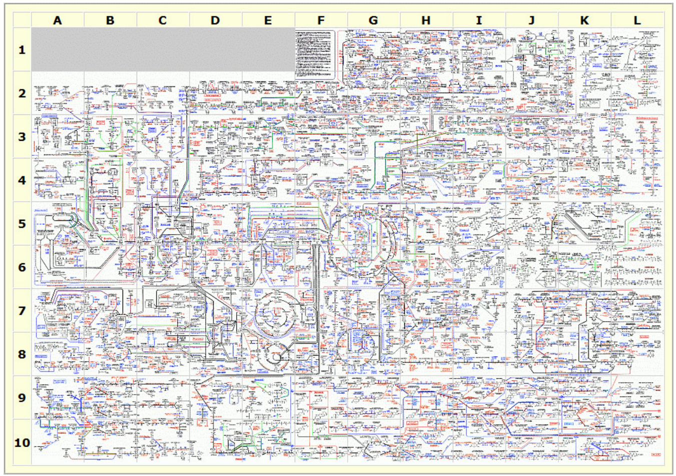


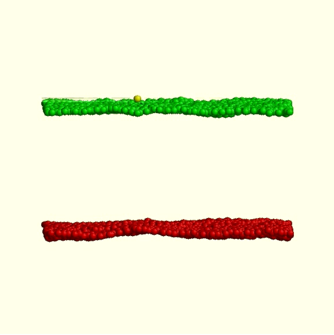


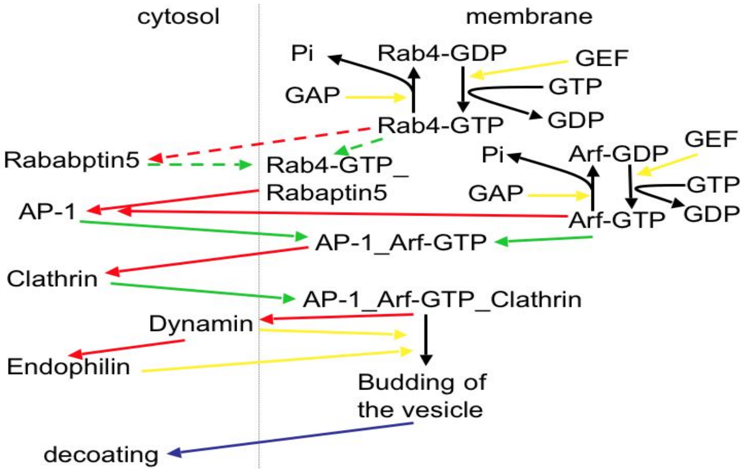
Cell as a dynamical network of physico – chemcial interaction

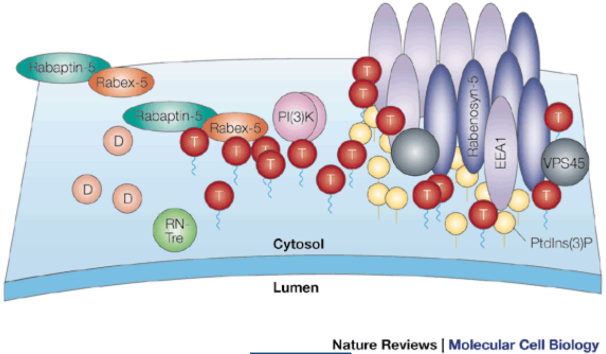
Multi – Scale Processes: Endocytosis

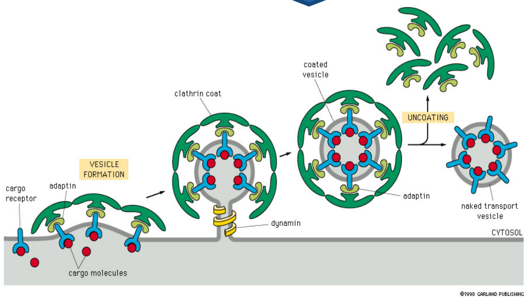
Receptor – mediated endocytosis:

- Chemical reactions
- Supramolecular self – assembly
- Membrane physics







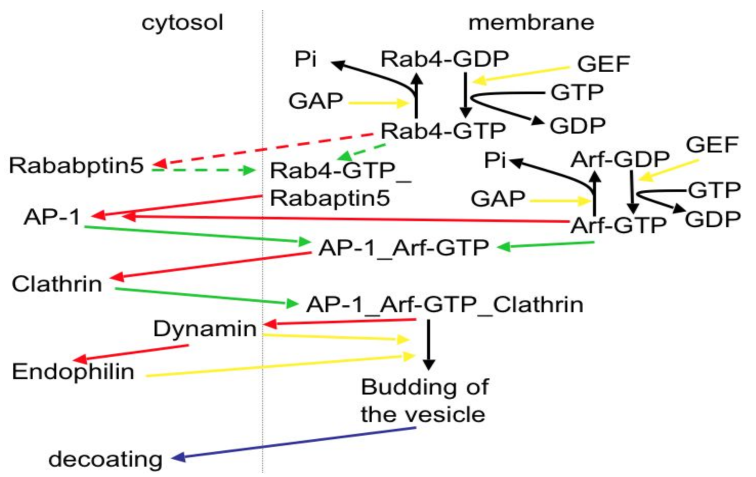


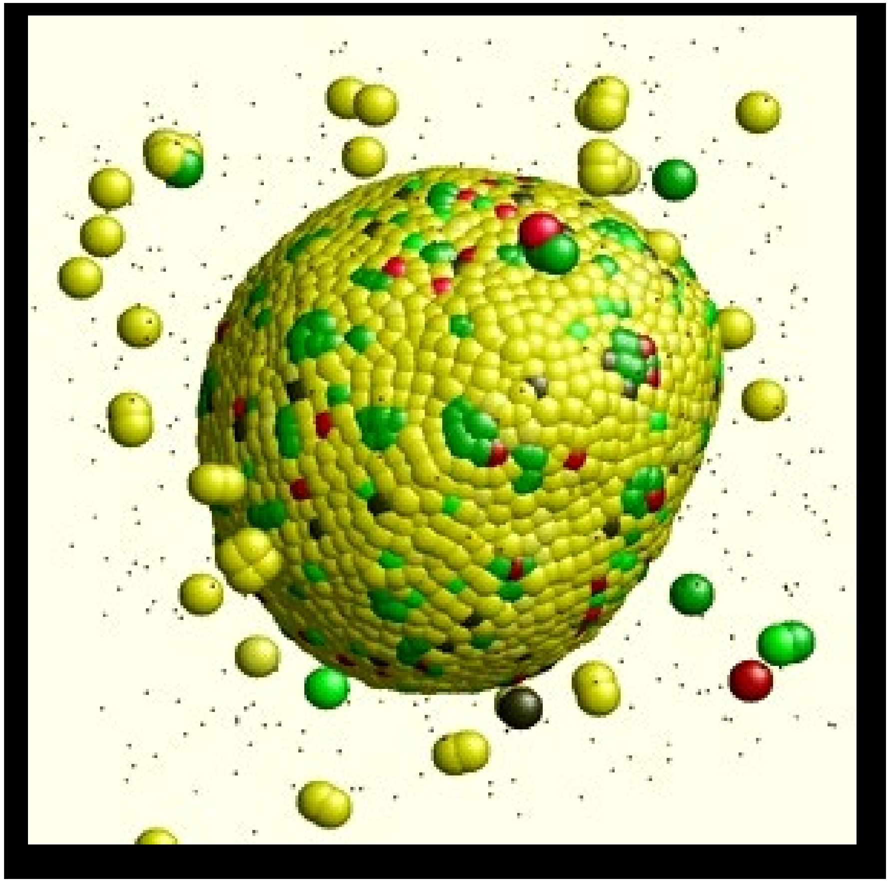
M. Zerial

H. McBride

Endocytosis is an attractor of a non – equilibrium system.

