EVOLUTIONARY GAME THEORY AND EVO-DEVO DYNAMICS

VON NEUMANN, LIFE AND EVOLUTION

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John von Neumann是何许人也

- 电子计算机之父

EDVAC（1945），冯·诺依曼结构（二进制、内存）

- 博弈论之父

与Oskar Morgenstern合著《博弈论和经济行为》（1944）

- 对基础数学、应用数学、量子力学以及曼哈顿计划等都作出大量杰出的贡献。

- 晚年研究自动机（Automata），即能够进行自我复制的机器，提出了“转录”和“翻译”的概念；闲暇时曾用计算机对进化进行数值模拟。

（1903~1957）

Game Theory

	A	B
A	a	b
B	c	d

Example1：夫妻打扫卫生🧹

妻子的收益

	她打扫	她不打扫	总分
他打扫	10	4	14
他不打扫	2	0	2
总分	12	4	16

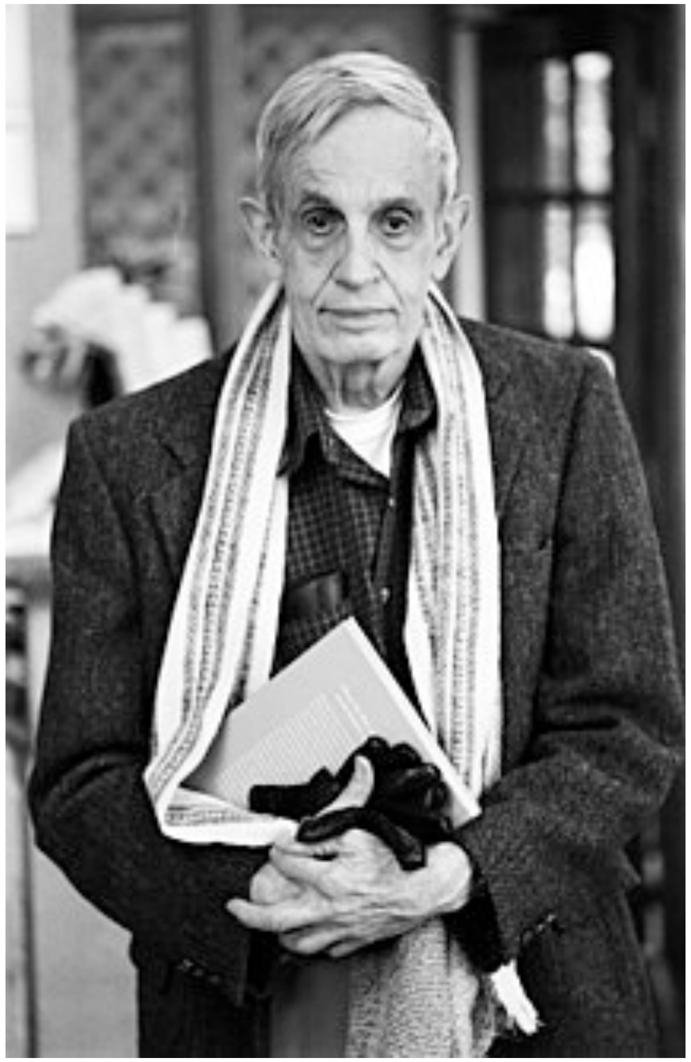
丈夫的收益

	她打扫	她不打扫	总分
他打扫	8	2	10
他不打扫	7	2	9
总分	15	4	19

Nash Equilibrium

	A	B
A	a	b
B	c	d

如果a>c，那么A策略是纳什均衡；
如果d>b，那么B策略是纳什均衡。



John Forbes Nash Jr.
(1928 – 2015)

Example2: 鹰鸽博弈（斗争策略）

win: b = benefit
lose: c = cost
b < c

	鹰🦅	鸽🐦
鹰🦅	(b-c)/2	b
鸽🐦	0	b/2

J. Maynard Smith
(1920 - 2004)

ESS(进化稳定策略)

Example3：求偶策略的博弈

追求者的收益

	Coy	Fast
Faithful	15-10-3=2	15-10=5
Philander	0	15

被追求者的收益

	Coy	Fast
Faithful	15-20-3=2	15-10=5
Philander	0	15-20=-5

prisoner's dilemma

	沉默（合作）	认罪（背叛）
沉默（合作）	-1	-10
认罪（背叛）	0	-7

Five Rules for Cooperations:
1. Direct reciprocity(直接互惠)

Robert Trivers
(1943~)

ALLD vs GRIM

	合作	背叛
合作	R	S
背叛	T	P

T>R>P>S，
且R>(T+S)/2

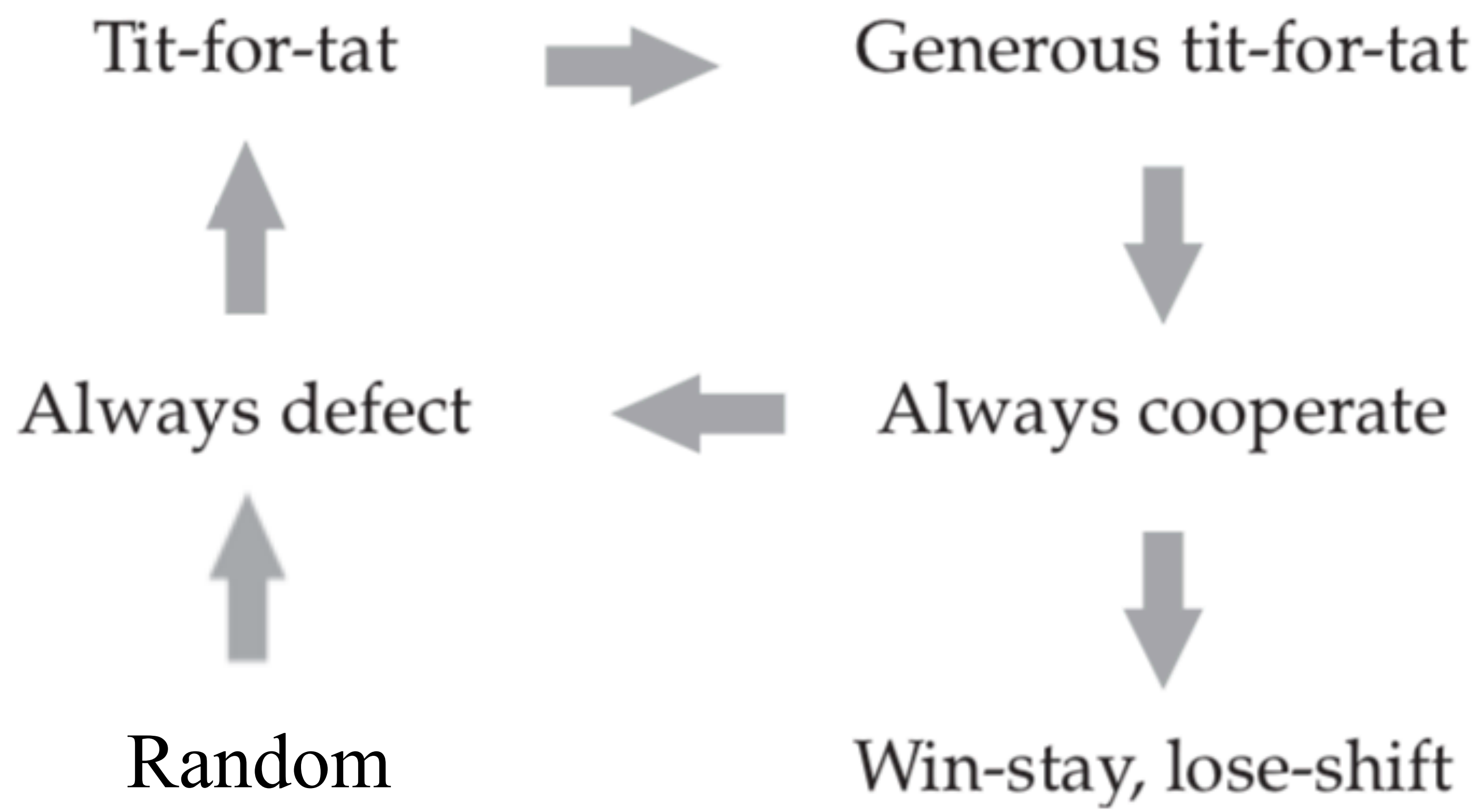
	GRIM	ALLD
GRIM	mR	S+(m-1)P
ALLD	T+(m-1)P	mP

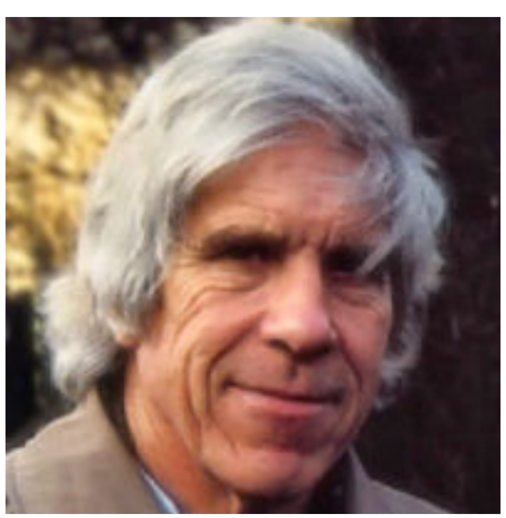
m代表博弈局数 $mR > T + (m-1)P \longrightarrow m > (T-P)/(R-P) \longrightarrow w > c/b$

w代表一局结束再来一局的概率 $m = 1/(1-w)$，令T = b、R = b - c、P = 0和S = - c

Five Rules for Cooperations:
1. Direct reciprocity(直接互惠)

