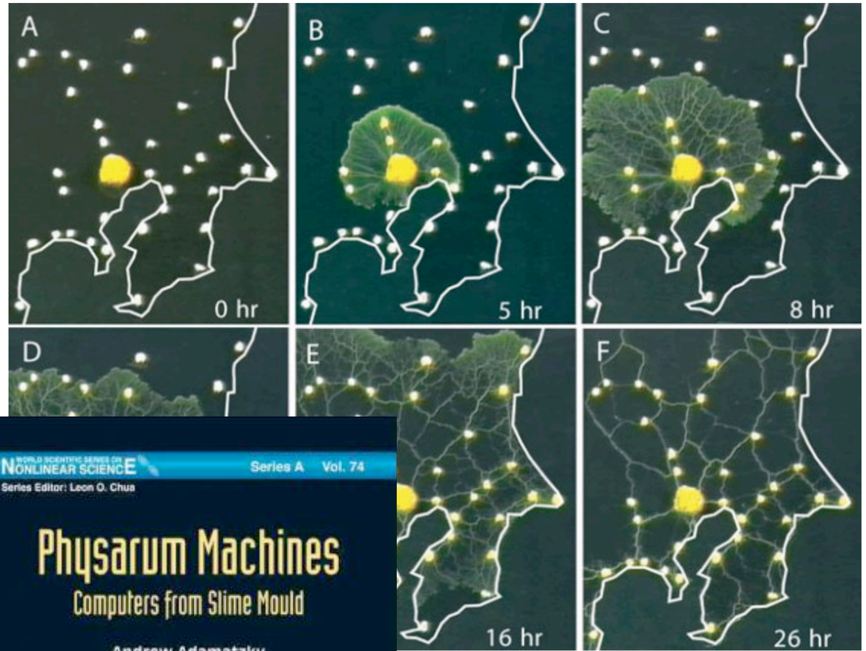
Computability

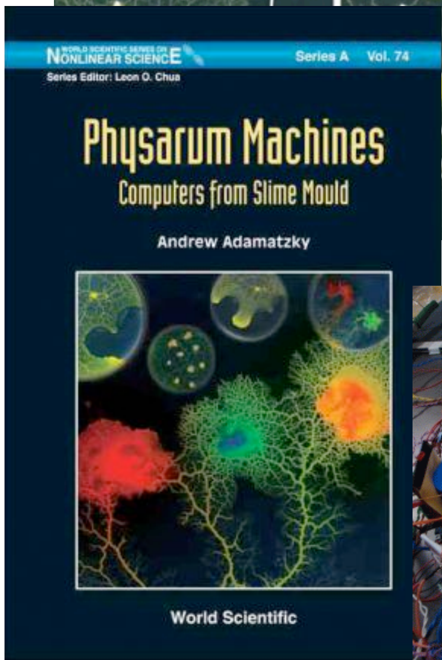
- Turing complete
  - Something that has been shown to have the same computational power as a Turing machine
  - Computes anything that other computers can compute

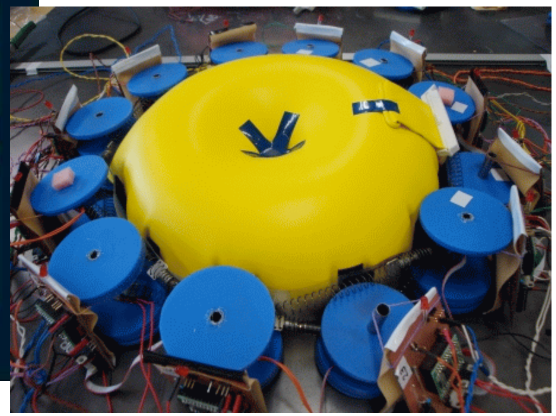
- A lot of things are Turing complete
  - Includes CAs, GRN models, billiards, MRI machines
  - Is cheese Turing-complete? Probably!
  - This motivates some *interesting* approaches…

Computability

- Slime mould:







http://www.ageekinjapan.com/tokyos-rail-network-grows-like-slime-mold/

http://www.technologyreview.com/view/427185/amoeboid-robot-navigates-without-a-brain/

Computability

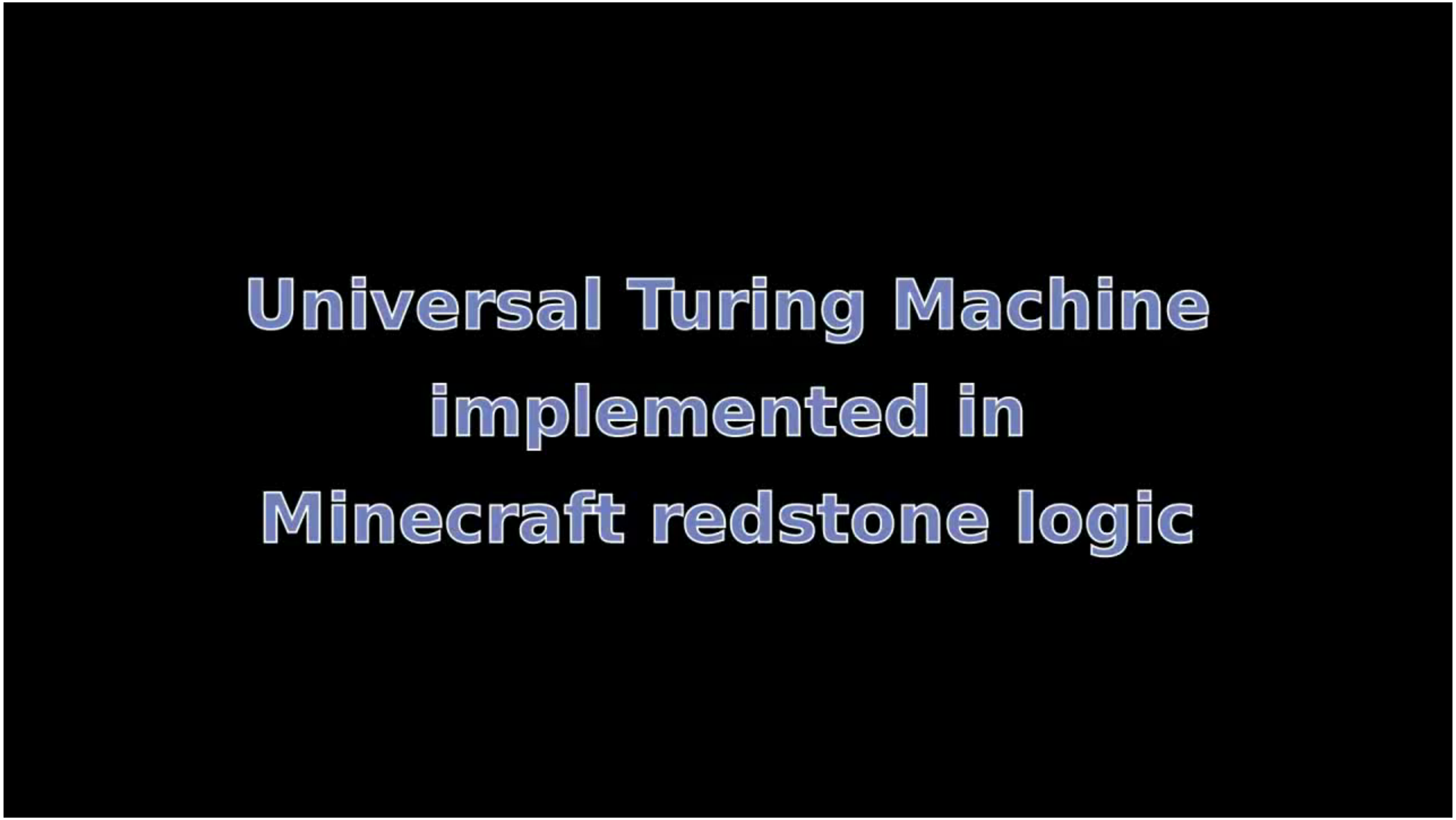
https://www.newscientist.com/article/dn24012-robot-face-lets-slime-mould-show-its-emotional-side/

Computability

- Turing completeness says nothing about:
  - Efficiency,
  - or programmability,
  - or the best way to implement a particular computation

- However, these are important in practice!

Computability



https://www.youtube.com/watch?v=1X21HQphy6I

Gene Regulatory Models II

Dr. Michael Lones
Room EM.G31
M.Lones@hw.ac.uk

Artificial Genome

- This is at the other end of the GRN model spectrum
  - Captures genome organisation and gene products

This is how a GRN is encoded in a typical artificial genome

TAAGCTACTATAGAAACTGCGCGTATAAGCAAATGCGCGTATAAGCA

Artificial Genome

- This is at the other end of the GRN model spectrum
  - Captures genome organisation and gene products

This pattern is used to locate genes

The 3 characters after the locator site are interpreted as a gene

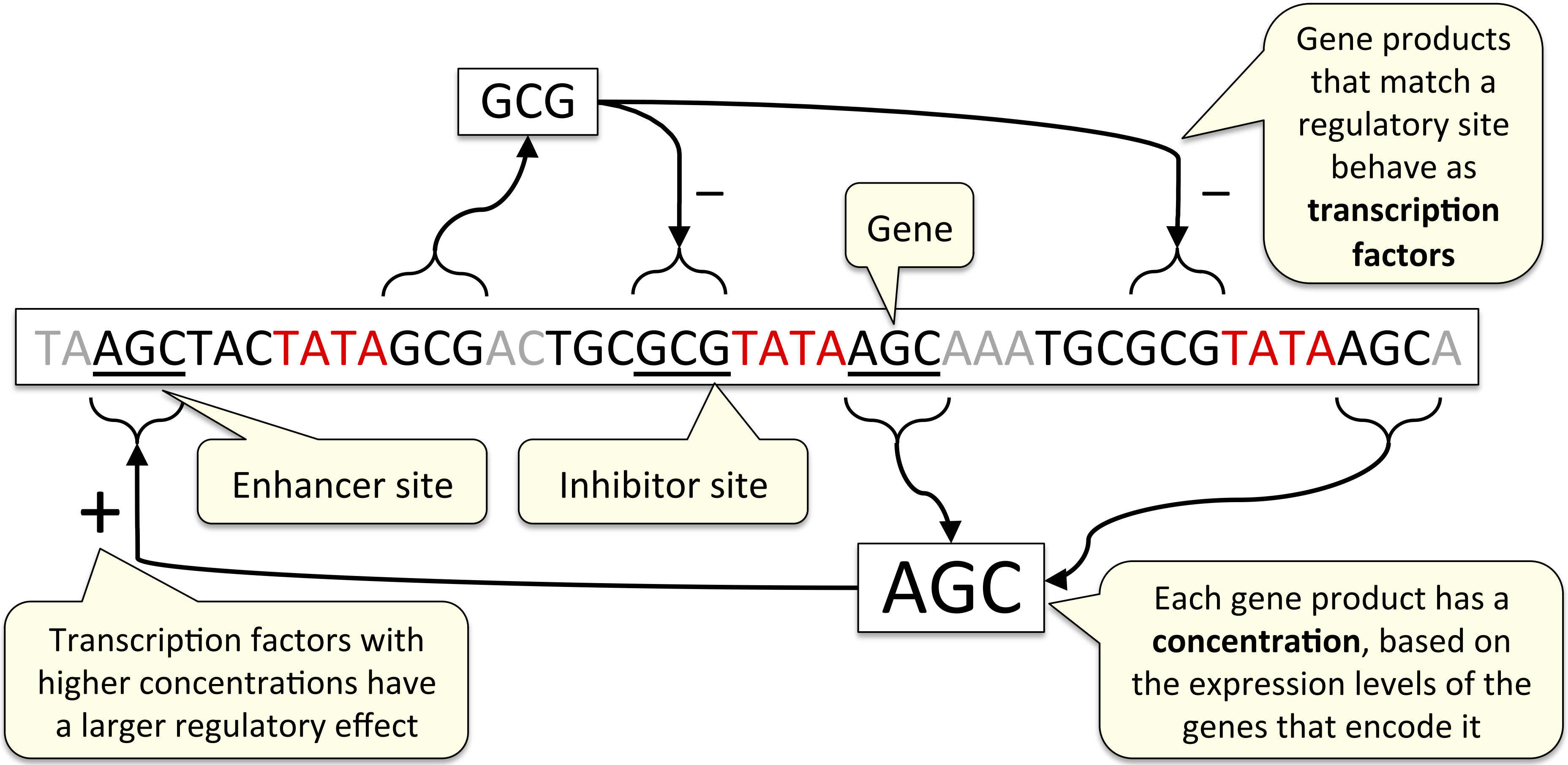
TAAGCTACTATAGCGACTGCGCGTATAAGCAAATGCGCGTATAAGCA

The 6 characters before the locator site are interpreted as a regulatory region (an **enhancer** followed by an **inhibitor**).