Endocytosis





Lesson learnt: Molecular pathways have to be complemented by multi-scale dynamics.

R. M. Füchslin, T. Maeke, and J. S. McCaskill (2009). *Europ. Phys. J. E: 29:4 p 431-448.*

Visualization: N. Mennes and T. Maeke

Two Types of Diseases

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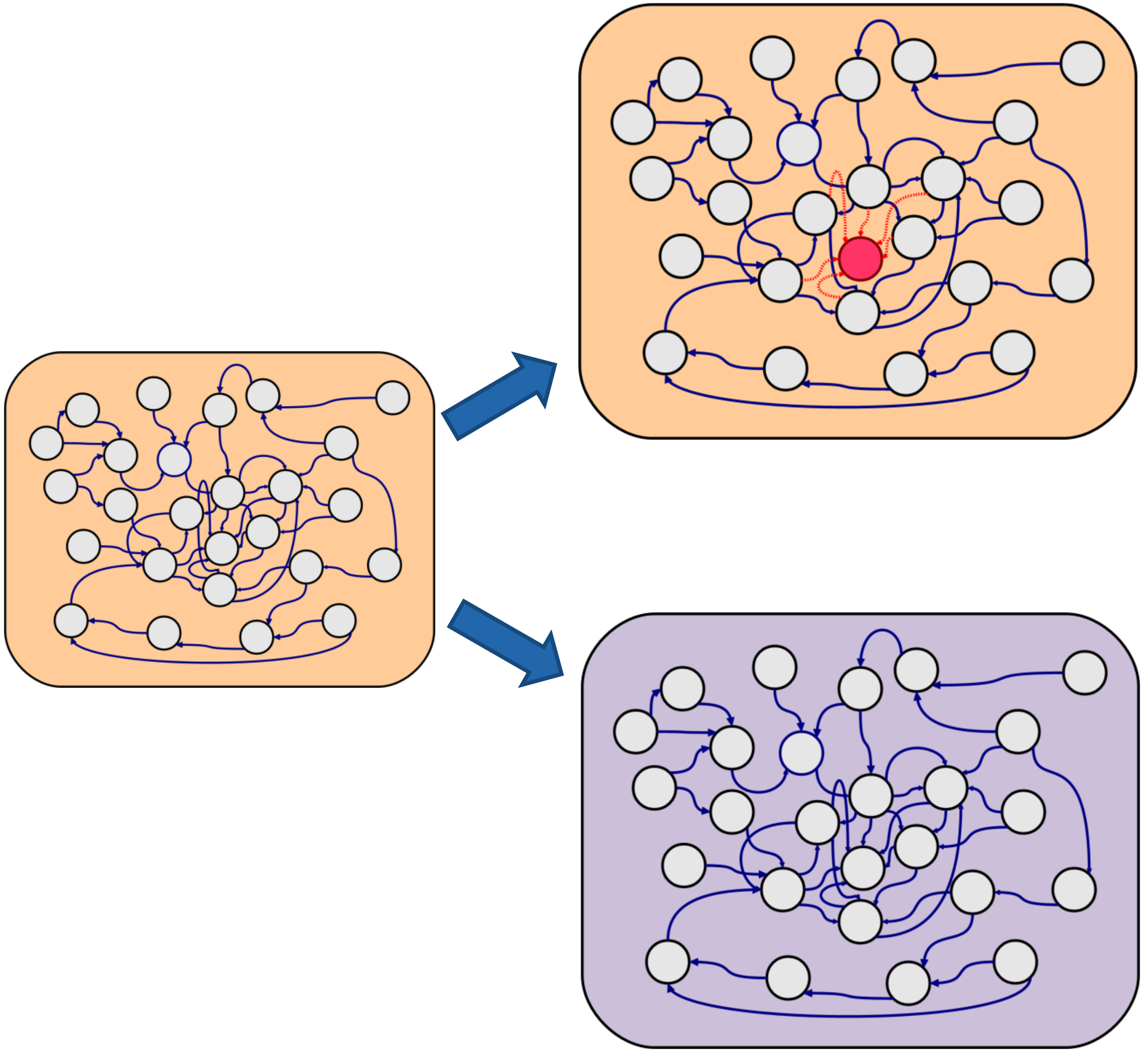


One ore several nodes are dysfunctional ➔ network functionality may be affected.

All system components are functional, but system is in wrong basin of attraction.