Tit-for-tat



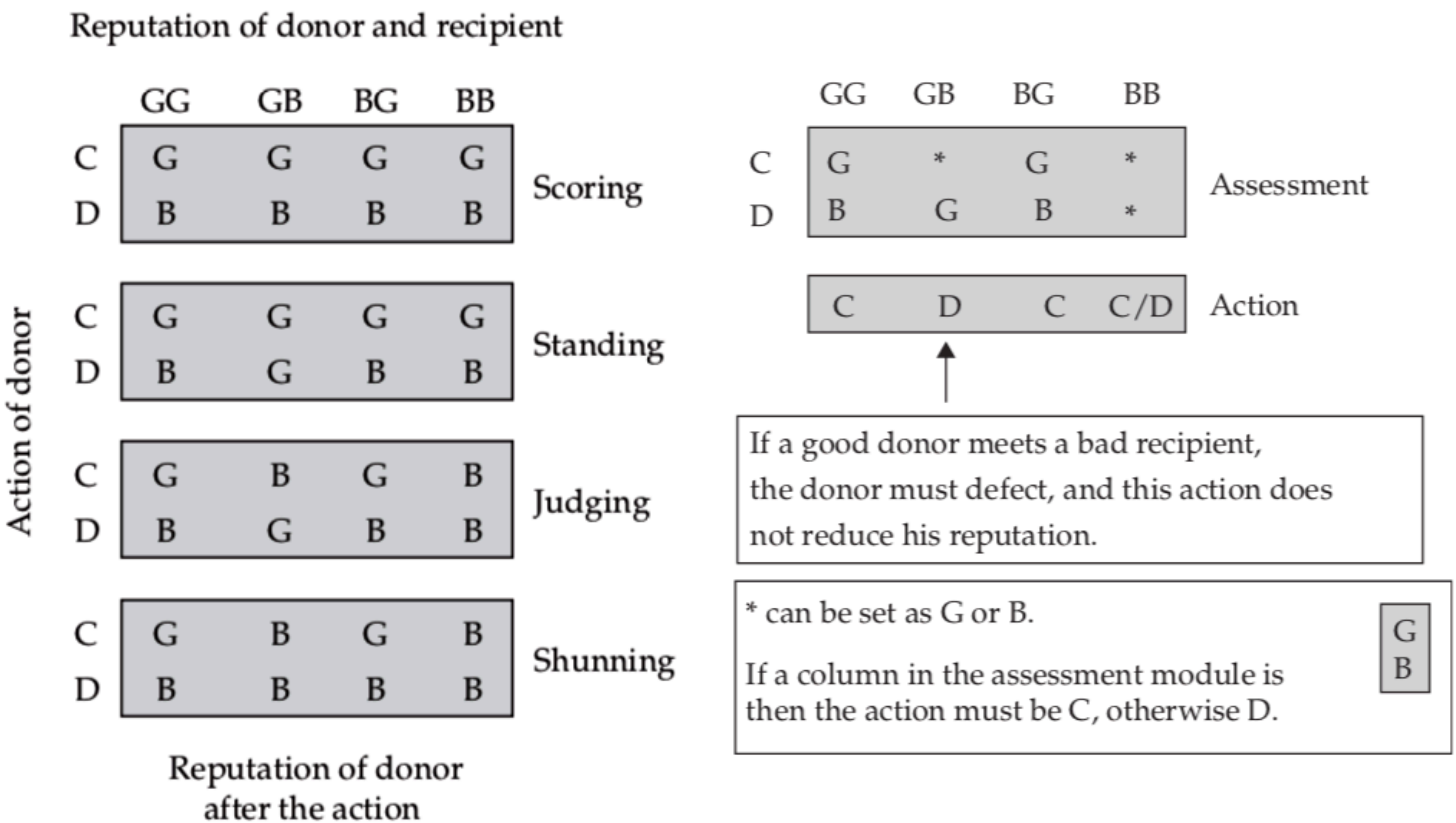

W. D. Hamilton


Robert Axelrod


Karl Sigmund

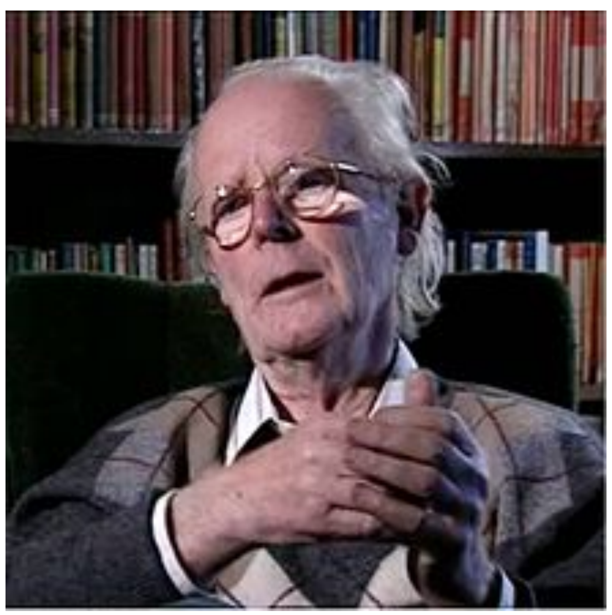

Martin Nowak

Five Rules for Cooperations:
2. Indirect reciprocity(间接互惠)

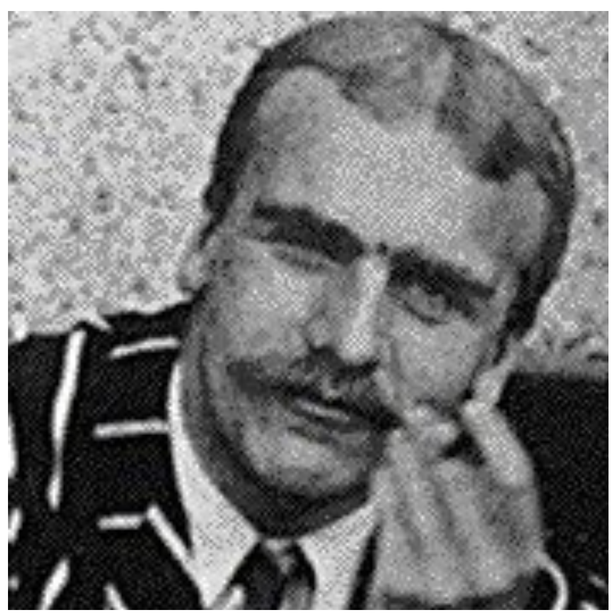


Five Rules for Cooperations: 3. Kin Selection(亲缘选择)