Characters in between genes are ignored. They are analogous to non-coding DNA

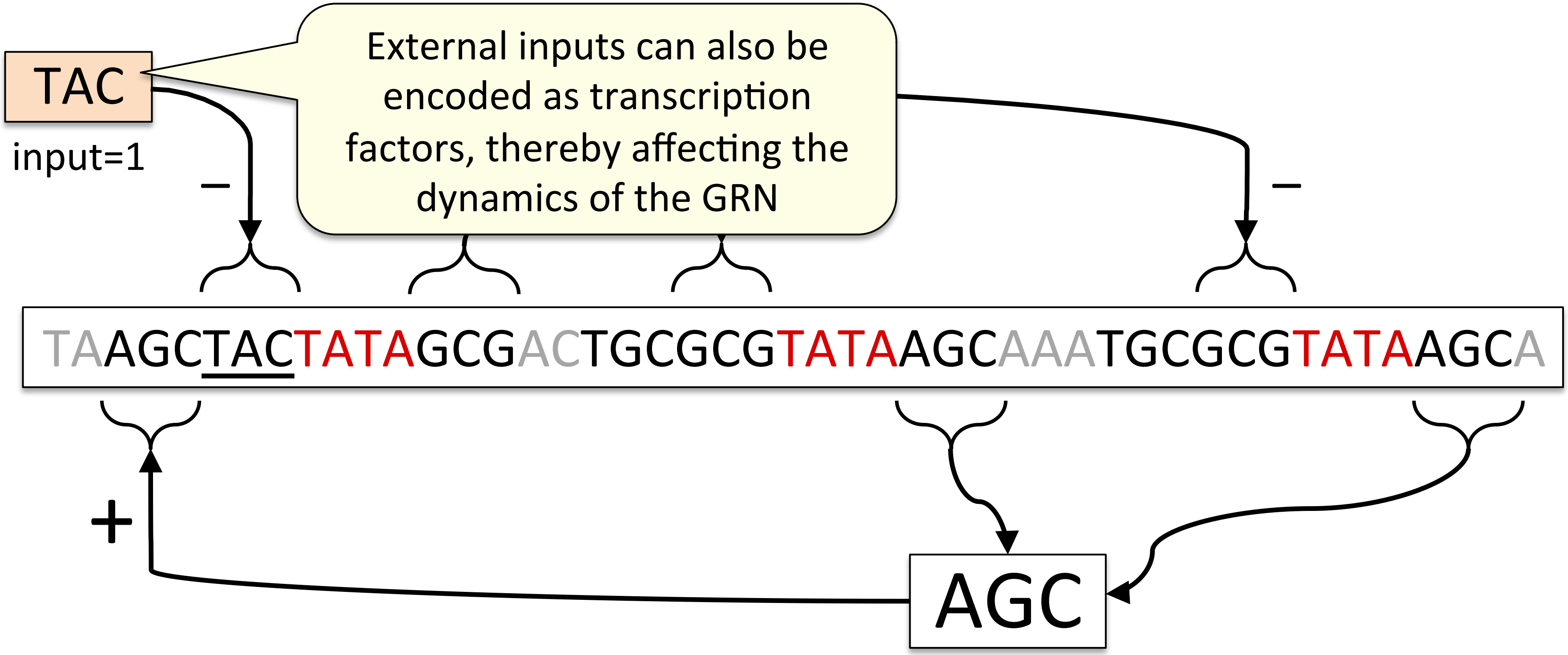
Artificial Genome

- This is at the other end of the GRN model spectrum
  - Captures genome organisation and gene products



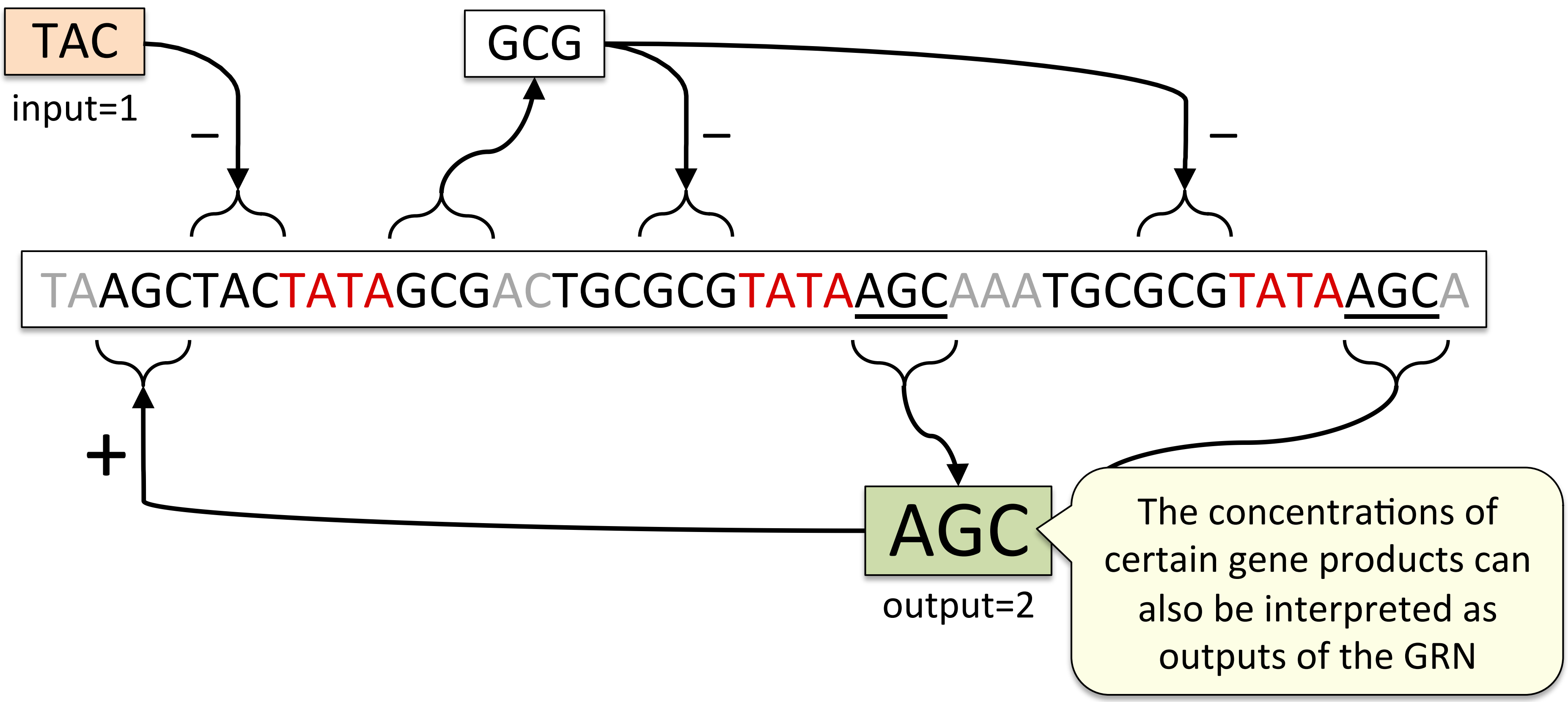
Artificial Genome

- This is at the other end of the GRN model spectrum
  - Captures genome organisation and gene products



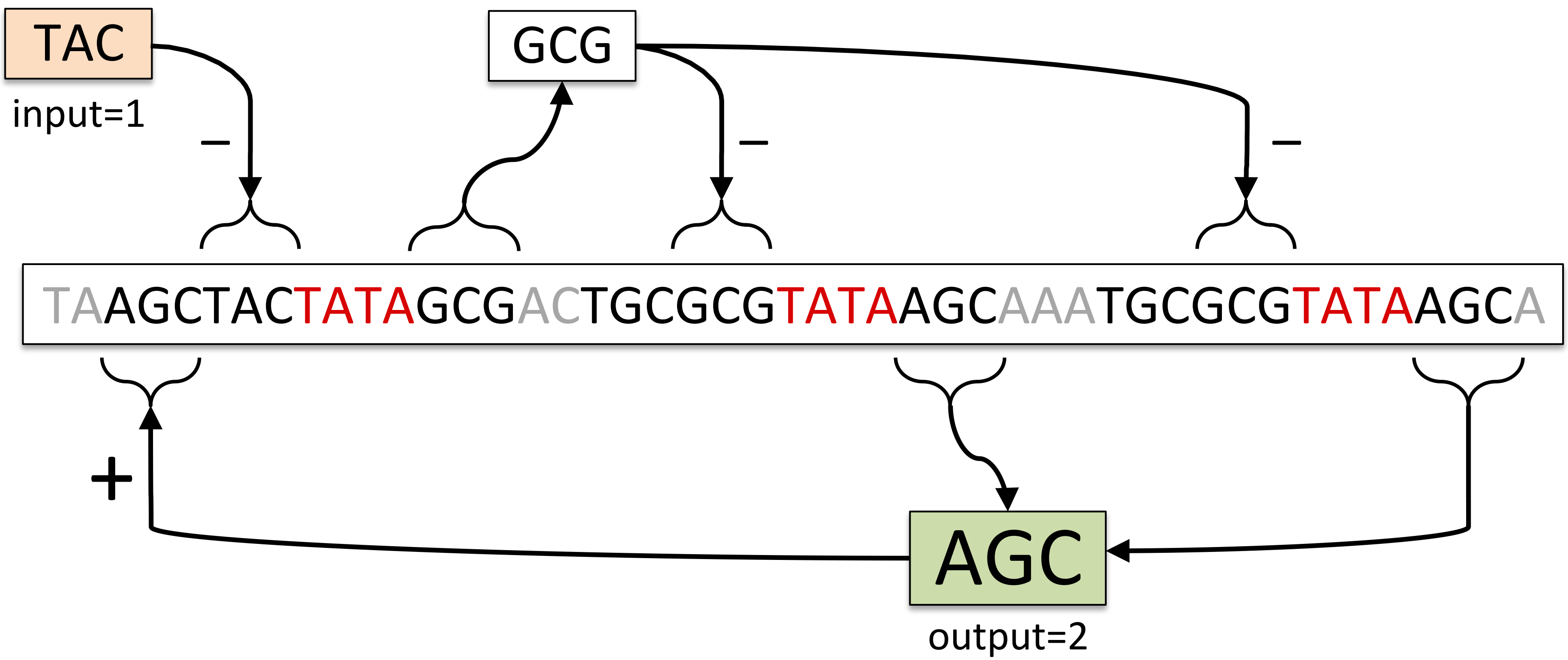
Artificial Genome

- This is at the other end of the GRN model spectrum
  - Captures genome organisation and gene products



Artificial Genome

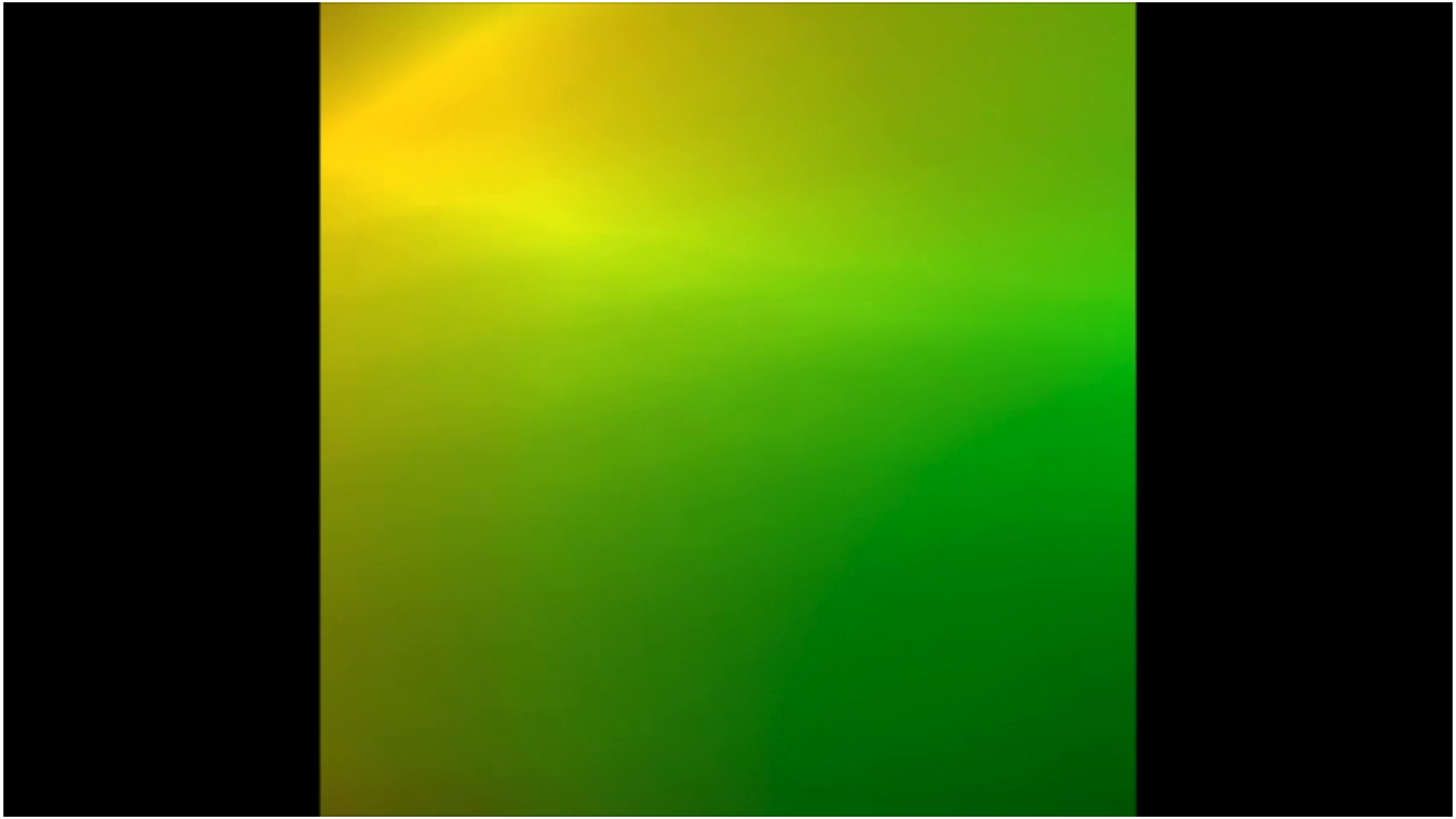
- This is at the other end of the GRN model spectrum
  - Captures genome organisation and gene products