Evolutionary Medicine

OPINION

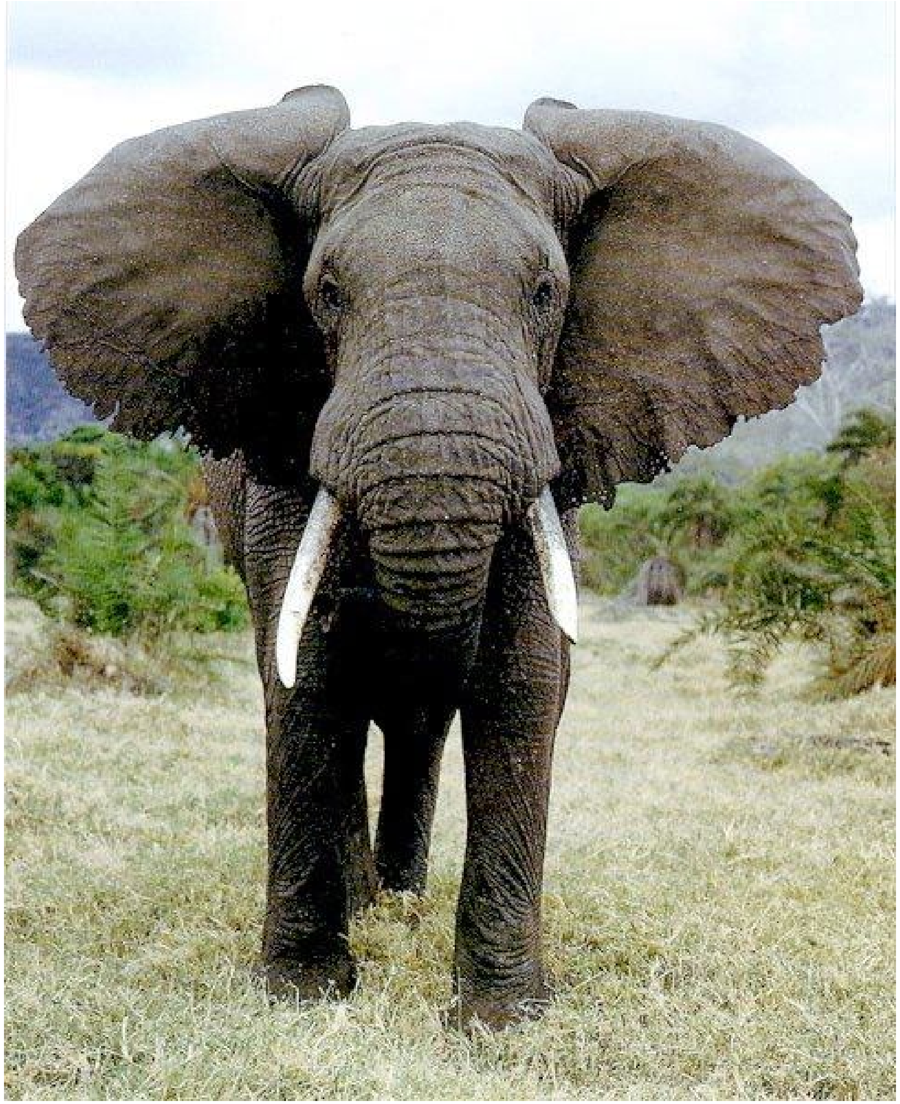
Darwinian medicine: a case for cancer

Mel Greaves

Abstract | Epidemiological, genetic and molecular biological studies have collectively provided us with a rich source of data that underpins our current understanding of the aetiology and molecular pathogenesis of cancer. But this perspective focuses on proximate mechanisms, and does not provide an adequate explanation for the prevalence of tumours and cancer in animal species or what seems to be the striking vulnerability of *Homo sapiens*. The central precept of Darwinian medicine is that vulnerability to cancer, and other major diseases, arises at least in part as a consequence of the 'design' limitations, compromises and trade-offs that characterize evolutionary processes.

M. Greaves, Nature Reviews Cancer 7, 213 – 221 (2007).

Mice and Elephants



Cells as Dynamical Systems

OPEN ACCESS Freely available online
PLoS one

A Dynamical Model of Genetic Networks for Cell Differentiation

March 2011 | Volume 6 | Issue 3 | e17703

Marco Villani[1,2], Alessia Barbieri[1], Roberto Serra[1,2]*

1 Modelling and Simulation Laboratory, Department of Communications and Economics, University of Modena and Reggio Emilia, Reggio Emilia, Italy, 2 European Centre for Living Technology, Venice, Italy

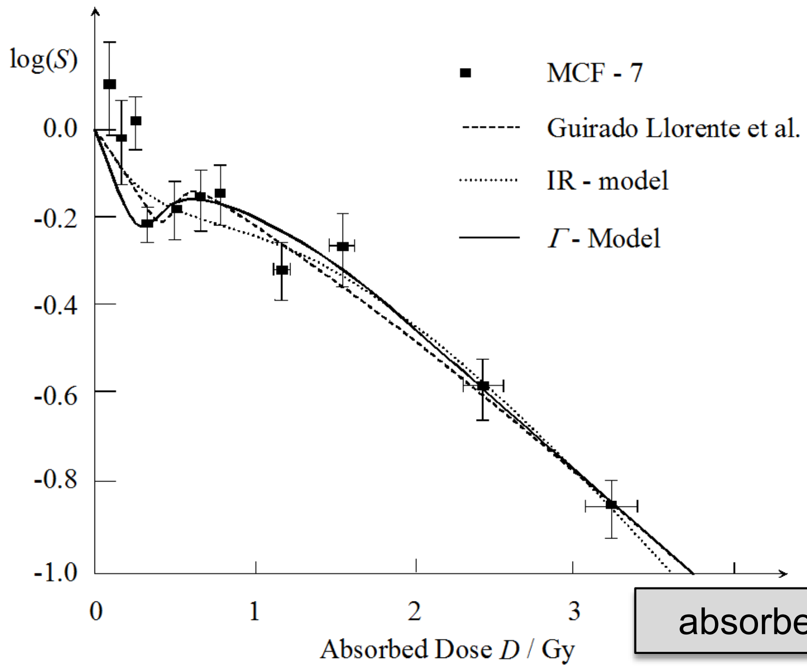
M. Villani

R. Serra

Use of abstract random Boolean networks.

A Puzzle in Radiotherapy

log of survival rate



absorbed dose

S. Scheidegger

Conundrum: Reaction of cells to irradiation highly non-linear. "The more intensity, the more (long-term) damage" does not hold (Fig. by S. Scheidegger).

Scheidegger, S.; Füchslin, R.M.; Timm, O.; Eberle, B.; Bodis, S. (2015). **A novel approach for thermal dosimetry**. In: Proc. of the ESHO Annual Meeting 2015. (26). Zurich: European Society for Oncological Hyperthermia.

Embodied Process Control

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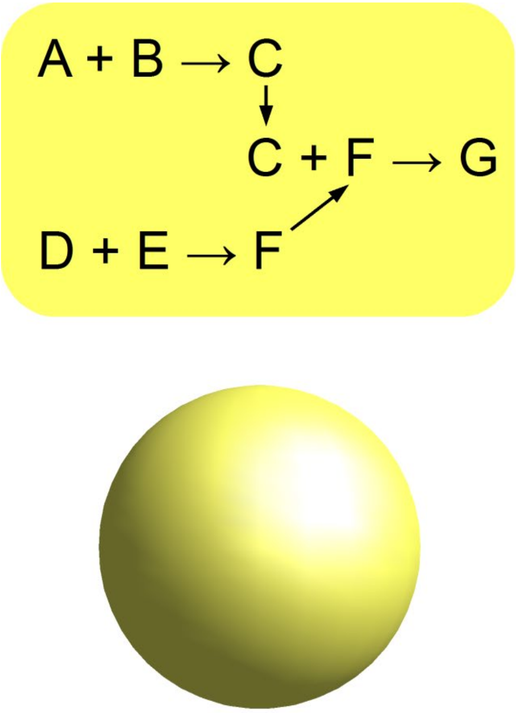

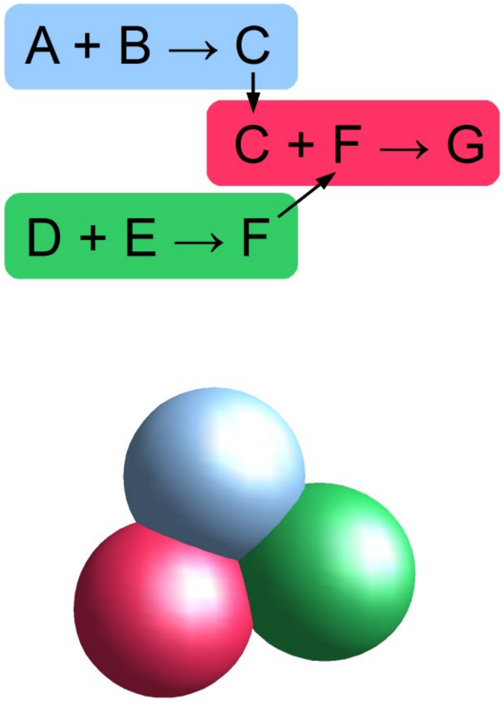

Conditions have to be suitable for all reactions.