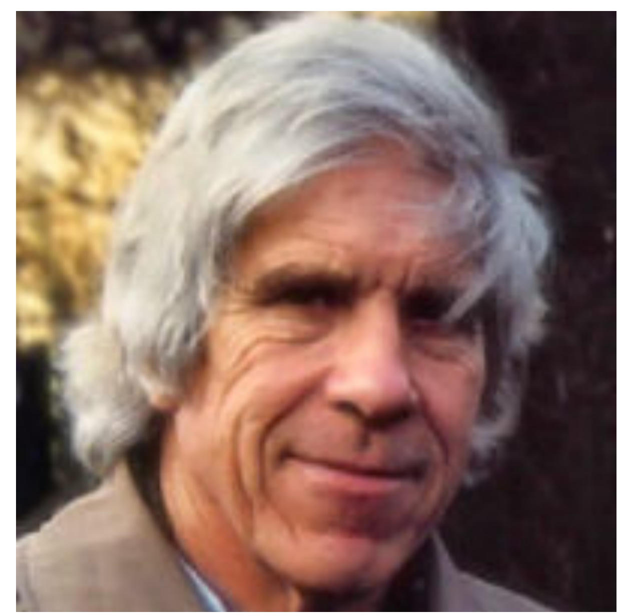
$$cost < r * benefit$$



J. Maynard Smith (1920 - 2004)



J. B. S. Haldane (1892 - 1964)



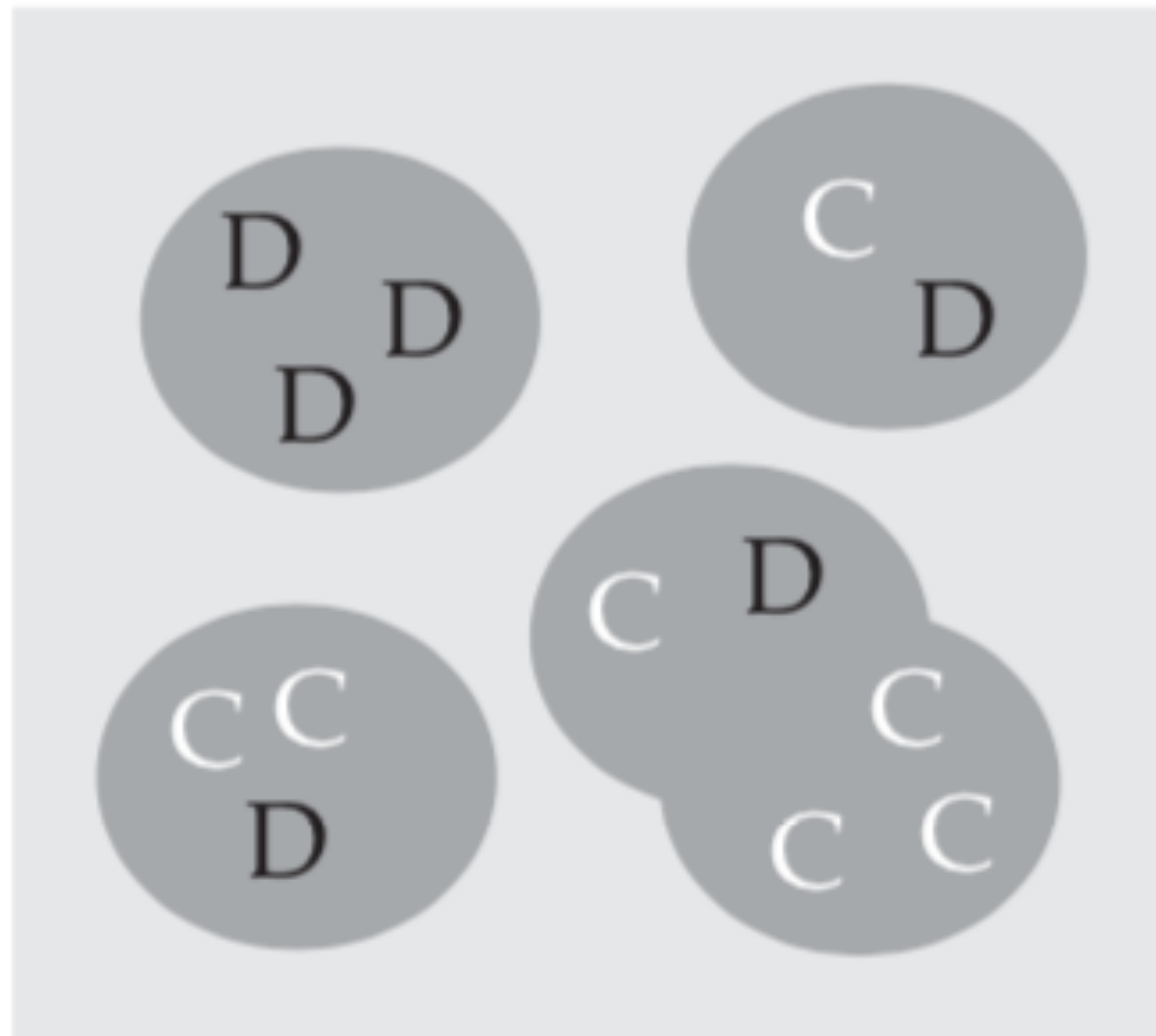
W. D. Hamilton (1936–2000)

George C. Williams (1926-2010)

Five Rules for Cooperations: 4. Group Selection

George C. Williams
(1926-2010)

挑战



Five Rules for Cooperations: 4. Group Selection

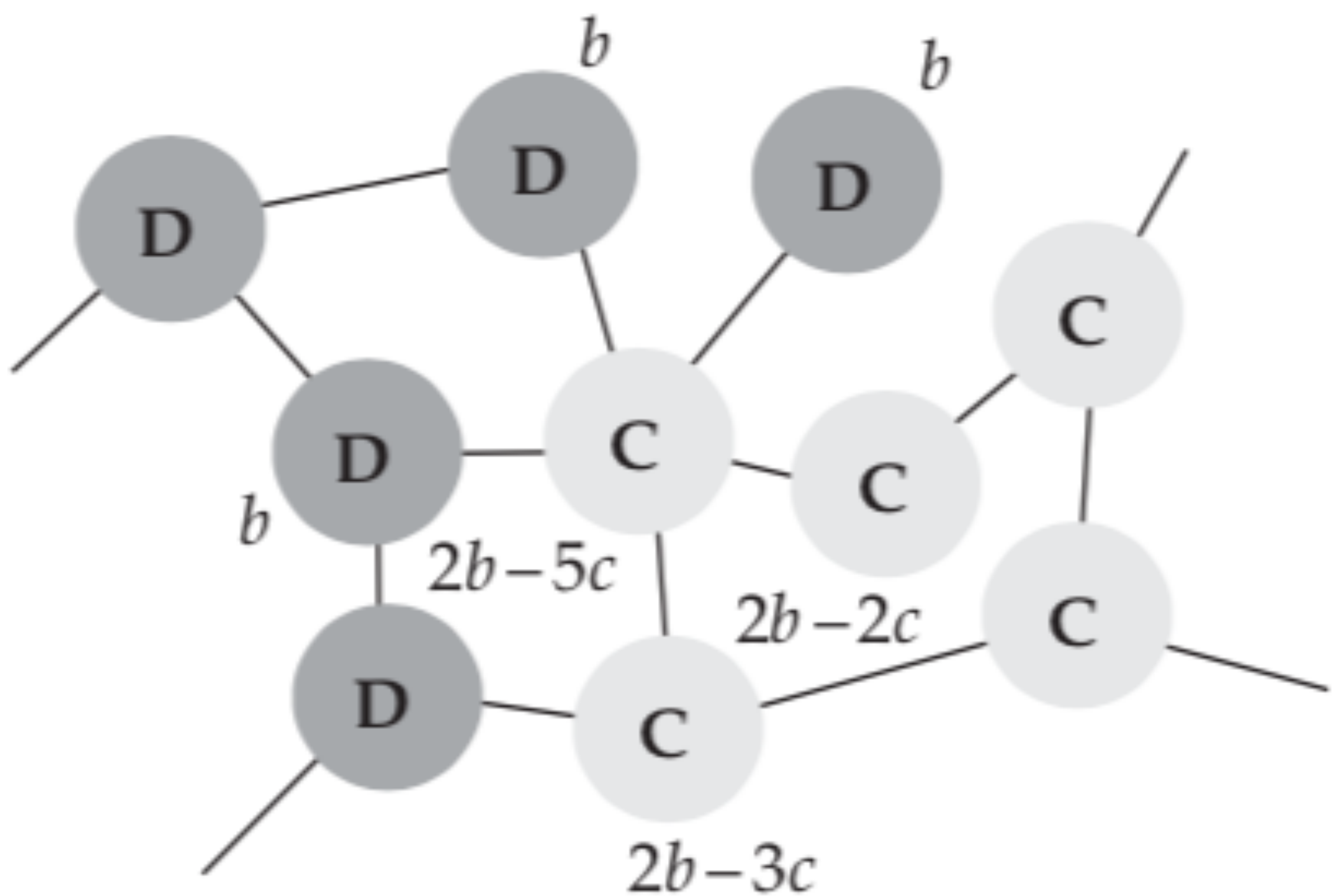
代	1+0.4	1	1.1+0.4	1.1	sum
0	10*10*(10/200)=5	10-5=5	10*10*(190/200)=95	190-95=95	200
1.0	7	5	142.5	104.5	259
1	12*10*(12/259)=5.56	12-5.56=6.44	12*10*(247/259)=114.44	247-114.44=132.56	259
2.0	7.784	6.44	171.66	145.816	331.7

助他个体从5%降到4.6%再到4.2%　　**Simpson's paradox**

代	1+0.4	1	1.1+0.4	1.1	B	sum
0	10*10*(10/100)=10	10-10=0	10*10*(90/100)=90	90-90=0	100	200
1.0	14	0	135	0	110	259
1	14*10*(14/149)=13.15	14-13.15=0.85	14*10*(135/149)=126.85	135-126.85=8.15	110	259
2.0	18.41	0.85	190.275	8.965	121	339.5