Artificial Genome

- Strengths
  - Much easier to encode inputs/outputs
  - Likely to be more expressive
  - Captures the way in which genomes evolve
  - So also likely to be more evolvable [Banzhaf 2003]
- Weaknesses
  - Lots of parameters
  - Which might make it harder to optimise
  - Pattern matching is computationally expensive
  - So slower to evaluate, and therefore evolve

Expressiveness



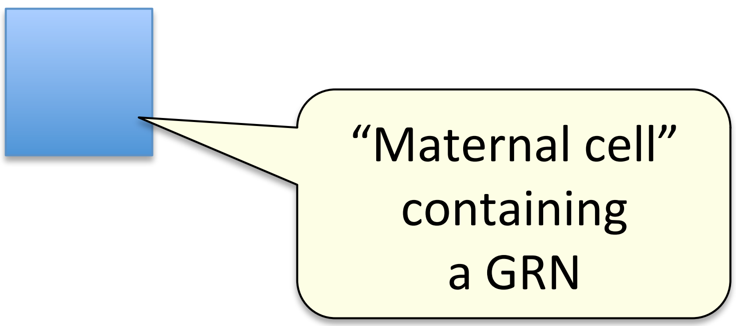
http://www.irit.fr/~Sylvain.Cussat-Blanc/ColorfulRegulation/index_en.php

Robustness

Stéphane Sanchez and Sylvain Cussat-Blanc
http://www.irit.fr/~Sylvain.Cussat-Blanc/GRNDriver/index_en.php

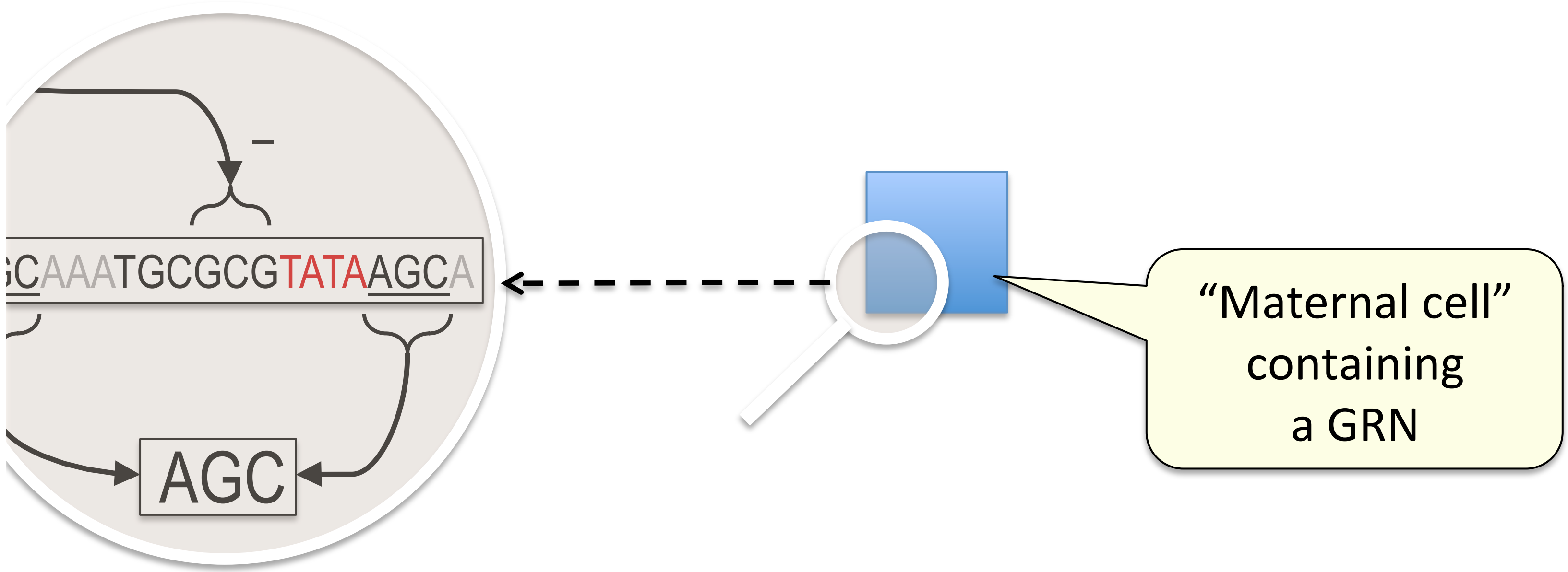
Artificial Development

- GRNs can be used to generate structures
  - Makes use of their ability to generate patterns
  - Often hybridised with a model of cell division



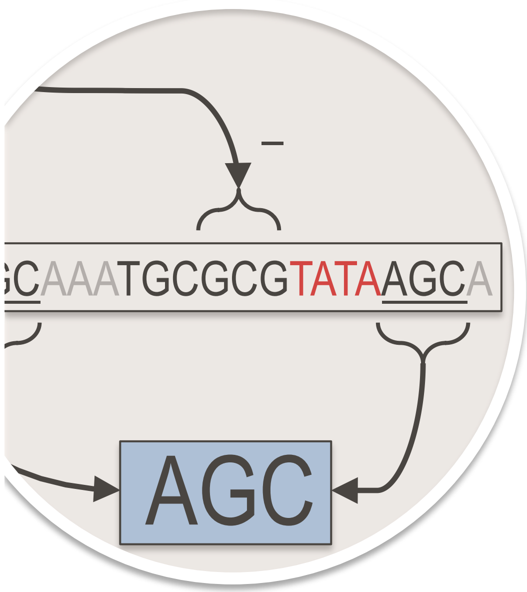
Artificial Development

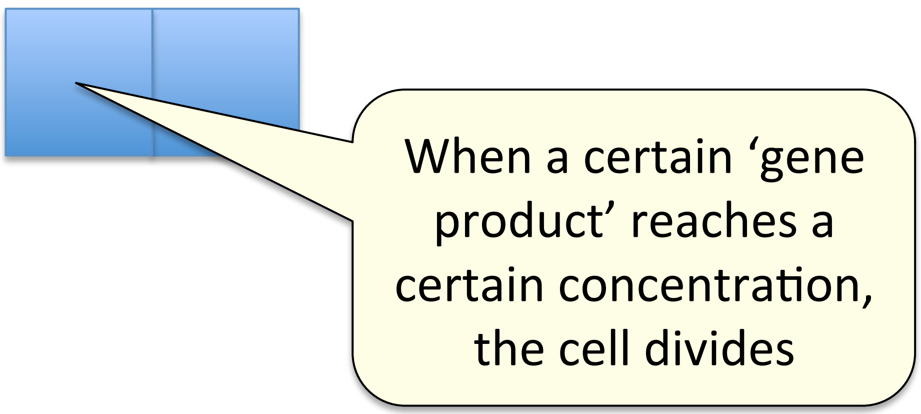
- GRNs can be used to generate structures
  - Makes use of their ability to generate patterns
  - Often hybridised with a model of cell division



Artificial Development

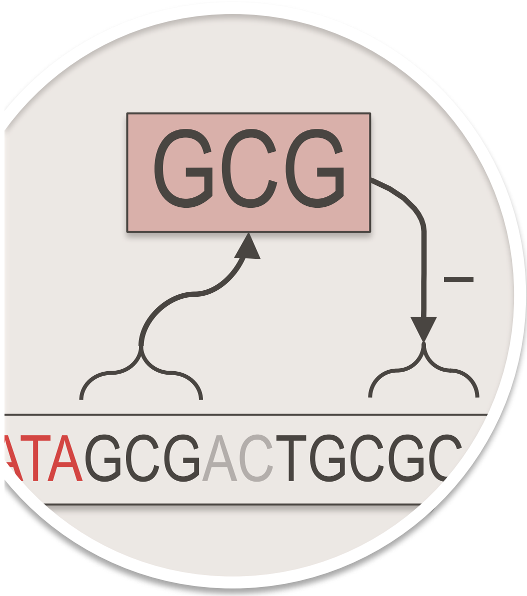
- GRNs can be used to generate structures
  - Makes use of their ability to generate patterns
  - Often hybridised with a model of cell division

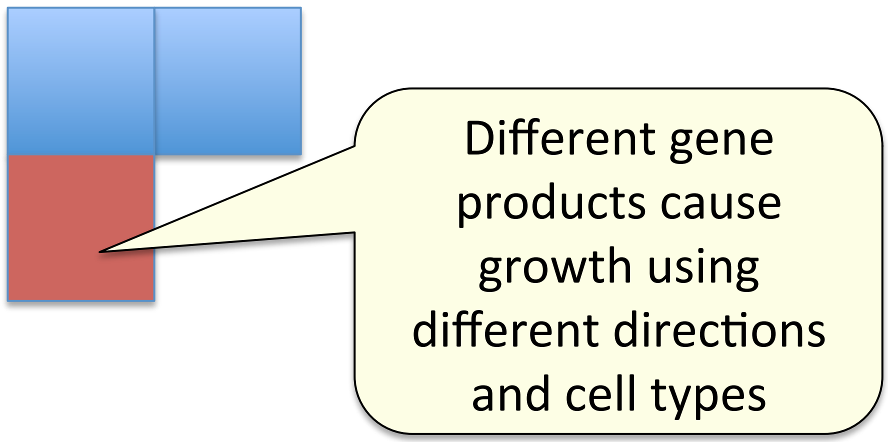




Artificial Development

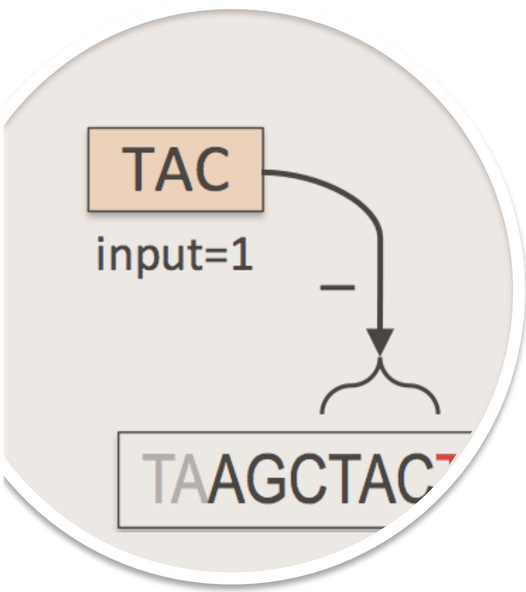
- GRNs can be used to generate structures
  - Makes use of their ability to generate patterns
  - Often hybridised with a model of cell division