Reactions take place in an optimal environment

Optimization by Compartmentalization

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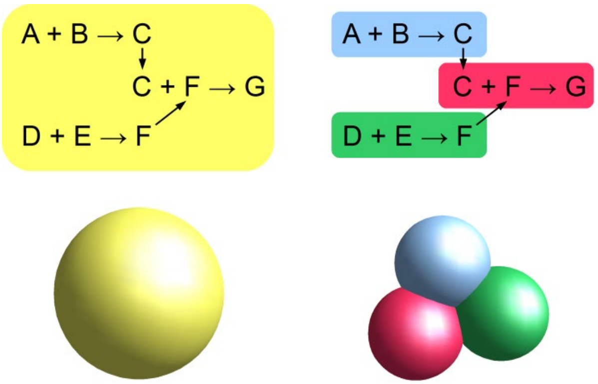
- **Pro: Compartmentalization ➔ optimization by branch-specific choice of chemical conditions.**
- **Con: Matter and information has to be transported between the compartments.**



Programming by Arranging

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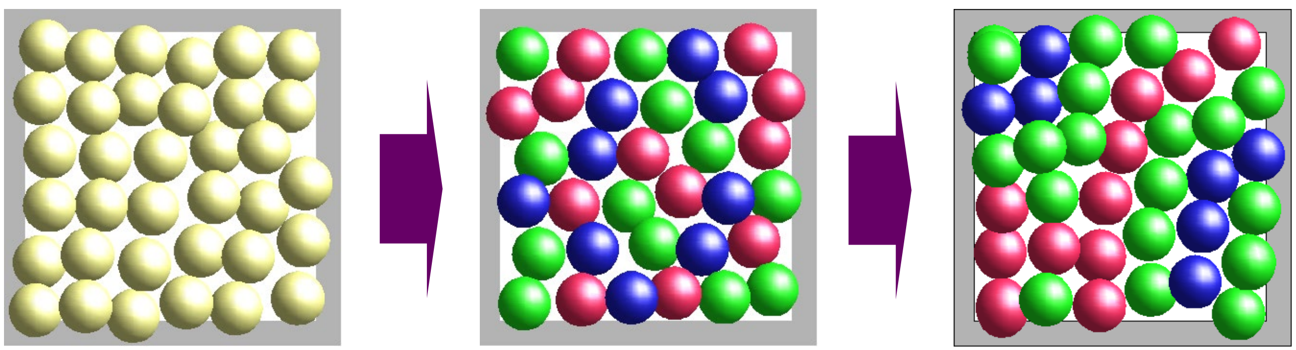
- Matter and signal transport takes place between **adjacent containers**.
- The **arrangement influences the overall reaction**.