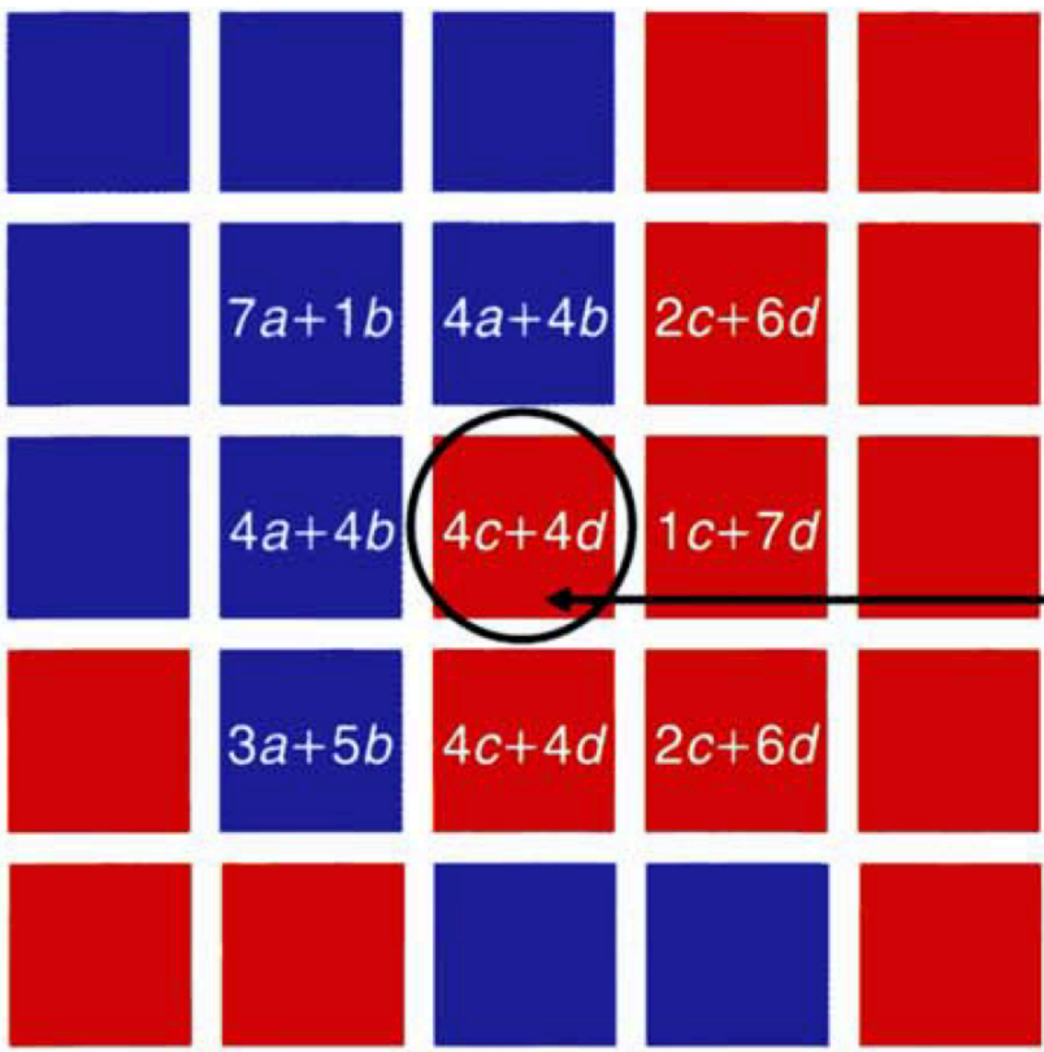
在Group A，助他个体从10%降到9.4%再到8.7%；相对于总体，则是从5%升到5.4%再到5.6%

Five Rules for Cooperations: 5. Graph Selection



Spatial Games = Cellular Automata + Game Theory

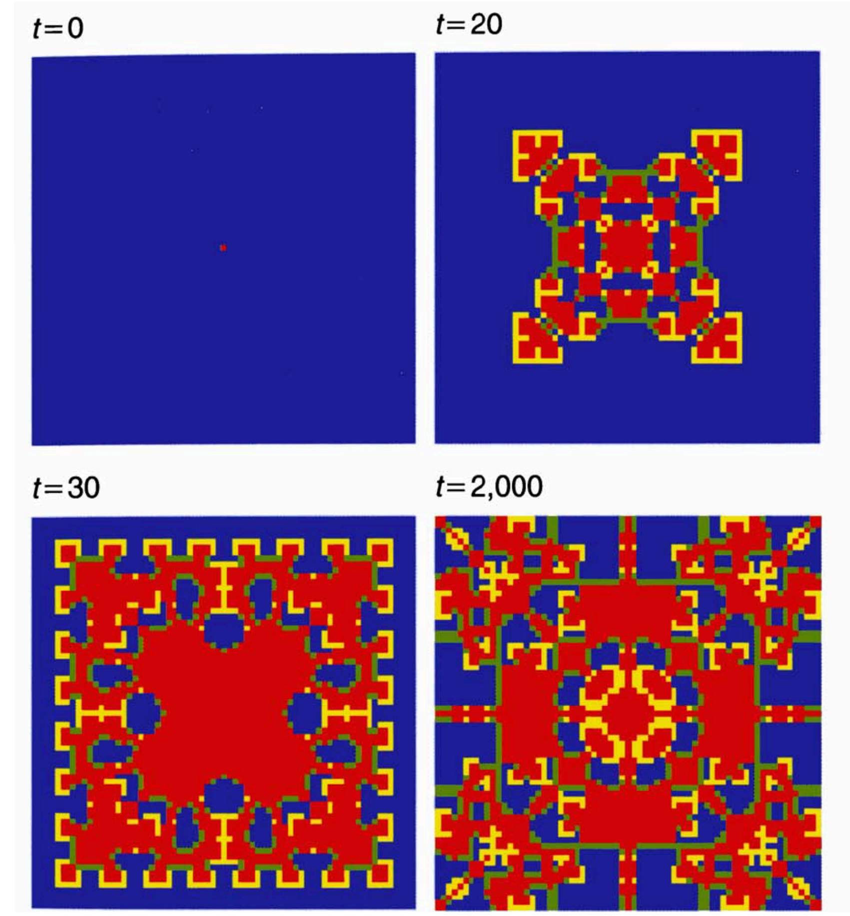
Spatial games



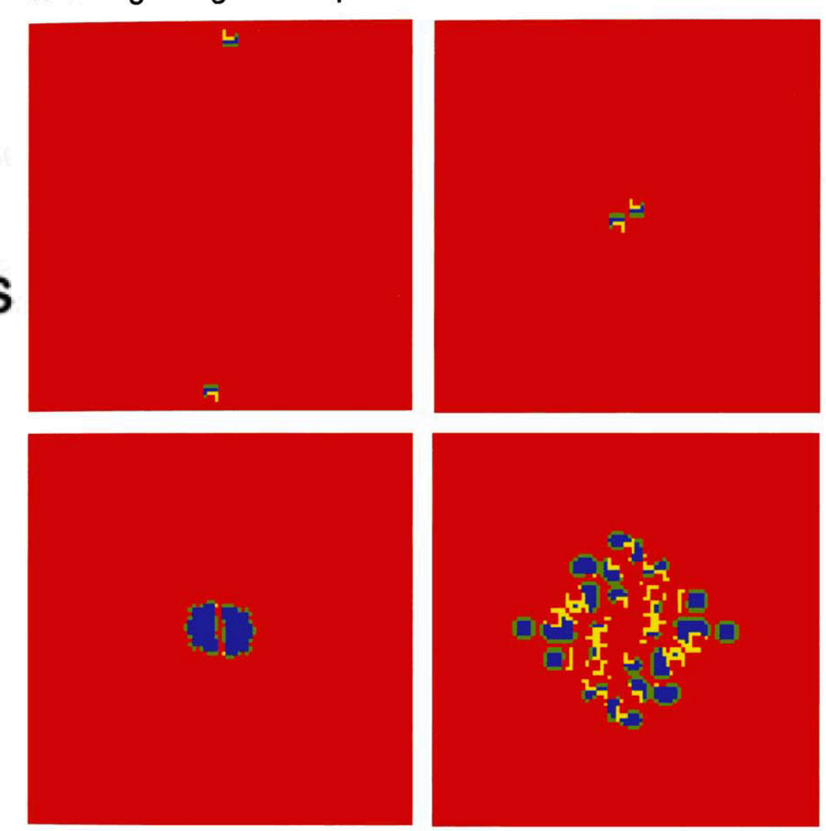
Payoff matrix:

	A	B
A	a	b
B	c	d

The focal cell will be taken over by whoever has the highest payoff among the 8 neighbors and the cell itself

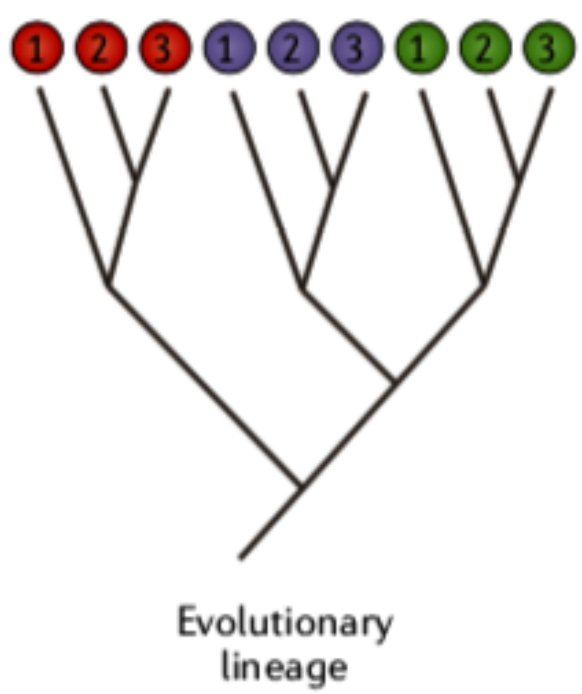


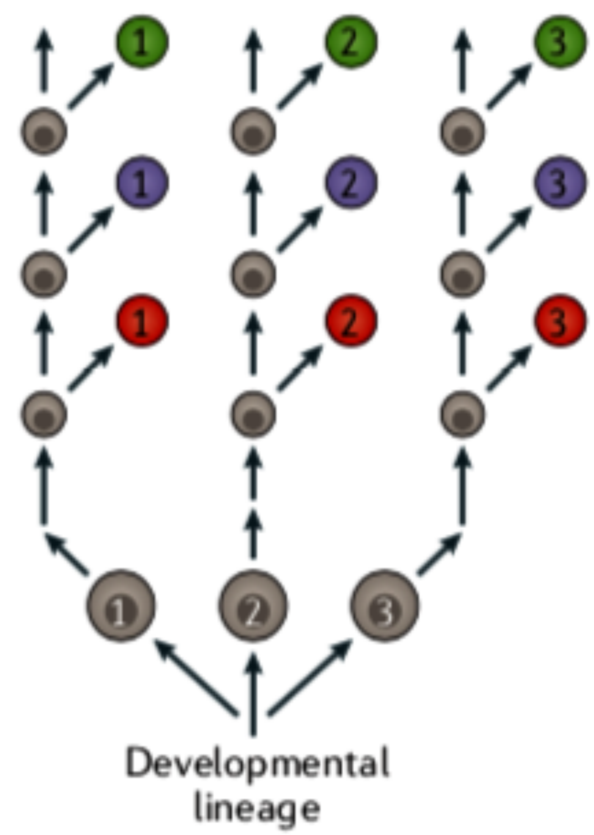
A collision of two "walkers" can lead to a "big bang" of cooperation

