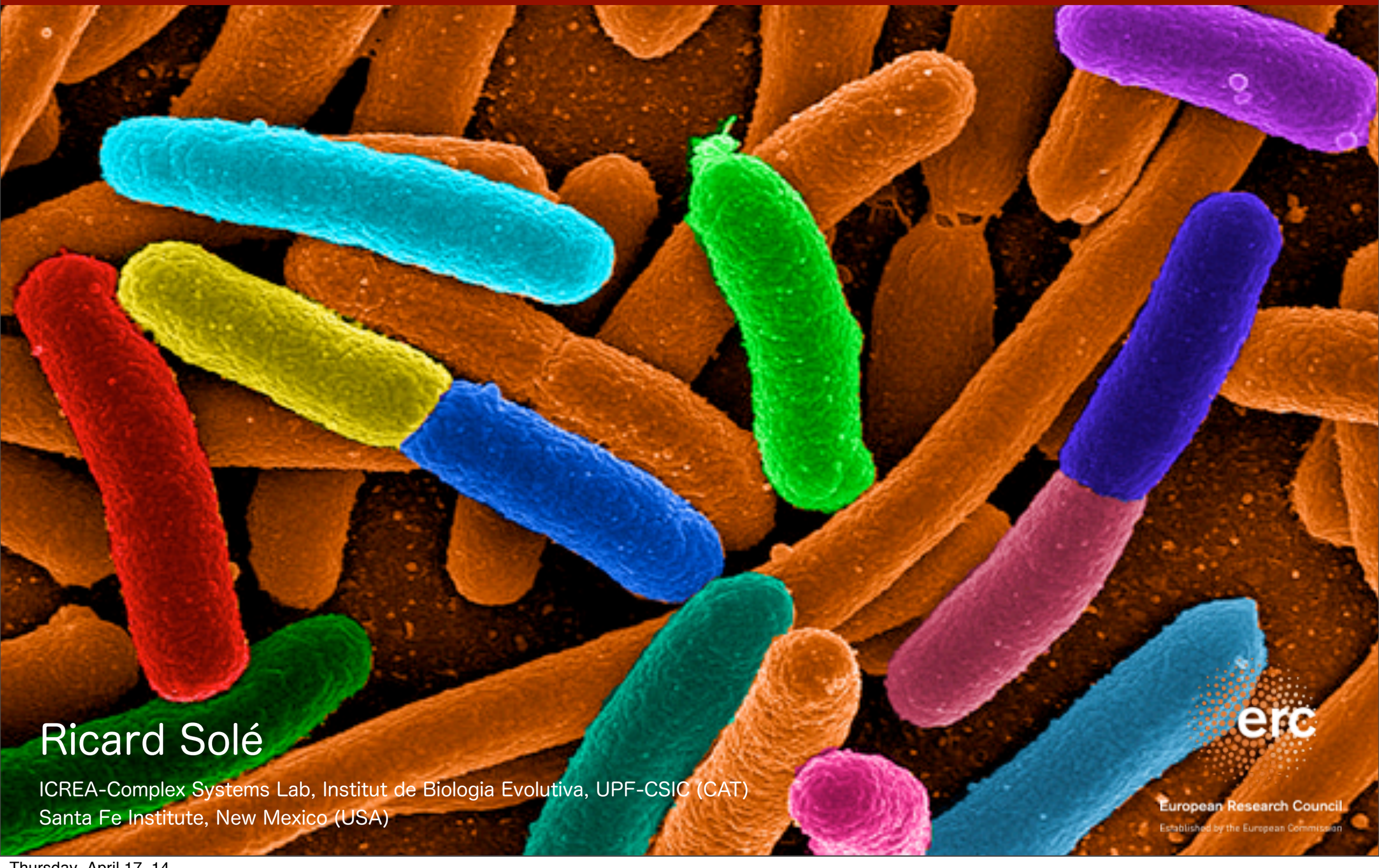
Towards the major transitions in synthetic evolution

Hidden Connections Workshop, NTU Singapore, March 2014



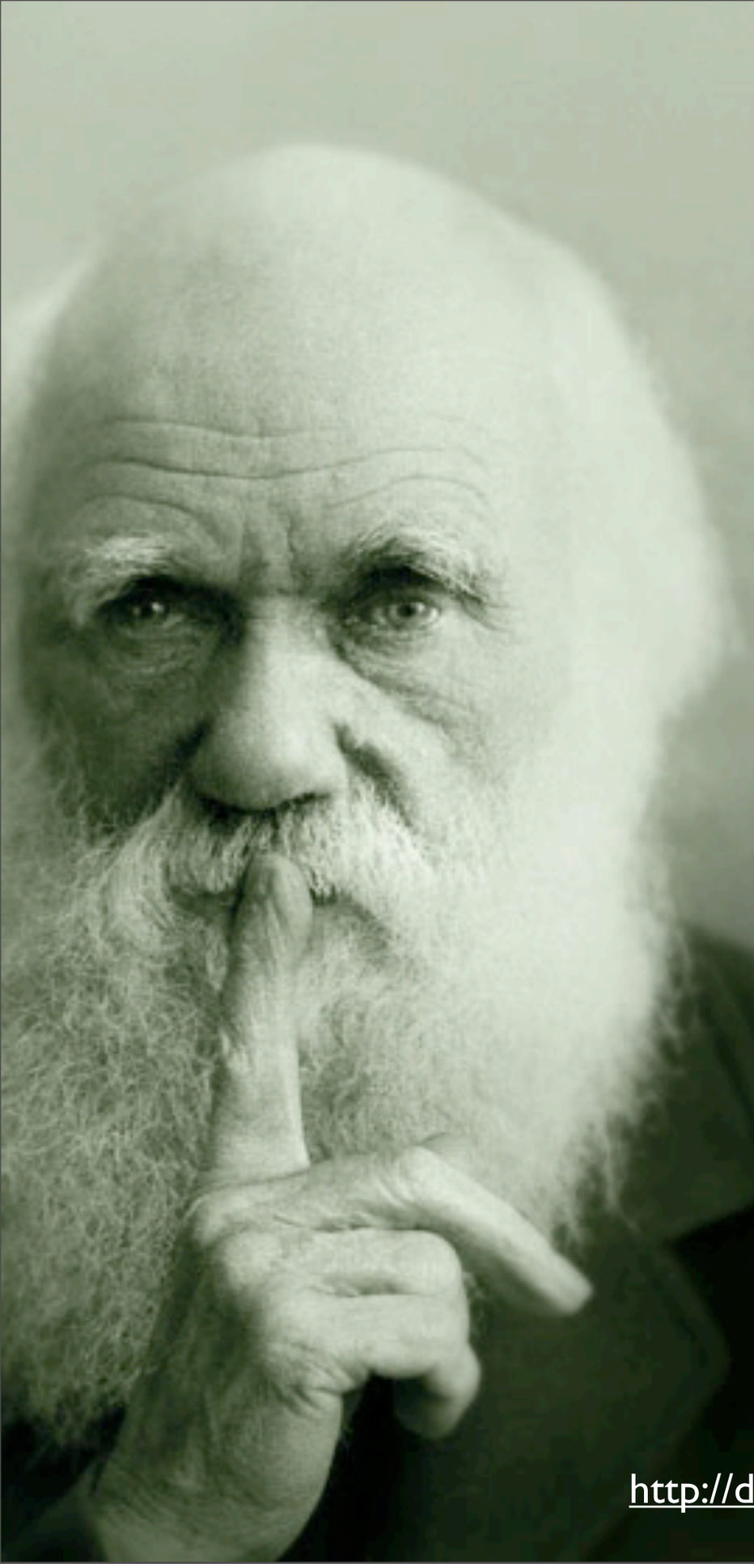
Ricard Solé

ICREA-Complex Systems Lab, Institut de Biologia Evolutiva, UPF-CSIC (CAT)

Santa Fe Institute, New Mexico (USA)

European Research Council

Established by the European Commission



How the universe originated? (Why there is something...)

What defines life? How life originated?

Cell origins / Can we build artificial cells from scratch?

How complex cells emerged?

How did multicellularity arise?

Can we break evolutionary barriers related to aging and death?

What defines consciousness and/or intelligence?

Can we build a conscious machine?

Is technology the sixth kingdom?

We'll we survive?

http://darwin-online.org.uk/

Innovations and major transitions

REVIEW ARTICLE

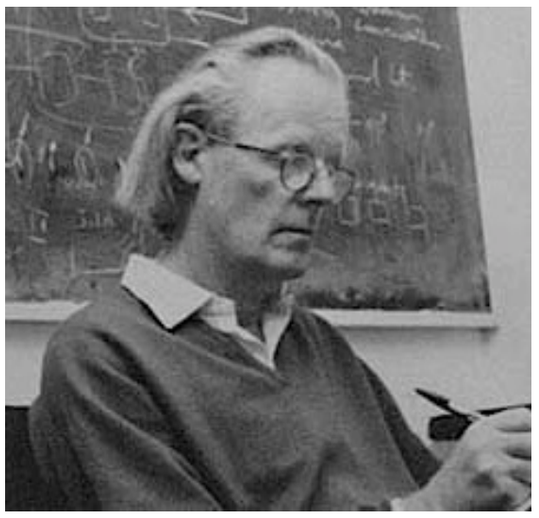
The major evolutionary transitions

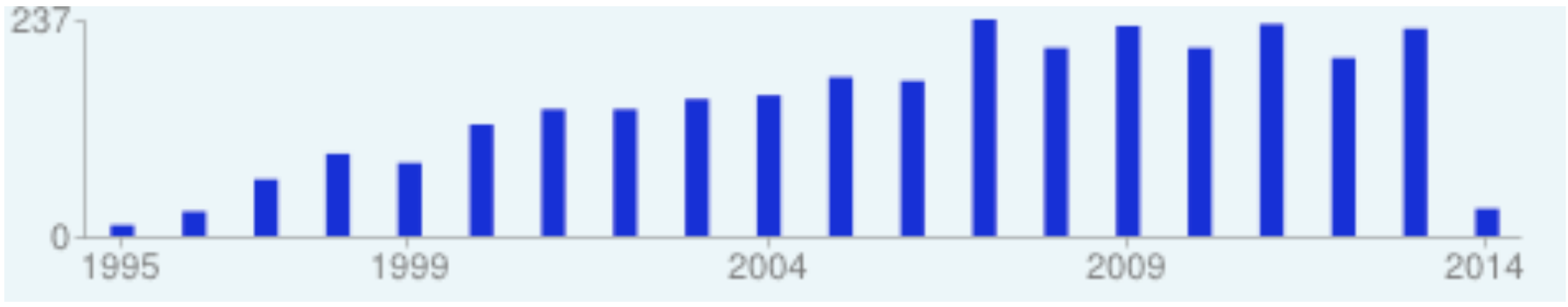
Eörs Szathmáry & John Maynard Smith

There is no theoretical reason to expect evolutionary lineages to increase in complexity with time, and no empirical evidence that they do so. Nevertheless, eukaryotic cells are more complex than prokaryotic ones, animals and plants are more complex than protists, and so on. This increase in complexity may have been achieved as a result of a series of major evolutionary transitions. These involved changes in the way information is stored and transmitted.

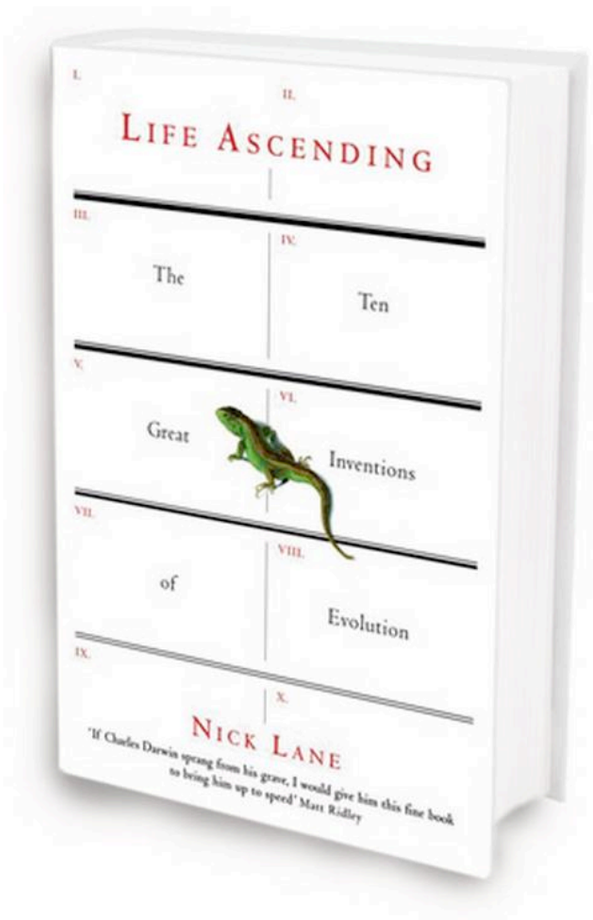
TABLE 1 The major transitions[1]

Replicating molecules to populations of molecules in compartments
Unlinked replicators to chromosomes
RNA as gene and enzyme to DNA and protein (genetic code)
Prokaryotes to eukaryotes
Asexual clones to sexual populations
Protists to animals, plants and fungi (cell differentiation)
Solitary individuals to colonies (non-reproductive castes)
Primate societies to human societies (language)





Innovations and major transitions



Origin of life
DNA
Photosynthesis
The complex cell
Sex
Movement
Sight
Hot Blood
Consciousness
Death

Life ascending: then great inventions of evolution
Nick Lane (2010)

NewScientist

Top 10: Life's greatest inventions

9 April 2005 by Rachel Nowak

The major transitions in evolution
J. Maynard Smith & E. Szathmary (1998)

1. Multicellularity

2. The eye

3. The brain

4. Language

5. Photosynthesis

6. Sex

7. Death

8. Parasitism

9. Superorganism

10. Symbiosis

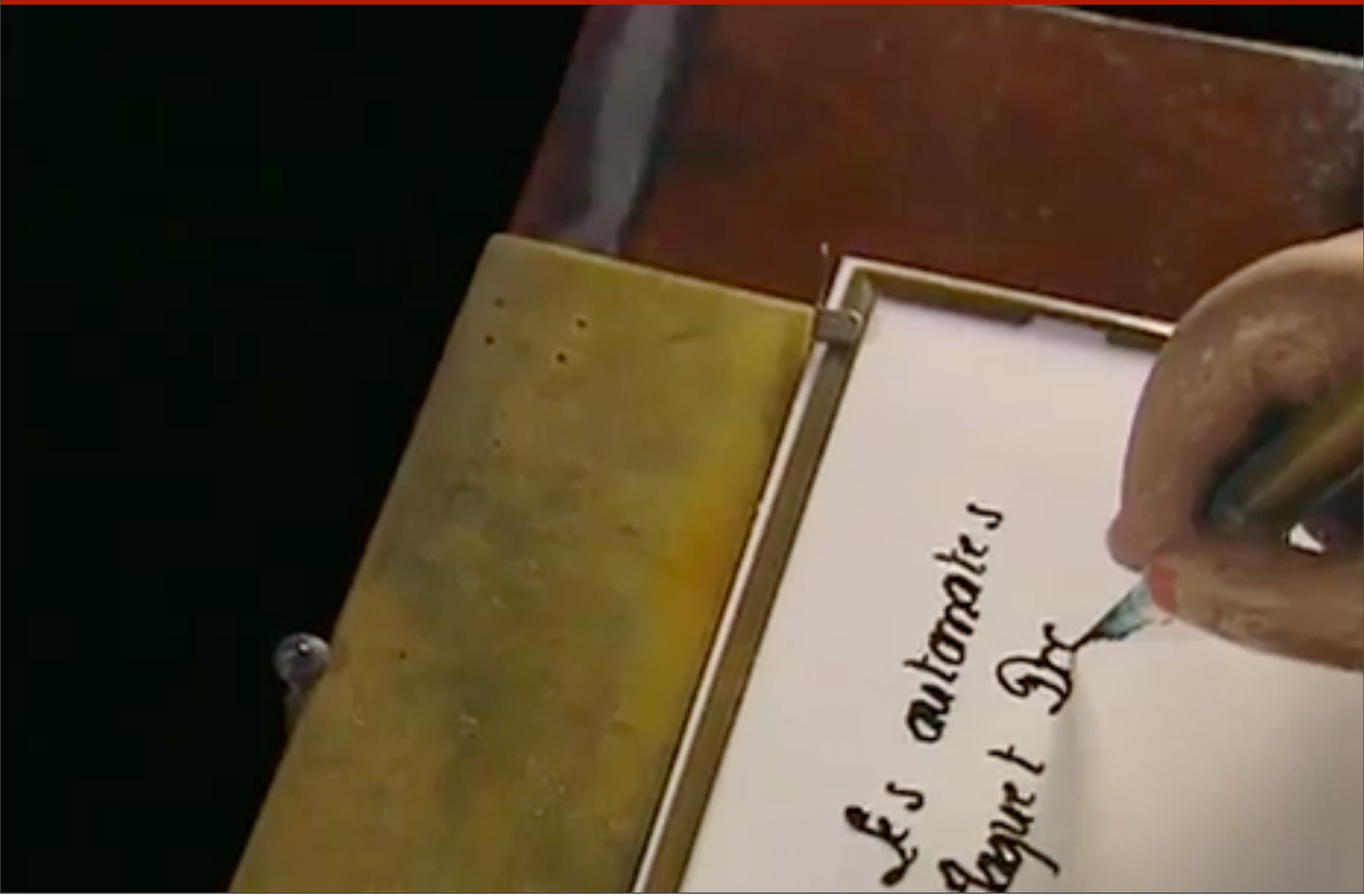
Innovations and major transitions

1. Multicellularity (tissue engineering, stem cells)
2. The eye (artificial eyes, brain-chip interfaces)
3. The brain (artificial brains, brain implants)
4. Language (Robotic languages)
5. Photosynthesis (synthetic cells-energy sources)
6. Death (aging therapies, telomere engineering)
7. Parasitism (engineered microbiomics)
8. Superorganisms (synthetic collective intelligence)
9. Symbiosis (new synthetic tissue implants)

Artificial life?

What is life and can we imitate it?

Artificial life?



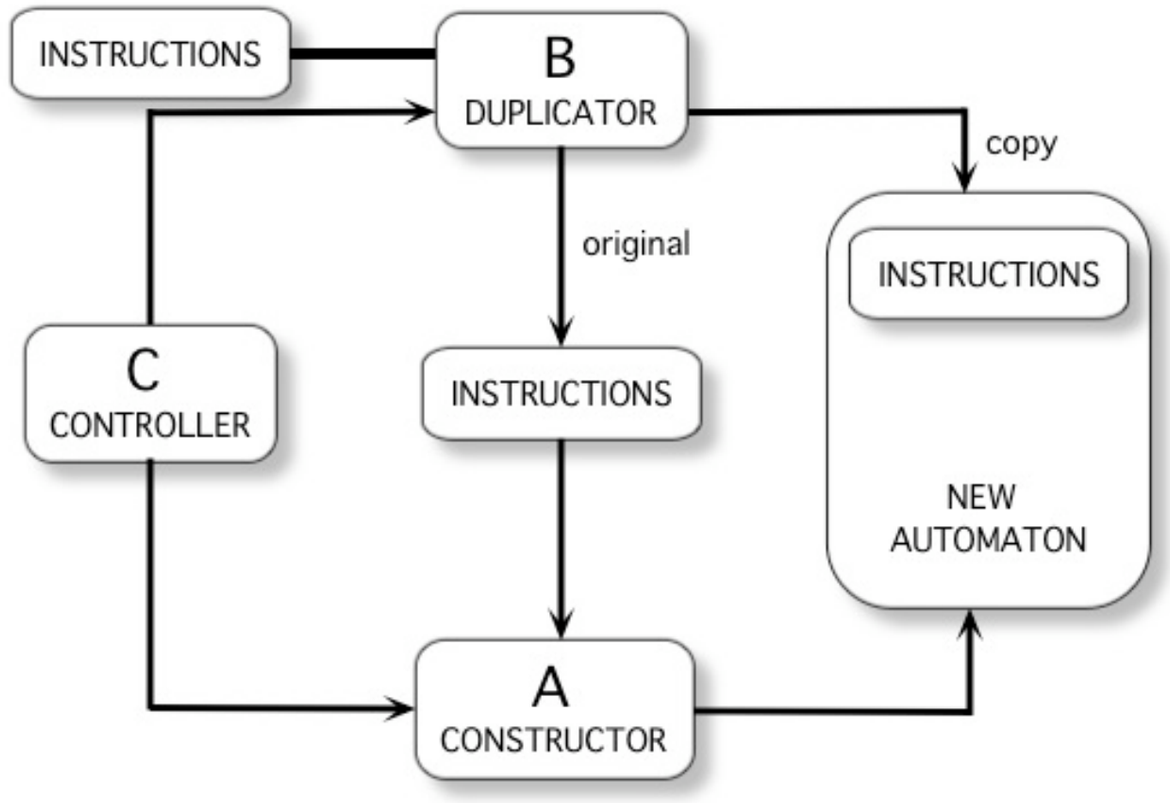
Synthetic biology

“I have not neglected the other branches of science. (...) If your wish is to become really a man of science, (...) I should advise you to apply to every branch of natural philosophy, including mathematics.”

Frankenstein, chapter 4

Synthetic biology

Synthetic machines: von Neumann

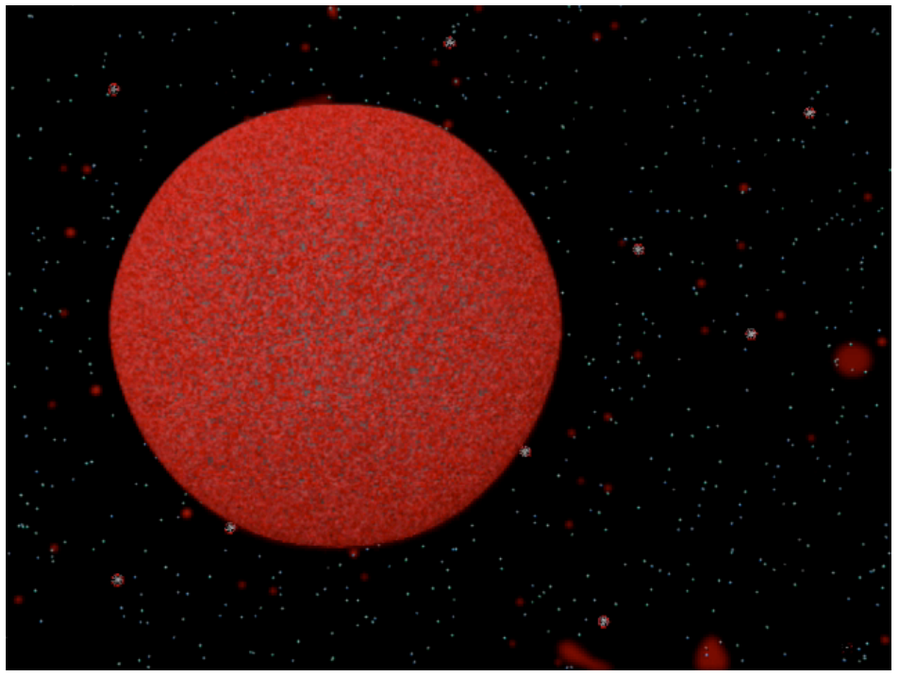


Instruction set: DNA

Duplicator: DNA polymerase + other elements of the replication machinery

Constructor: RNA polymerase and translation machinery

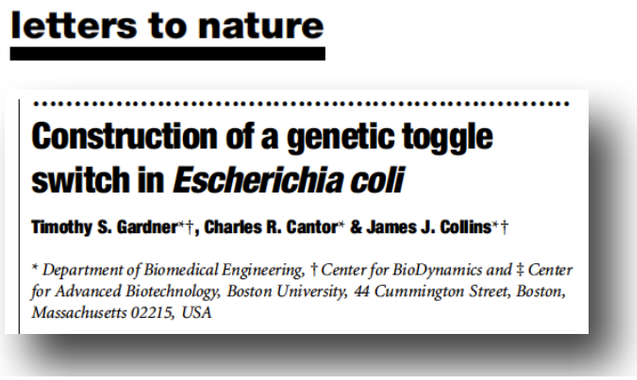
Controller: regulation of transcription and translation

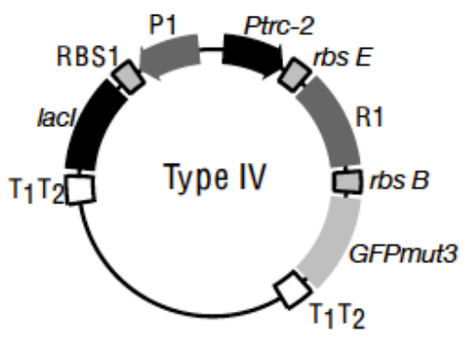


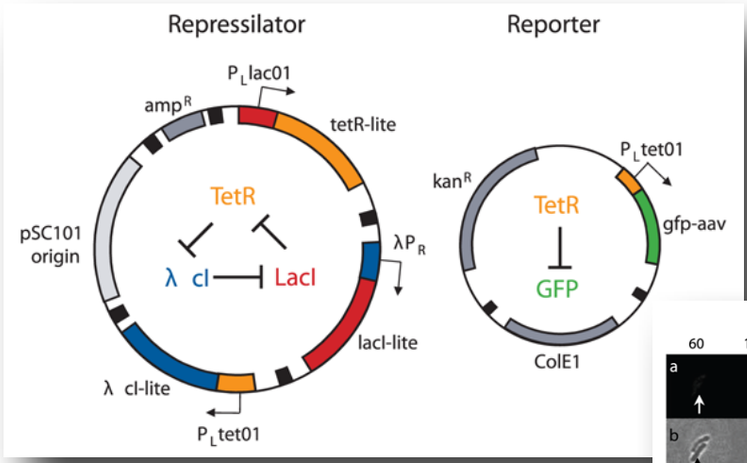
Engineering biology

How can we engineer (existing) cells and tissues?