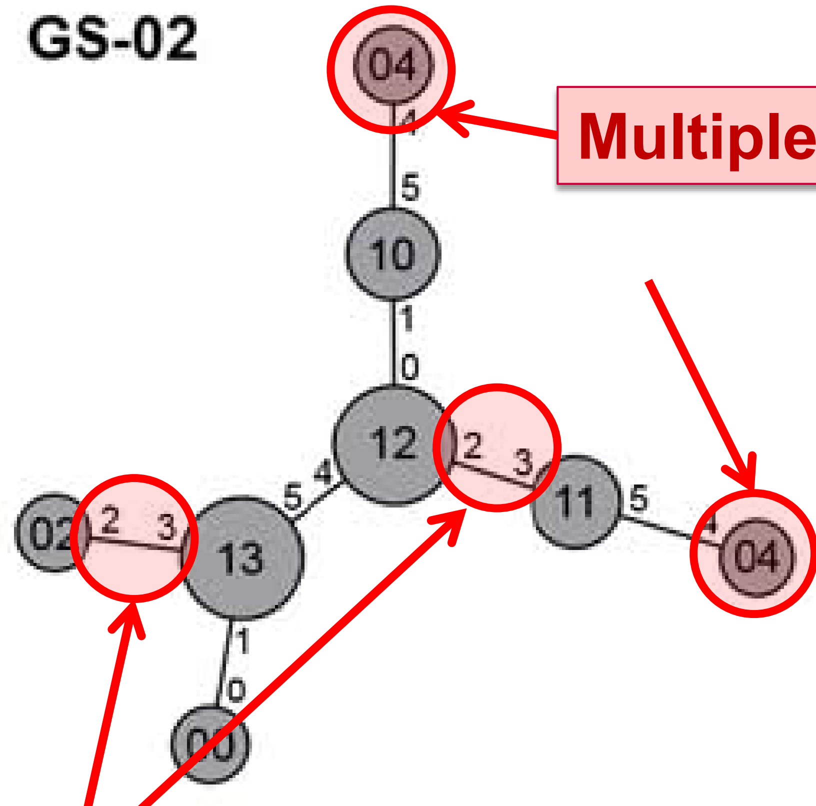


Optimization by compartmentalization

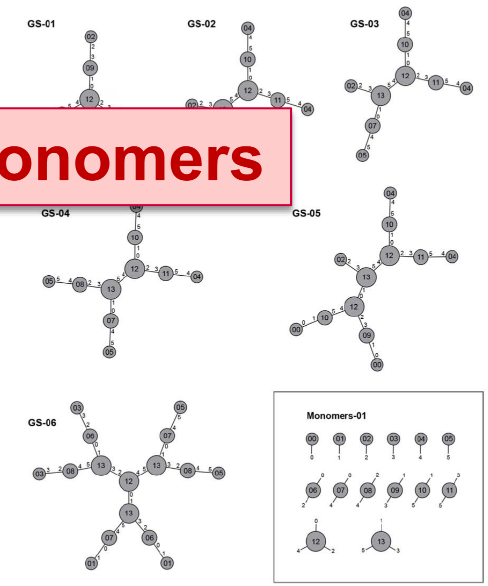
Control by influencing matter transport

Artificial Branched Molecules

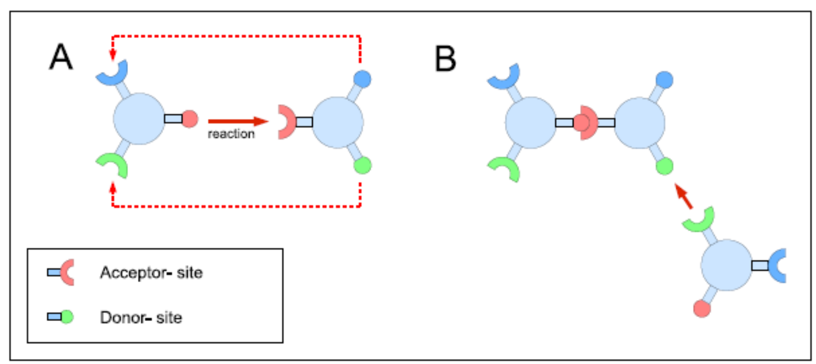
GS-02



Multiple use of monomers



Same linkers allow wrong assembly



Monomer: Up to 3 linkers

Synthetizing Branched Molecules *in silico*

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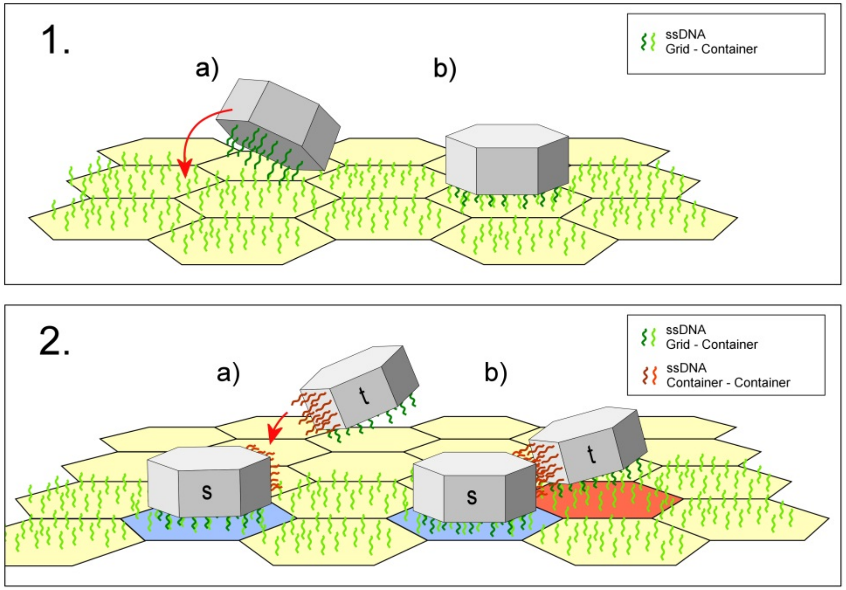
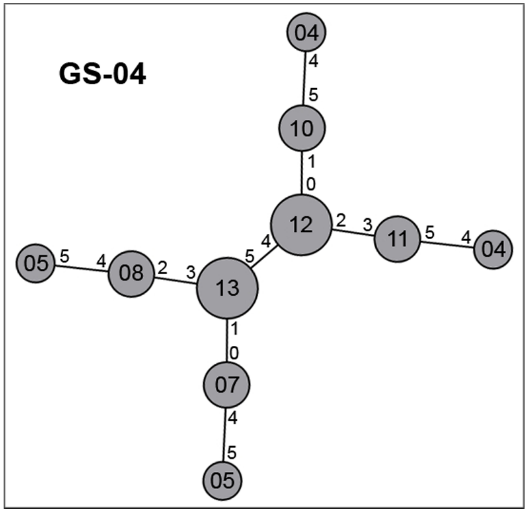
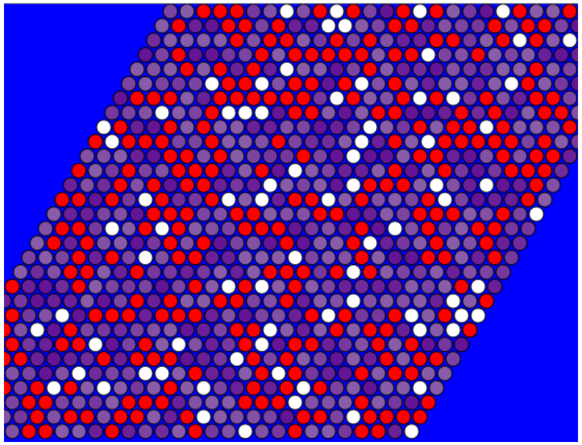




- Each type of container performs a specific synthesis step.
- Containers arranged by stochastic self-assembly.

Benedikt Reller, R. Füchslin (MATCHIT)



MATCHIT Automaton

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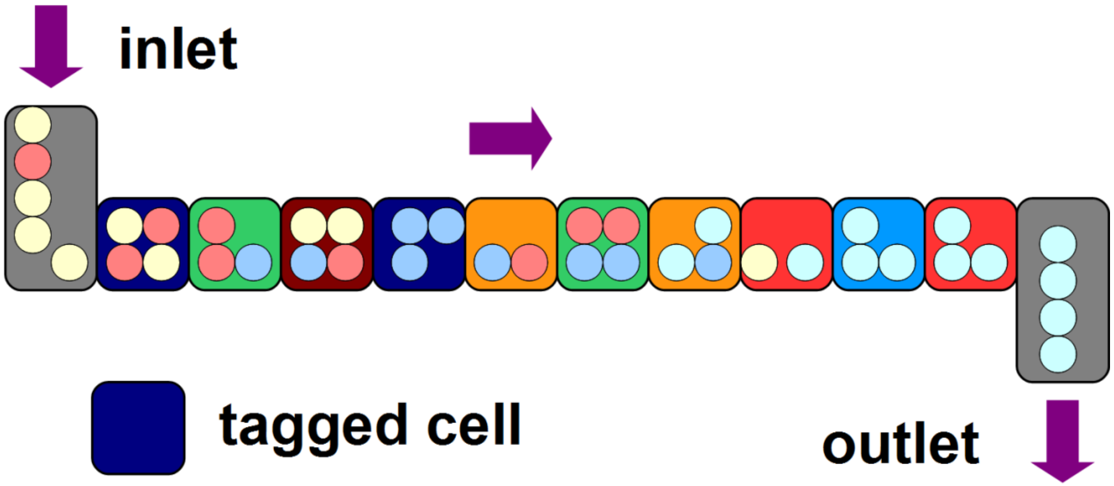


D. Lancet, S. Rasmmussen

J. McCaskill

Mathias Weyland

- 1 dim channel
- So called chemtainers (e.g. vesicles) interact with channel and each other.
- Control by DNA – computing

Weyland, M. S.; Fellermann, H.; Hadorn, M.; Sorek, D.; Lancet, D.; Rasmussen, S.; Füchslin, R.M. (2013). **The MATCHIT Automaton: Exploiting Compartmentalization for the Synthesis of Branched Polymers. Computational and Mathematical Methods in Medicine**, 2013, Article ID 467428.

Evolution vs. Compilation

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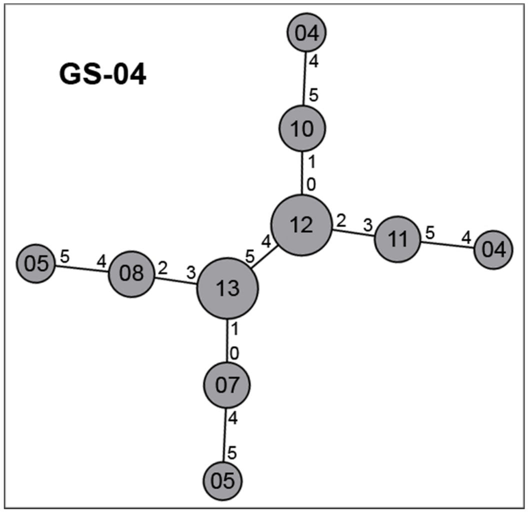
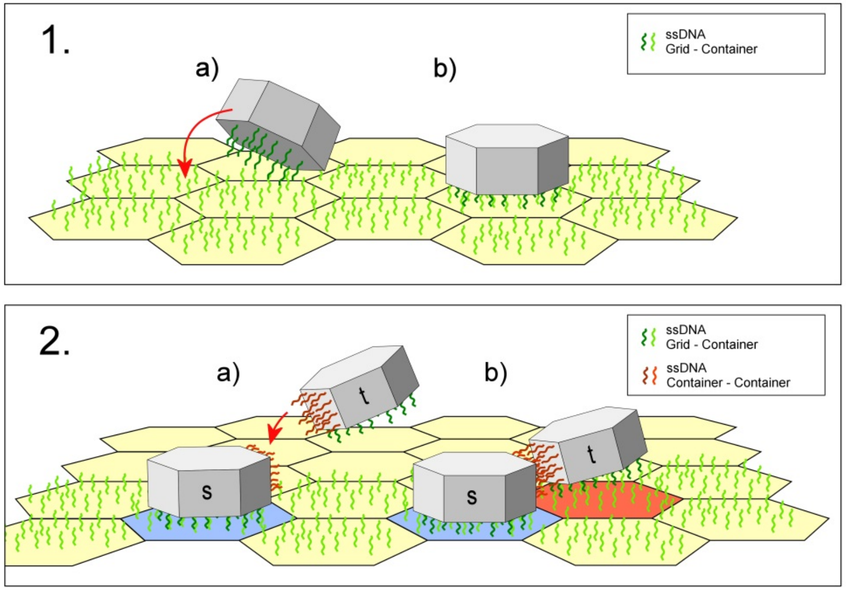
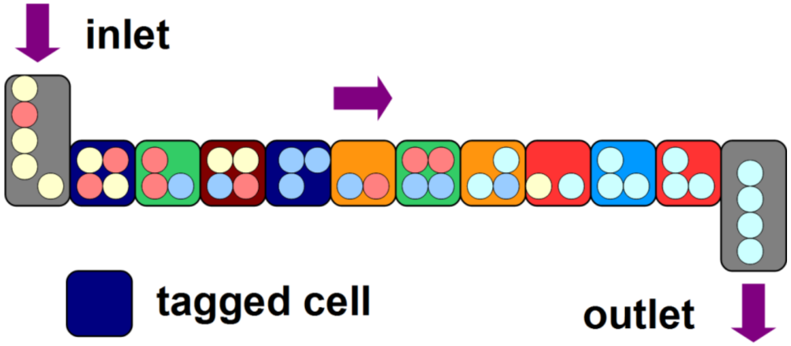