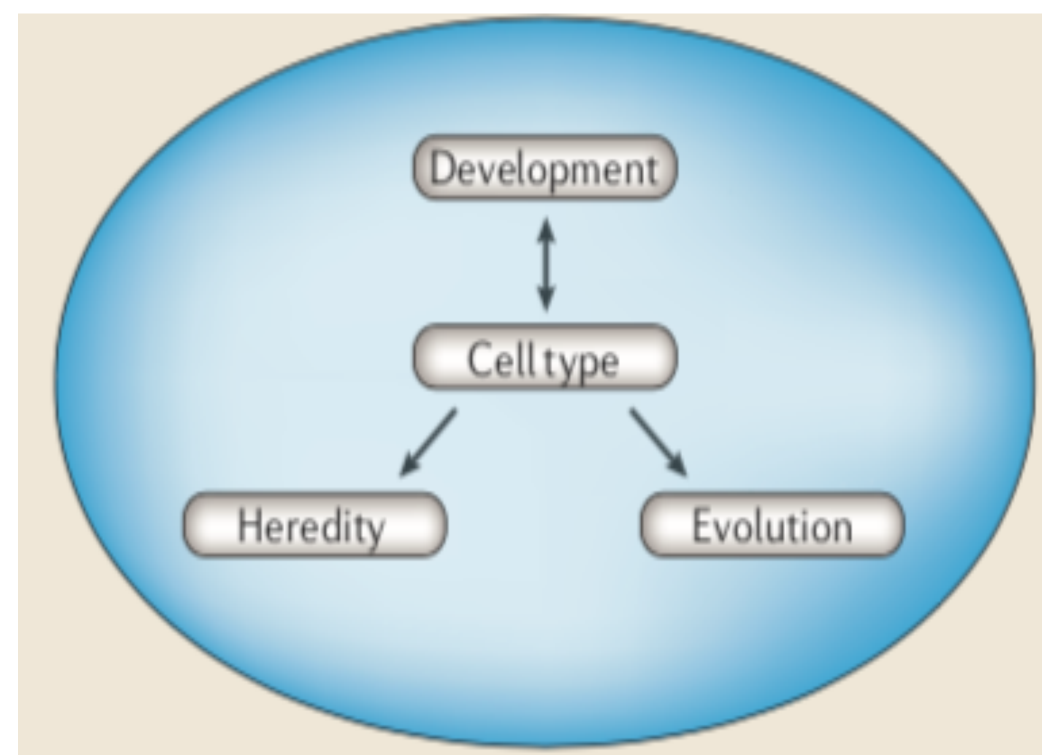


What is the Cell Type?

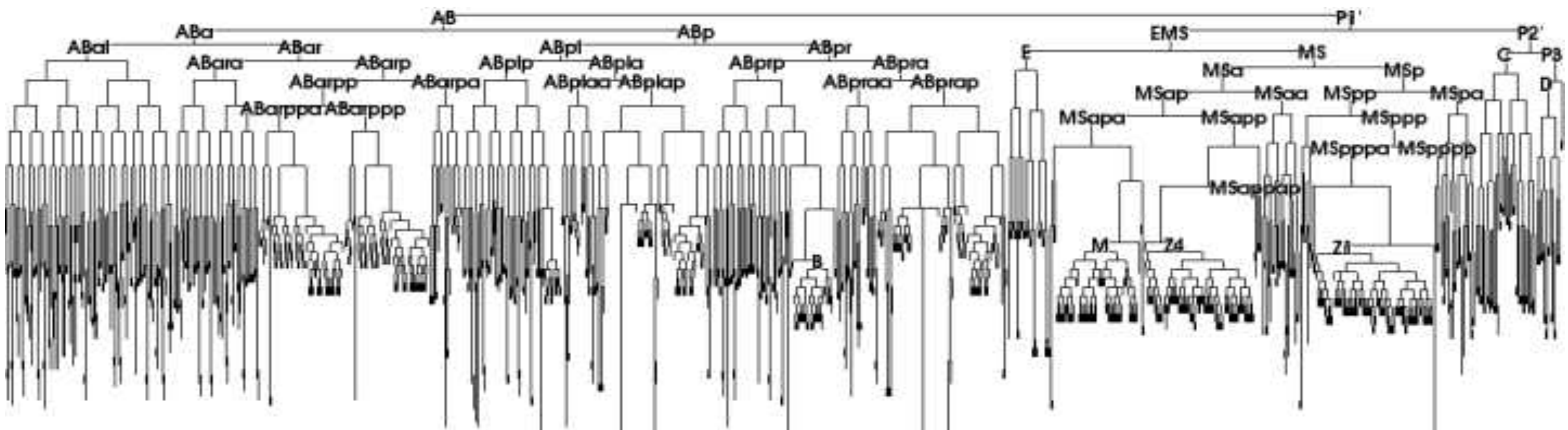
Cell Type Classification foundation:
Molecular fingerprints,
Cellular modules,
Sister cell types,
Gene expression level,
etc.







The embryonic cell lineage of the nematode *C. elegans*



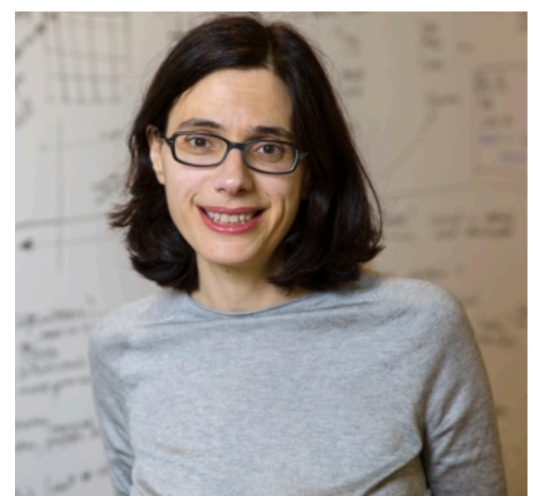
John Sulston
(1942-2018)