Synthetic biology







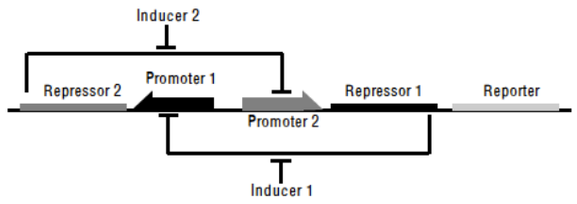
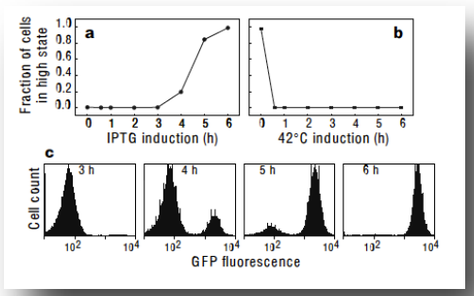
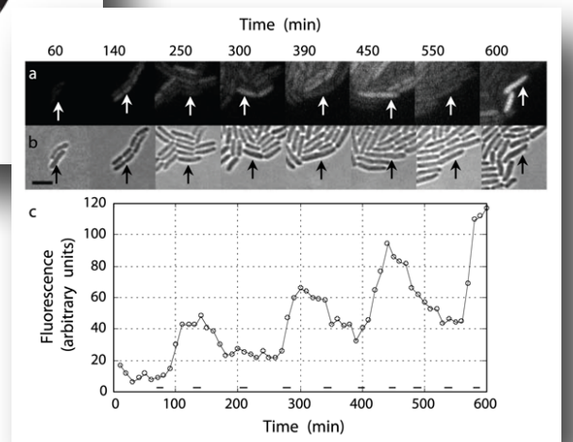


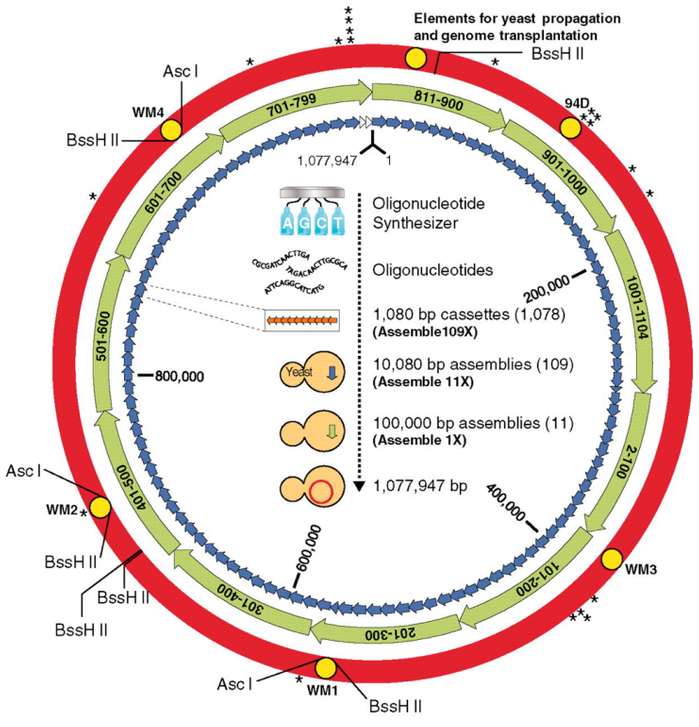
Figure 1 Toggle switch design. Repressor 1 inhibits transcription from Promoter 1 and is induced by Inducer 1. Repressor 2 inhibits transcription from Promoter 2 and is induced by Inducer 2.



$$\frac{dm_i}{dt} = -m_i + \frac{\alpha}{(1+p_j^n)} + \alpha_0 \qquad \begin{pmatrix} i = lacI, tetR, cI \\ j = cI, lacI, tetR \end{pmatrix}$$

$$\frac{dp_i}{dt} = -\beta(p_i - m_i)$$

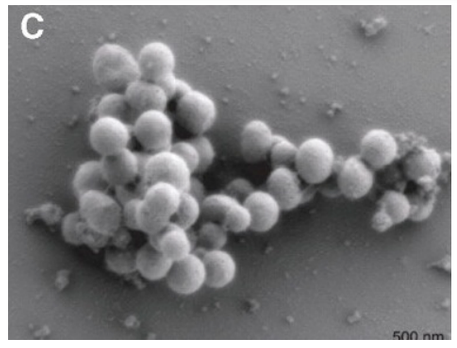




RESEARCH ARTICLE

Creation of a Bacterial Cell Controlled by a Chemically Synthesized Genome

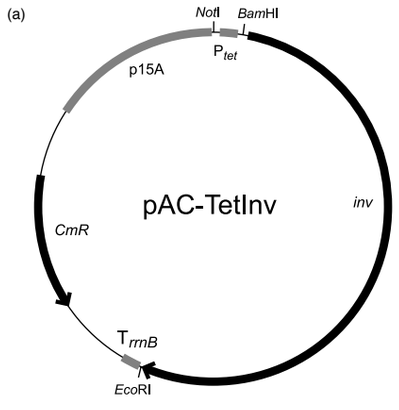
Daniel G. Gibson,[1] John I. Glass,[1] Carole Lartigue,[1] Vladimir N. Noskov,[1] Ray-Yuan Chuang,[1] Mikkel A. Algire,[1] Gwynedd A. Benders,[2] Michael G. Montague,[1] Li Ma,[1] Monzia M. Moodie,[1] Chuck Merryman,[1] Sanjay Vashee,[1] Radha Krishnakumar,[1] Nacyra Assad-Garcia,[1] Cynthia Andrews-Pfannkoch,[1] Evgeniya A. Denisova,[1] Lei Young,[1] Zhi-Qing Qi,[1] Thomas H. Segall-Shapiro,[1] Christopher H. Calvey,[1] Prashanth P. Parmar,[1] Clyde A. Hutchison III,[2] Hamilton O. Smith,[2] J. Craig Venter[1,2]*

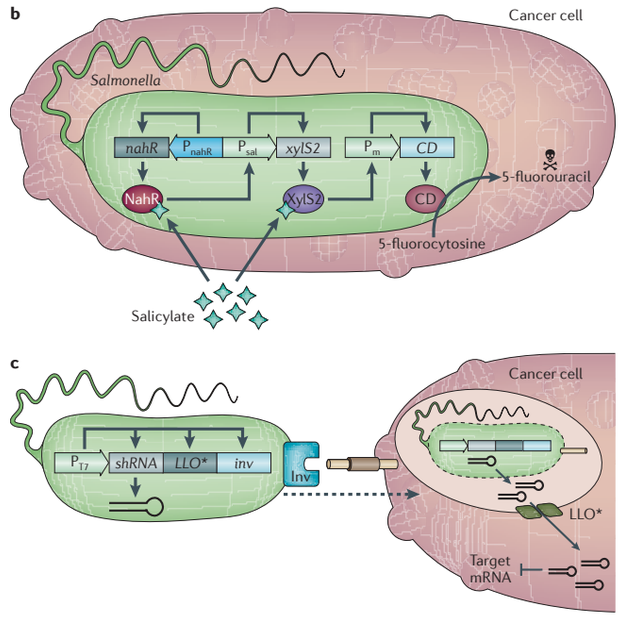


doi:10.1016/j.jmb.2005.10.076 J. Mol. Biol. (2006) 355, 619–627
JMB
Available online at www.sciencedirect.com
SCIENCE DIRECT
ELSEVIER

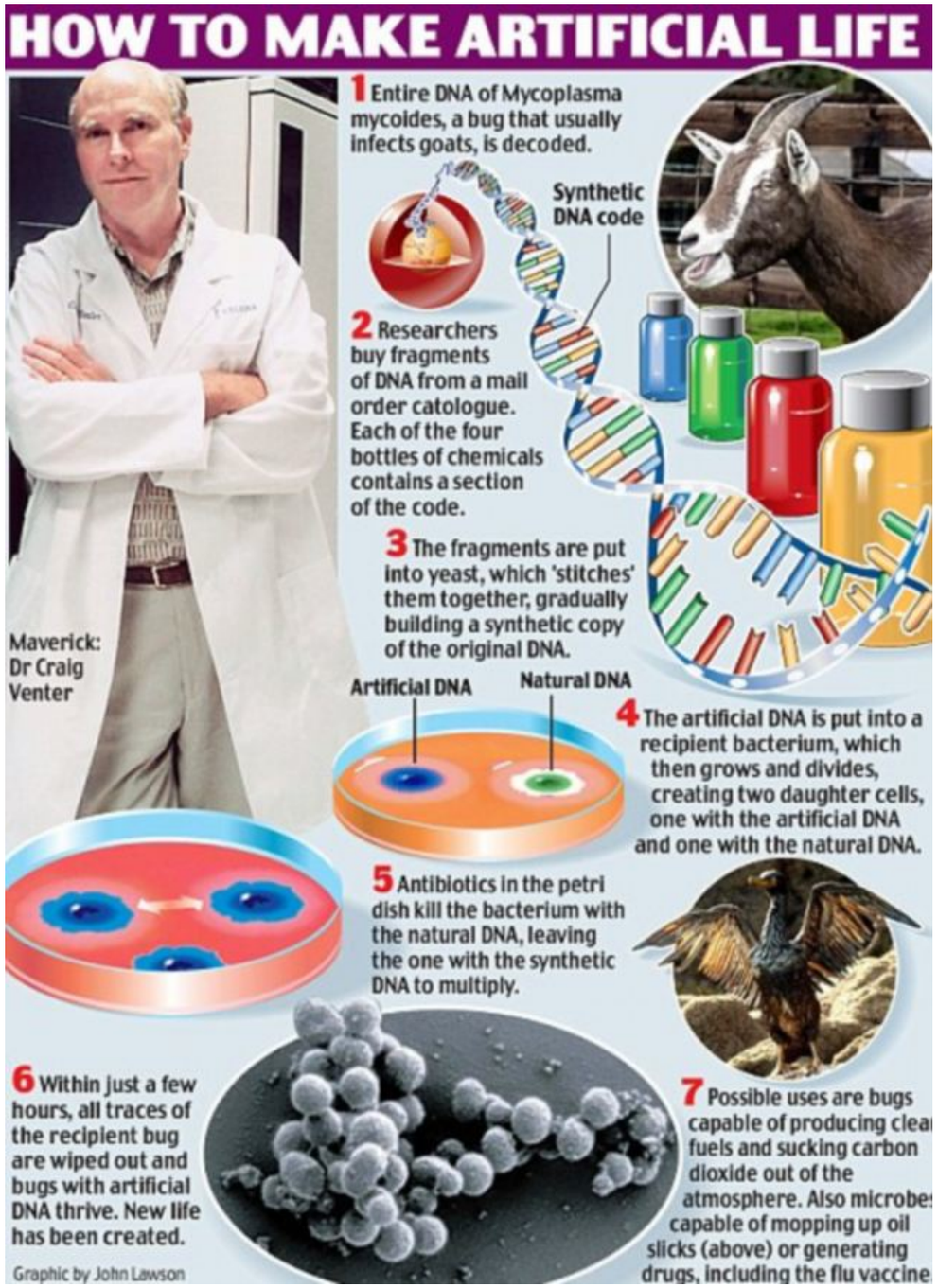
Environmentally Controlled Invasion of Cancer Cells by Engineered Bacteria

J. Christopher Anderson[1,3], Elizabeth J. Clarke[3], Adam P. Arkin[1,2]* and Christopher A. Voigt[2,3]





Synthetic biology



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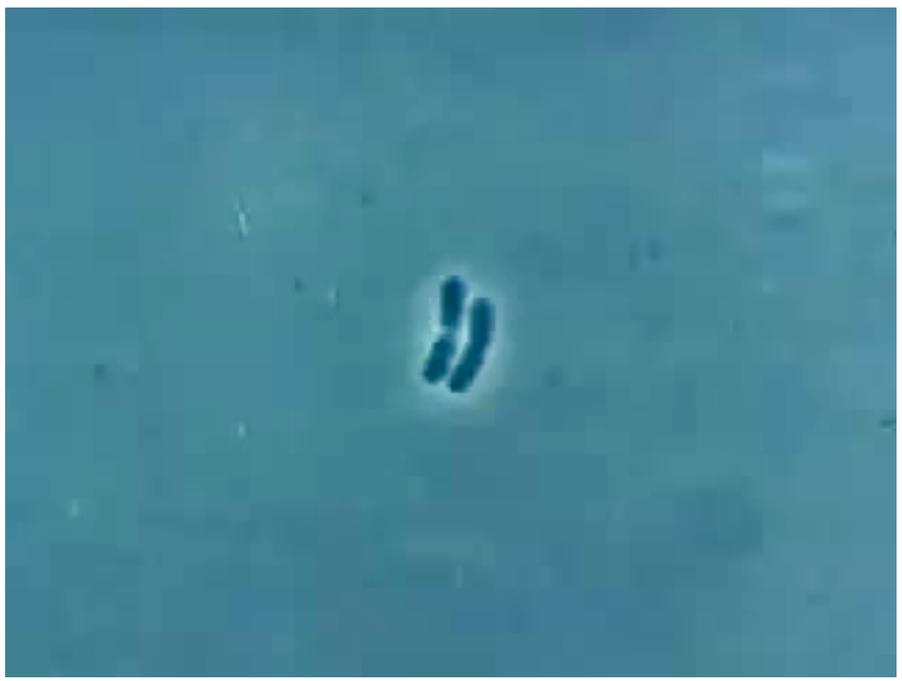
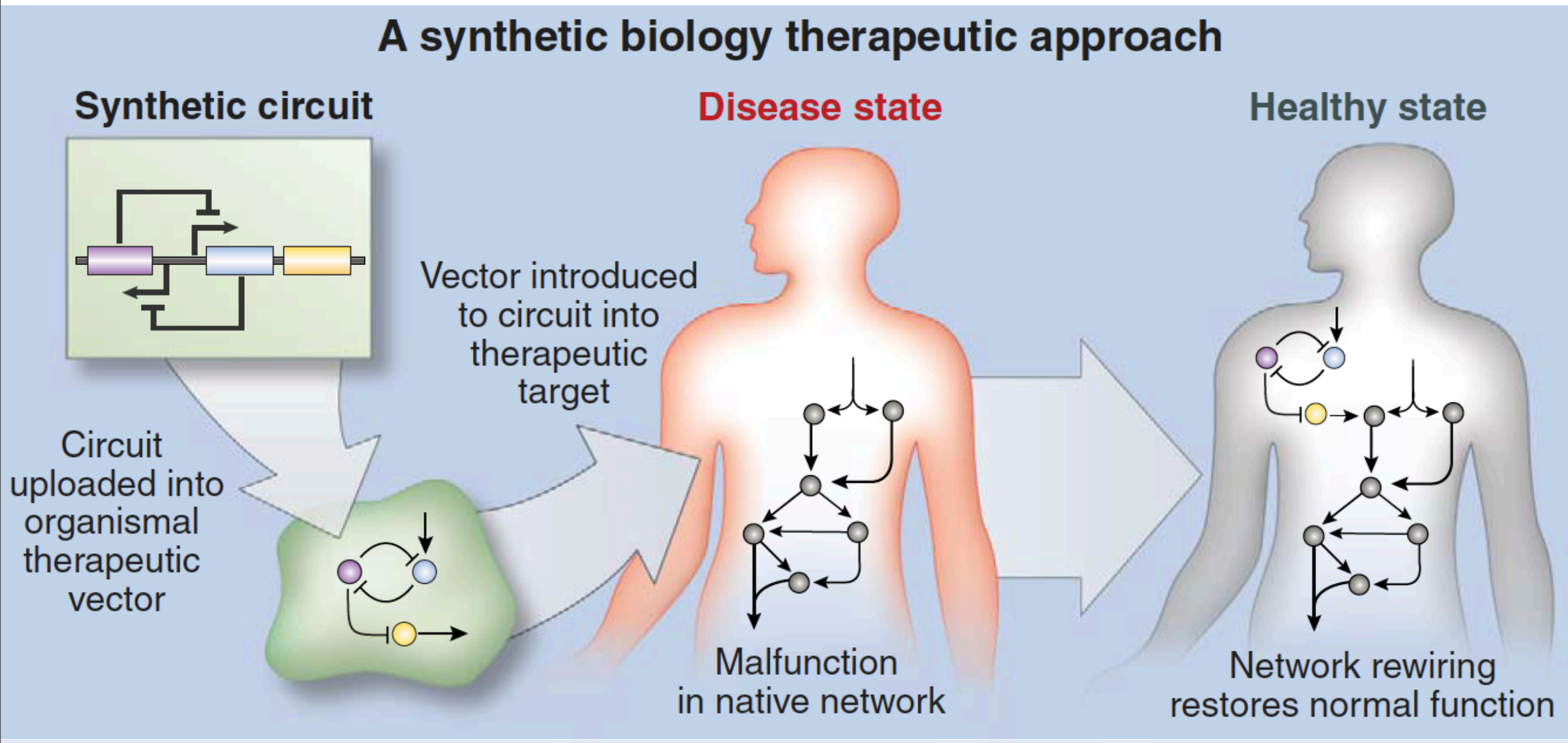


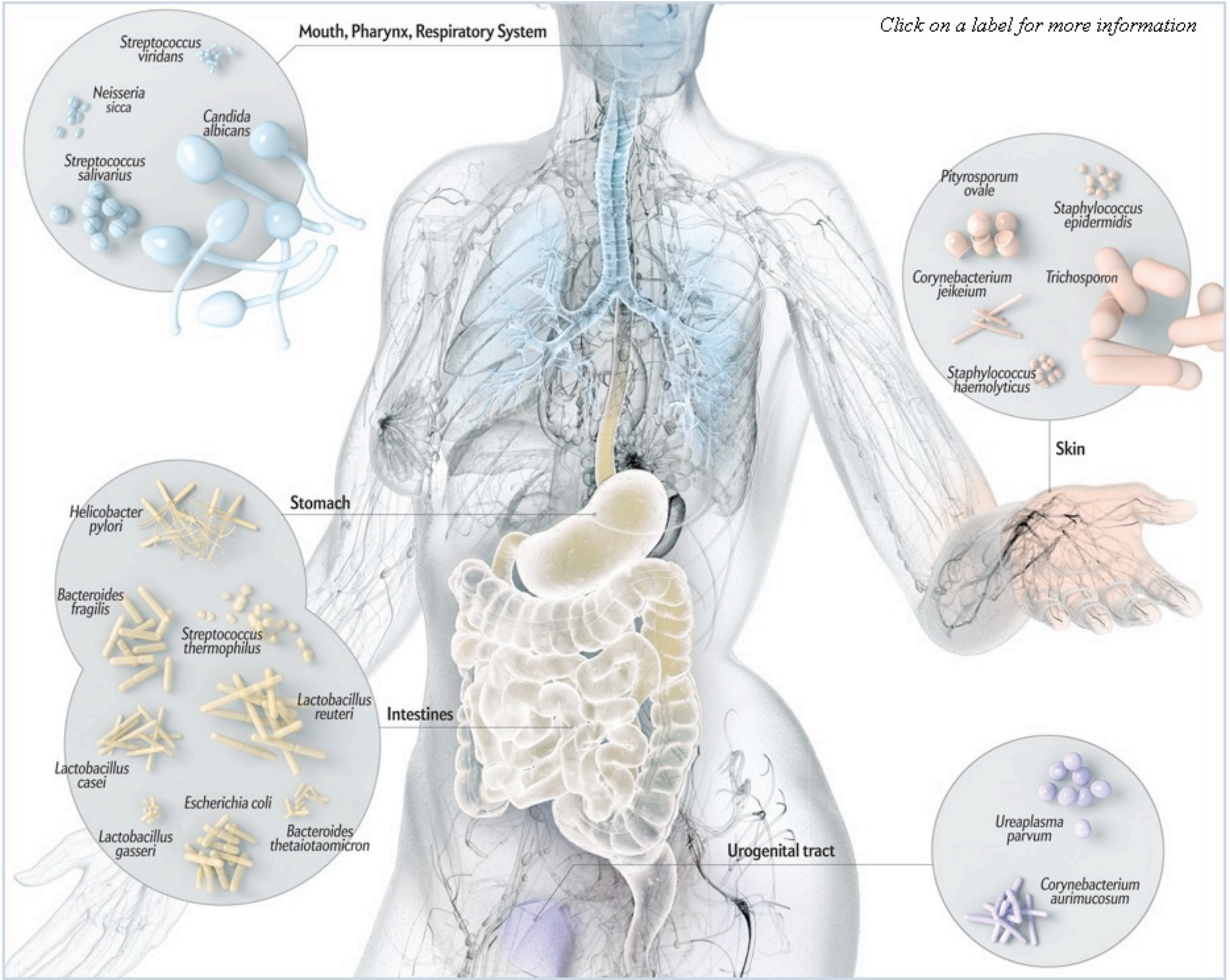
Synthetic biology for complex diseases

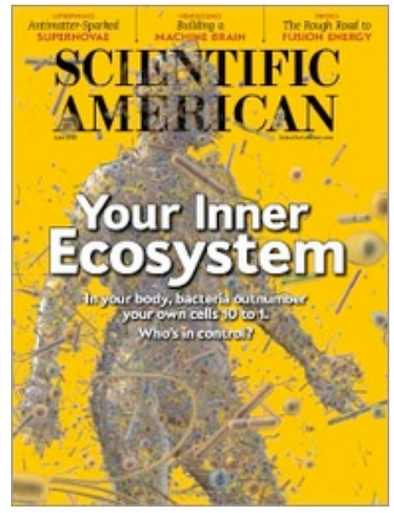


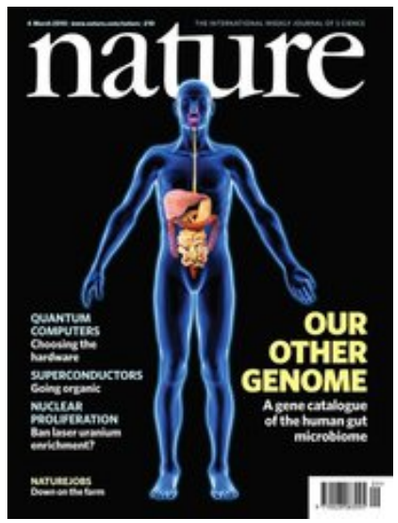
Science
AAAS

Synthetic Biology Moving into the Clinic
Warren C. Ruder *et al.*
Science **333**, 1248 (2011);
DOI: 10.1126/science.1206843

Engineering the microbiome

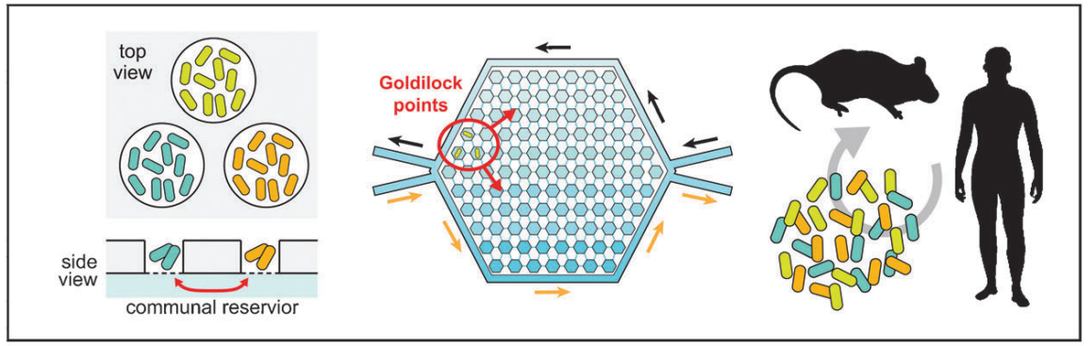




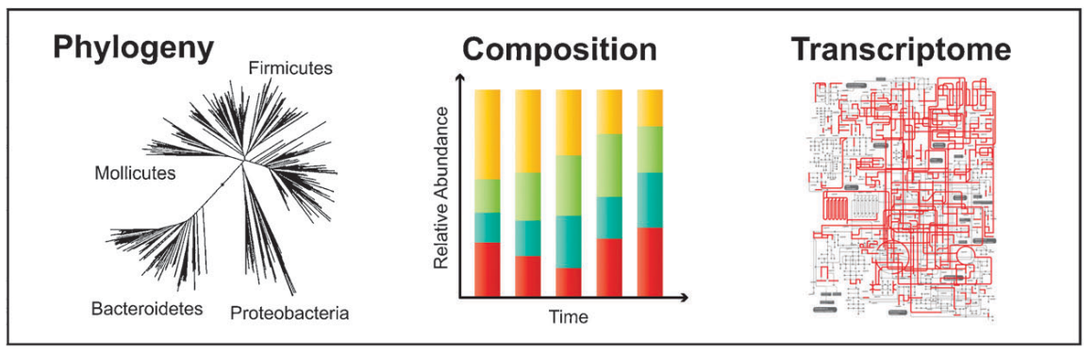


Engineering ecosystems?

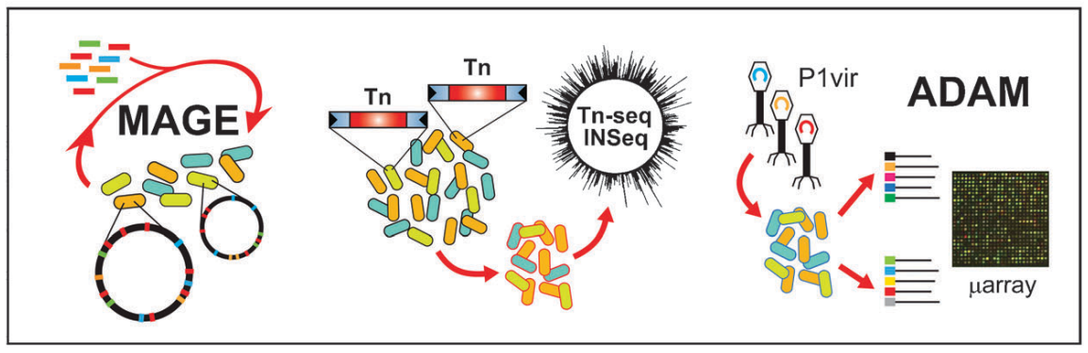
environment control



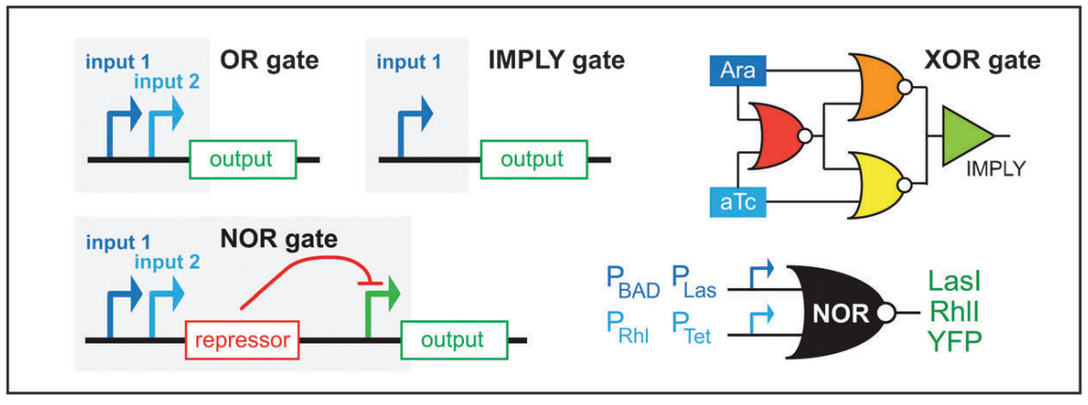
population profiling



genome engineering



synthetic circuits



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Cite this: *Mol. BioSyst.*, 2012, **8**, 2470–2483

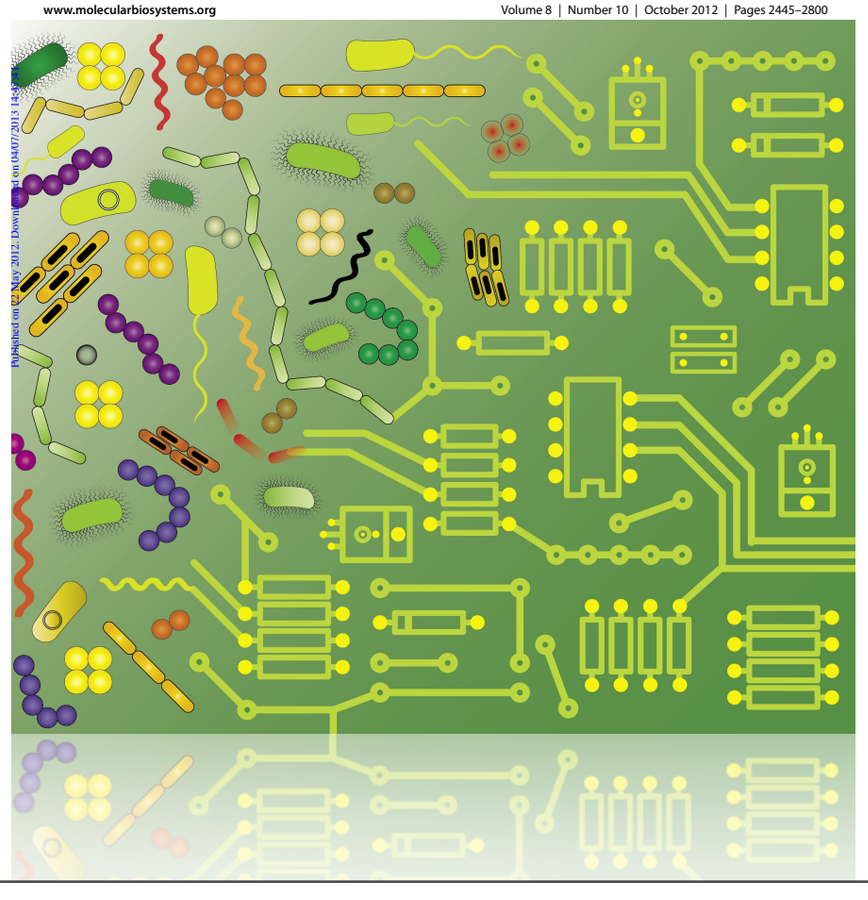
www.rsc.org/molecularbiosystems

REVIEW

Engineering ecosystems and synthetic ecologies†

Michael T. Mee[ab] and Harris H. Wang*[cd]

Received 4th April 2012, Accepted 18th May 2012
DOI: 10.1039/c2mb25133g



Engineering biology

Can we engineer life?