Evolved

Compiled

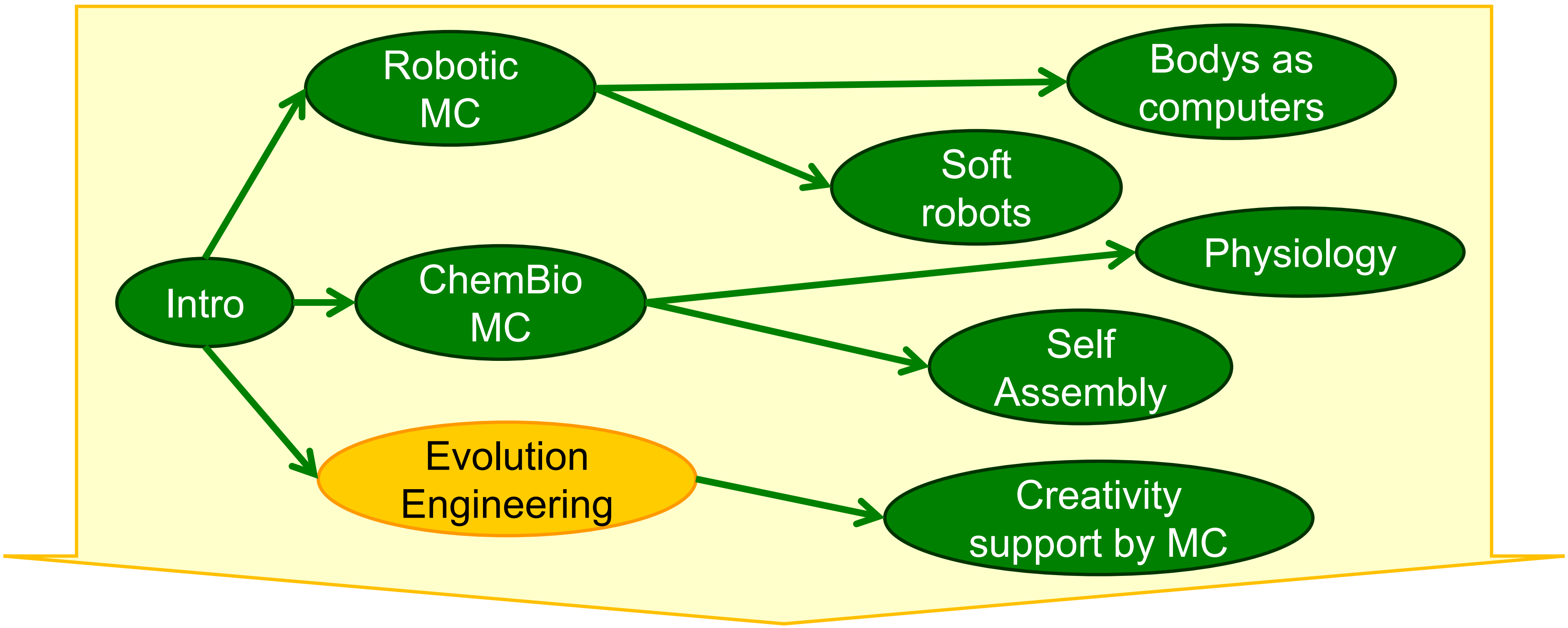
Golgi Apparatus

http://jennarever.weebly.com/index.html

Production of oligosaccharides (among other things)

Overview

Hardware ⇄ **Software**



MorphComp: Blur hard / software

Rational and Evolutionary Design

- Humans tend to design in a modular manner: The resulting structures are comprehensible. **This comprehensibility supports rational planning and usage.**
- **Nature has no rational**; solution only need to be effective but don't need to be comprehensible.
- Evolution can only perform optimizations which immediately yield a benefit, but not follow e.g. "platform strategy" which deliberately facilitates future extensions**.** **The evolutionary approach yields efficient and yet robust solutions**

Living Technology Manifesto

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Living technology aims at developing and exploiting the combination of both approaches: **The structural unboundedness of evolution with the potential of human foresight.**

Living Technology does not only transfer the **means** of nature in an artificial and designed context but also tries to learn from nature's **ways** (organization and process control).