The Human Cell Lineage
Flagship Initiative

Human Cell
Lineage Tree

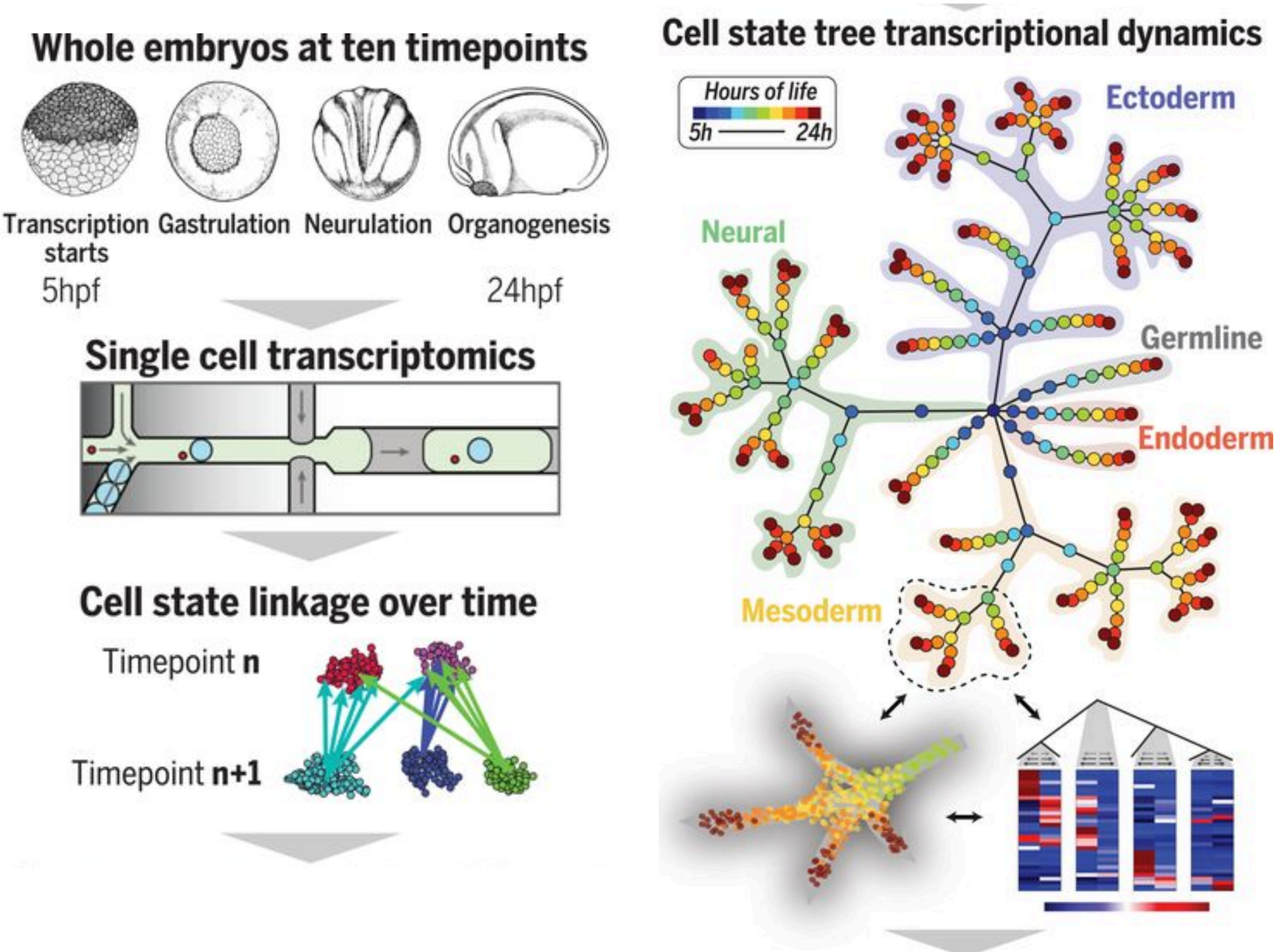
Ehud Shapiro@Weizmann

HUMAN
CELL
ATLAS

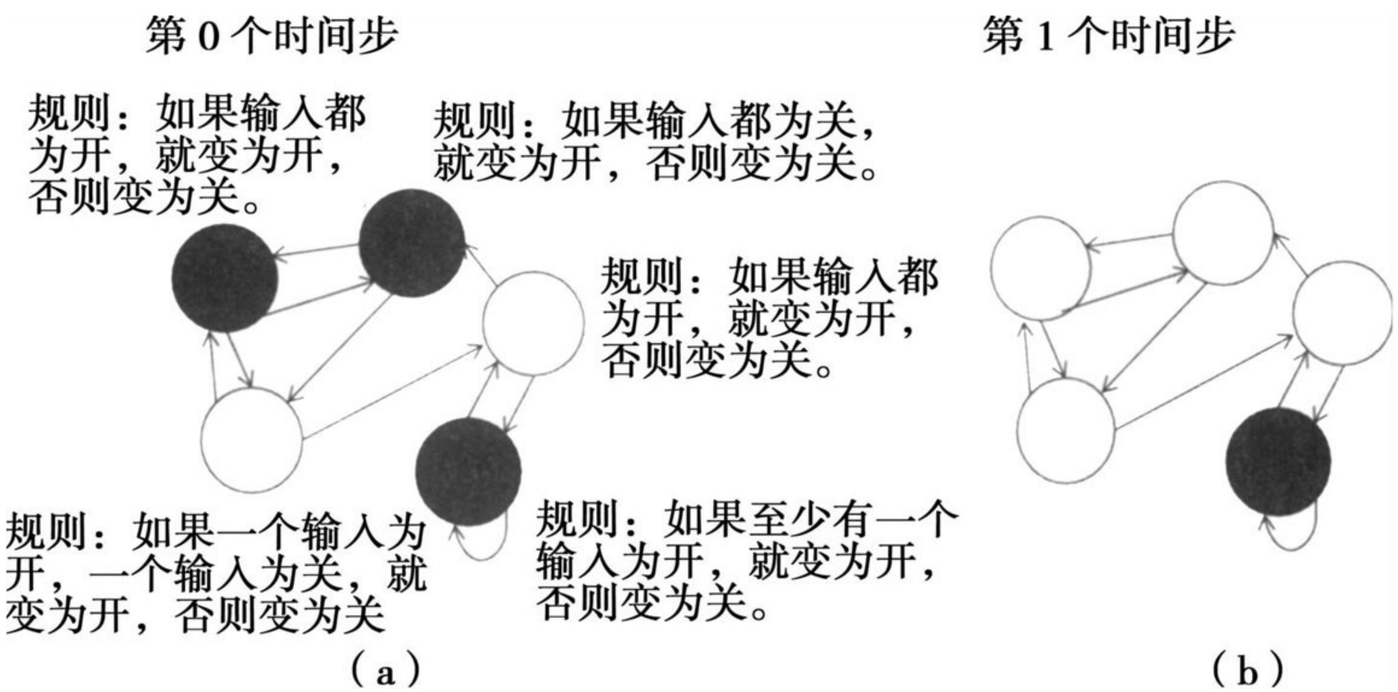


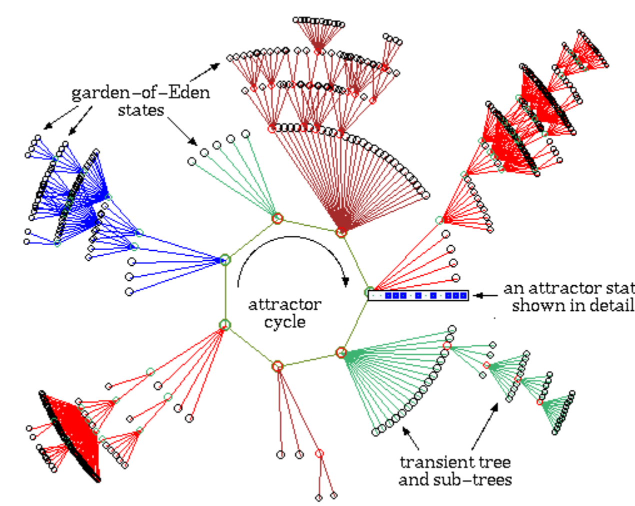
Aviv Regev@Broad

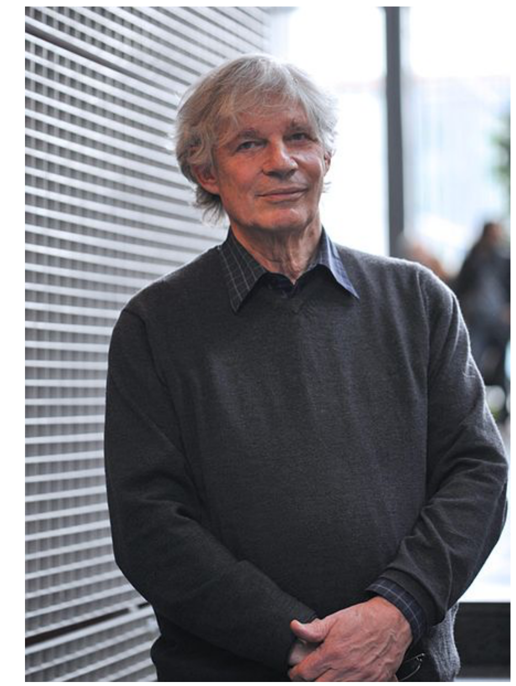
Sarah Teichmann@Sanger


Whole embryos at ten timepoints
Transcription starts
Gastrulation
Neurulation
Organogenesis
5hpf
24hpf
Single cell transcriptomics
Cell state linkage over time
Timepoint **n**
Timepoint **n+1**
Cell state tree transcriptional dynamics
Hours of life
5h
24h
Ectoderm
Neural
Germline
Endoderm
Mesoderm

Stuart Kauffman and Artificial Gene Regulatory Networks







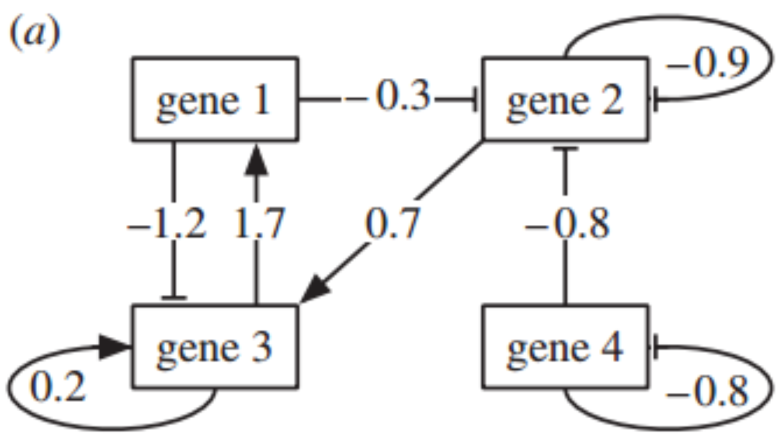
Limitations:

1. Binary states (boolean)
2. Ignore expression level
3. Discrete time simultaneously
4. Ignore noises (mutation and uncertain bias from environment)

He used **random boolean networks**, proposing that **cell types** are dynamical **attractors** in gene regulatory networks and that cell **differentiation** can be understood as **transitions** between attractors, argued that **natural selection** is not necessary in genesis of complex life.