What are the limits (if any)?

Can bioengineers avoid tinkering?

Can we break evolved solutions?

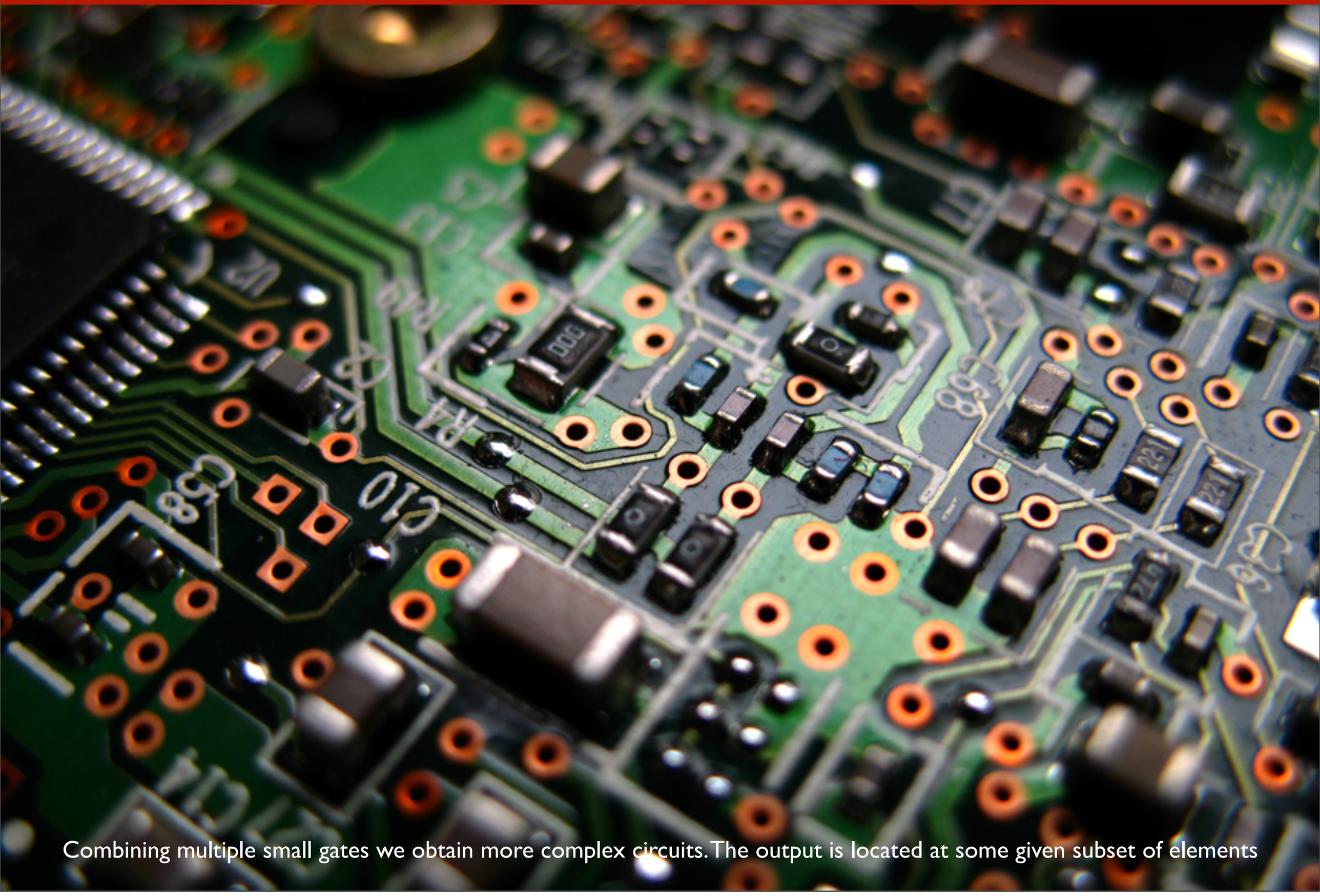
Can we engineer new innovations?

Cells as (entangled) chips

"Inside the biological microchip called a cell there are components inside components and wiring so dense and so fluid that it sometimes seems impossible to tease strands apart."

The long trail of cancer's clues
George Johnson
Sci. Am. November 2013

Engineering biology: inspiration?



Combining multiple small gates we obtain more complex circuits. The output is located at some given subset of elements

Can we get solutions from enginering?

Nucleic Acids Research, 2003, Vol. 31, No. 22 ***6663–6673***
DOI: 10.1093/nar/gkg877

Molecular flip–flops formed by overlapping Fis sites

Paul N. Hengen, Ilya G. Lyakhov, Lisa E. Stewart[1] and Thomas D. Schneider[1,*]

Intramural Research Support Program, SAIC and [1]Laboratory of Experimental and Computational Biology, NCI Frederick, Frederick, MD, USA

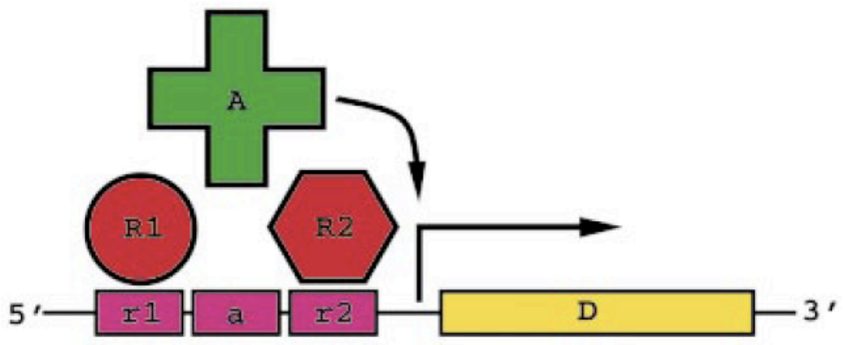
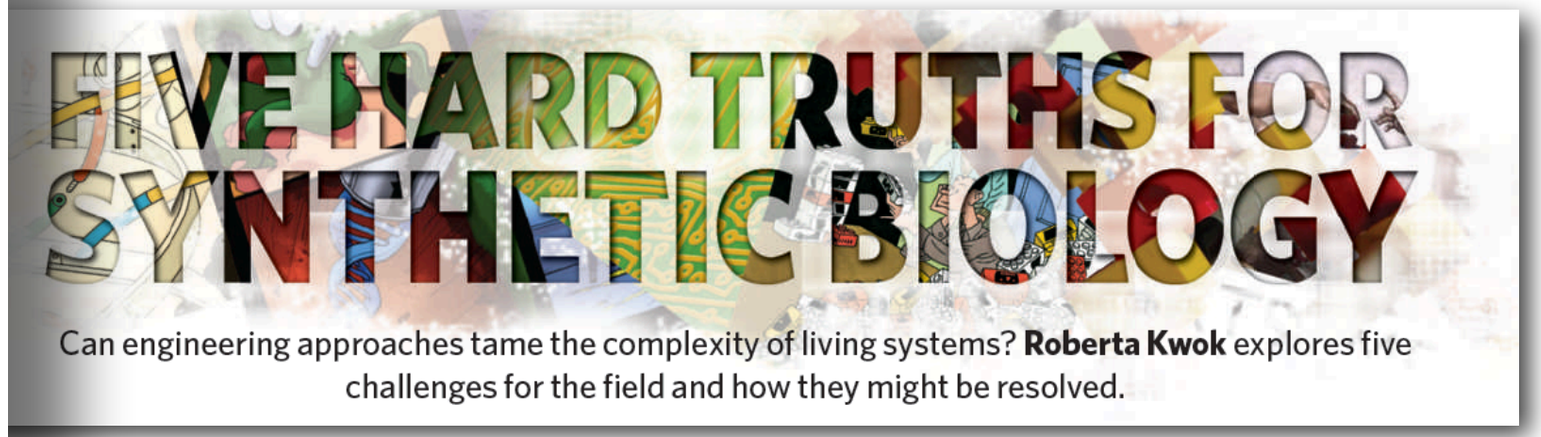


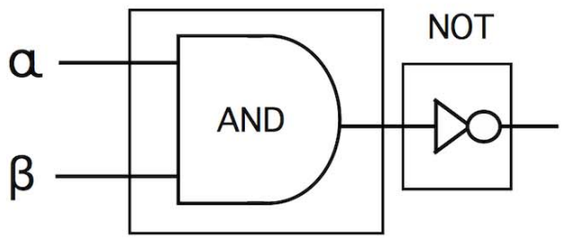
Figure 8. NOR gate molecular computer. An activator protein molecule **A** (green plus) binds to a DNA molecule at position **a**. When the activator binds, it turns on the promoter for gene D. Two repressor protein molecules **R1** and **R2** (red circle and red hexagon, respectively) bind to DNA at positions **r1** and **r2**. Binding to either **r1** or **r2** interferes with binding by **A**, so the activator can only bind when the two repressors are absent. Assigning the presence of a molecule as '1' or 'true' and the absence as '0' or 'false', then **D = R1 NOR R2**. By connecting such NOR gates together, any computer circuit can be built.

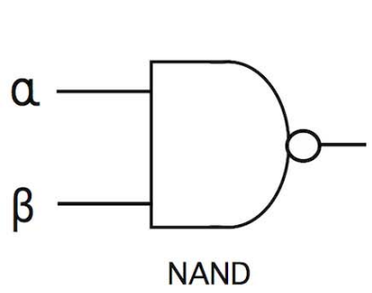


Problems: wiring and combinatorics

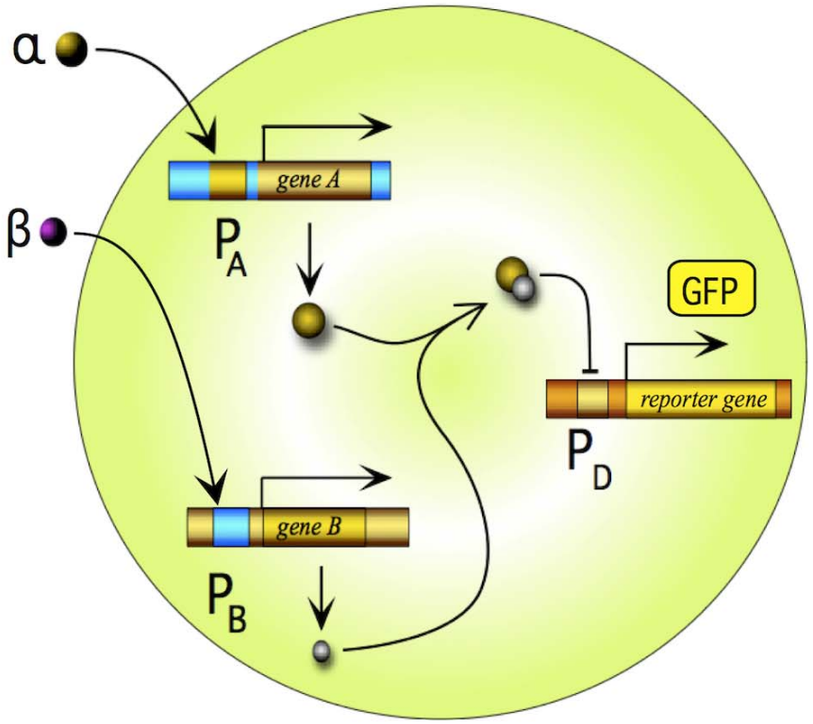
Engineering biology: inspiration?

a

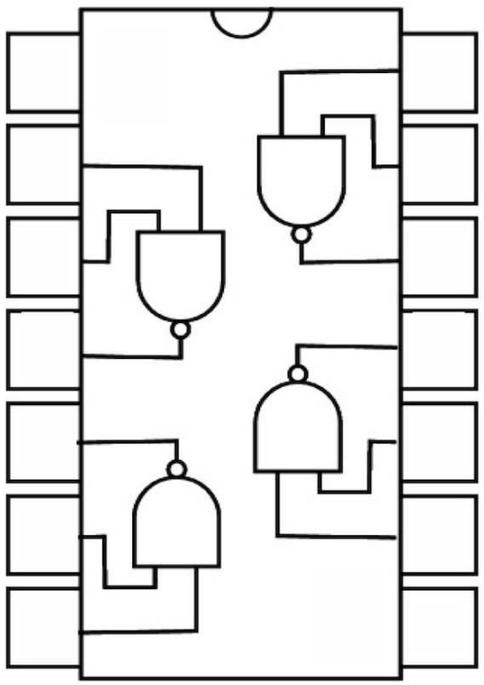




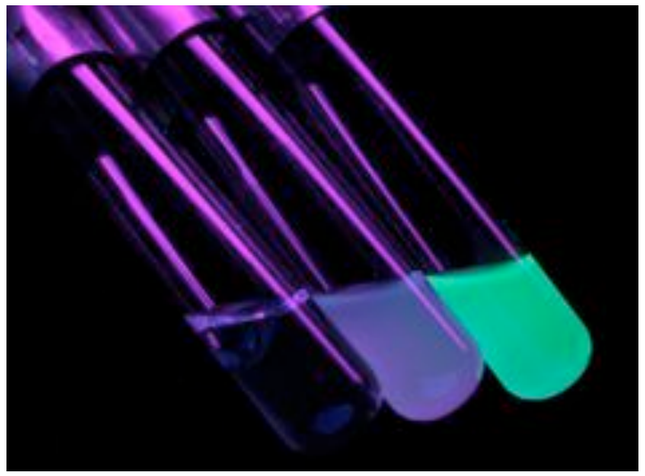
α	β	OUT
0	0	1
0	1	1
1	0	1
1	1	0



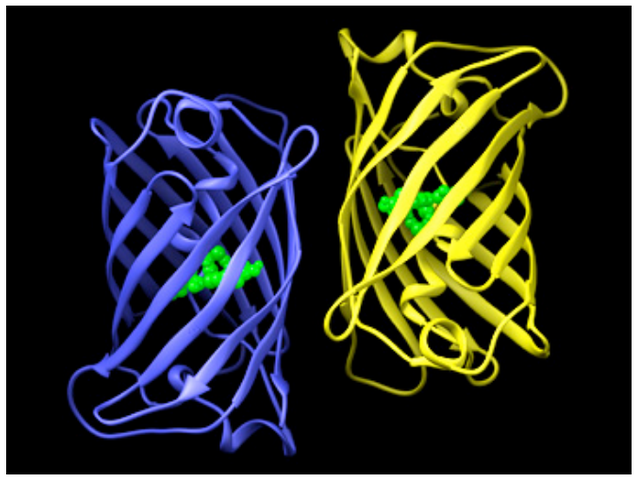
c



b



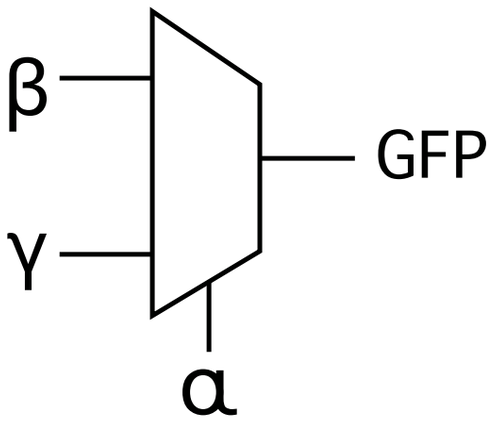
d



Single cells can be engineered to perform desired, simple functionalities

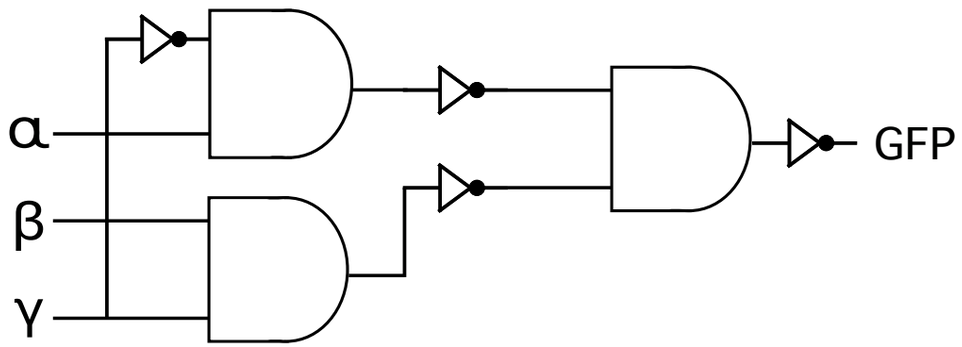
Engineering biology: the wiring problem

a



α	β	γ	GFP
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	0
1	1	1	1

b



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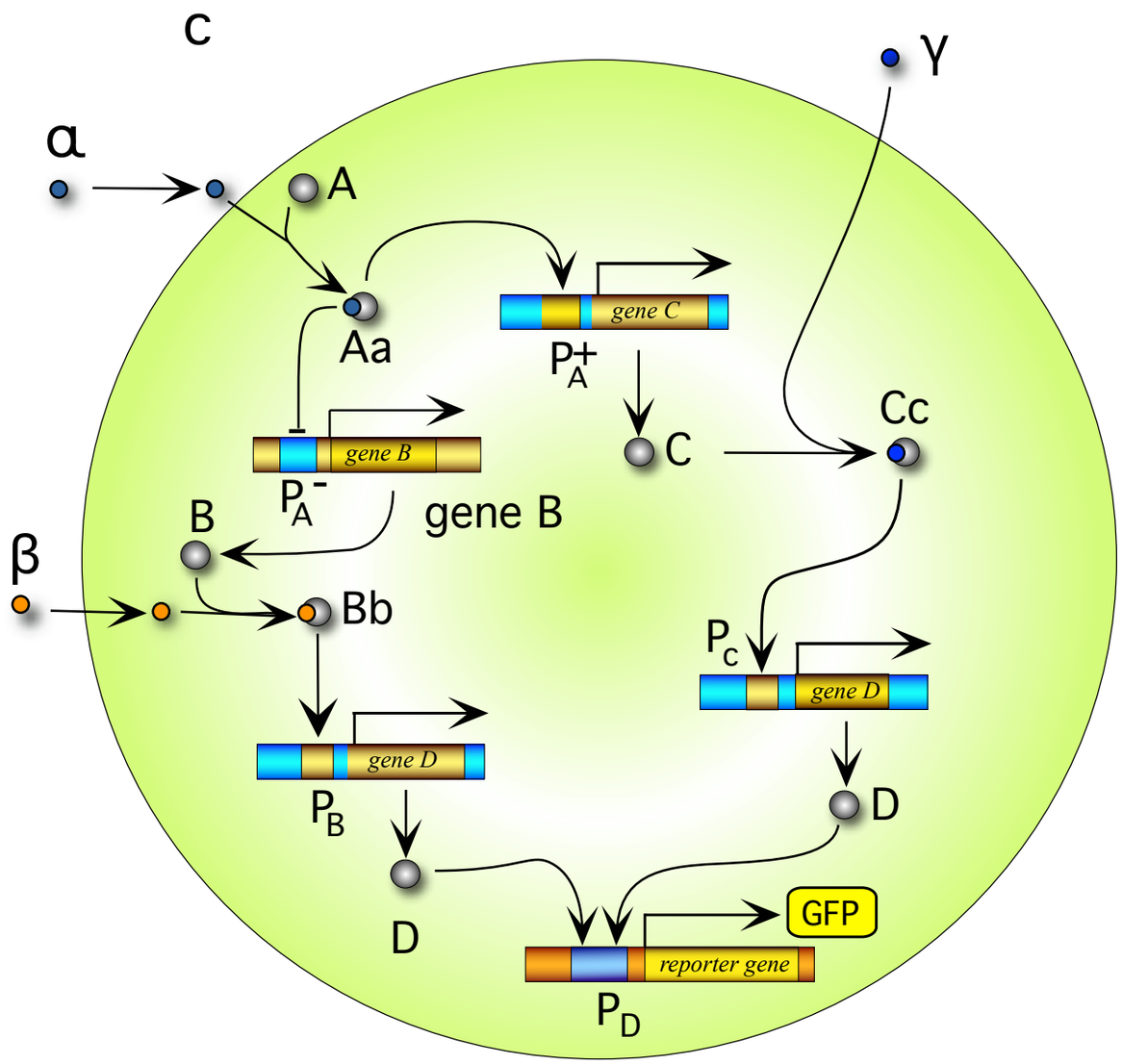
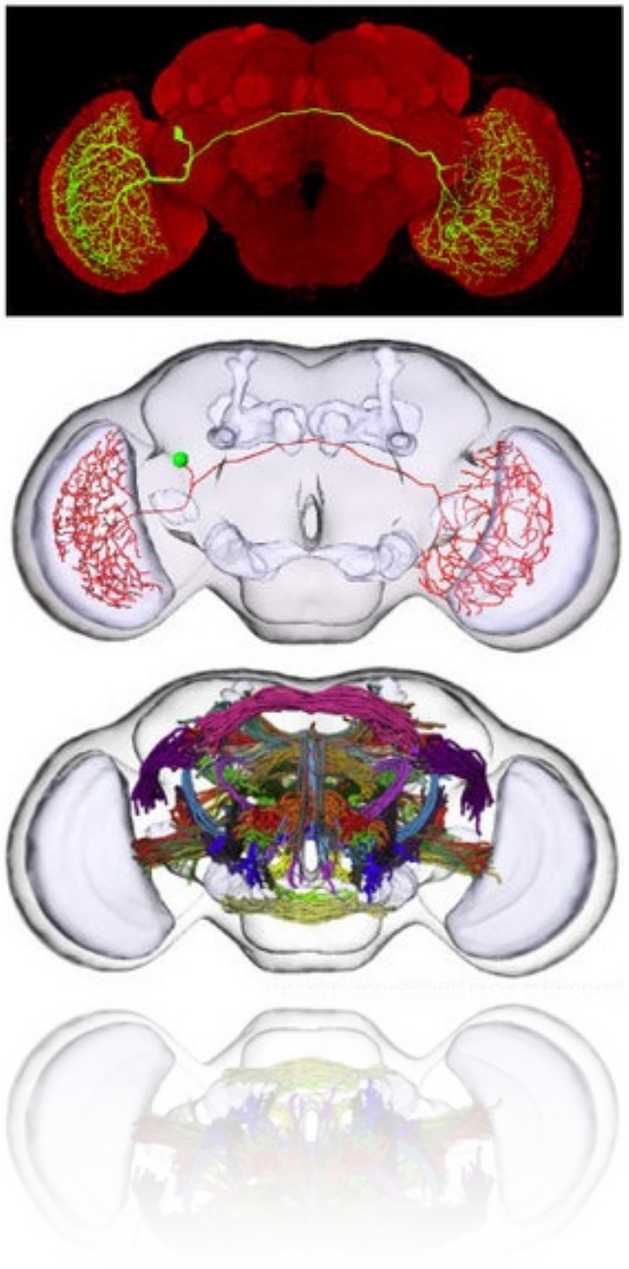


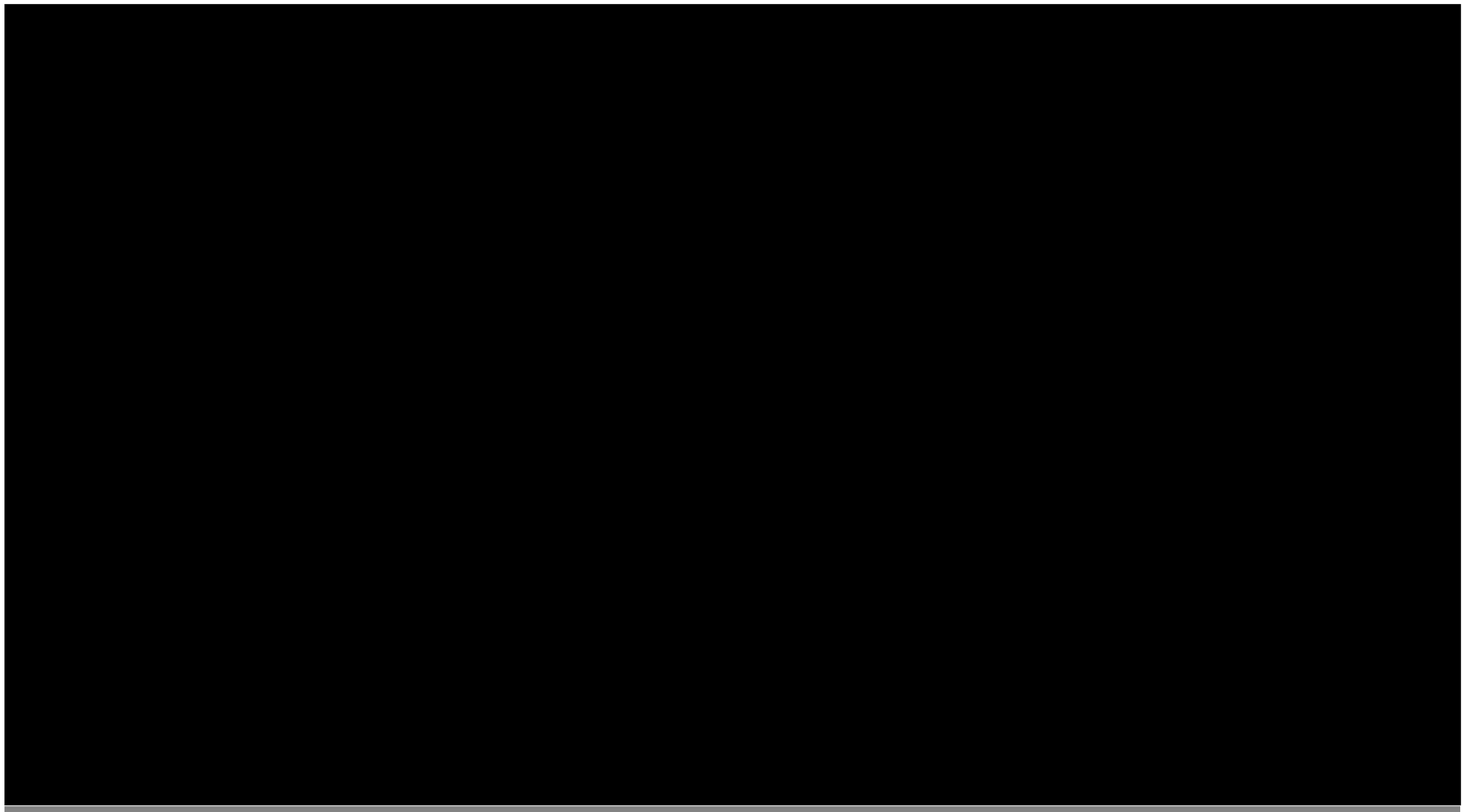
Wiring diversity increases with
+ Reuse strongly limited