Overview

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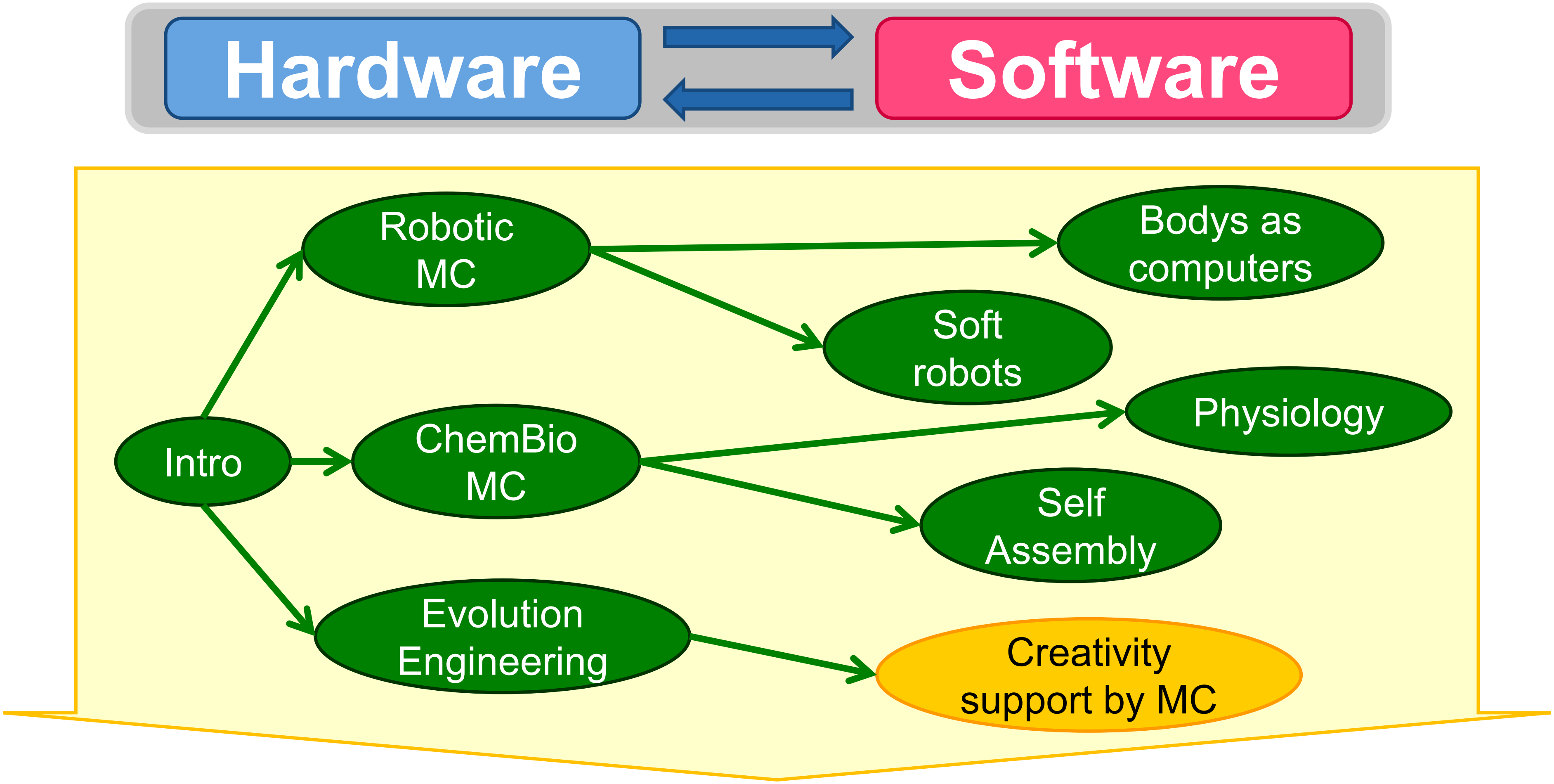

MorphComp: Blur hard / software

Understanding Life?

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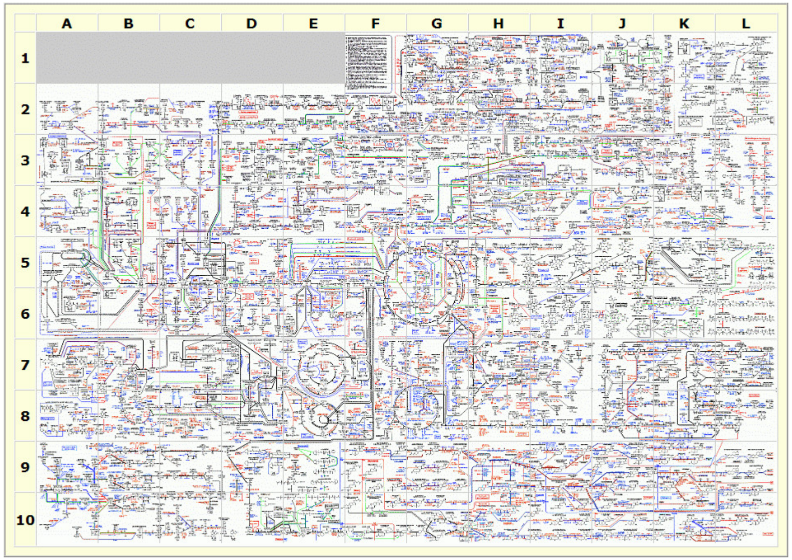

?

Analyzing Evolved Structures

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If one analyzes biological systems always observe:

- **Genotype encodes the physiology and is subject to variation / inheritance.**
- **Phenotype is the subject of selection.**

Genotype ↔ Syntax

Phenotype ↔ Semantics

Analyzing Evolved Structures

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If you want to understand an evolved system, consider:

- **You will not understand a program such as Powerpoint by analyzing the dynamics of the bits and bytes in your laptop.**
- **You will not understand the content of a book by counting the frequency of individual letters in a text.**

Analyzing evolved systems requires to find level of semantics, not the one of syntax!

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European Centre for Living Technology

- Research
  - Living Technology
  - Applied Statistics
  - Complex Systems
  - Social Sciences
  - Environmental research

Some Results, Some Claims

- **Morpho - computational power of body may be restored by mechanical means.**
- **The dynamic systems perspective opens a new look on cell dynamics.**
- **Logic can be transferred into geometry and self – assembly can support induction.**
- **Spatially structured reaction environments: Synthetizing branched polymers.**
- **Morphological control offers a non – enumerative mechanism for protecting replication systems.**
- **From an engineering perspective, a coupling between nervous and immune system is plausible.**

Acknowledgements

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- D. Lancet
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- R. Luchisnger
- J. McCaskill
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- N. Packard
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- M. Weyland

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THANKS
for your
Attention!

Abstract

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Present computer science distinguishes sharply between hard- and software. Stripping off all physics from the abstract concept of computation yields such wonderful results as higher – level languages, abstraction and portability. However, there is a price to pay: Controlling physical processes, e.g. a robot, requires bringing back physics via a lot of coding. Additionally, distinguishing hard- and software may facilitate the work of human engineers and programmers but seems to be less relevant in control systems resulting from an evolutionary process.

This talk presents the concept of morphological control. The physical dynamics of a computing system are not anymore regarded as something that, in the best case, doesn't disturb a computation but is an essential part of it. In short, morphological control exploits physical dynamics for control purposes. This approach requires a close collaboration between experts from computer science, dynamical systems theory, control theory and machine learning. Morphological control offers new perspectives to Creativity Support Systems by presenting a control paradigm that is intended to be closer to biological systems. Biomimetic technology aims at exploiting the ways and means of nature for the purpose of optimizing engineered systems. Whereas most bionics focusses on the means (materials), the focus in morphological control is put on the ways (organizational principles) and to learn how nature's evolved process management can be used in rationally planned engineering.

Most often, morphological control is illustrated by and used for applications in robotics. Our interpretation broadens the concept and includes also systems that are governed statistical mechanics. This means that also cellular dynamics can be understood from the perspective of morphological control. With respect to applications, this talk also includes instances of morphological control in biology and medicine and analyses them from a practical as well as theoretical perspective.nt computer science distinguishes sharply between hard- and software.

Question (Roland Scholz, ETHZ): Is there a non – enumerative way to detect non - default states in the states of tissues?

Danger Signals

- Classical view (simplified): The adaptive immune system learn to discriminate between the self and the non - self.
- P. Matzinger developed an alternative view: The immune system is activated by general signs of danger, not (only) by foreignness.
- Among other things, the model explains
  - Why the immune system can respond to tumors
  - Why one needs adjuvents to make vaccines effective.

Polly Matzinger: The Danger Model: A Renewed Sense of Self, Science 296, 301 (2002)

Detecting Danger by Morphology

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- Fact: Chain molecules may fold up and get a non – trivial morphology.
- Fact: This fold is determined by
  – the molecules sequence (proteins: amino acids)
  – the conditions under which the fold takes place.