Node of net means a **gene**, **N** is the number of nodes; **Edge** of net means **gene interaction**, **K** is **half** the number of edges. When K=2, He found that the number of attractors (cell types) is approximately $\sqrt{N}$. So with the theory, number of types in Nematodes is nearly $\sqrt{20470 + 1300} = 148$, as human is $\sqrt{21306 + 21856} = 208$

A generative bias towards average complexity in artificial cell lineages



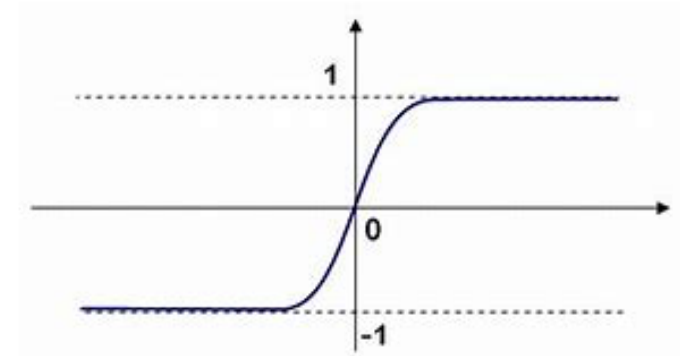
- **Gene 1** is a **cell-cycle regulator.**
- If **gene 1** is **ON**, the cell divides instantaneously, and **gene 1** is **turned OFF** in both daughter cells.
- **Gene 2** is a **asymmetric cell division** gene.
- **Gene *i*** is **ON** when 0< $s_i(t)$ <=1, and **OFF** when -1<= $s_i(t)$<=0.
- The gene expression pattern **S**(t)

Gene 2 Regulatory Rules

	Gene 1 is ON
Gene 2 is ON	Divide asymmetrically, $s_{2L}(t)=-1, s_{2R}(t)=s_2(t)$
Gene 2 is OFF	Divide symmetrically.

$$s_i(t+1) = f[\sum_{j=i}^{N} r_{ij} s_j(t)]$$

$$f(x) = 2/(1+e^{-ax}) - 1$$



Parameters:

- **R,** the **genotype (mutant** with random !0 element substitution **)**
- **S**(0), the **epigenetic** state
- D_{max} and t_{max} of **development**
- N, **K** and **Rules(General)**
- a in the **sigmoidal filter function**

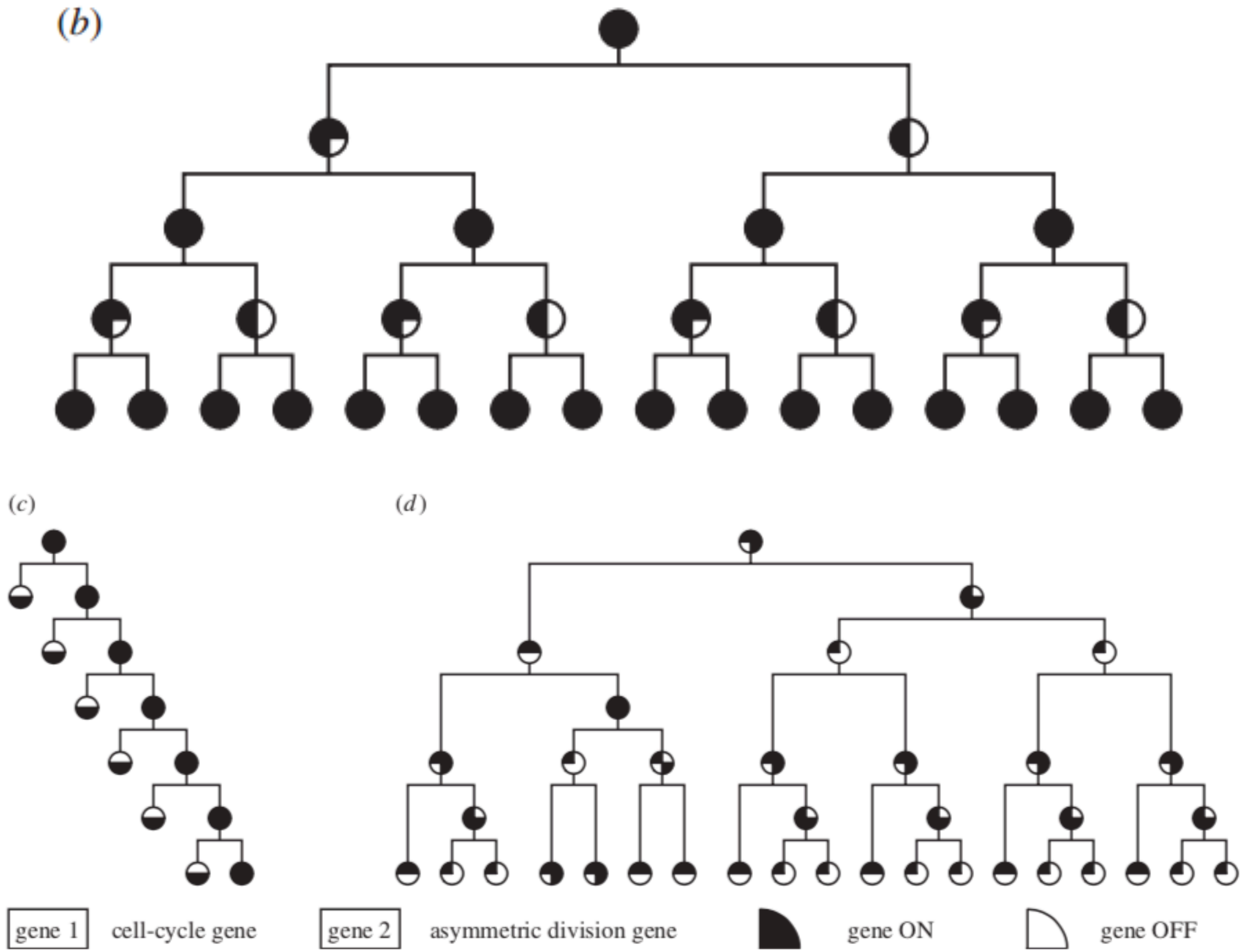
For example.

$$R = \begin{vmatrix} 0 & 0 & 1.7 & 0 \\ -0.3 & -0.9 & 0 & -0.8 \\ -1.2 & 0.7 & 0.2 & 0 \\ 0 & -0.8 & 0 & -0.8 \end{vmatrix}$$

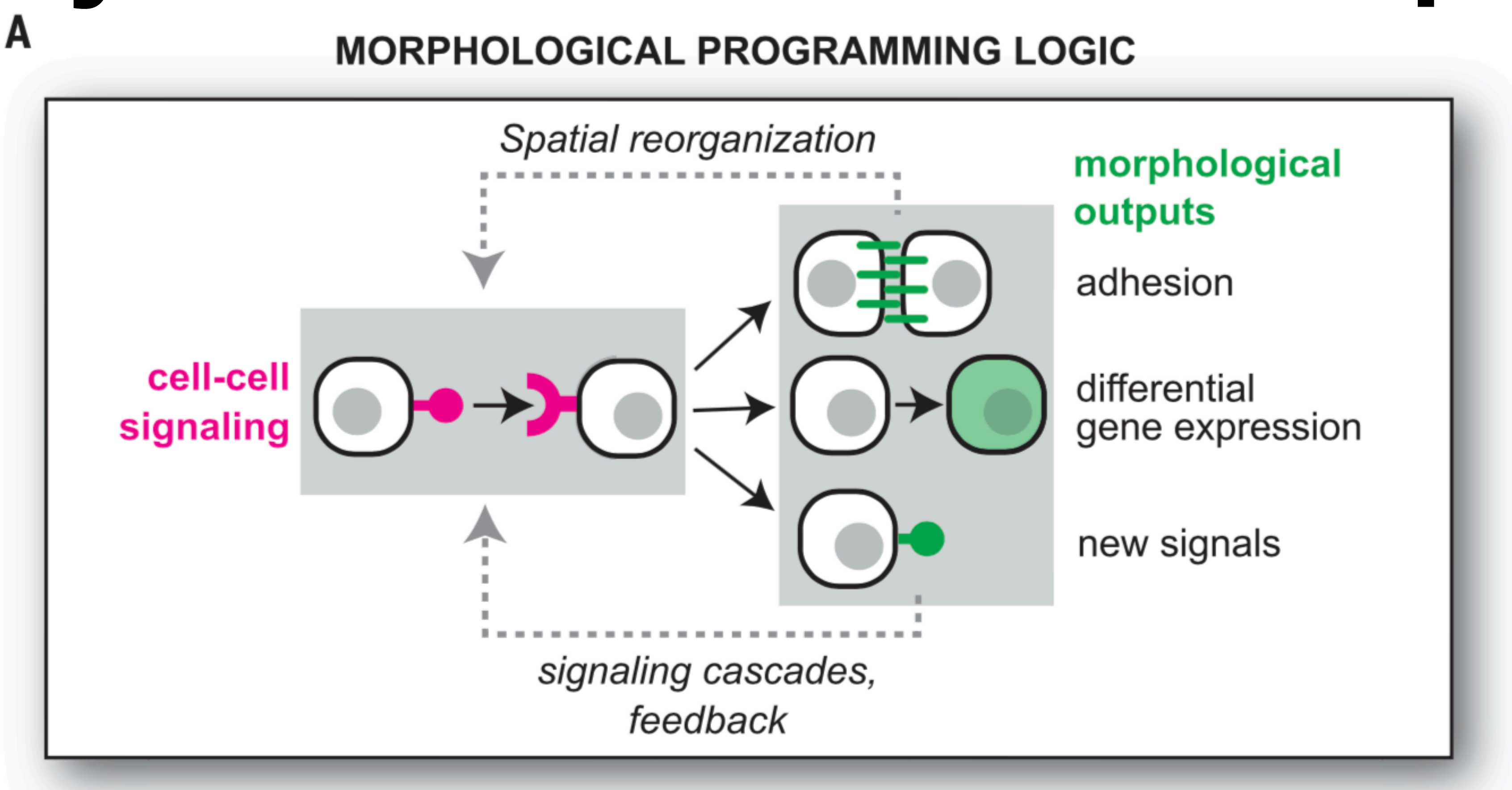
$S(t) = \begin{vmatrix} 1 \\ 1 \\ 1 \\ 1 \end{vmatrix}$. After **cell divide**, two daughter cells are born, which are $S_L(t) = \begin{vmatrix} -1 \\ -1 \\ 1 \\ 1 \end{vmatrix}$ and $S_R(t) = \begin{vmatrix} -1 \\ 1 \\ 1 \\ 1 \end{vmatrix}$.