Collective intelligence and computation



No central control

Distributed decisions
Simple individuals, complex CI



PHYSICAL REVIEW E VOLUME 55, NUMBER 3 MARCH 1997

Collective-induced computation

Jordi Delgado [1,2,3] and Ricard V. Solé [2,3]
[1] *Departament de Llenguatges i Sistemes Informatics, Universitat Politecnica de Catalunya, Pau Gargallo 5, 08028 Barcelona, Spain*
[2] *Complex Systems Research Group, Departament de Física i Enginyeria Nuclear, Universitat Politècnica de Catalunya, Sor Eulàlia d'Anzizu s/n, Campus Nord, Mòdul B4, 08034 Barcelona, Spain*
[3] *Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, New Mexico 87501*
(Received 26 August 1996)

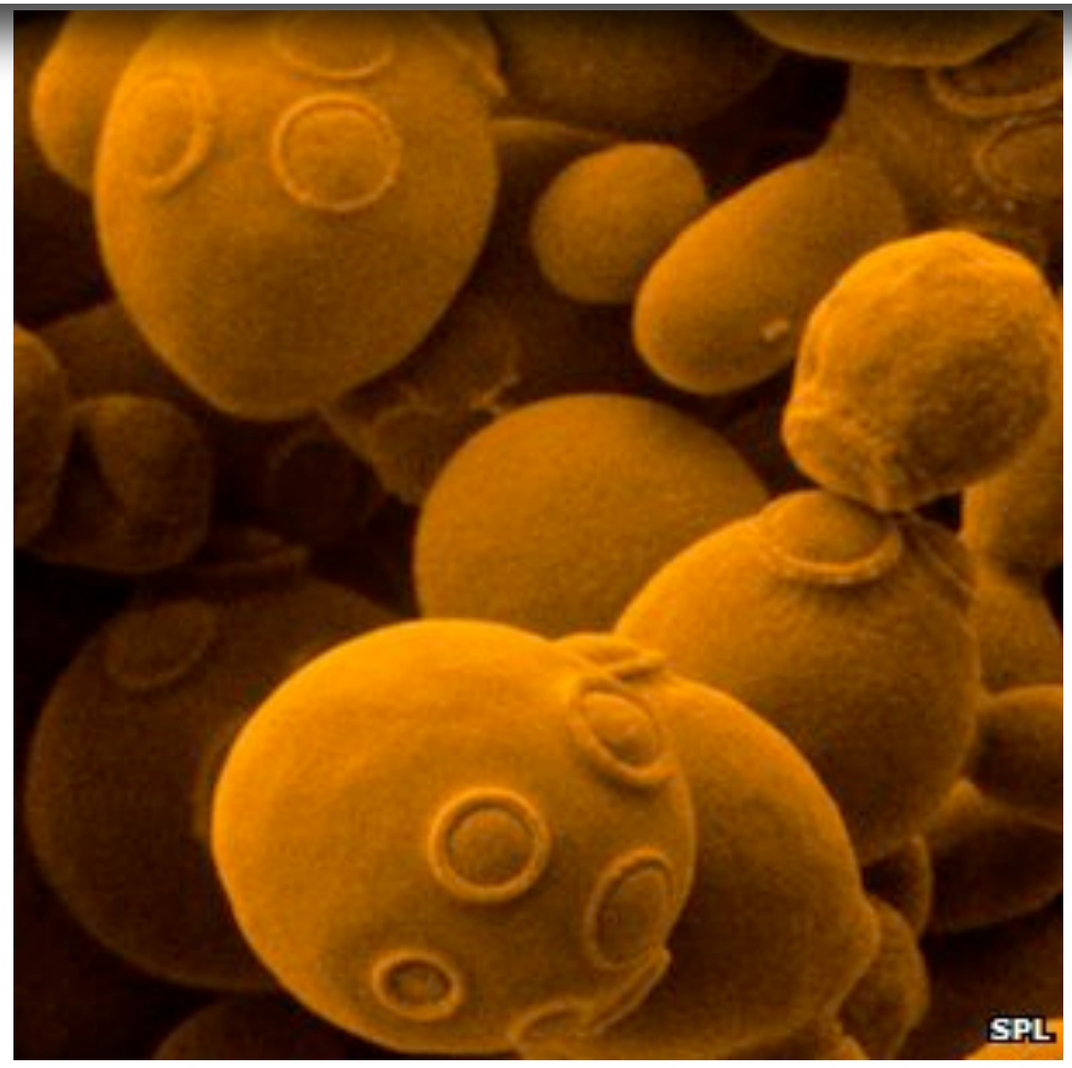
Multicellular distributed computing

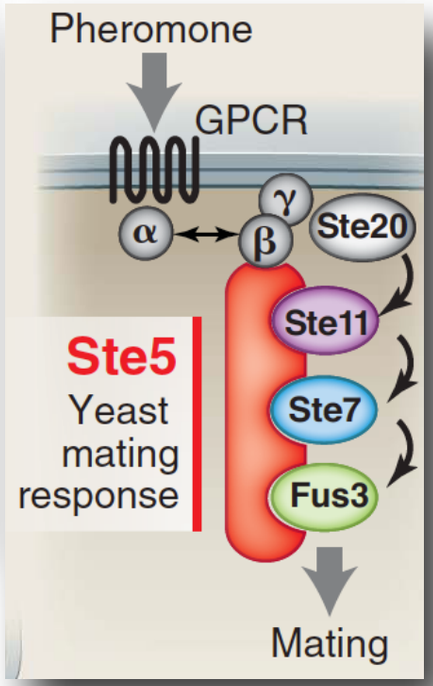
LETTER

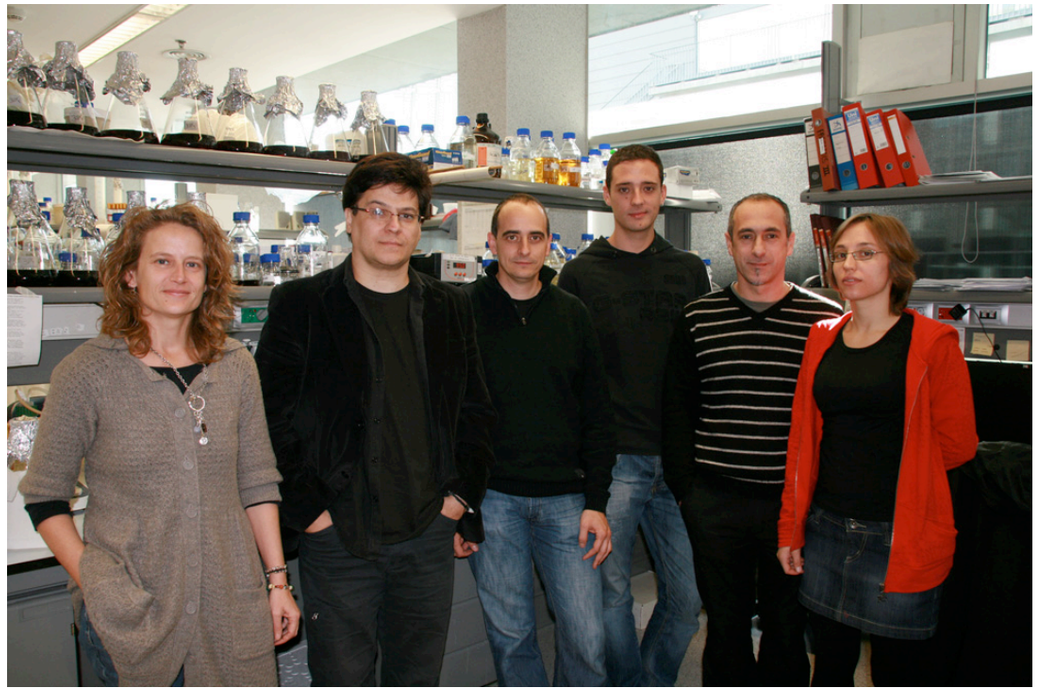
doi:10.1038/nature09679

Distributed biological computation with multicellular engineered networks

Sergi Regot[1]*, Javier Macia[2]*, Núria Conde[1,2], Kentaro Furukawa[3], Jimmy Kjellén[3], Tom Peeters[1], Stefan Hohmann[3], Eulàlia de Nadal[1], Francesc Posas[1] & Ricard Solé[2,4,5]







Breaking some rules

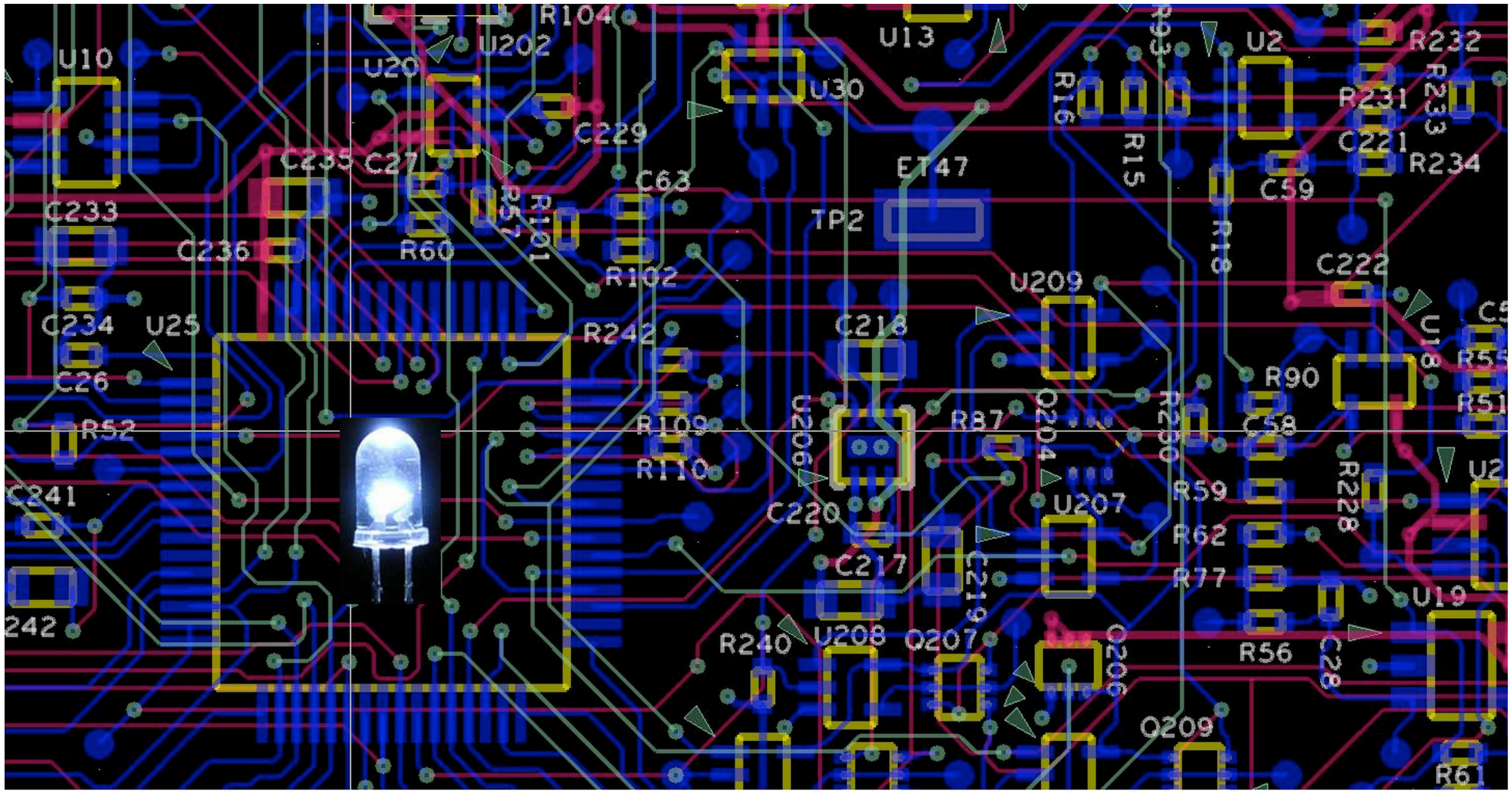
1. Multicellular circuit

2. The circuit can be broken into disconnected parts

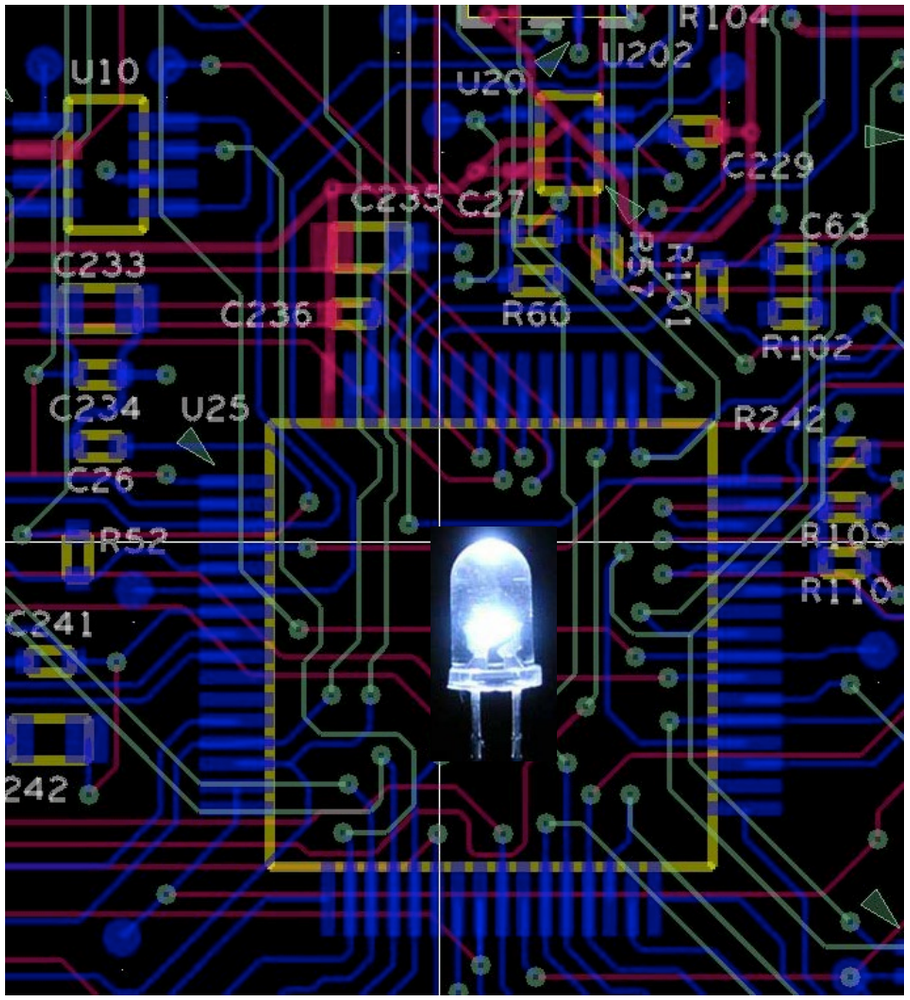
3. Different parts can give the output

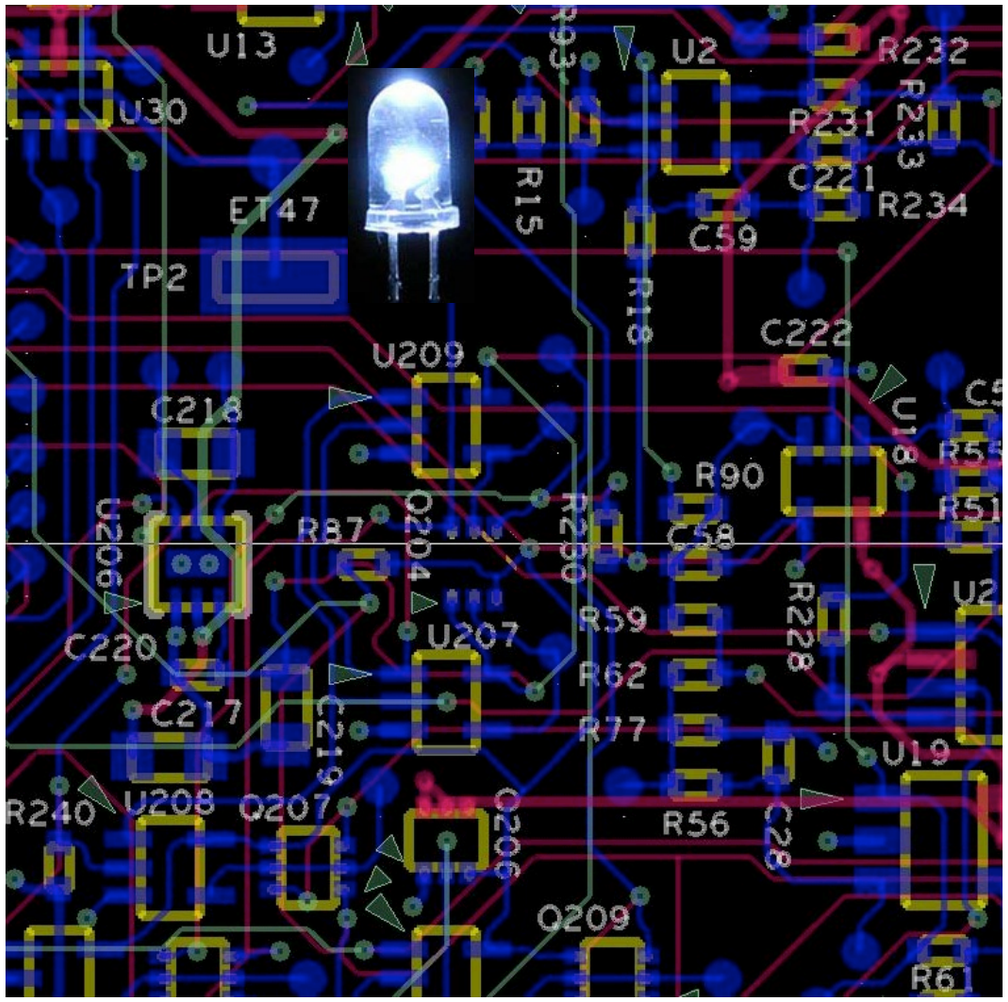
Distributed biological computation with multicellular engineered networks
S Regot, J. Macia, N. Conde et al Nature (2011)