Detecting Danger by Morphology

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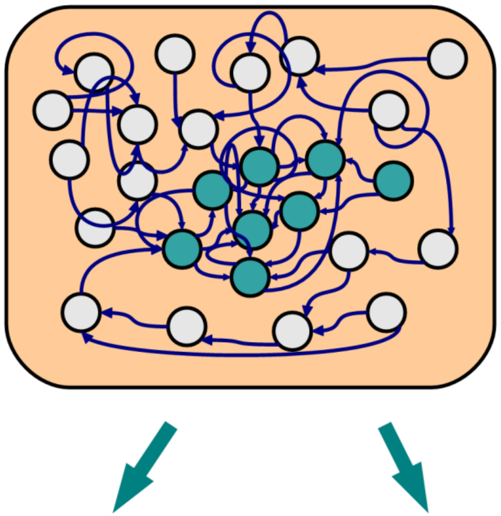
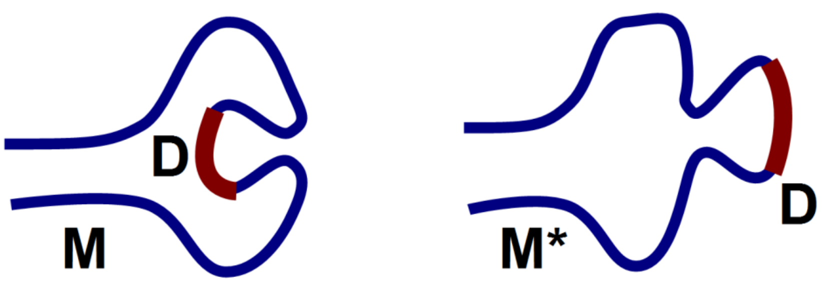
Cell with subnetwork



Assume a molecule M with a fold that is evolved to be highly susceptible to chemical conditions

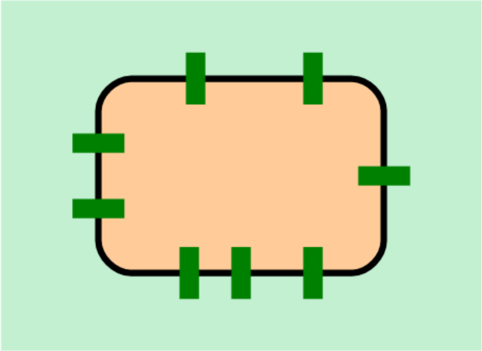


Default fold

“Something is wrong” fold
Epitope D activates IS

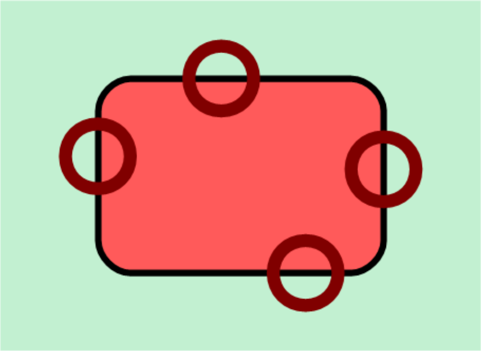
Detecting Danger by Morphology

Cell ok
Environment ok
➔ Default fold



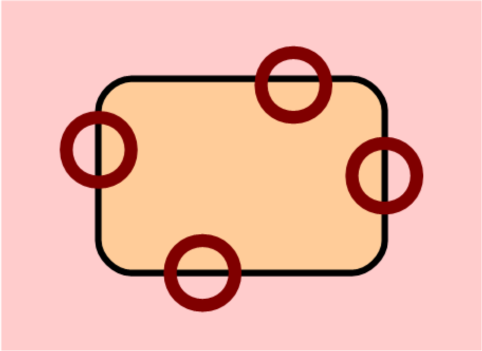
Immune system remains passive

Cell not ok
Environment ok
➔ Danger fold



Immune system activated

Cell ok
Environment not ok
➔ Danger fold



Immune system activated

Detecting Danger by Morphology

- Morphology of the molecule is sort of a "checksum".
- We don't claim that the mechanism is present in biological systems, but it may be implemented in artificial evolvable replication systems.

John McCaskill

Stephan Altmeyer

S. Altmeyer, R. M. Füchslin, J. S. McCaskill, “Folding stabilizes the evolution of catalysts”, Artificial Life 10 (1): 23-38 (2004).
R. M. Füchslin, S. Altmeyer, J.S. McCaskill, “Evolutionary stabilization of generous replicases by complex formation”, Europ. Phys J. B 38 (1): 103-110 (2004).

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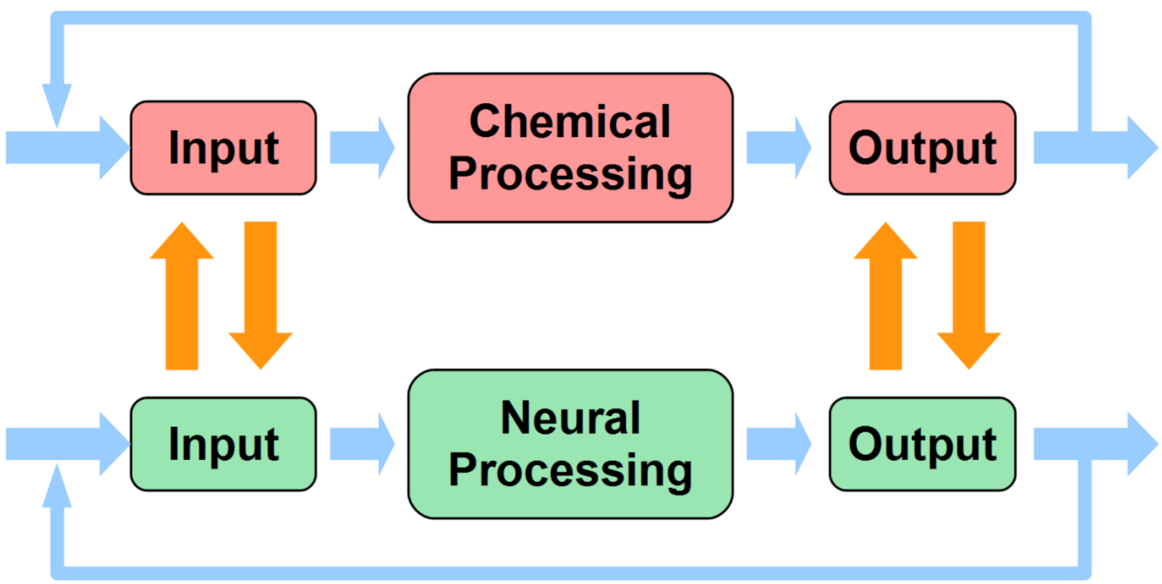
The chemical immune systems know that and what is going wrong

-

The nervous system knows where it is going wrong

Hypothesis

- Nervous and immune system are coupled.
- Rolf Pfeifer: Find the optimal balance between nervous system and morphological control



Counterargument: Depression

- There is only limited evidence for an influence of the psyche on the immune system.
- BUT: Mental processes have, if at all, only indirect influence on chemical processing.

Free interpretation of a concept developed by Roland Scholz