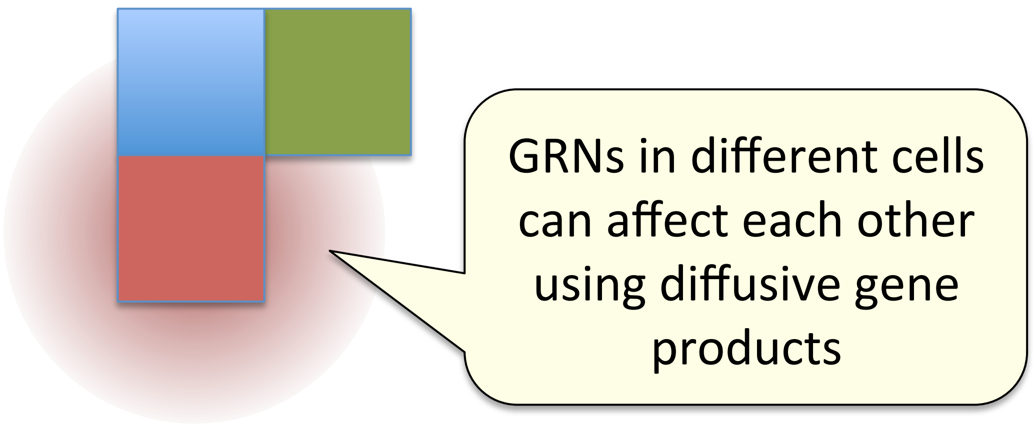




Artificial Development

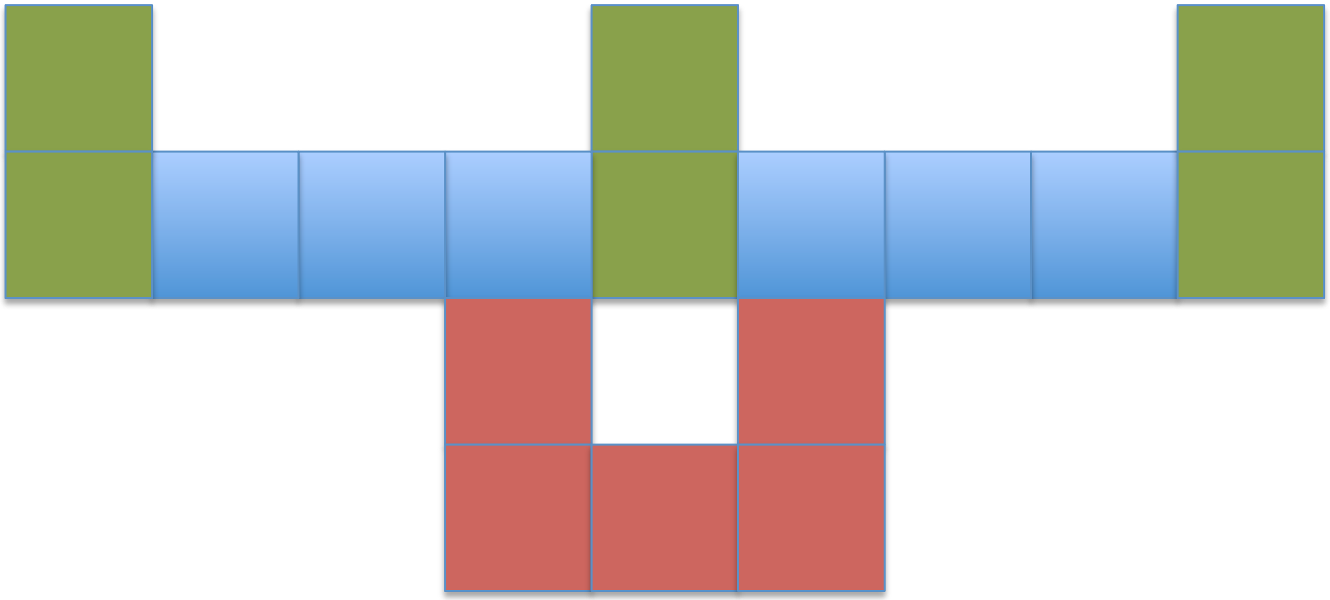
- GRNs can be used to generate structures
  - Makes use of their ability to generate patterns
  - Often hybridised with a model of cell division





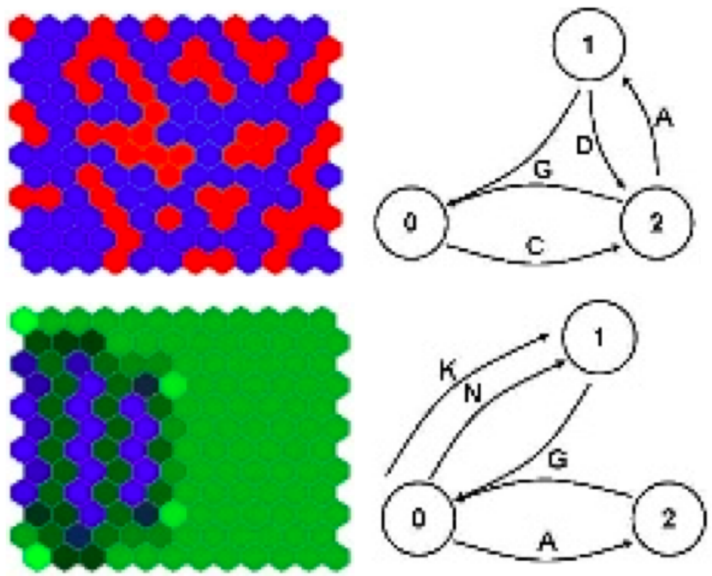
Artificial Development

- GRNs can be used to generate structures
  - Makes use of their ability to generate patterns
  - Often hybridised with a model of cell division



Artificial Development

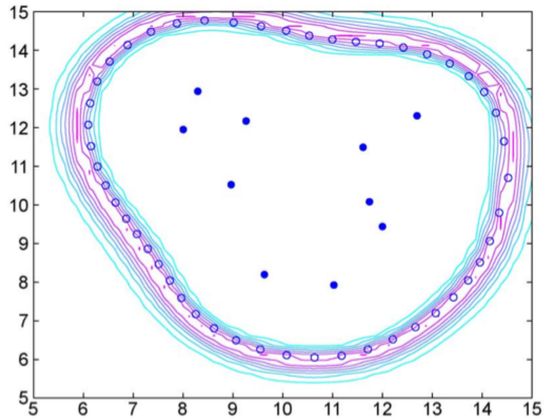
- GRNs can be used to generate structures
  - Makes use of their ability to generate patterns
  - Often hybridised with a model of cell division
- Applications have included
  - Evolutionary art and music
  - Design of neural networks
  - Design of electronic circuits
  - Design of artificial organisms
  - Image compression
  - Biological development ➔



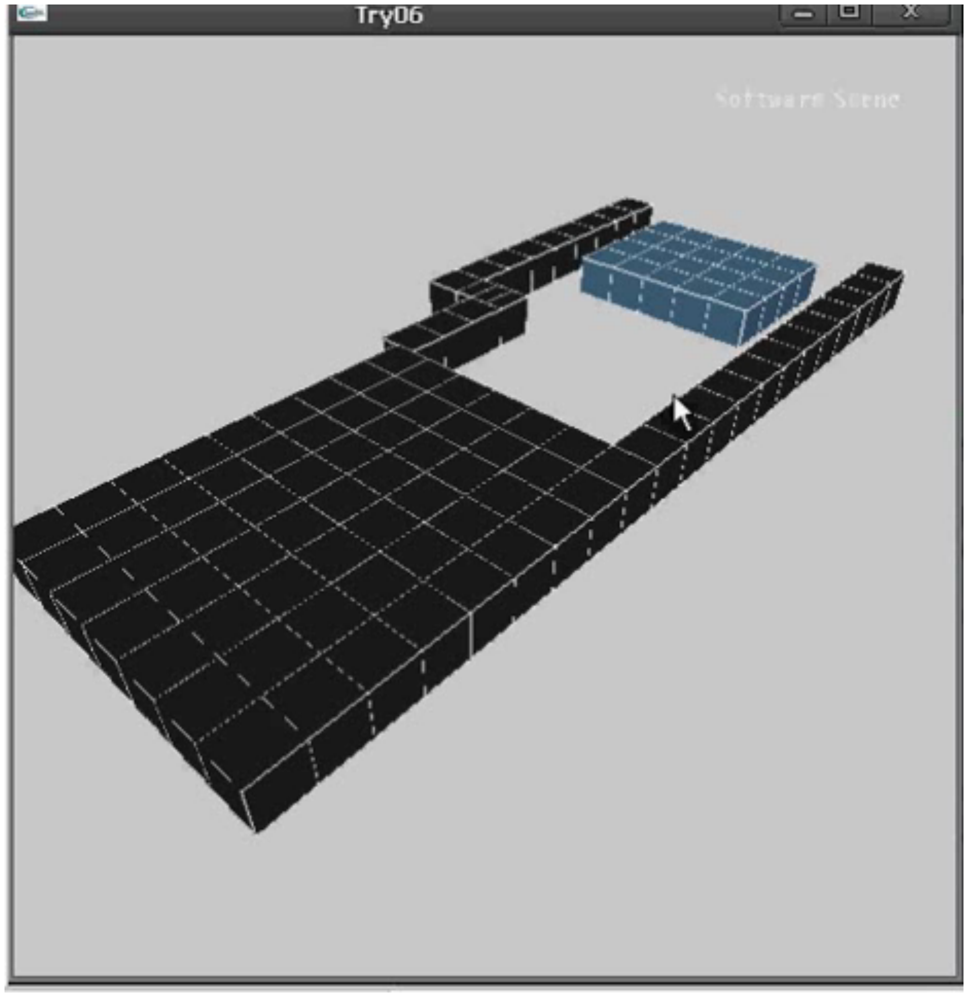
From [Flann et al., 2005]

Morphogenetic Robotics

- Controlling the growth of an artificial organism
  - The organism's body is 'grown' from a single cell
- Sometimes controls movement
  - Either directly or indirectly
  - e.g. by growing a neural network
- Also applied to multi-robotics
  - Patterning robot swarms
  - e.g. [Jin et al, 2012] ➔
  - Modular robotics