Multicellular distributed computing

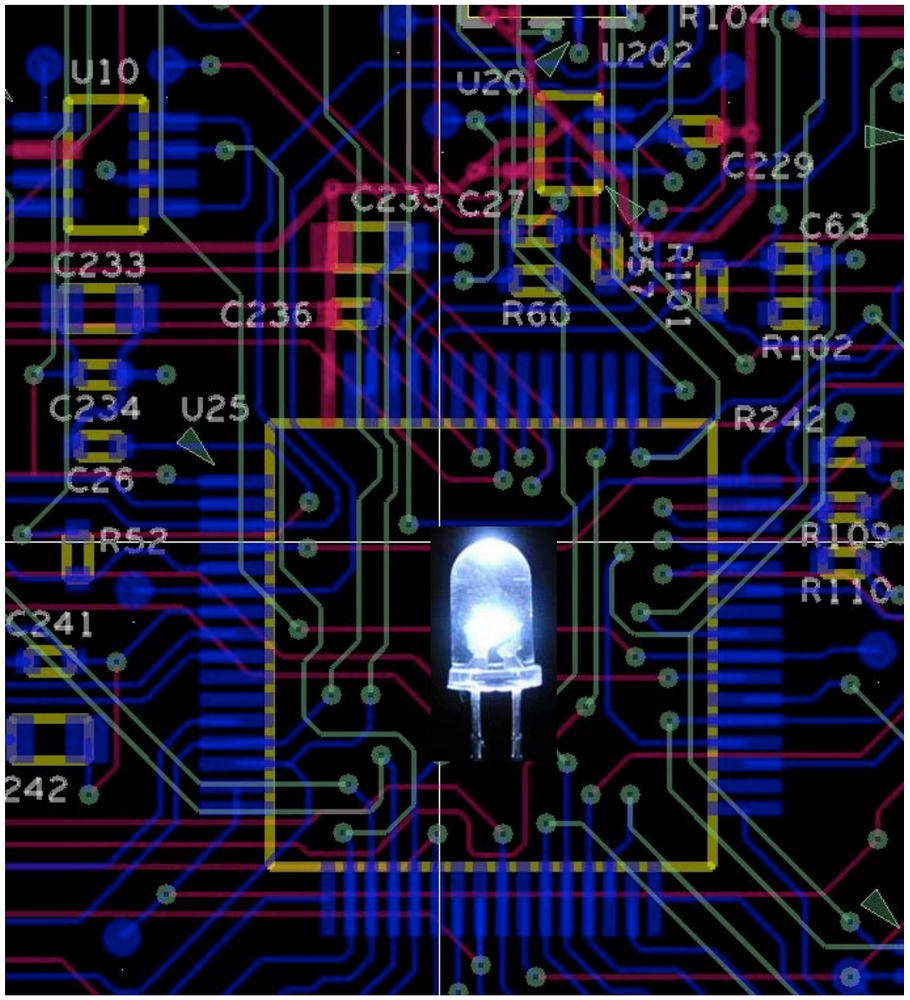


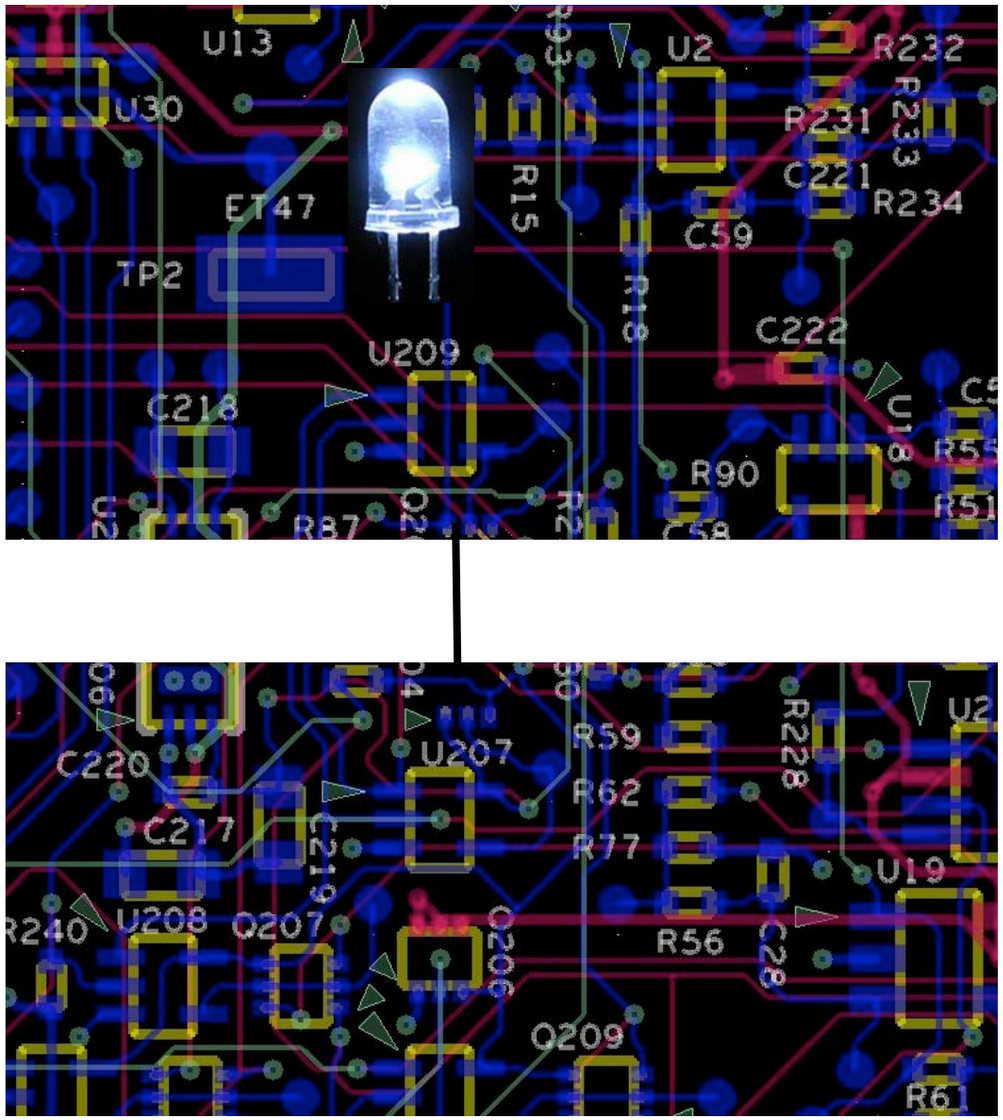
Multicellular distributed computing



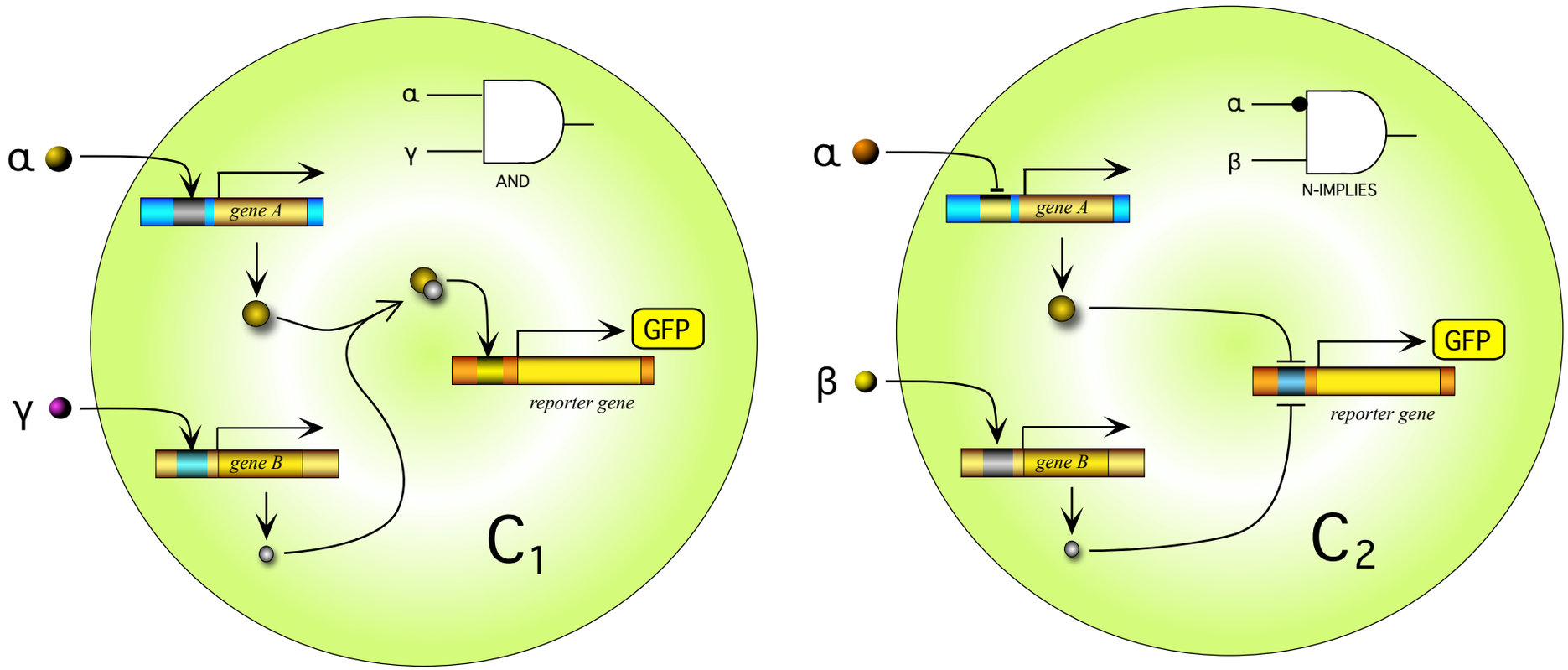


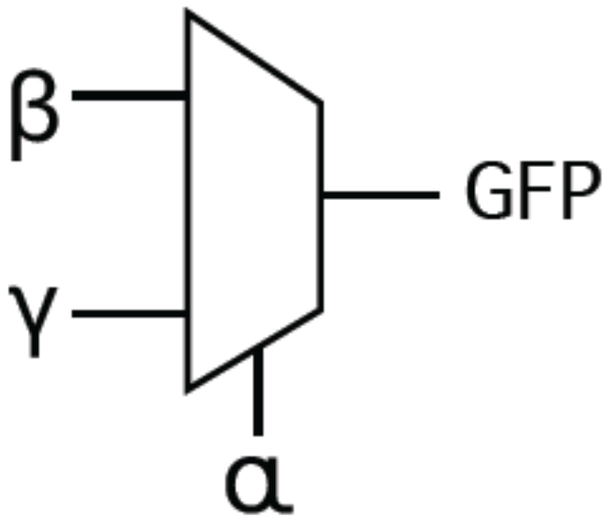
Multicellular distributed computing





Multicellular distributed computing

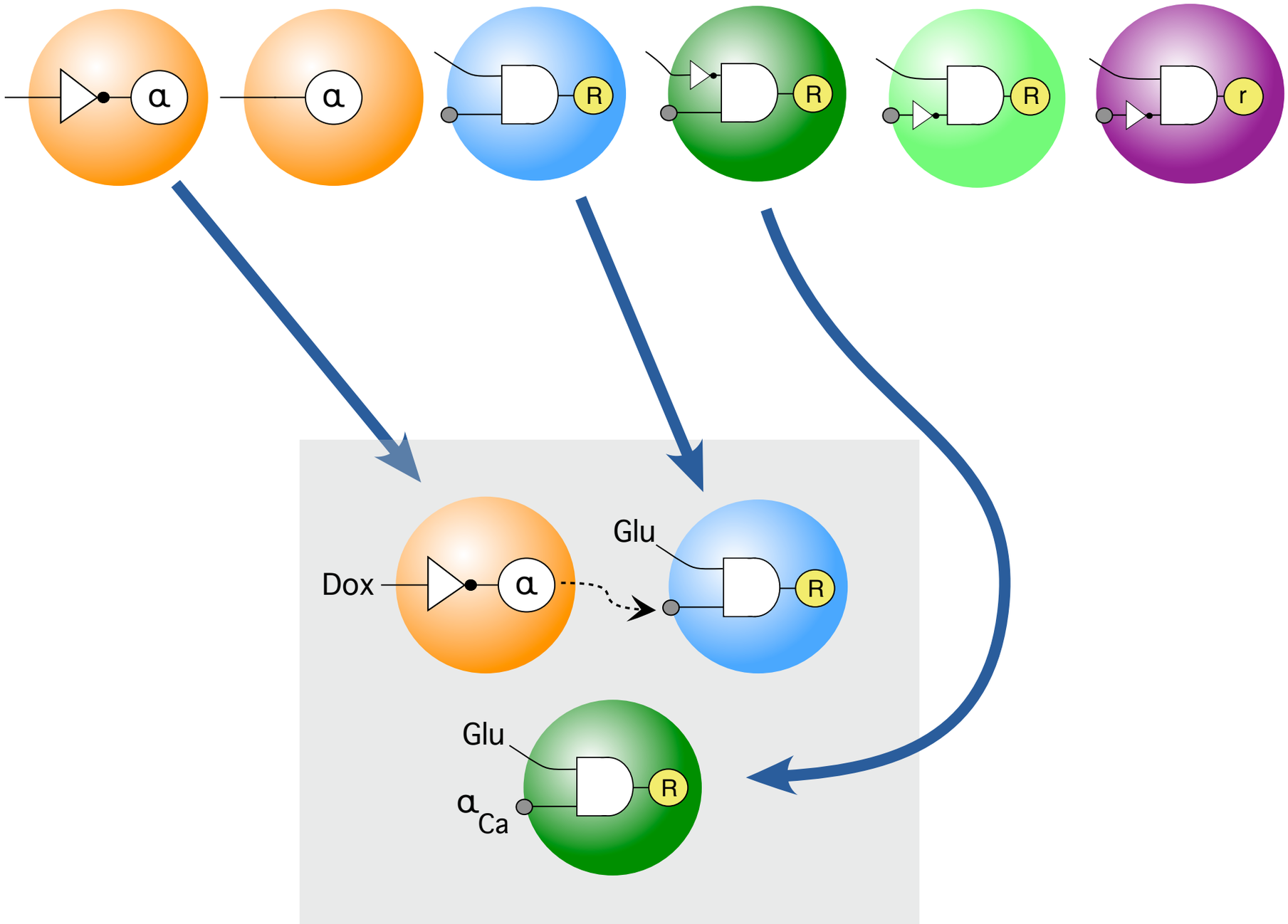




α	β	γ	GFP
0	0	0	0
0	0	1	0
0	1	0	1
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	0
1	1	1	1

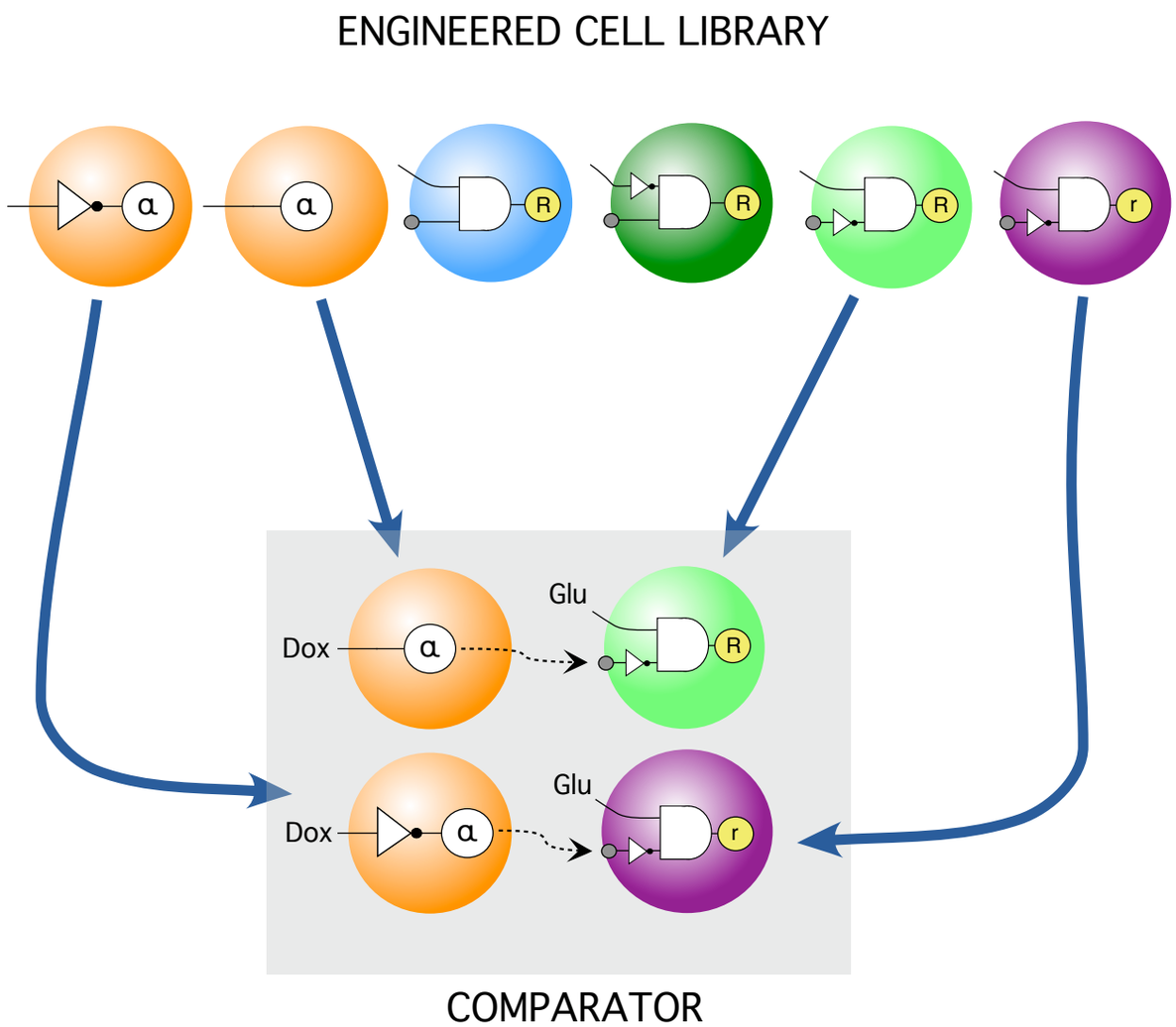
LEGO-like

ENGINEERED CELL LIBRARY



MULTIPLEXOR

LEGO-like


ENGINEERED CELL LIBRARY
a
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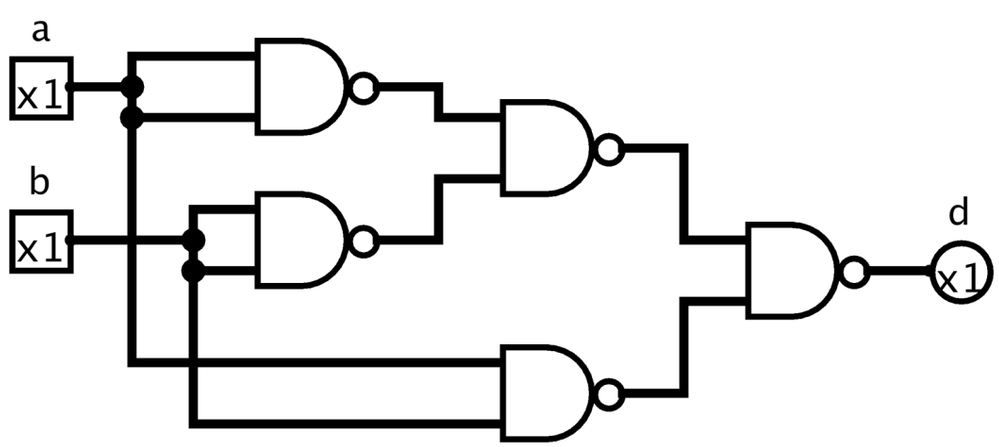
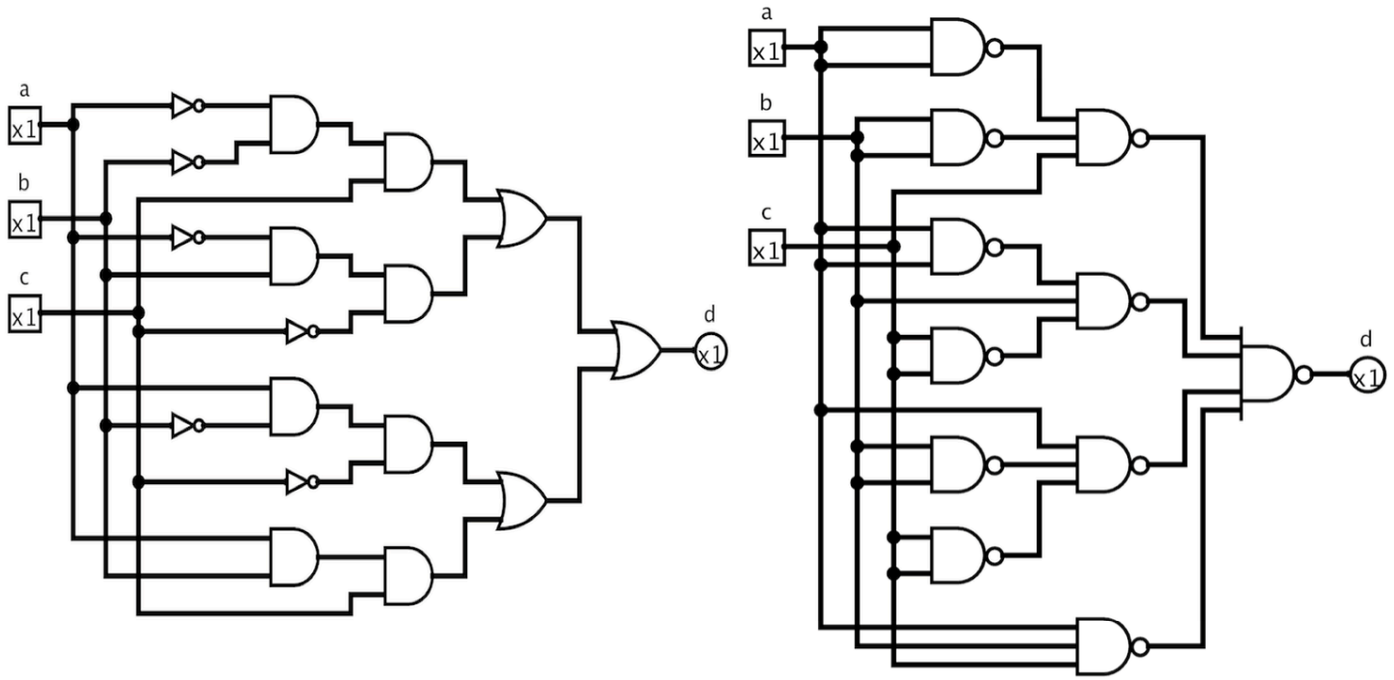
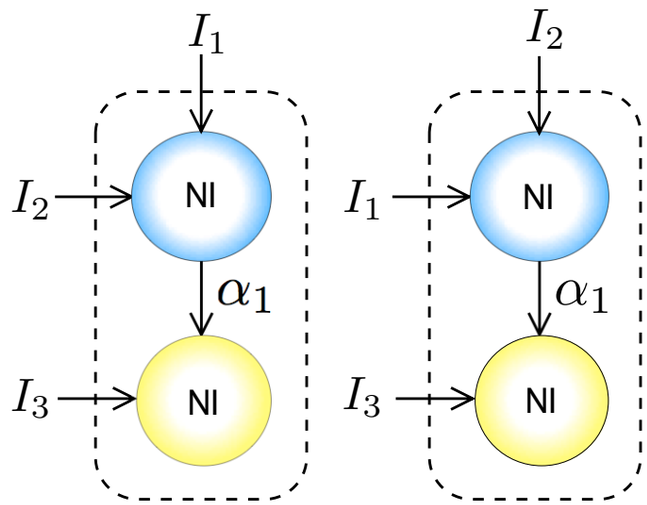
COMPARATOR

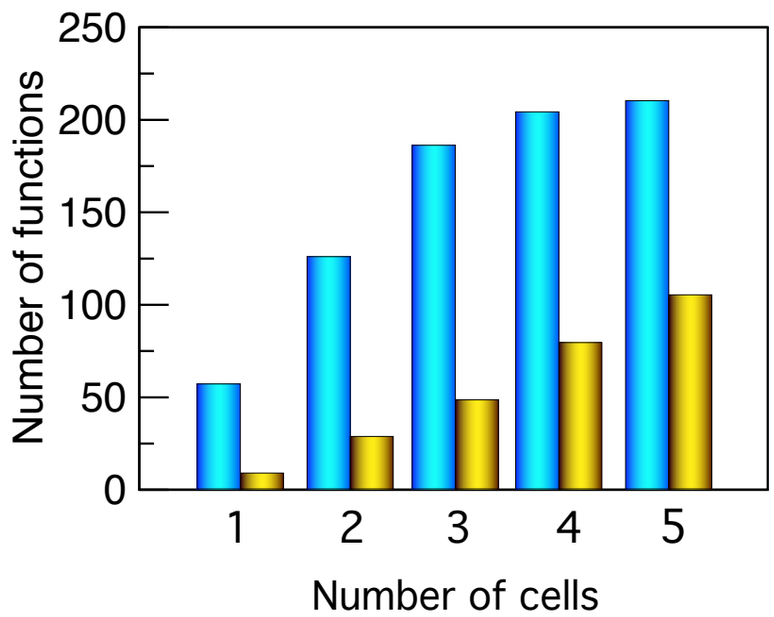

a
x1
b
x1
d
x1

Multicellular distributed computing

$$f(x_1, x_2, x_3) = 1 \Longleftrightarrow \sum_j x_j \;\; odd$$







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PLOS ONE

How to Make a Synthetic Multicellular Computer

Javier Macia[1,2]*, **Ricard Sole**[1,2,3]*

1 ICREA-Complex Systems Lab, Universitat Pompeu Fabra, Barcelona, Spain, **2** Institut de Biologia Evolutiva, UPF-CSIC, Barcelona, Spain, **3** Santa Fe Institute, Santa Fe, New Mexico, United States of America

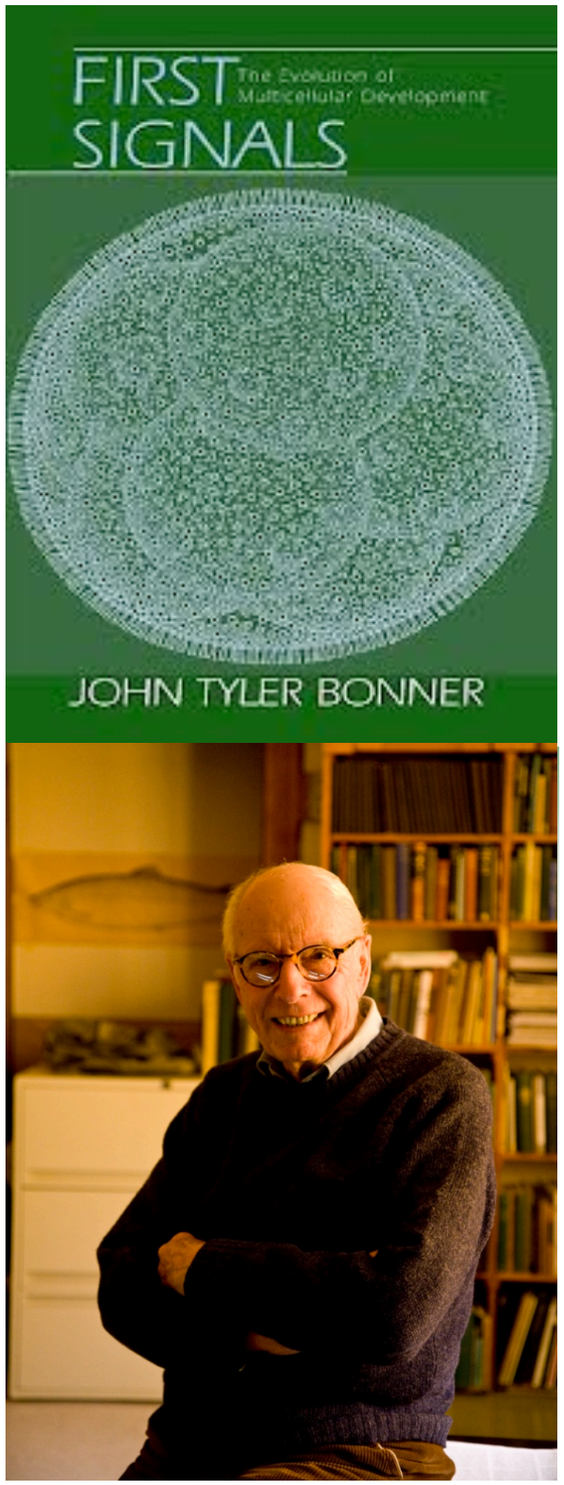
Beyond cells

How did multicellular life emerged?

Can we create tissues and organs from scratch?

Beyond cells: aging, human engineering

Differentiation-symmetry breaking

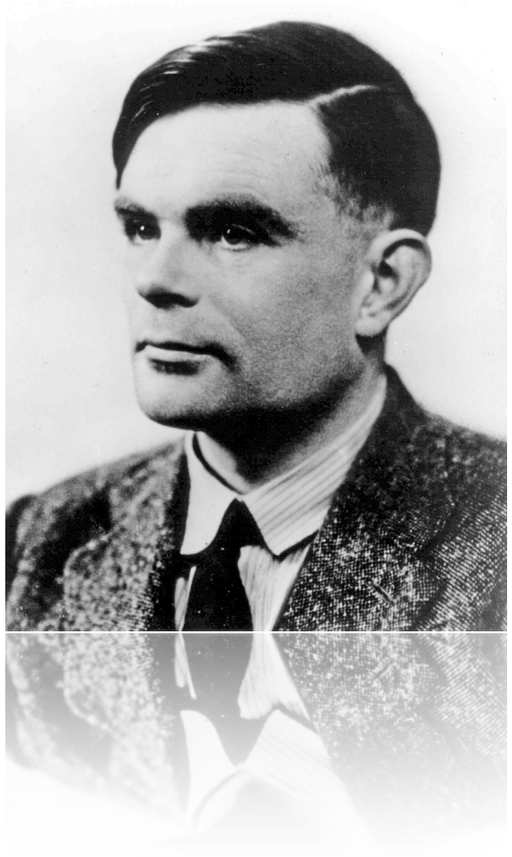


THE CHEMICAL BASIS OF MORPHOGENESIS

By A. M. TURING, F.R.S. *University of Manchester*

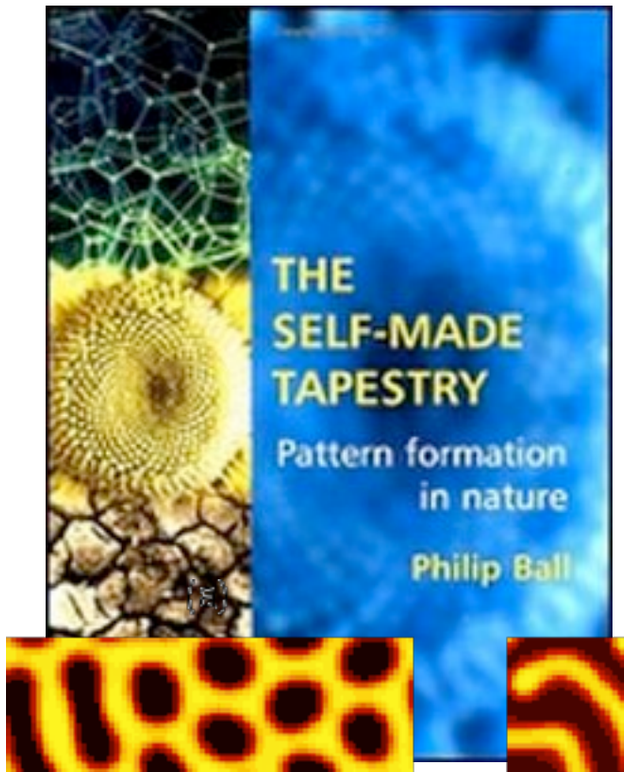
(*Received* 9 *November* 1951—*Revised* 15 *March* 1952)

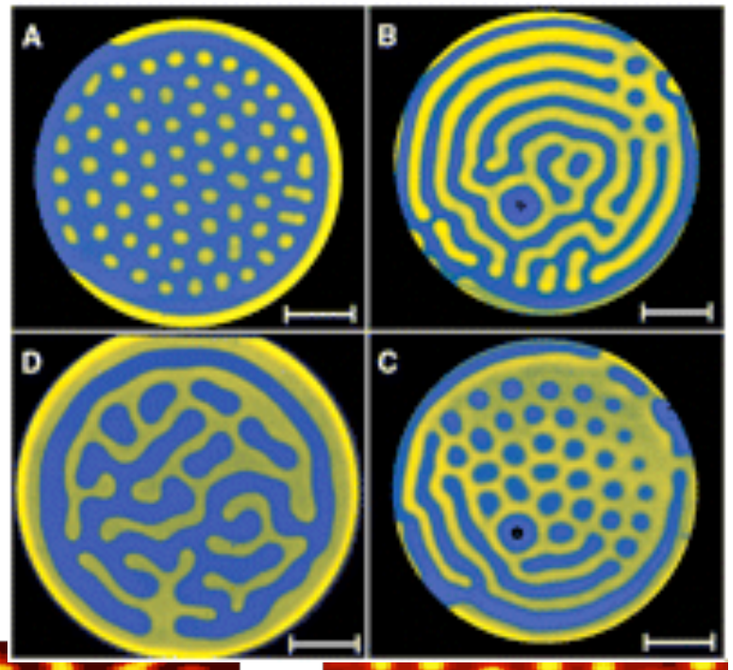
$$\left.\begin{aligned}\frac{dX_r}{dt} &= f(X_r, Y_r) + \mu(X_{r+1} - 2X_r + X_{r-1}) \\ \frac{dY_r}{dt} &= g(X_r, Y_r) + \nu(Y_{r+1} - 2Y_r + Y_{r-1})\end{aligned}\right\} \quad (r = 1, \ldots, N)$$

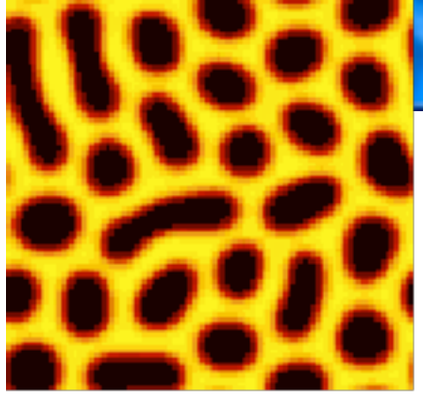


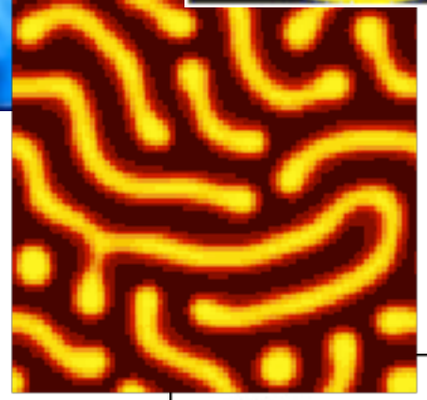
It must be admitted that the biological examples which it has been possible to give in the present paper are very limited. This can be ascribed quite simply to the fact that biological phenomena are usually very complicated. Taking this in combination with the relatively elementary mathematics used in this paper one could hardly expect to find that many observed biological phenomena would be covered. It is thought, however, that the imaginary biological systems which have been treated, and the principles which have been discussed, should be of some help in interpreting real biological forms.