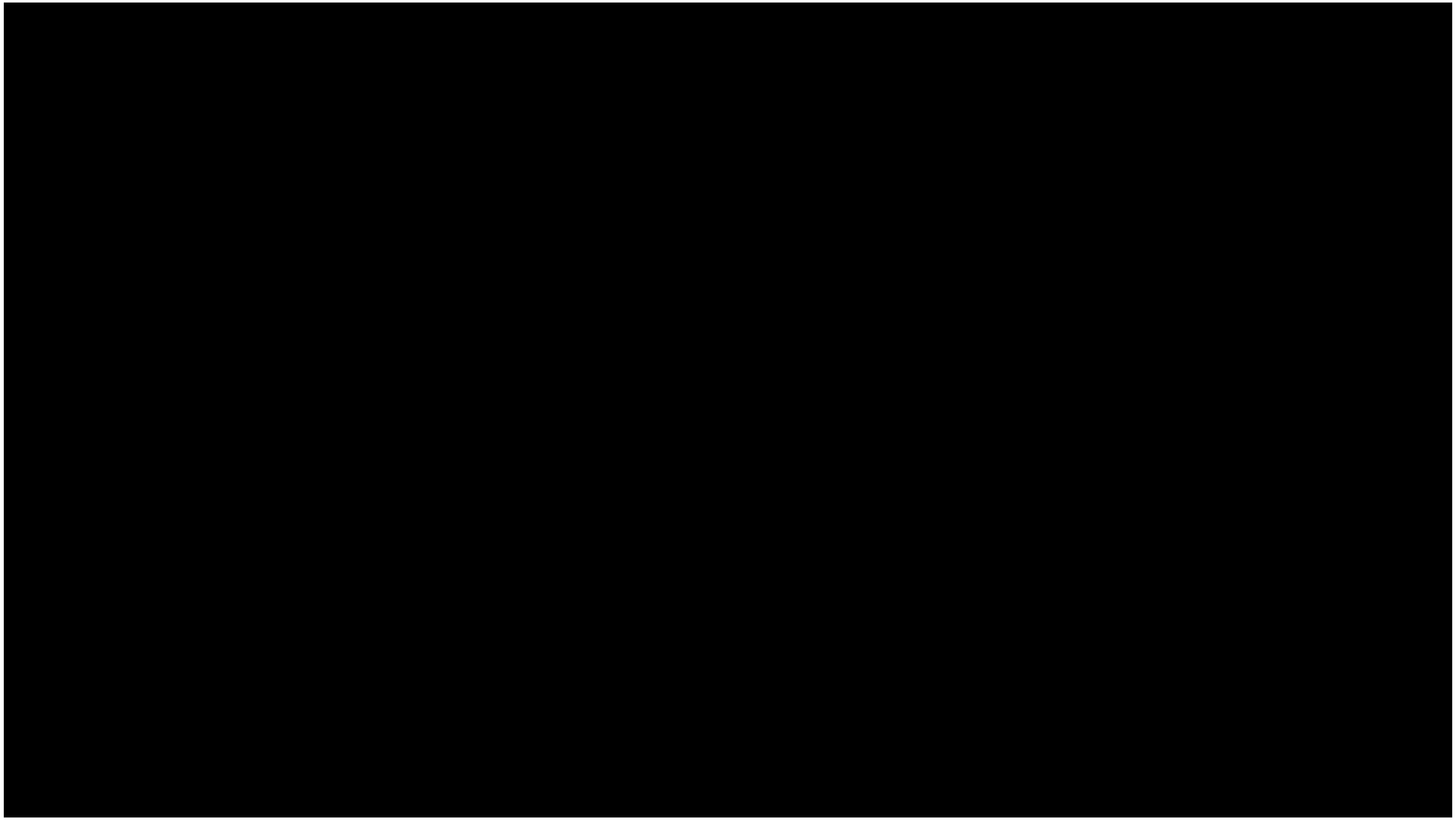


Jin et al., 2012



https://www.youtube.com/watch?v=09TirOH8OIM

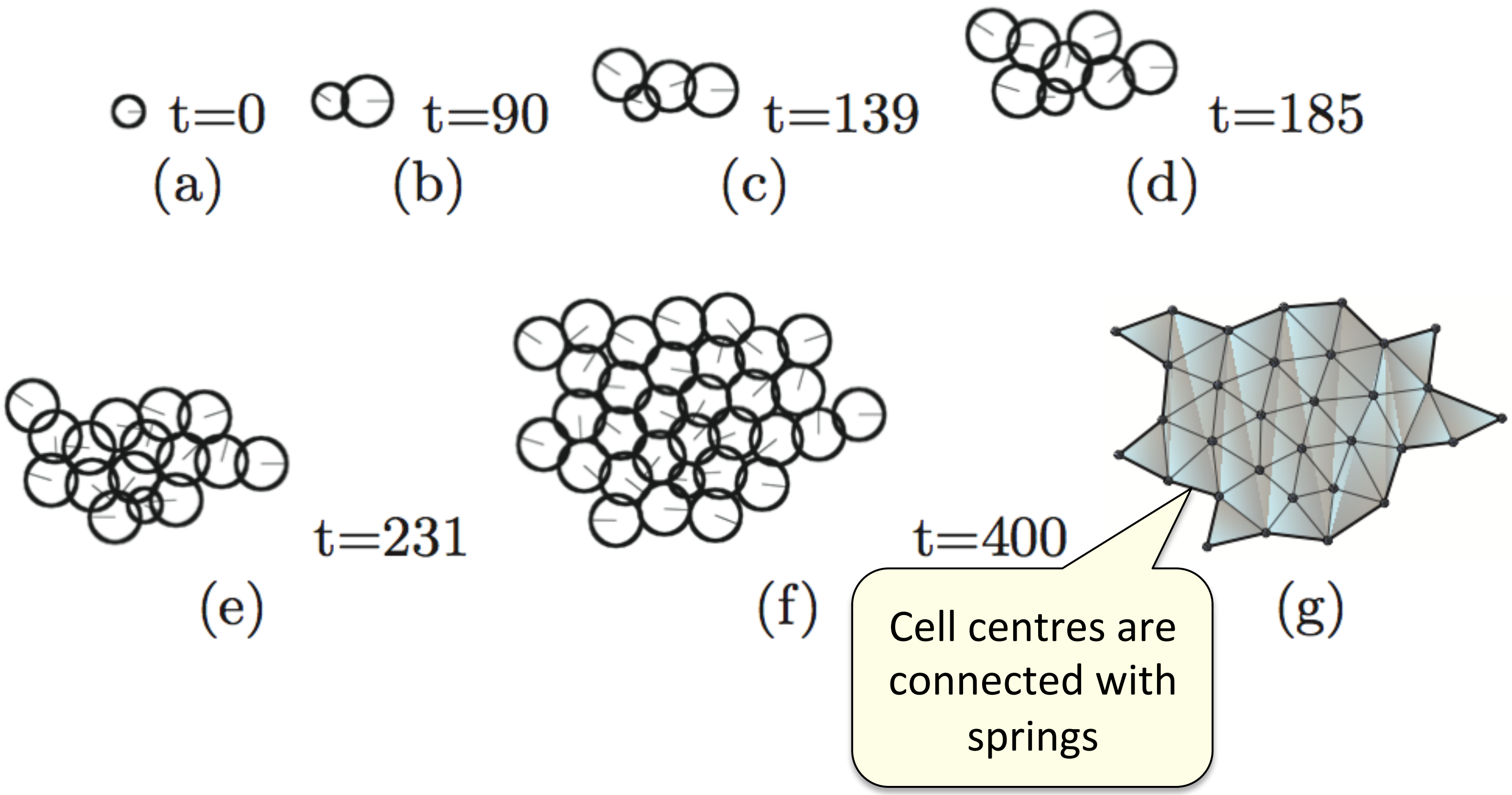
Joachimczak et al.



https://www.youtube.com/watch?v=JJYpHfccnwA

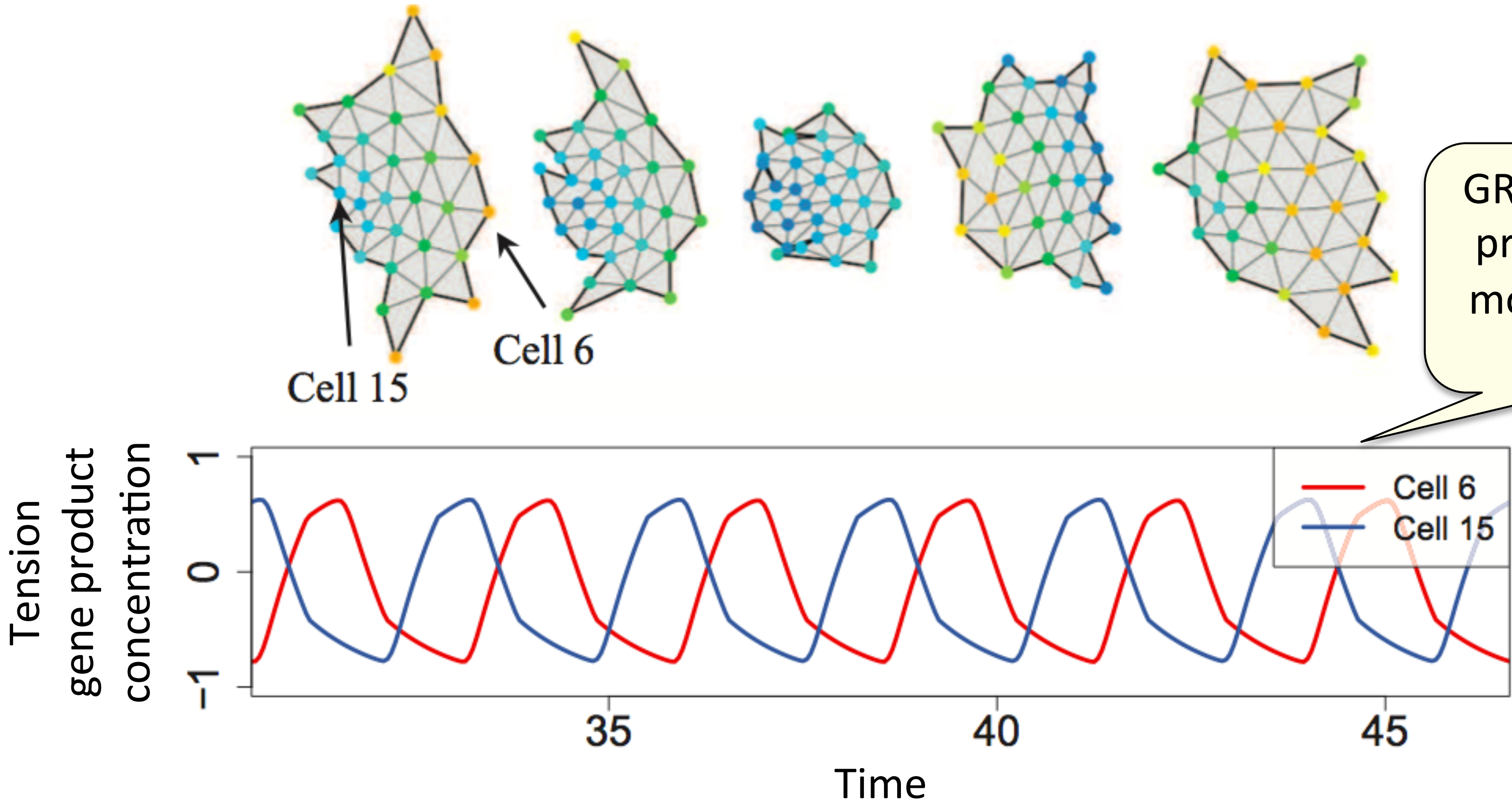
Morphogenetic Robotics

- Evolving soft-bodied swimming animats
  - See [Joachimczak et al. 2012]



Morphogenetic Robotics

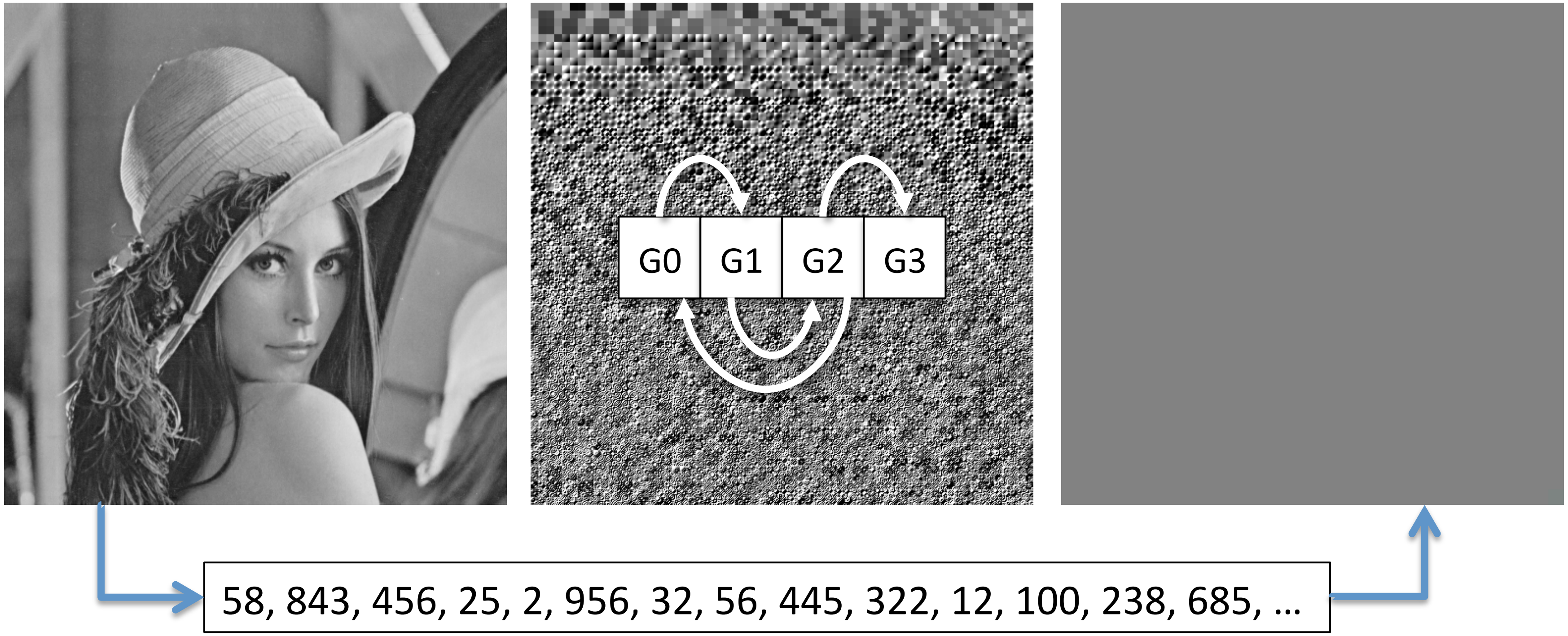
- Evolving soft-bodied swimming animats
  - See [Joachimczak et al. 2012]



GRNs produce proteins that modify spring tensions

Image Compression

- Generative code books for compression [Trefzer'10]
  - GRN generates a series of 8x8 patterns
  - Their indices are then used to encode an image