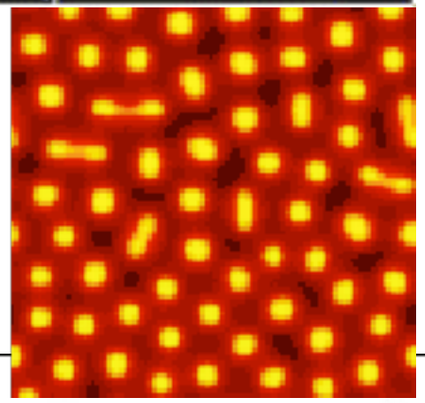
Turing patterns

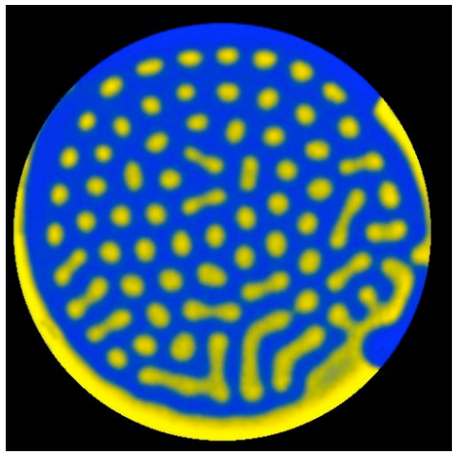


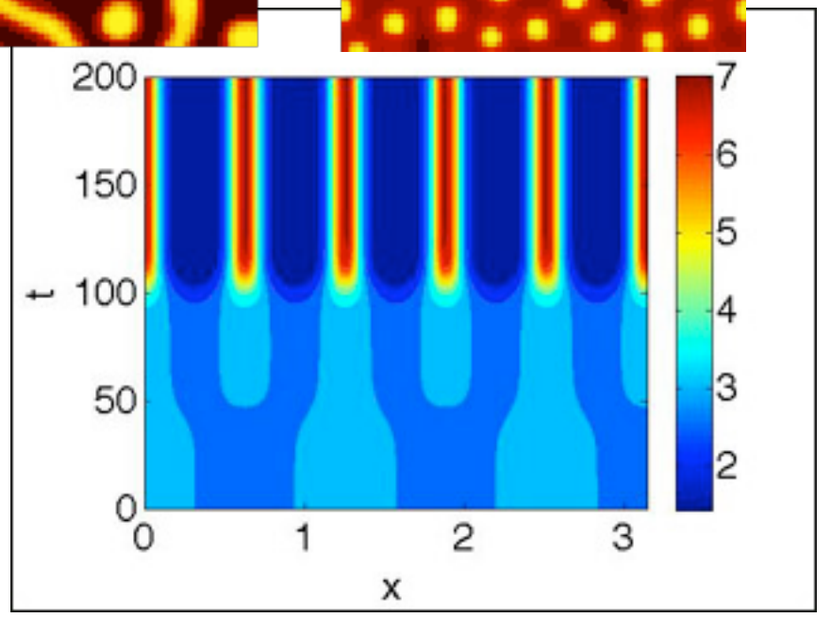












SCIENTIFIC CORRESPONDENCE

Turing patterns in fish skin?

SIR — Kondo and Asai[1] interpret observations on the time evolution of skin patterns of the angelfish (*Pomacanthus*) as the first instance of a Turing (reaction–diffusion) pattern in biology. But we believe that reaction–diffusion systems *per se* cannot provide a mechanistic basis for one of the main patterns reported in ref. 1.

Reaction–diffusion systems are characterized by an intrinsic spatial wavelength of the self-organized concentration pattern, that is, the distance between adjacent peaks of chemical concentrations is determined solely by the system parameters (kinetic constants and diffusion coefficients). Although on a two-dimensional domain such as the fish skin, several equidistant geometrical arrangements of the concentration peaks are possible, the nonlinear terms of the reaction dynamics usually select only one of these possibilities — for the system chosen by Kondo and Asai, a regular array of stripes. These two features, an intrinsic wavelength and a strong tendency to form stripes, are the essential ingredients of the simulations they presented in ref. 1. Many pattern-forming systems other than reaction–diffusion are known which select an intrinsic spatial wavelength and pattern geometry[2], among them biologically relevant mechanisms involving chemotactic or haptotactic cell movement and mechanical forces[3]. Therefore, there is no justification for equating observed patterns with a particular mechanism, as suggested in ref. 1.

Although our point does not exclude the possibility that a Turing system underlies the *Pomacanthus* skin patterns, we demonstrate here that its properties are not sufficient to explain perhaps the most striking observation of the paper, the regular insertion of new stripes between older ones during the growth of *Pomacanthus semicirculatus*. We have solved the authors' reaction–diffusion equations on a growing, two-dimensional domain — a more realistic representation of the fish skin than the one-dimensional domain used in ref. 1.

Our results show that regular stripe-doubling sensitively depends on the artificial geometrical constraints of the one-dimensional domain (see figure). As the restriction of one-dimensionality is removed, complete spatial rearrangement of the pattern occurs on the growing domain, which clearly is not seen in the fish. This behaviour is

Synthetic Multicellularity in silico

Opinion

Cell PRESS

Special Issue – Synthetic Cell Biology

Synthetic multicellularity

Michel M. Maharbiz

Department of Electrical Engineering and Computer Science, University of California, Berkeley, CA 94720, USA

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PLOS | ONE

Before the Endless Forms: Embodied Model of Transition from Single Cells to Aggregates to Ecosystem Engineering

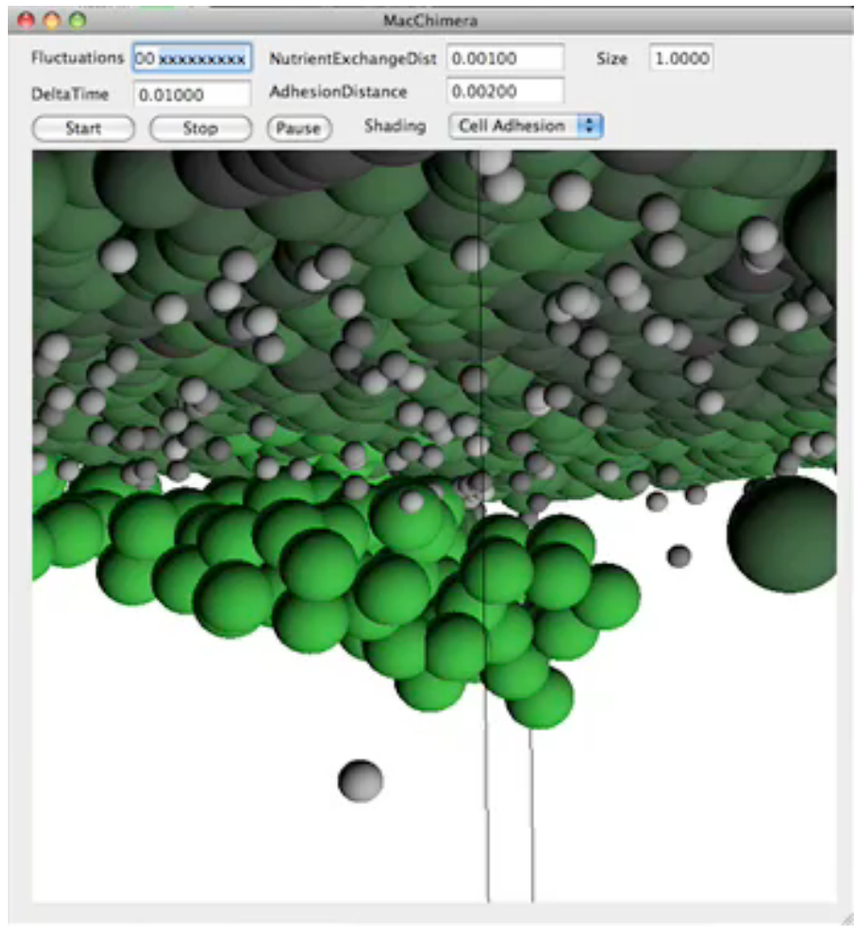
Ricard V. Solé[1,2,3,4]*, Sergi Valverde[1,3,4]

1 ICREA-Complex Systems Lab, Universitat Pompeu Fabra, Barcelona, Spain, **2** Santa Fe Institute, Santa Fe, New Mexico, United States of America, **3** Institut de Biologia Evolutiva, UPF-CSIC, Barcelona, Spain, **4** European Centre for Living Technology, C Foscari University of Venice, Venice, Italy

Abstract

The emergence of complex multicellular systems and their associated developmental programs is one of the major problems of evolutionary biology. The advantages of cooperation over individuality seem well known but it is not clear yet how such increase of complexity emerged from unicellular life forms. Current multicellular systems display a complex cell-cell communication machinery, often tied to large-scale controls of body size or tissue homeostasis. Some unicellular life forms are simpler and involve groups of cells cooperating in a tissue-like fashion, as it occurs with biofilms. However, before true gene regulatory interactions were widespread and allowed for controlled changes in cell phenotypes, simple cellular colonies displaying adhesion and interacting with their environments were in place. In this context, models often ignore the physical embedding of evolving cells, thus leaving aside a key component. The potential for evolving pre-developmental patterns is a relevant issue: how far a colony of evolving cells can go? Here we study these pre-conditions for morphogenesis by using CHIMERA, a physically embodied computational model of evolving virtual organisms in a pre-Mendelian world. Starting from a population of identical, independent cells moving in a fluid, the system undergoes a series of changes, from spatial segregation, increased adhesion and the development of generalism. Eventually, a major transition occurs where a change in the flow of nutrients is triggered by a sub-population. This ecosystem engineering phenomenon leads to a subsequent separation of the ecological network into two well defined compartments. The relevance of these results for evodevo and its potential ecological triggers is discussed.

Citation: Solé RV, Valverde S (2013) Before the Endless Forms: Embodied Model of Transition from Single Cells to Aggregates to Ecosystem Engineering. PLoS ONE 8(4): e59664. doi:10.1371/journal.pone.0059664



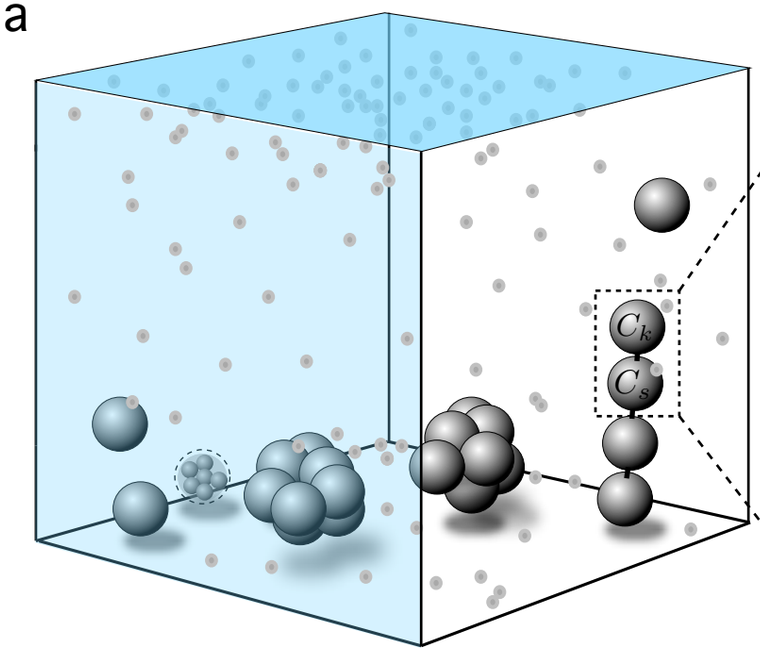
What about embodied MC with ecological and evolutionary dynamics?

What about the interplay between both?

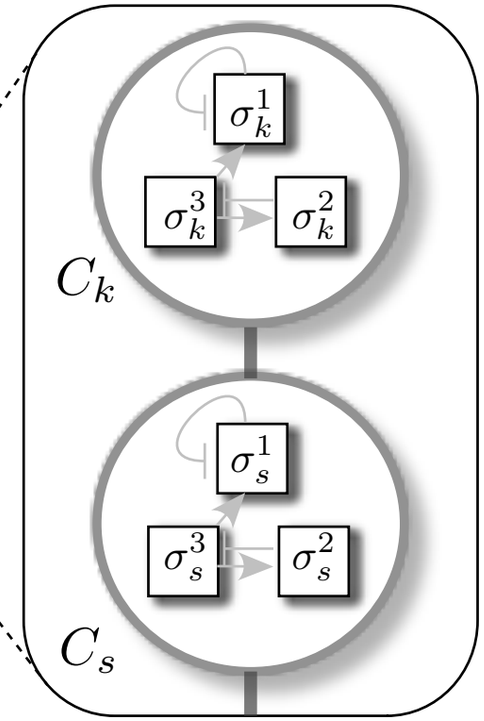
Before the endless forms: embodied model of transition from single cells to aggregates to ecosystem engineering
RVS & S Valverde PLOS ONE 2013

Physico-genetic model

a



b

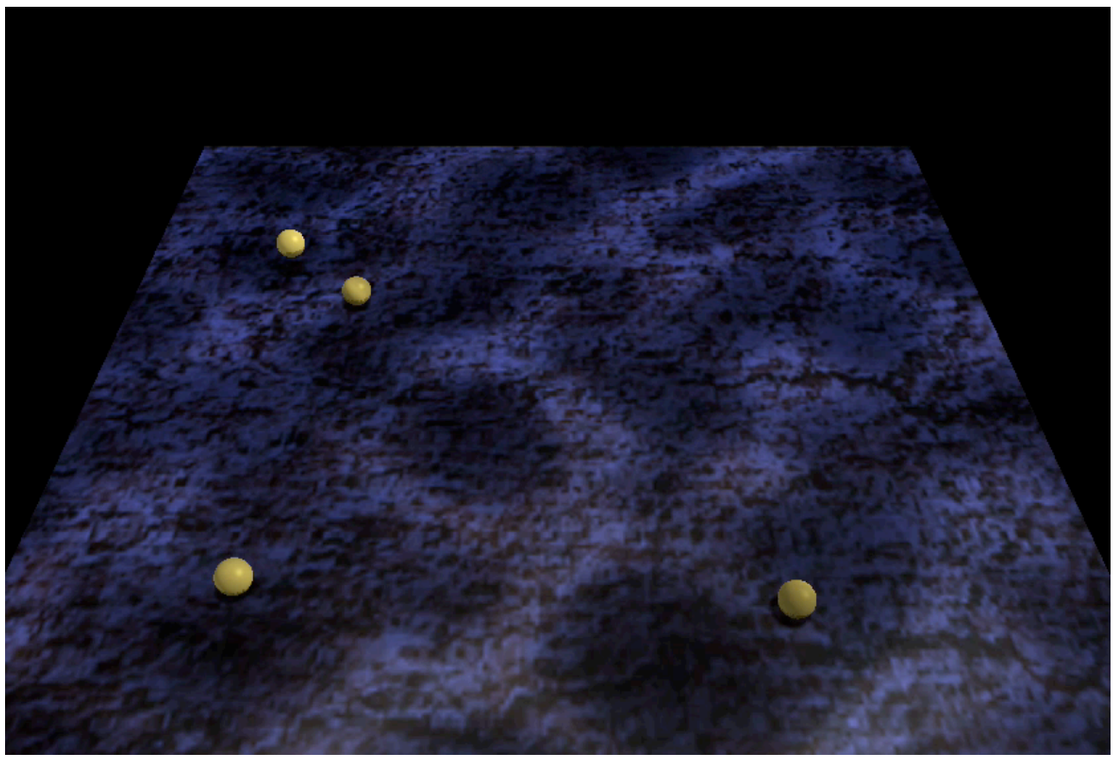


c

$$\Omega_k = \begin{pmatrix} \omega_{11}^k & \omega_{12}^k & .... & \omega_{1M}^k \\ \omega_{21}^k & \omega_{22}^k & .... & \omega_{2M}^k \\ ... & ... & ... & ... \\ \omega_{M1}^k & \omega_{M2}^k & .... & \omega_{MM}^k \end{pmatrix}$$

d

$$\sigma_j^k = \Theta\left[\sum_{\mu=1}^{M} \omega_{\mu j}^k \sigma_\mu^k - \theta_{jk}\right]$$



$$\mathcal{F} = \{A_c, A_F, T, D, G\} \cup \{S\} \cup \{\phi_1, \phi_2\}$$

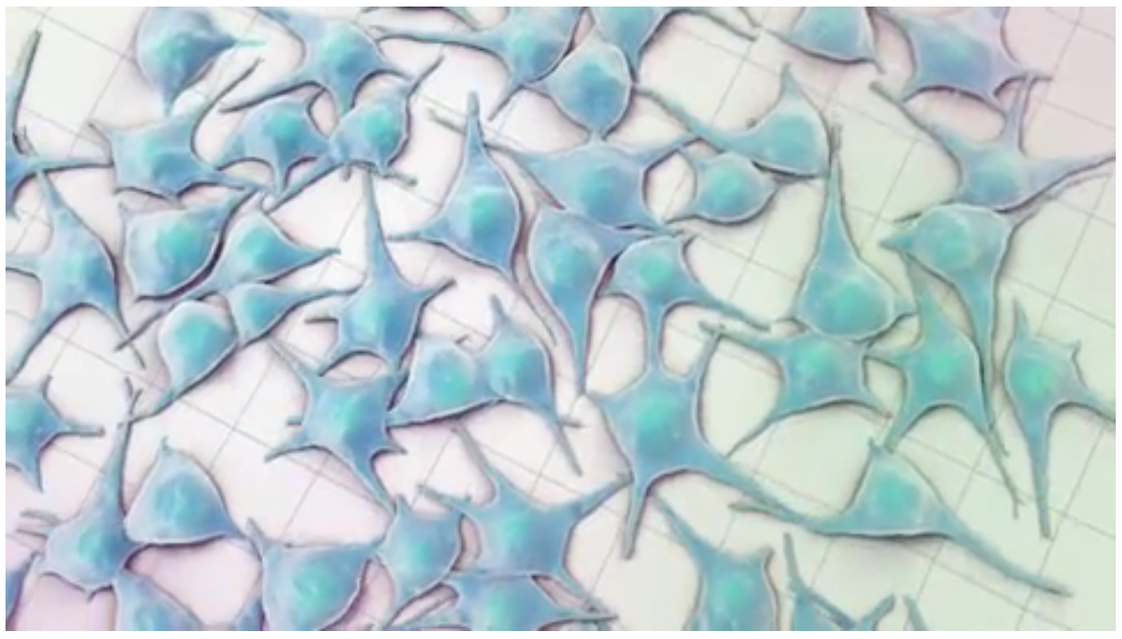
Chimera 2: evolving gene regulatory networks and development.

Cell reprogramming and regeneration

STEM CELLS

Systems biology of stem cell fate and cellular reprogramming

Ben D. MacArthur‡, Avi Ma'ayan‡ and Ihor R. Lemischka**



Vol 448|19 July 2007|doi:10.1038/nature05934 nature

ARTICLES

Generation of germline-competent induced pluripotent stem cells

Keisuke Okita[1], Tomoko Ichisaka[1,2] & Shinya Yamanaka[1,2]

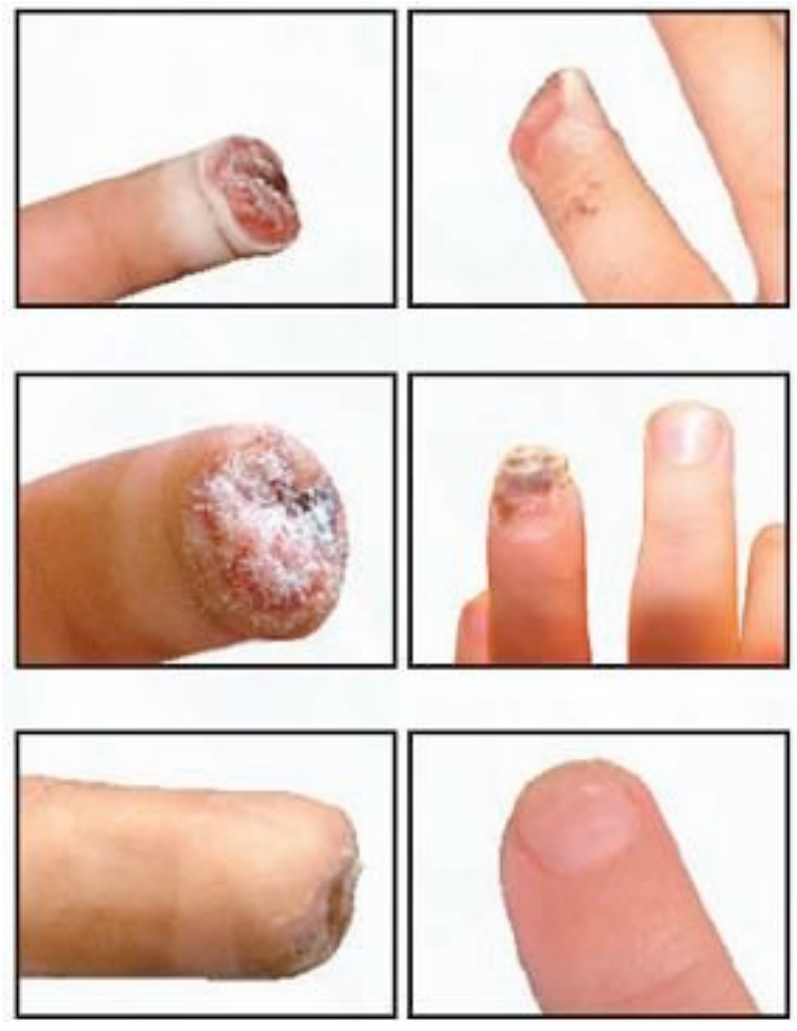
Review

Cell PRESS

Evolution of animal regeneration: re-emergence of a field

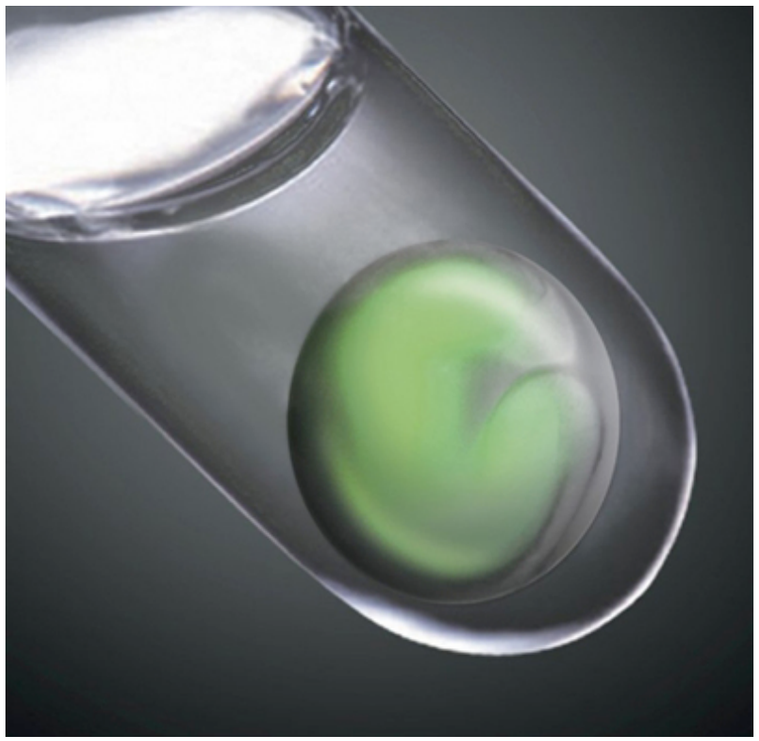
Alexandra E. Bely and Kevin G. Nyberg

Biology Department, University of Maryland, College Park, MD 20742, USA



Wnt activation in nail epithelium couples nail growth to digit regeneration .Takeo, M et al. Nature. 2013 Jul 11;499: 228-232.

Beyond cells



REVIEW

doi:10.1038/nature11859

Cytosystems dynamics in self-organization of tissue architecture

Yoshiki Sasai[1]

Our knowledge of the principles by which organ architecture develops through complex collective cell behaviours is still limited. Recent work has shown that the shape of such complex tissues as the optic cup forms by self-organization *in vitro* from a homogeneous population of stem cells. Multicellular self-organization involves three basic processes that are crucial for the emergence of latent intrinsic order. Based on lessons from recent studies, cytosystems dynamics is proposed as a strategy for understanding collective multicellular behaviours, incorporating four-dimensional measurement, theoretical modelling and experimental reconstitution.

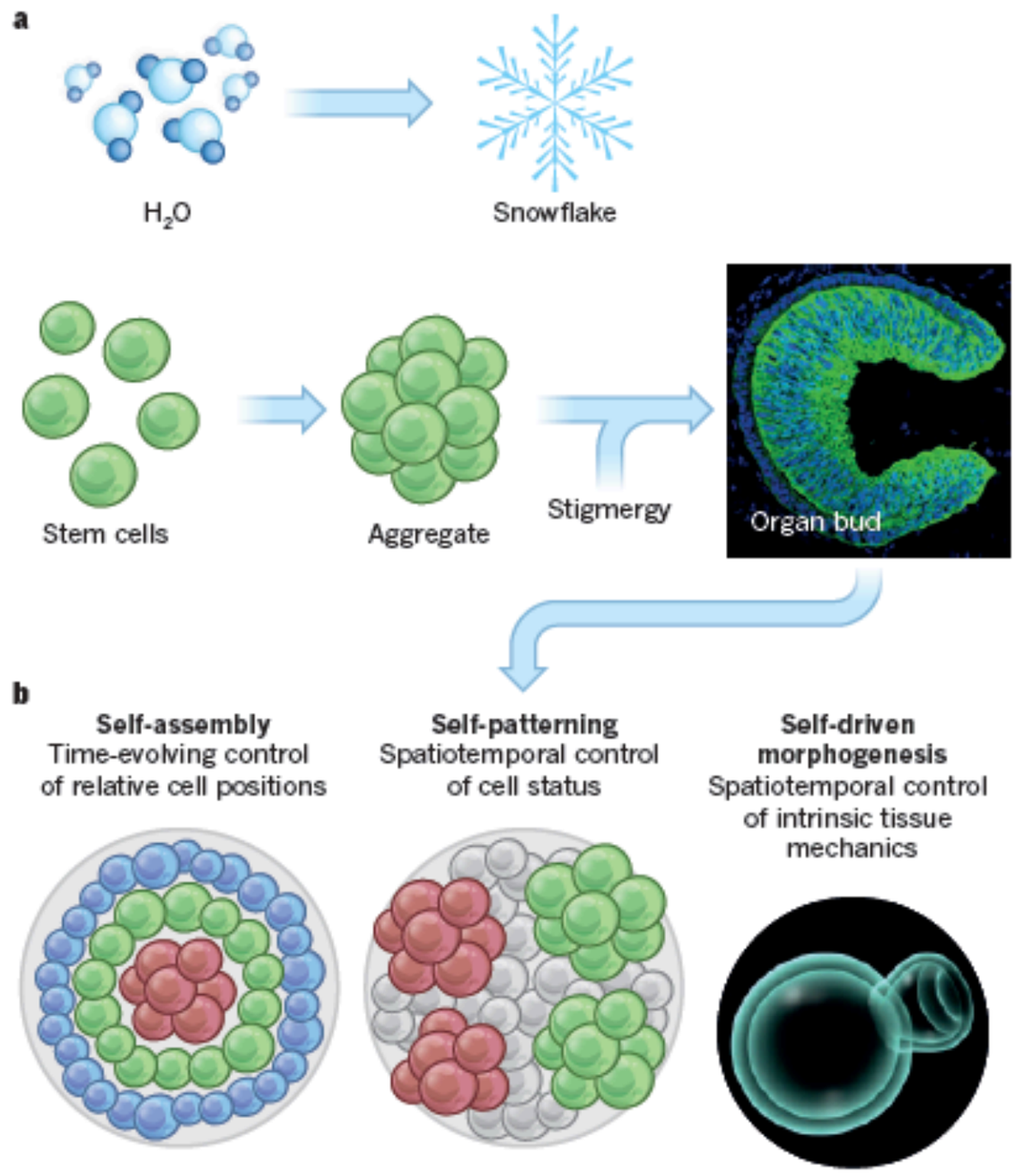


Figure 1 | Three basic mechanisms of tissue self-organization.