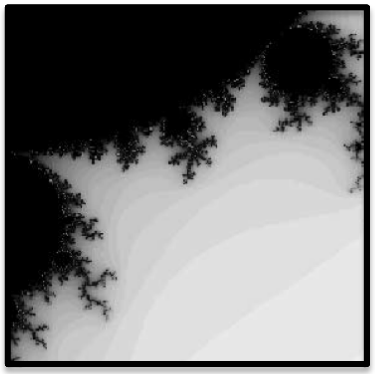
More Advanced Stuff

- The rest of this lecture isn't examinable…

Fractal GRNs

- A variant of the artificial genome [Bentley 2005]
  - Regulatory function uses properties of the Mandelbrot set
  - Approximates complexity of biochemical interactions
- Uses the concept of **fractal proteins**
  - A finite square of the Mandelbrot set
  - Defined by three real numbers (x,y,z)
  - e.g.:

(x = 0.132541887,
y = 0.698126164,
z = 0.468306528)



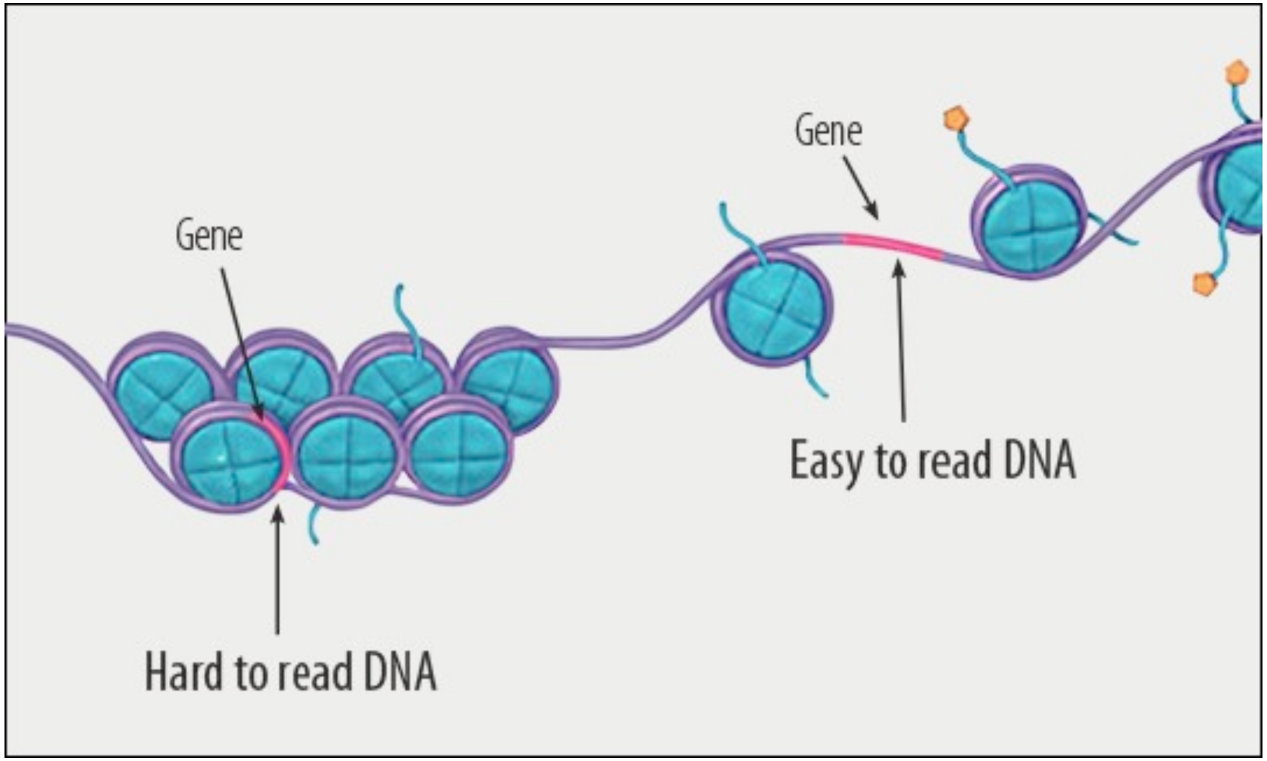
Fractal GRNs

- Regulation is based on **fractal chemistry**
  - Analogous to the physical-chemical interactions between TFs when forming a transcription complex

- Fractal GRNs shown to be expressive and robust
  - Bentley found they could implement a square root function only when the fractal chemistry was used

Artificial Epigenetic Networks

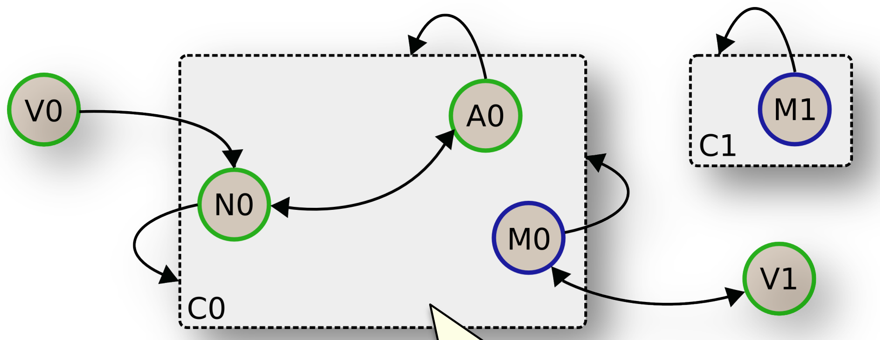
- GRN models that include *epigenetic* processes
  - DNA is wound over protein spindles; these are unwound prior to transcription; unwinding is controlled by genes

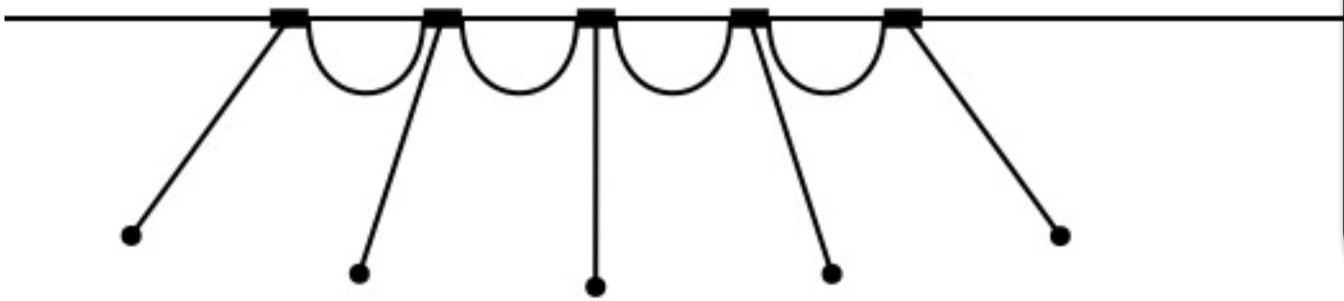


https://www.nichd.nih.gov/health/topics/epigenetics/conditioninfo/Pages/default.aspx

Artificial Epigenetic Networks

Artificial Epigenetic Network



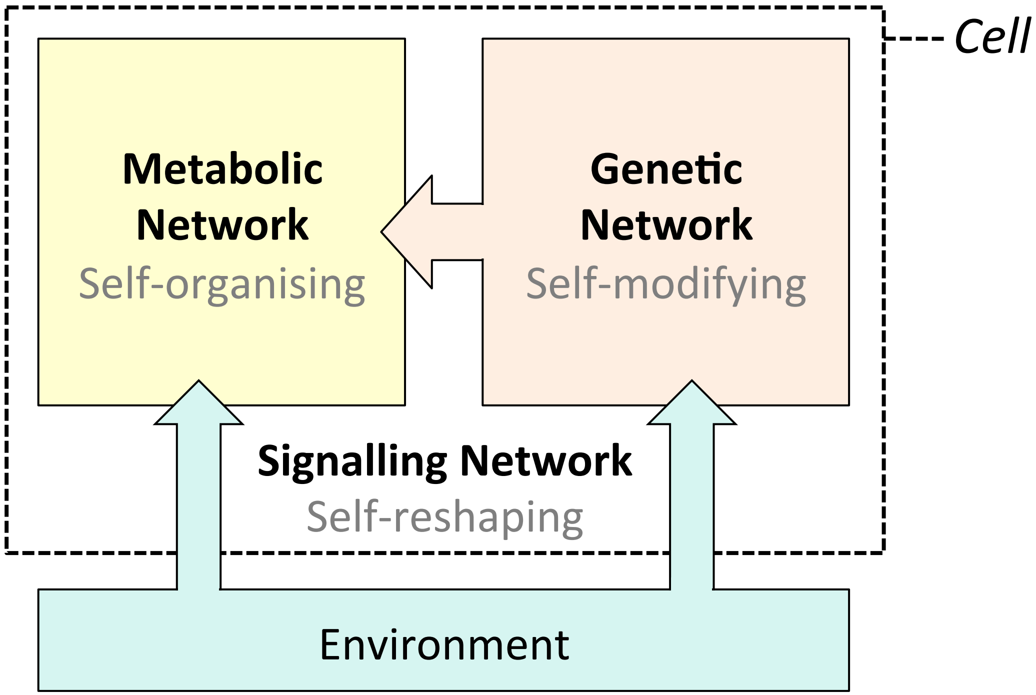


Whole regions of the network can be turned on and off, making it easier for one network to do multiple things

A. P. Turner, M. A. Lones et al., Artificial Epigenetic Networks: Automatic Decomposition of Dynamical Control Tasks using Topological Self-Modification, *IEEE Trans. Neural Nets and Learning Sys*, in press.

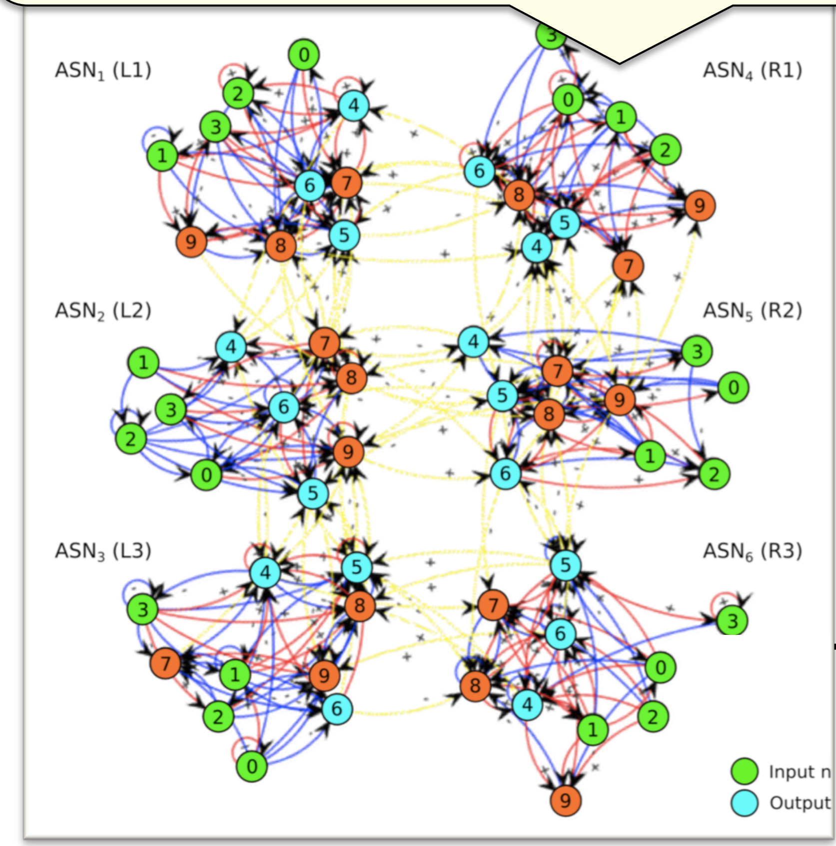
Artificial Biochemical Networks

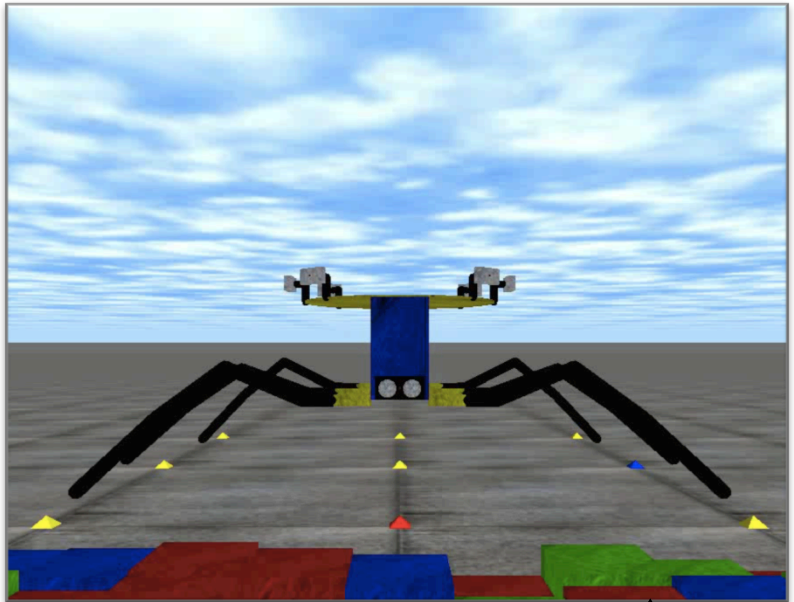
- These capture the wider biochemical networks that occur in cells, not just the genetic networks