Brains from self-organization

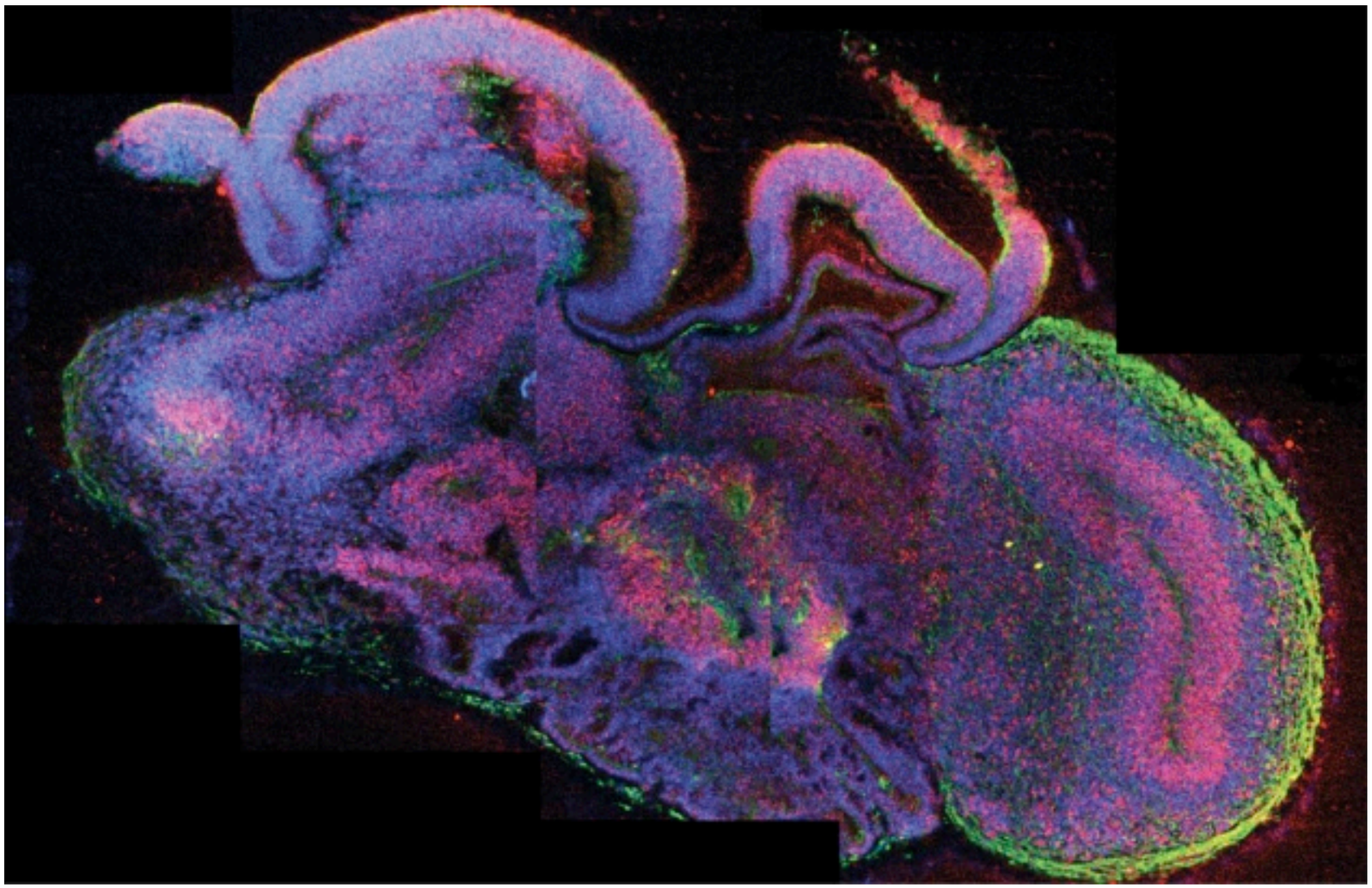
ARTICLE

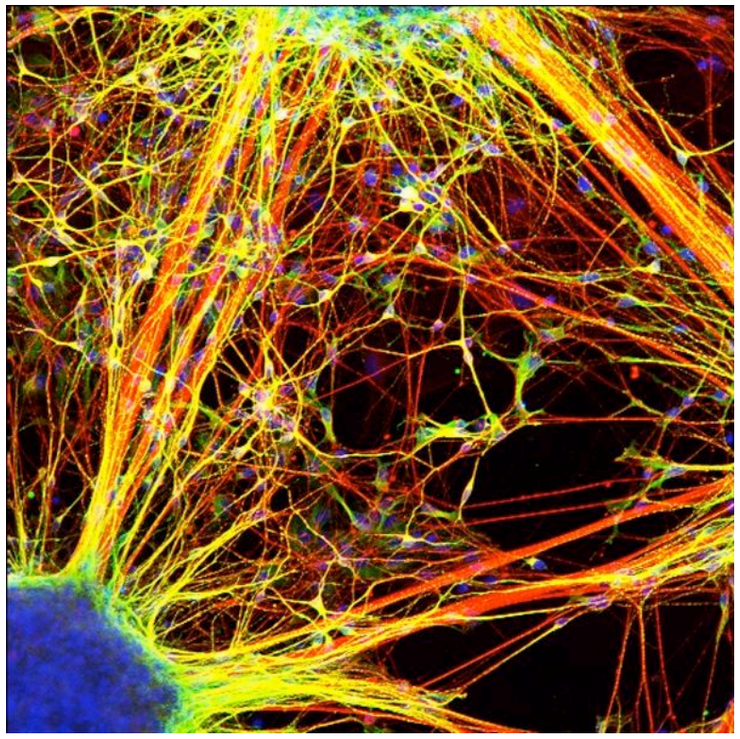
RESEARCH ARTICLE

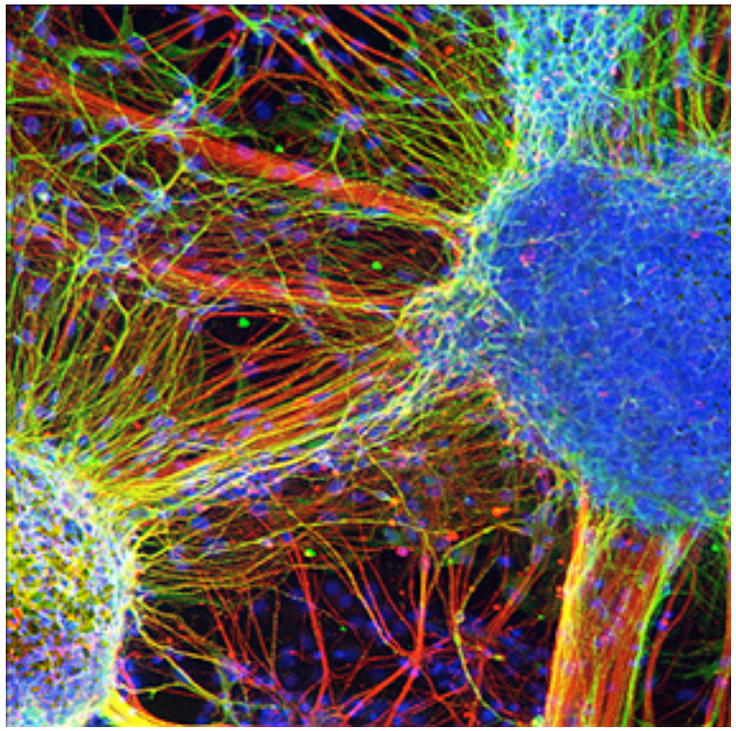
doi:10.1038/nature12517

Cerebral organoids model human brain development and microcephaly

Madeline A. Lancaster[1], Magdalena Renner[1], Carol-Anne Martin[2], Daniel Wenzel[1], Louise S. Bicknell[2], Matthew E. Hurles[3], Tessa Homfray[4], Josef M. Penninger[1], Andrew P. Jackson[2] & Juergen A. Knoblich[1]







Schizophrenia in a dish. Nature 13 April 2011

Beyond engineerinng?

ARTICLE

RESEARCH ARTICLE

doi:10.1038/nature12517

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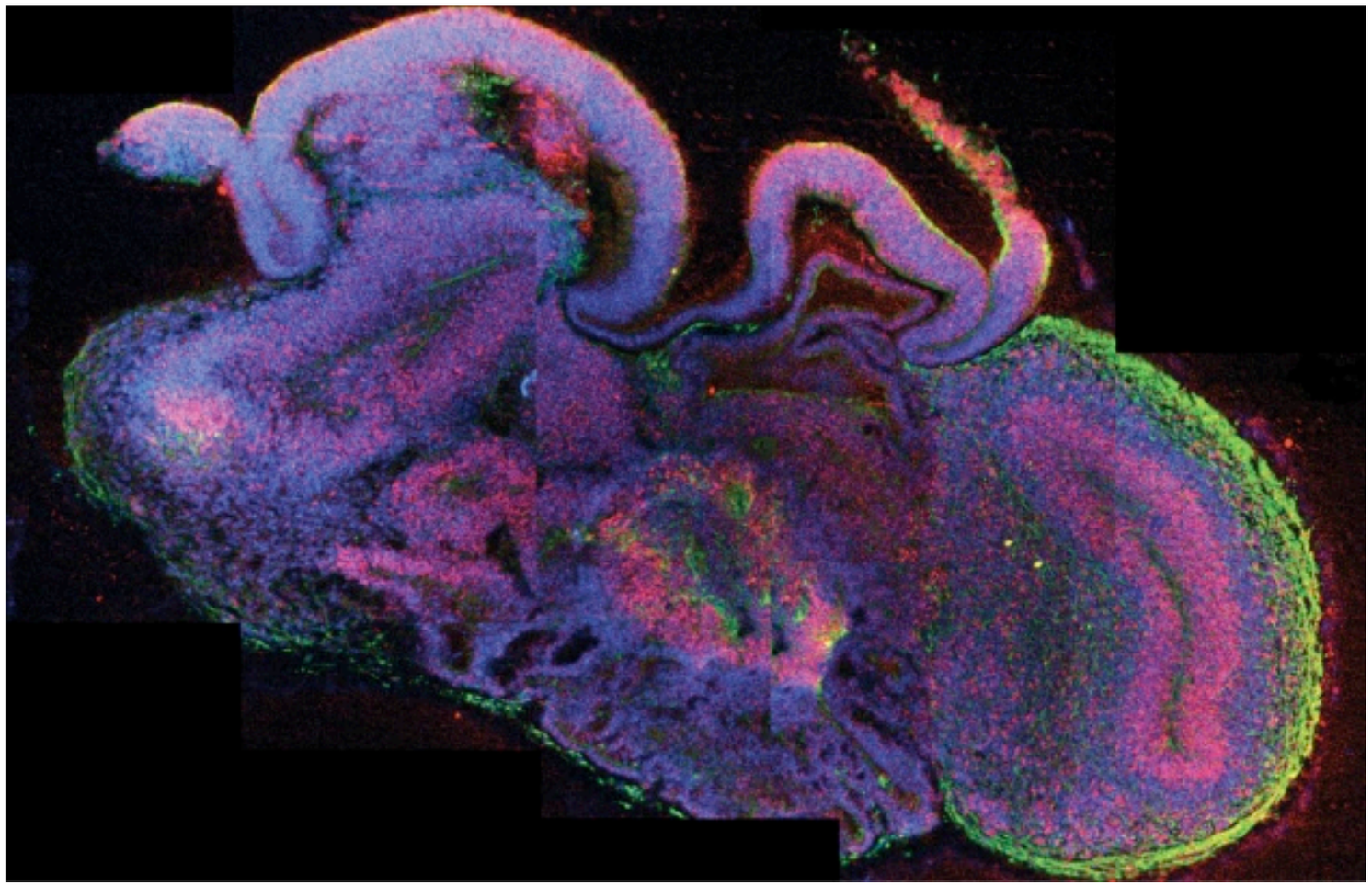
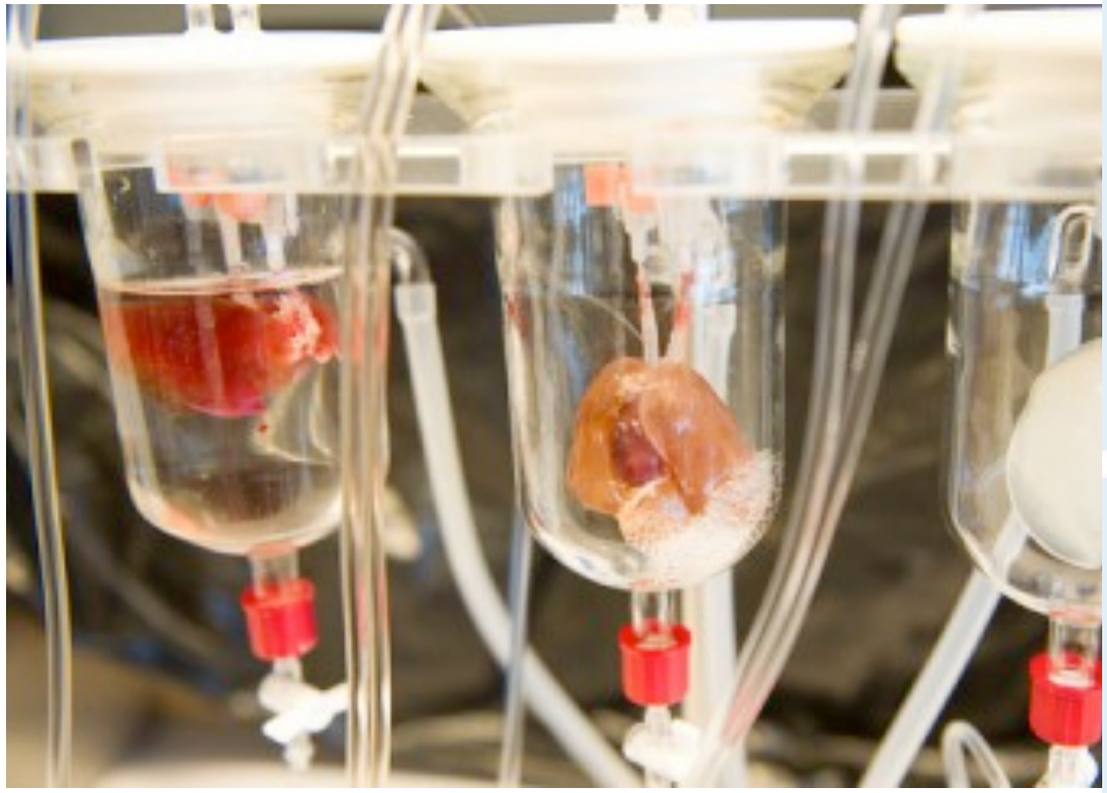
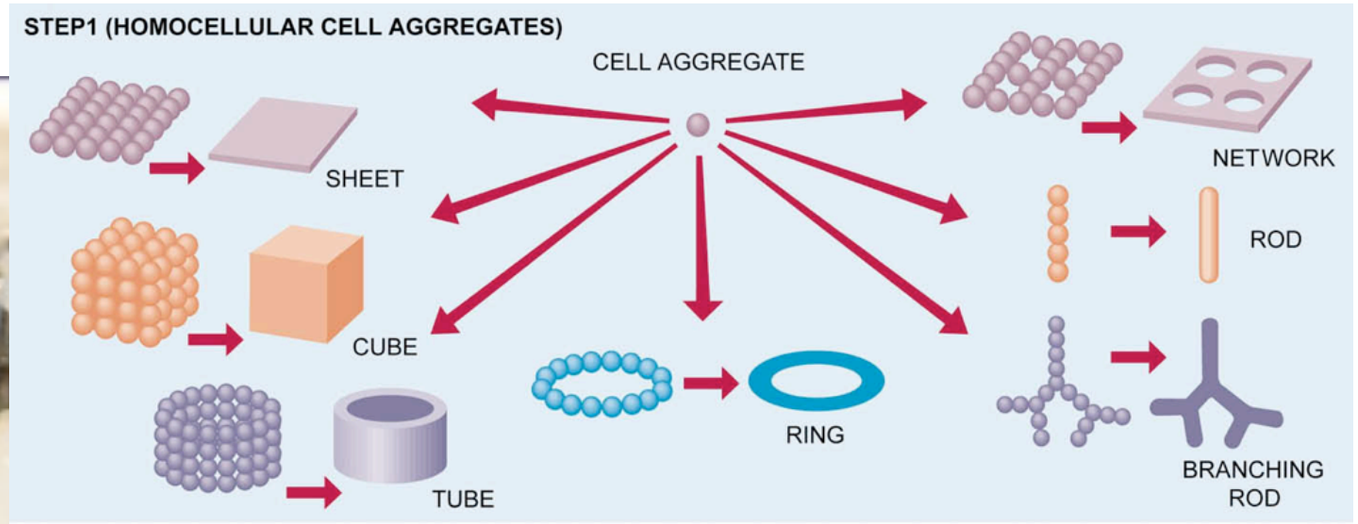
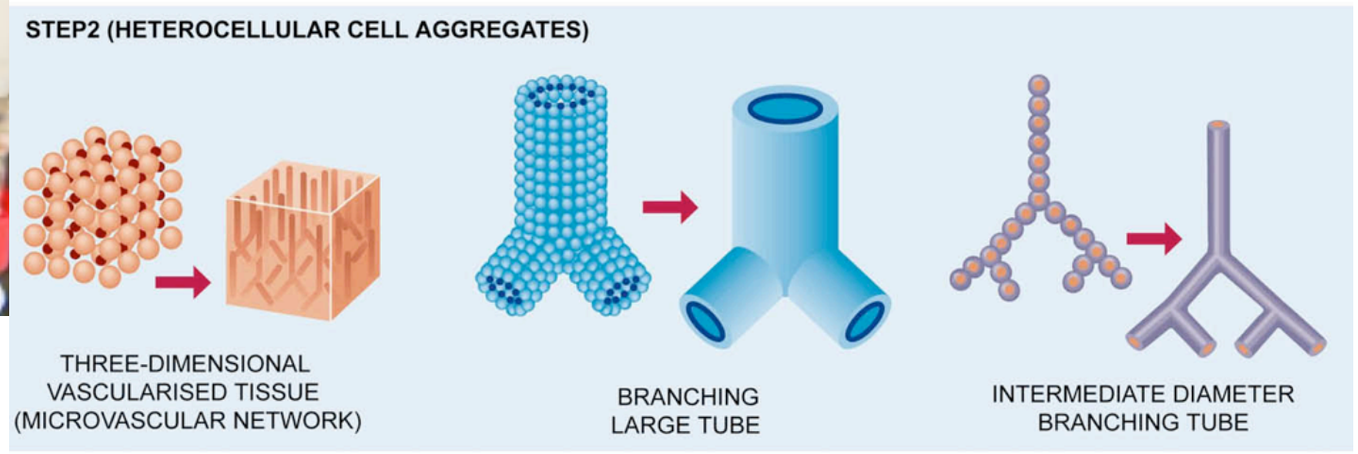
Madeline A. Lancaster[1], Magdalena Renner[1], Carol-Anne Martin[2], Daniel Wenzel[1], Louise S. Bicknell[2], Matthew E. Hurles[3], Tessa Homfray[4], Josef M. Penninger[1], Andrew P. Jackson[2] & Juergen A. Knoblich[1]

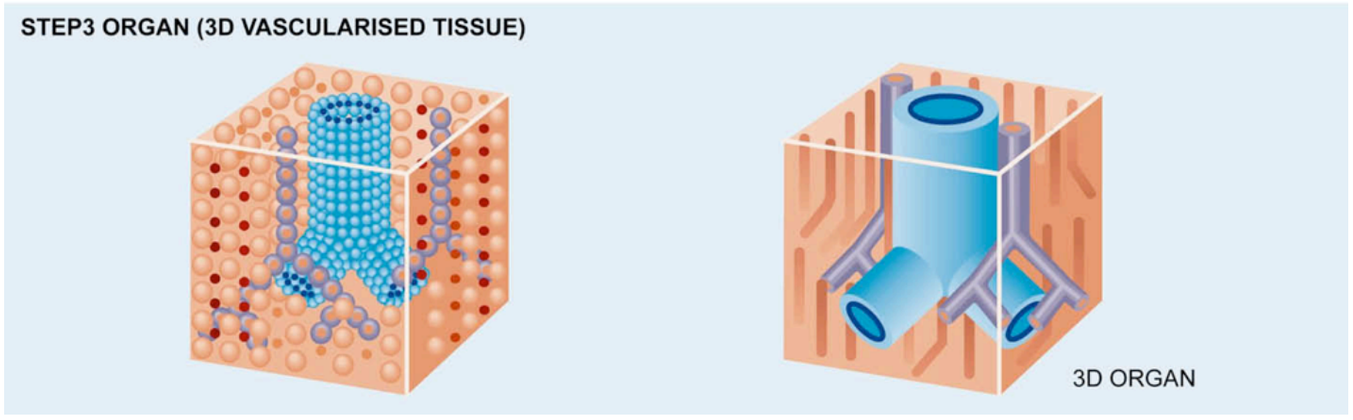


Artificial and printed organs









Biomaterials 30 (2009) 2164–2174

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Leading Opinion

Organ printing: Tissue spheroids as building blocks☆

Vladimir Mironov[a,*], Richard P. Visconti[a], Vladimir Kasyanov[b], Gabor Forgacs[c], Christopher J. Drake[a], Roger R. Markwald[a]

[a] Bioprinting Research Center, Cardiovascular Developmental Biology Center, Department of Cell Biology and Anatomy, Medical University of South Carolina, Charleston, SC 29425, USA
[b] Department of Anatomy and Anthropology, Riga Stradins University, Riga, Latvia
[c] Department of Physics, Biology and Biomedical Engineering, University of Missouri, Columbia, MO 65211, USA

Synthetic intelligence?

Can we create a synthetic **intelligence**?

Can we create a **conscious** machine?

(and if not, why not?)

Are these the right questions right now?

Can we create a **synthetic** collective intelligence?

Synthetic intelligence?

VOL. LIX. No. 236.] [October, 1950

MIND

A QUARTERLY REVIEW

OF

PSYCHOLOGY AND PHILOSOPHY

I.—COMPUTING MACHINERY AND INTELLIGENCE

BY A. M. TURING

1. *The Imitation Game.*

I PROPOSE to consider the question, 'Can machines think?' This should begin with definitions of the meaning of the terms 'machine' and 'think'. The definitions might be framed so as to reflect so far as possible the normal use of the words, but this attitude is dangerous. If the meaning of the words 'machine' and 'think' are to be found by examining how they are commonly used it is difficult to escape the conclusion that the meaning and the answer to the question, 'Can machines think?' is to be sought in a statistical survey such as a Gallup poll. But this is absurd. Instead of attempting such a definition I shall replace the question by another, which is closely related to it and is expressed in relatively unambiguous words.

The new form of the problem can be described in terms of a game which we call the 'imitation game'. It is played with

Synthetic minds?

NAS

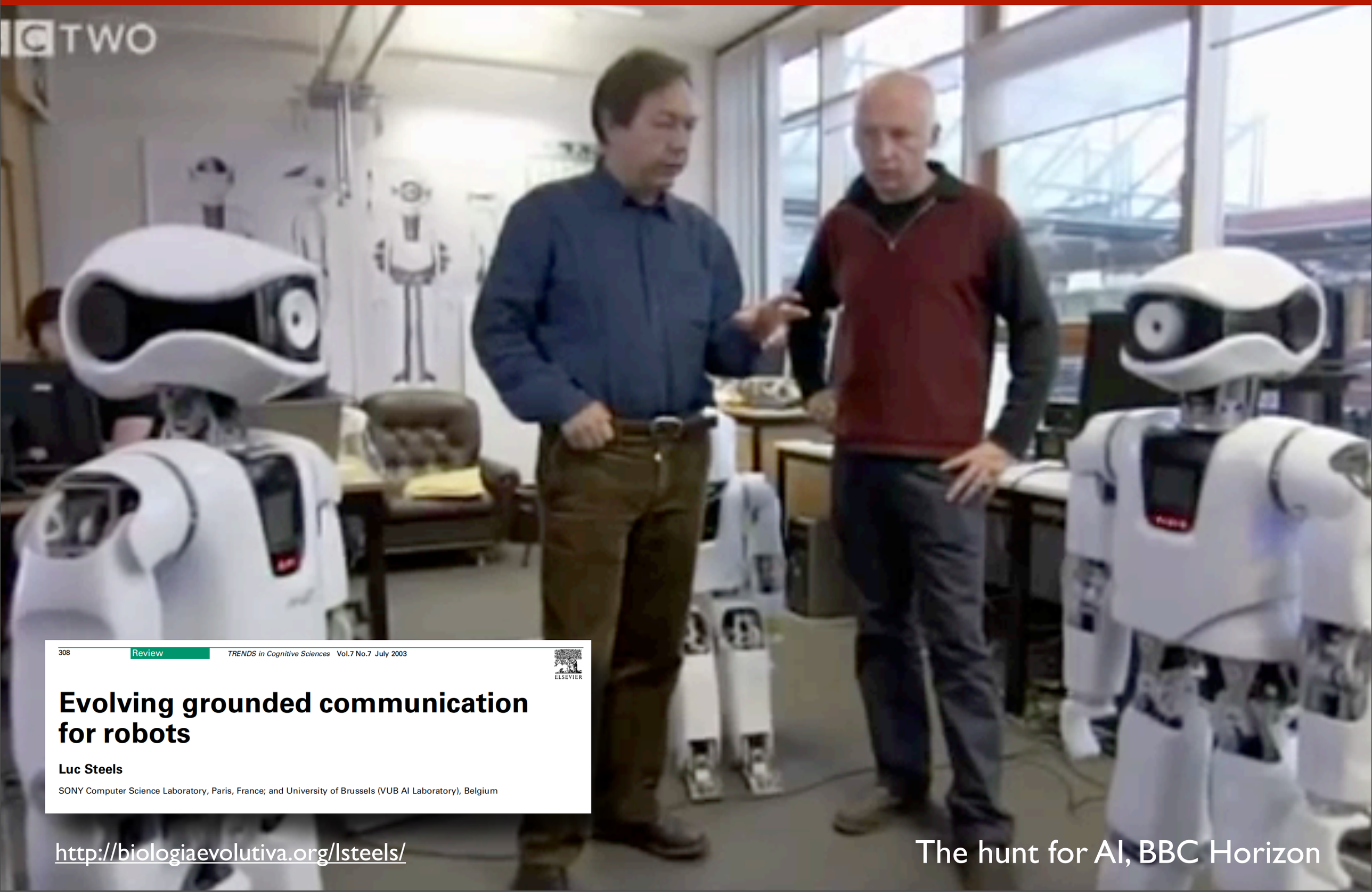
The evolution of information suppression in communicating robots with conflicting interests

Sara Mitri[a,1], Dario Floreano[a], and Laurent Keller[b,1]

[a]Laboratory of Intelligent Systems, Ecole Polytechnique Fédérale de Lausanne, Station 11, CH-1015 Lausanne, Switzerland; and [b]Department of Ecology and Evolution, Biophore, University of Lausanne, CH-1015 Lausanne, Switzerland

Edited by Raghavendra Gadagkar, Indian Institute of Science, Bangalore, India, and approved July 10, 2009 (received for review March 23, 2009)

Synthetic minds?