Artificial Signalling Networks

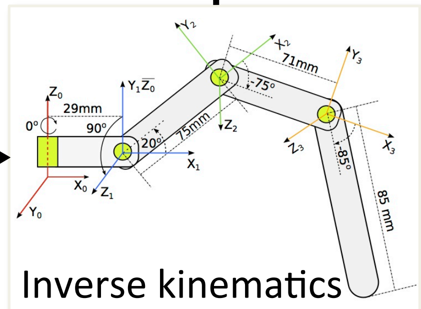
In biology, signalling networks are responsible for processing 'inputs' and generating control responses





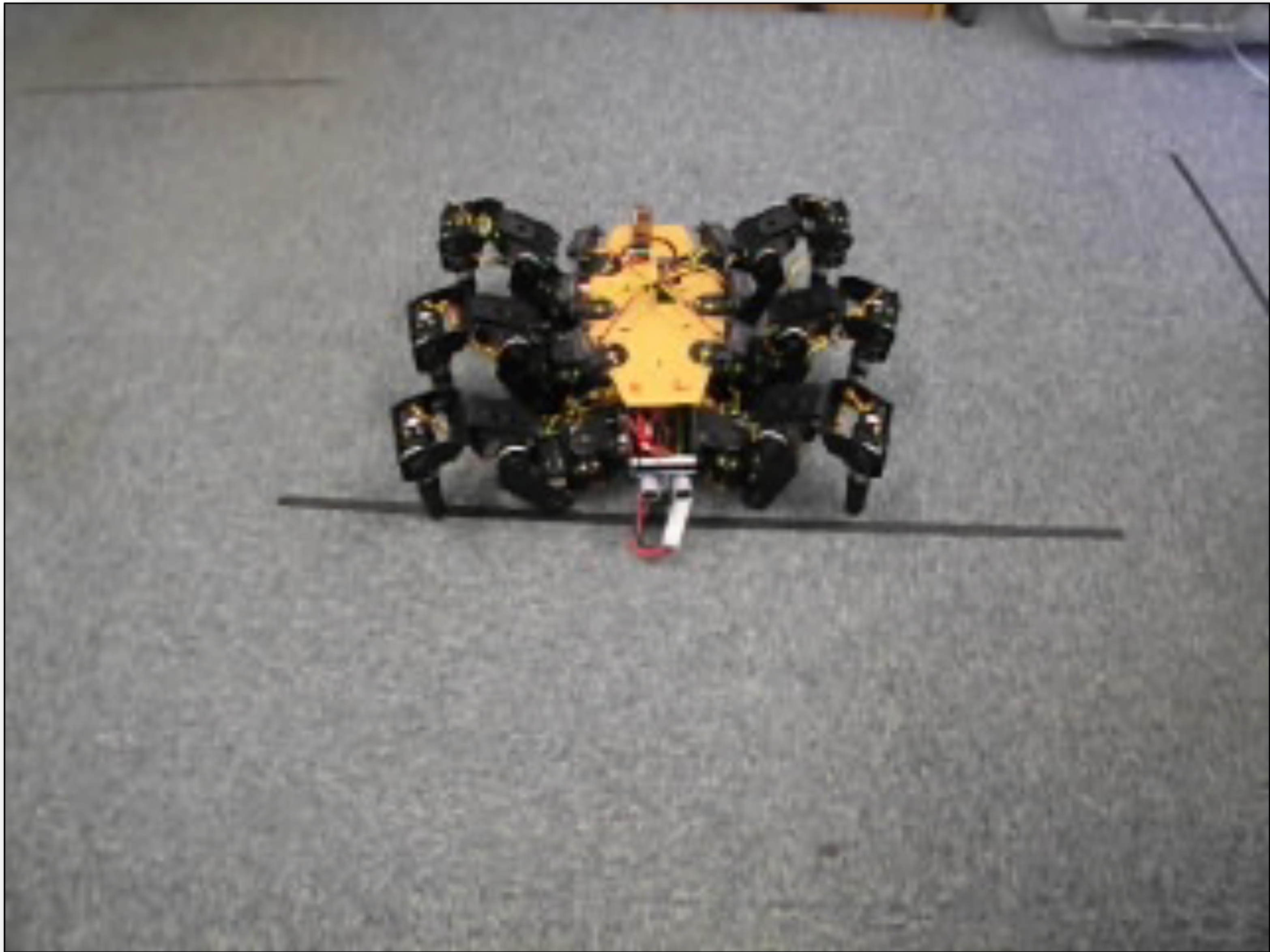
Oscillator network

$$\dot{x}_i = \alpha(\mu - r_i^2)x_i - \omega_i z_i$$
$$\dot{z}_i = \beta(\mu - r_i^2)z_i + \omega_i x_i$$

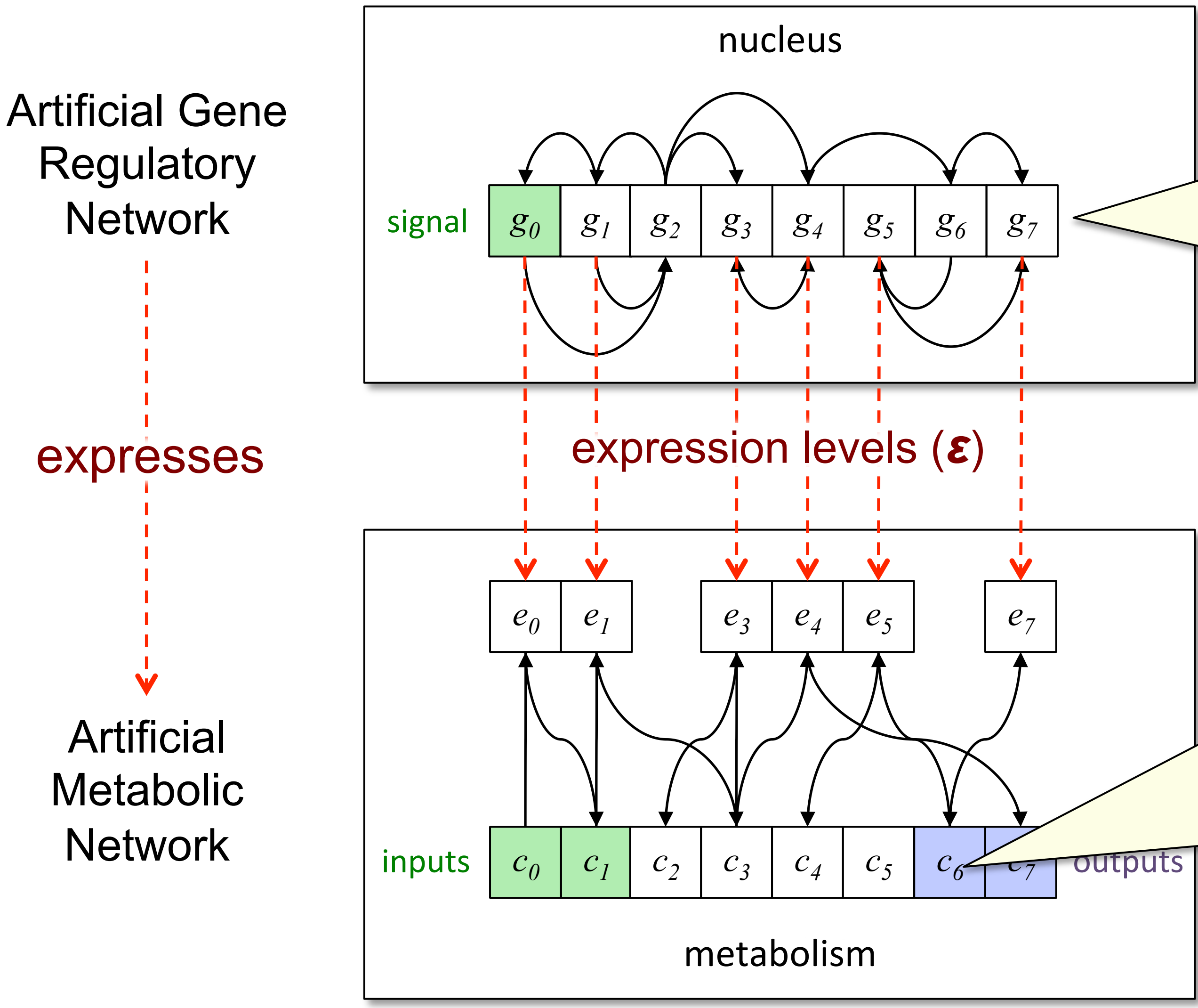


L. A. Fuente, **M. A. Lones** et al., Computational Models of Signalling Networks for Non-linear Control, *BioSystems*, 2013.
L. A. Fuente, **M. A. Lones** et al., Adaptive Robotic Gait Control using Coupled Artificial Signalling Networks…, Proc. CEC2013.

Artificial Biochemical Networks



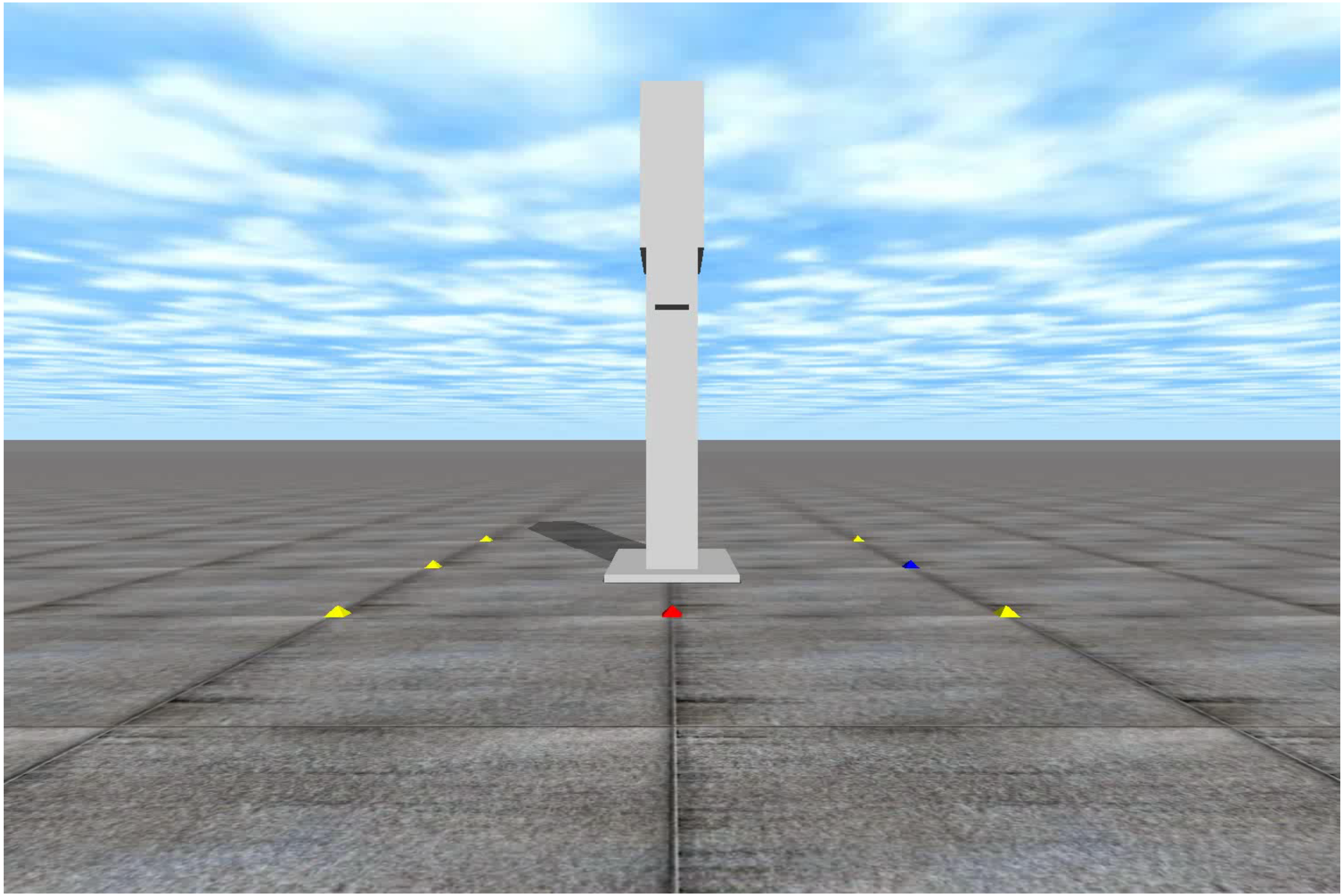
Coupled Biochemical Networks



This is similar to a Boolean network, but uses continuous-valued expression states

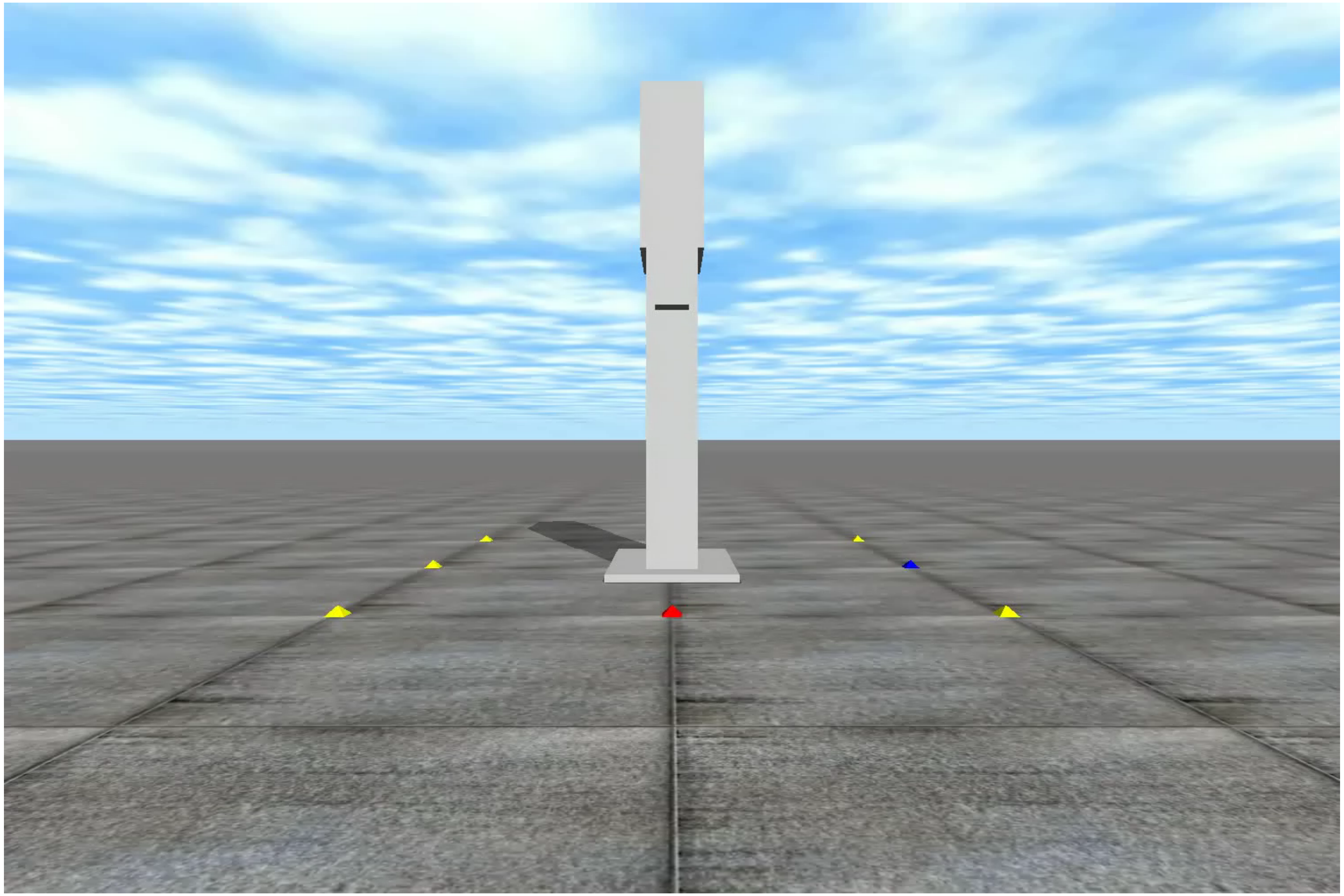
This is a kind of computational chemistry that captures the self-organising behaviour of metabolic networks

Bipedal Locomotion



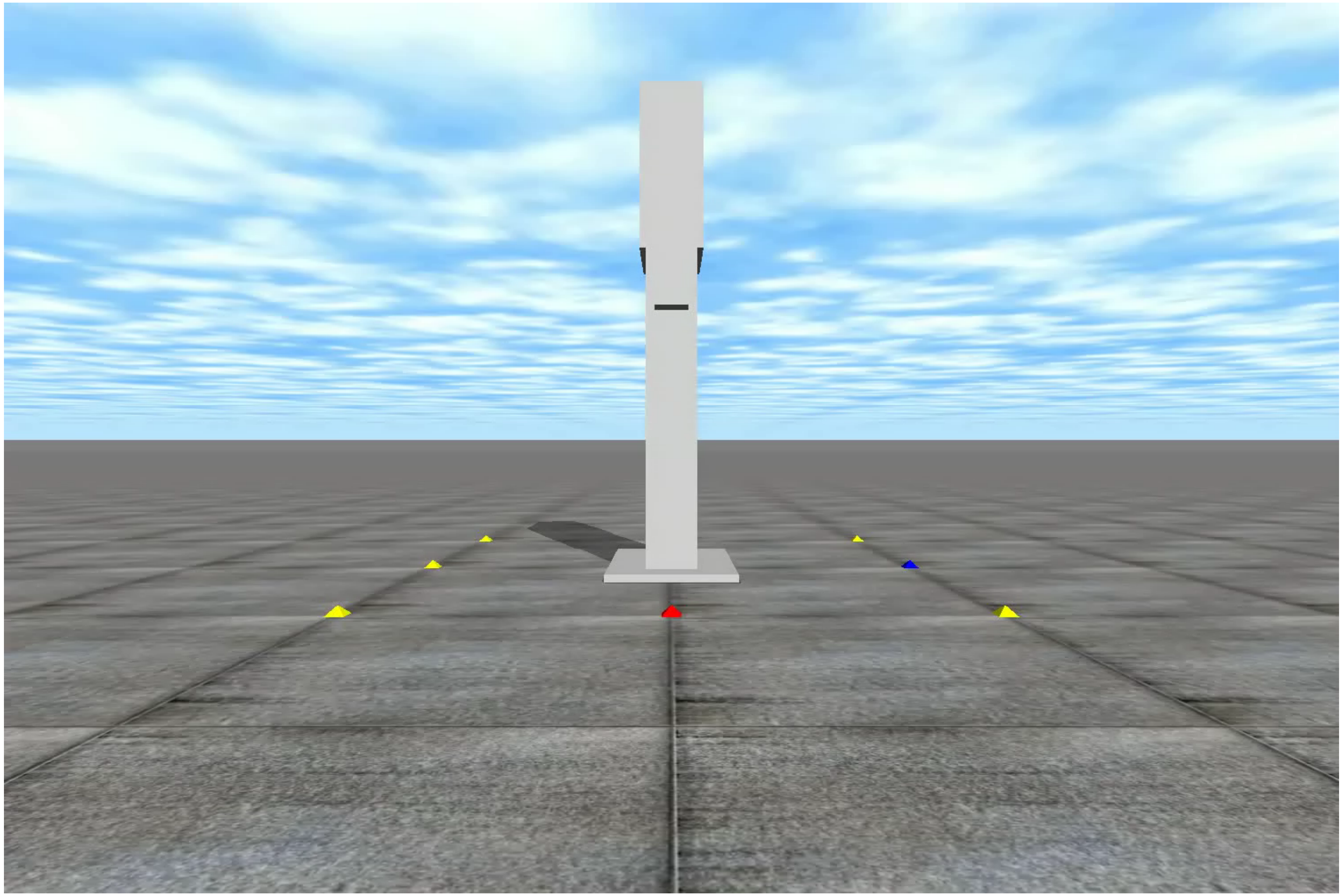
http://youtu.be/mT9qKZS7pds

Bipedal Locomotion



http://youtu.be/urSNnVC1VqY

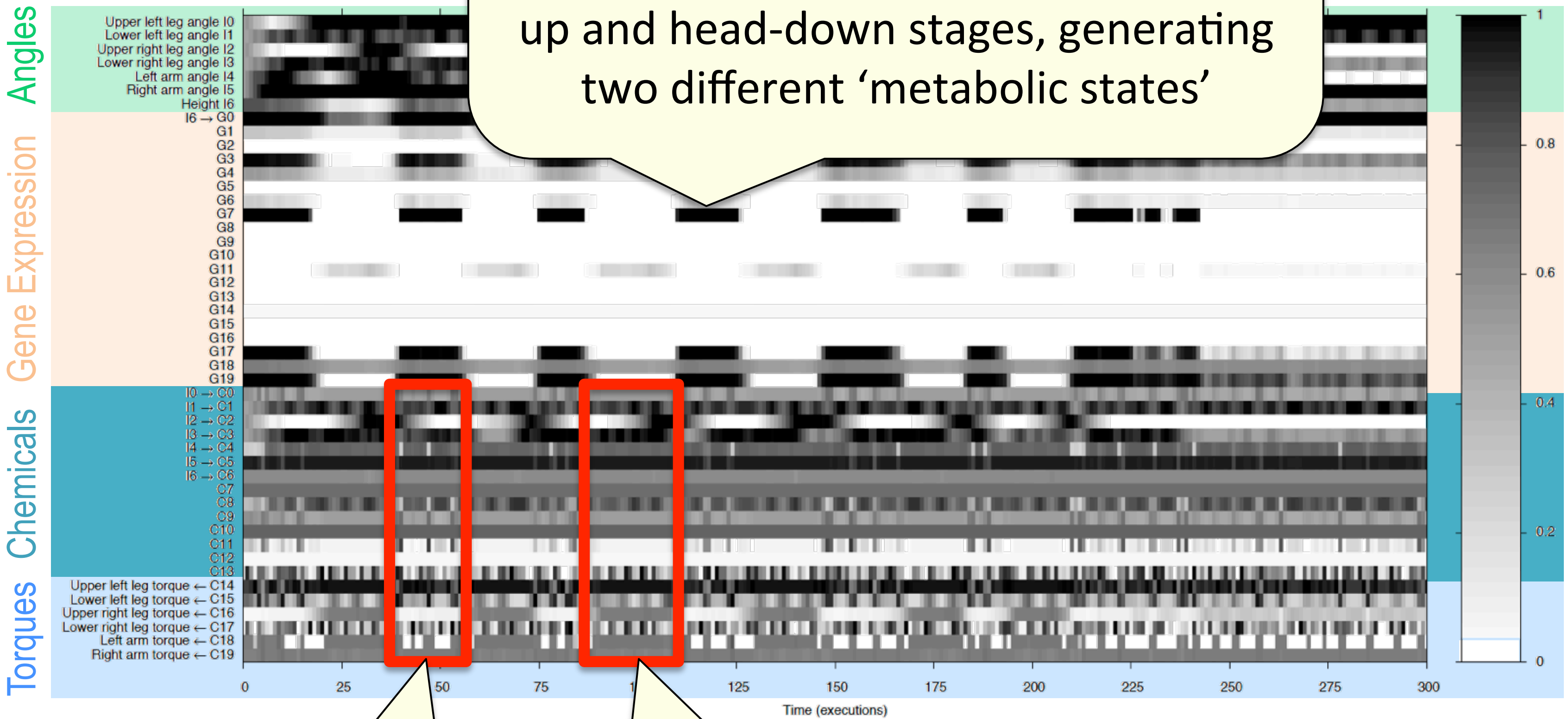
Bipedal Locomotion



http://youtu.be/gSrQlsvbD98

Bipedal Locomotion

Looking at ‘gene expression’ over time, it can be seen that different groups of genes turn on in the head-up and head-down stages, generating two different ‘metabolic states’



Head-up

Head-down

Summary

- Models of gene regulatory networks
  - Boolean networks and artificial genomes
- Main applications
  - Control, especially in robotics
  - Generating complex structures
  - Understanding biological systems
- Suggested reading
  - Introduction to Boolean networks [Gershenson 2004]
  - Applications [Joachimczak 2012, Sanchez 2014]

Things you should know

- Boolean networks
  - What are they? How are they different to a CA?
  - Awareness of attractors and their significance
  - What is criticality, and when does it occur?
  - How can you compute with them?

- Artificial genomes
  - A basic understanding of how they work
  - And how they can be used for artificial development
  - Ability to give examples of applications