308 Review *TRENDS in Cognitive Sciences* Vol.7 No.7 July 2003

Evolving grounded communication for robots

Luc Steels

SONY Computer Science Laboratory, Paris, France; and University of Brussels (VUB AI Laboratory), Belgium

http://biologiaevolutiva.org/lsteels/

The hunt for AI, BBC Horizon

Synthetic intelligence?

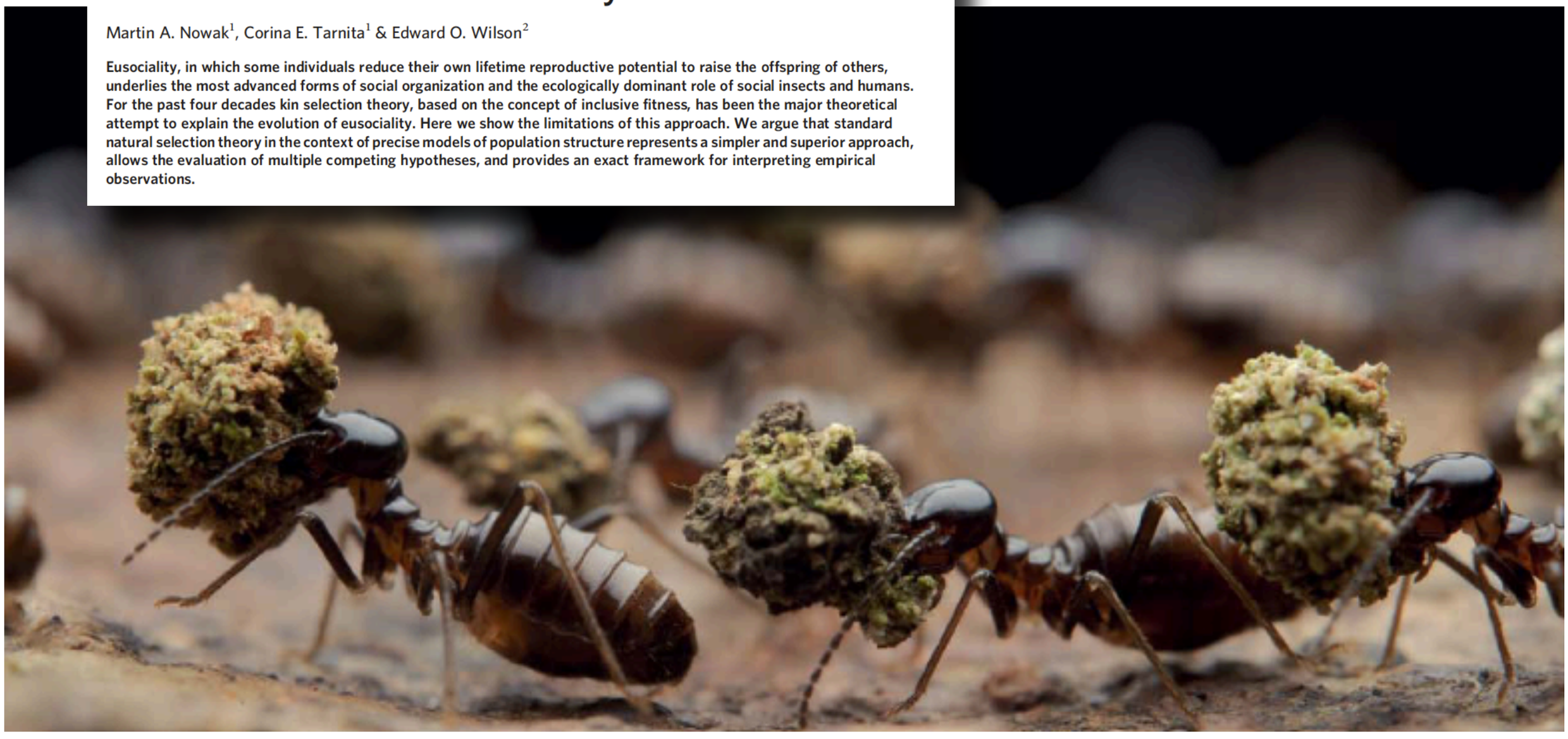
Vol 466|26 August 2010|doi:10.1038/nature09205 nature

ANALYSIS

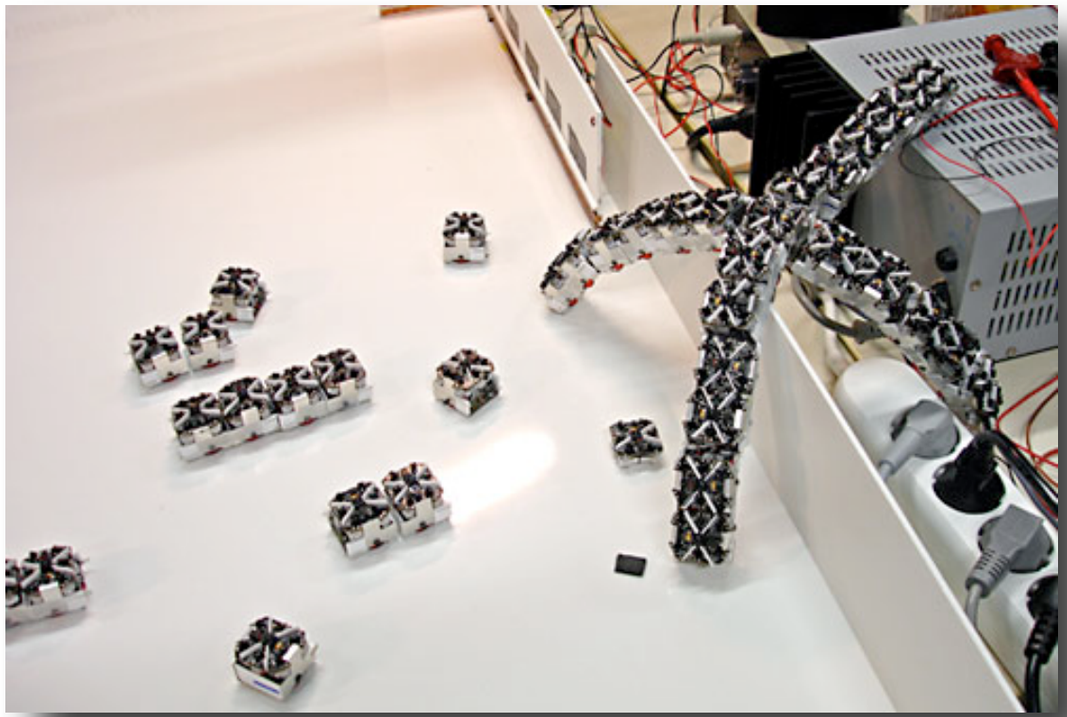
The evolution of eusociality

Martin A. Nowak[1], Corina E. Tarnita[1] & Edward O. Wilson[2]

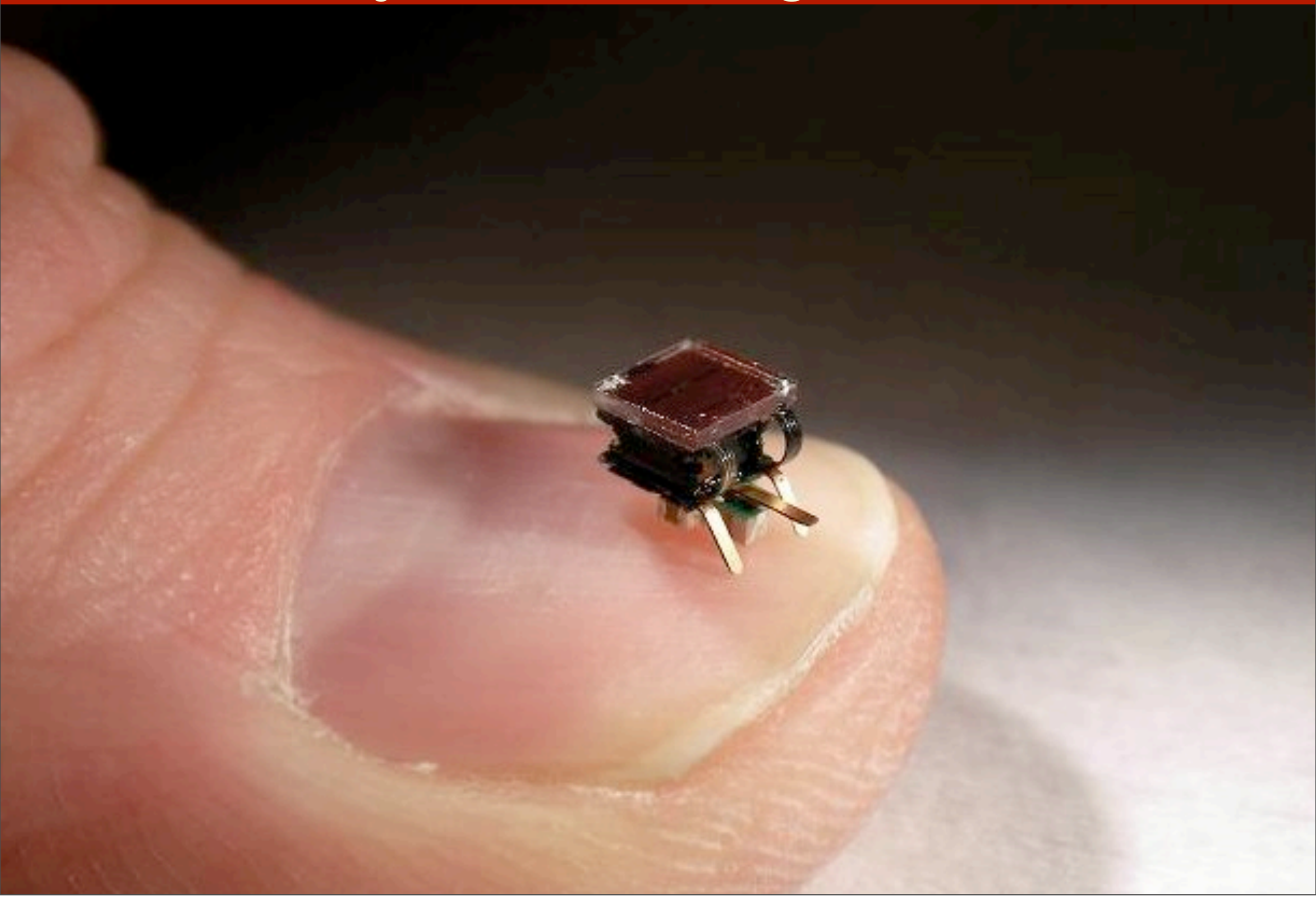
Eusociality, in which some individuals reduce their own lifetime reproductive potential to raise the offspring of others, underlies the most advanced forms of social organization and the ecologically dominant role of social insects and humans. For the past four decades kin selection theory, based on the concept of inclusive fitness, has been the major theoretical attempt to explain the evolution of eusociality. Here we show the limitations of this approach. We argue that standard natural selection theory in the context of precise models of population structure represents a simpler and superior approach, allows the evaluation of multiple competing hypotheses, and provides an exact framework for interpreting empirical observations.



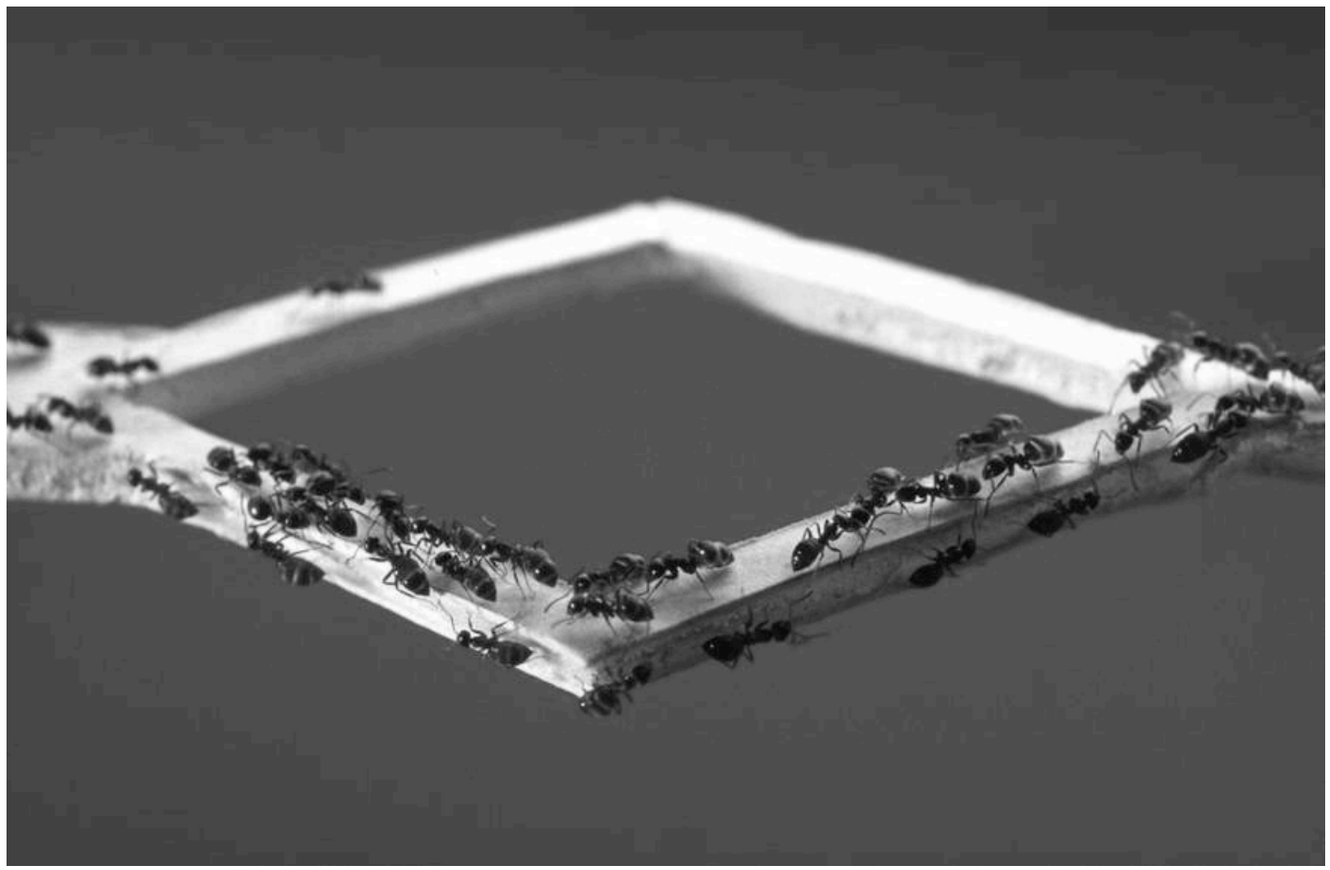
Synthetic intelligence?



Synthetic intelligence?



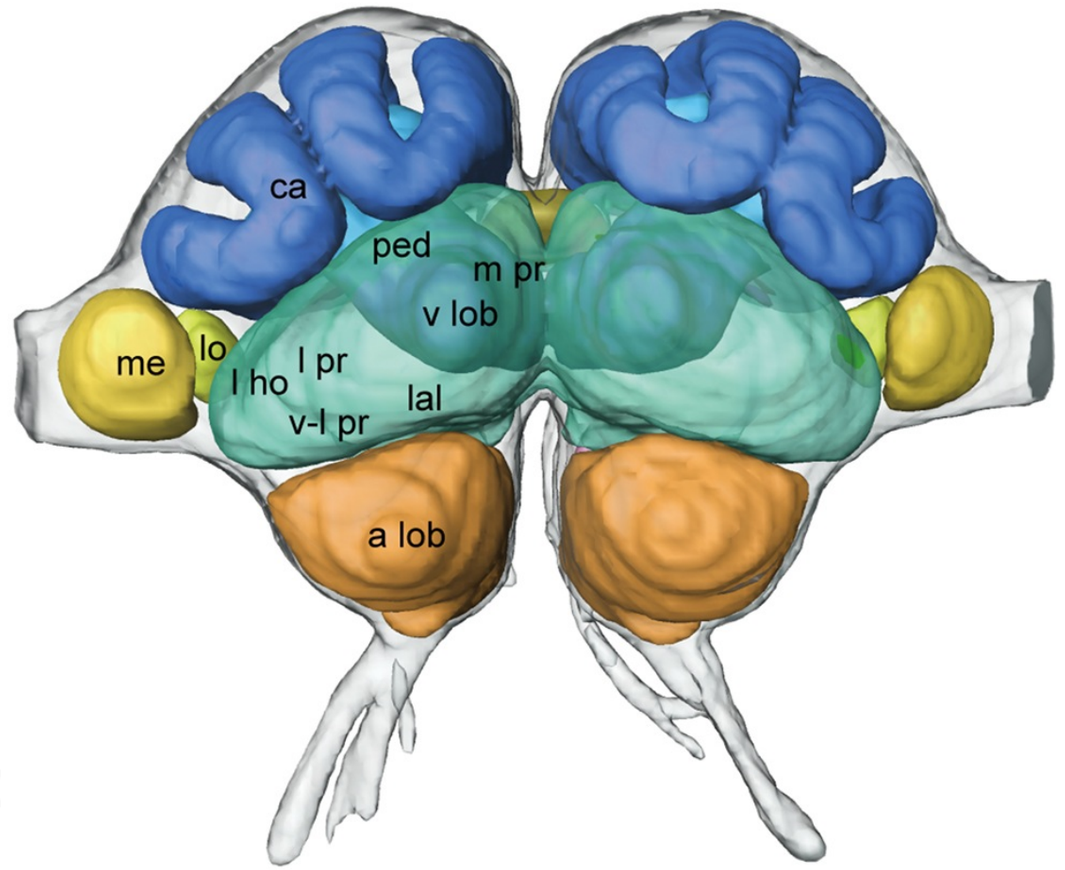
Synthetic swarm intelligence?



Ethology Ecology & Evolution 1: 295-311, 1989

Collective patterns and decision-making *

J.L. Deneubourg and S. Goss
Unit of Theoretical Behavioural Ecology, CP 231, Université Libre de Bruxelles, 1050 Bruxelles, Belgium



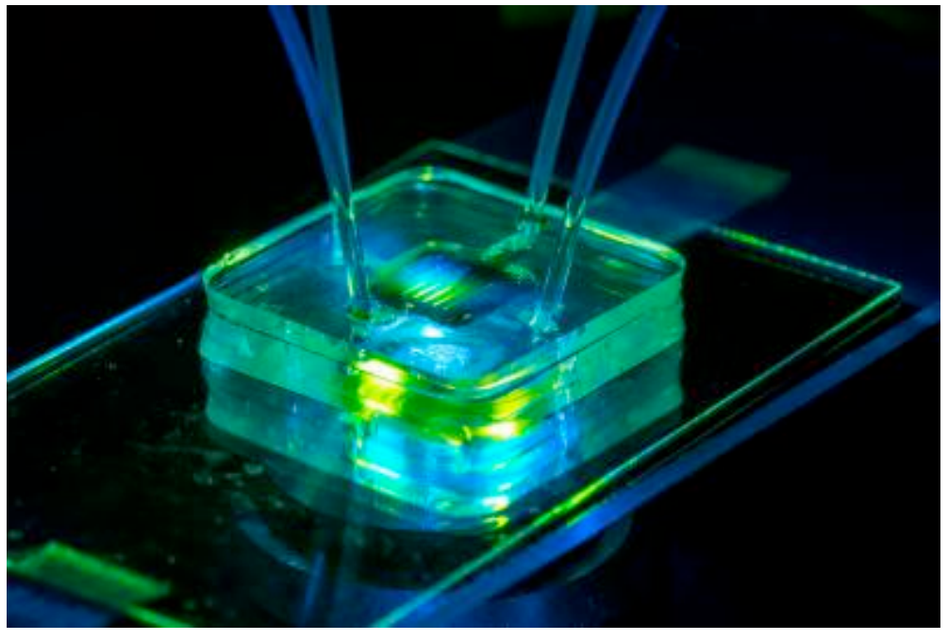
$$\frac{dx_1}{dt} = \mu q_1 P_1(x_1, x_2) - \nu x_1 \qquad \frac{dx_2}{dt} = \mu q_2 P_2(x_1, x_2) - \nu x_2 \tag{14.1}$$

$$P_i(x_1, x_2) = \frac{(x_i + K)^2}{\Theta(x_1, x_2)} \qquad \Theta(x_1, x_2) = \sum_{j=1,2}(x_j + K)$$

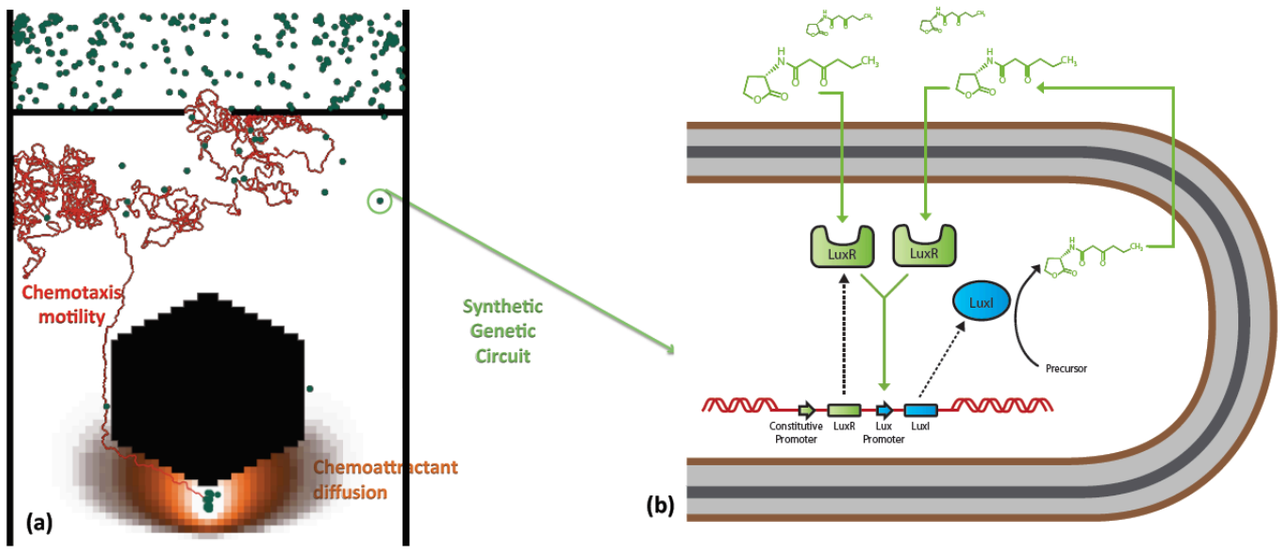
Complex Systems WETLab

No central control

Distributed decisions. Simple individuals, complex CI



http://complex.upf.edu/wet-lab/



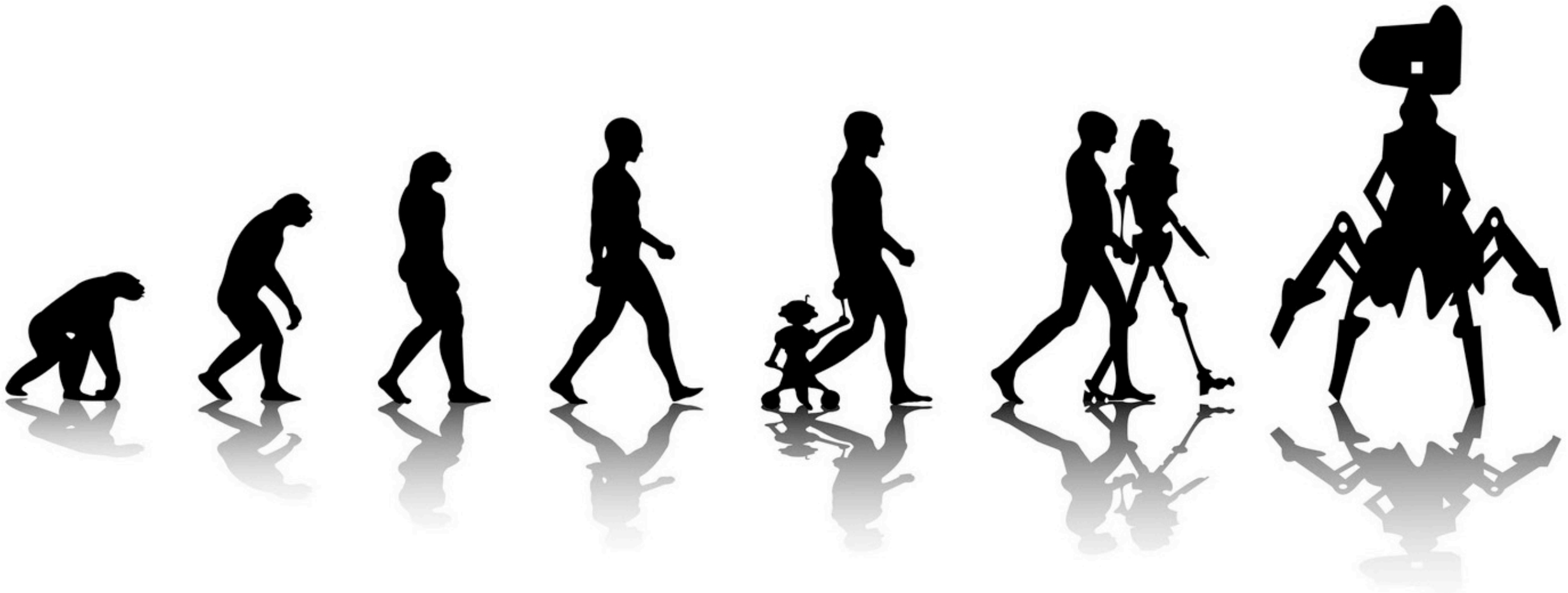
$$\frac{dLuxI}{dt} = \gamma_1 \frac{(LuxR - L1)^2}{\epsilon_1 + (LuxR - L1)^2} - \delta_I LuxI$$

$$\frac{dLuxR}{dt} = \gamma_R - \delta_R LuxR$$

$$\frac{dL_1}{dt} = \gamma_{L1} LuxI - \delta_{L1} L_1$$

Stigmergy, biomaterials...

keep evolving ...



http://complex.upf.es/