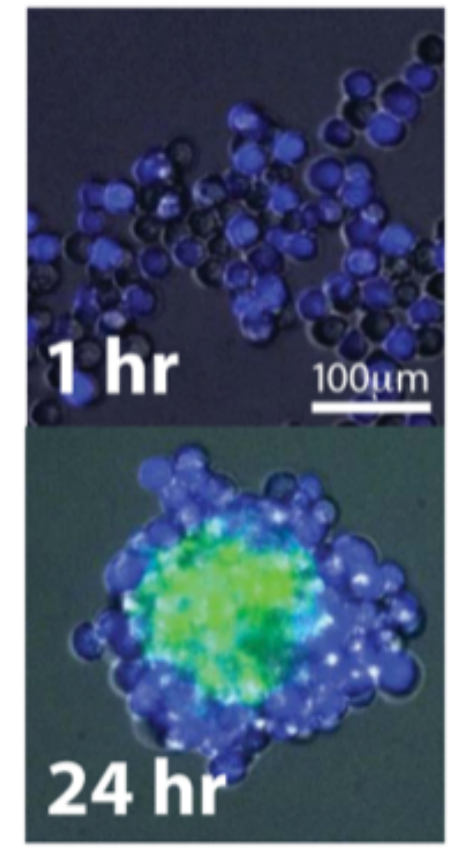
At time **t+1**, $S_L(t+1) = f(R * S_L(t))$

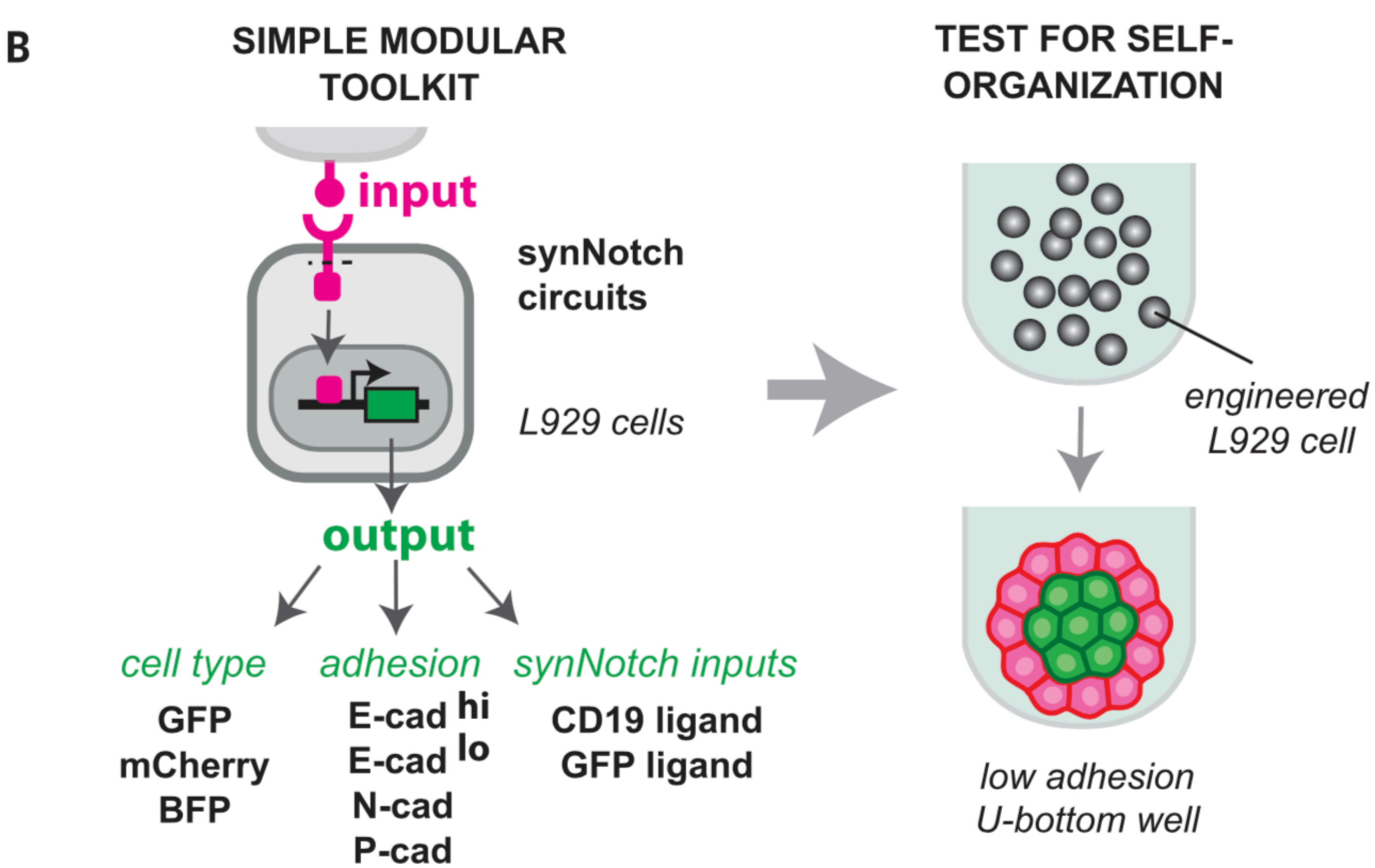
Artificial cell lineage Tree

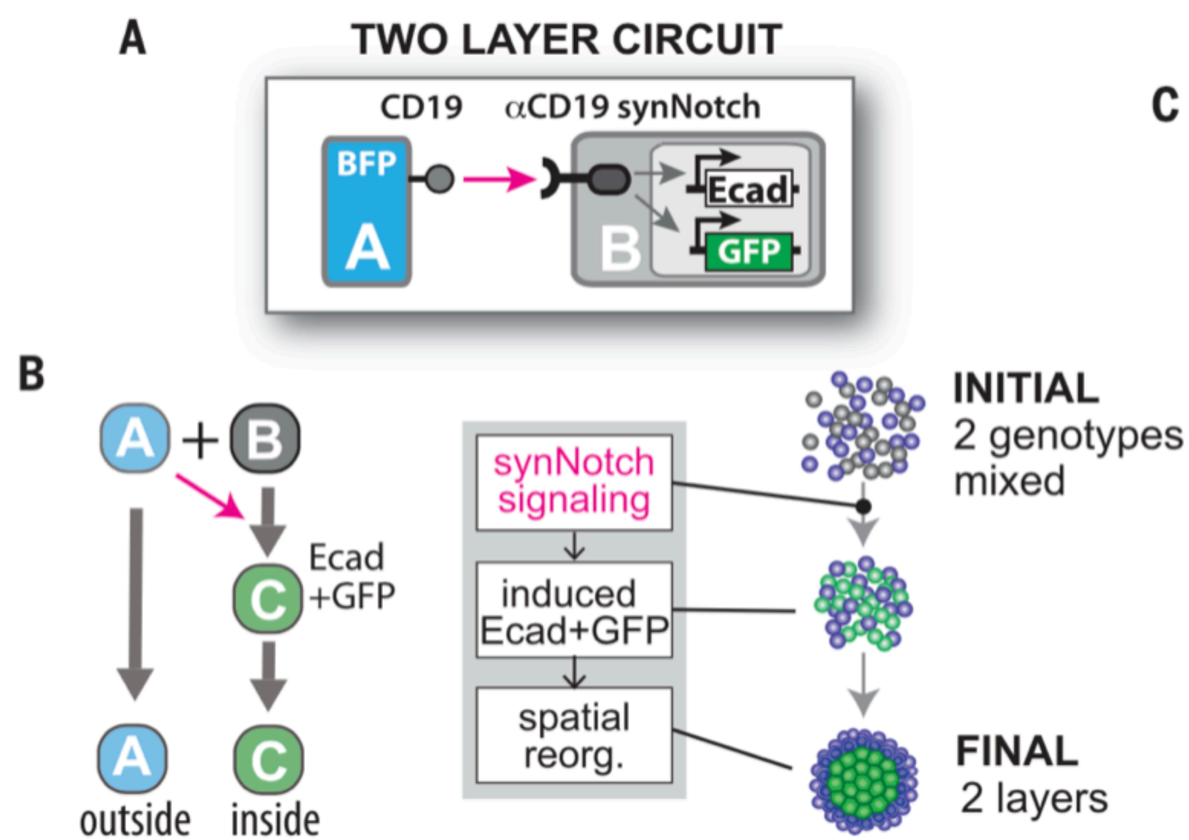


Synthetic Notch Receptor System



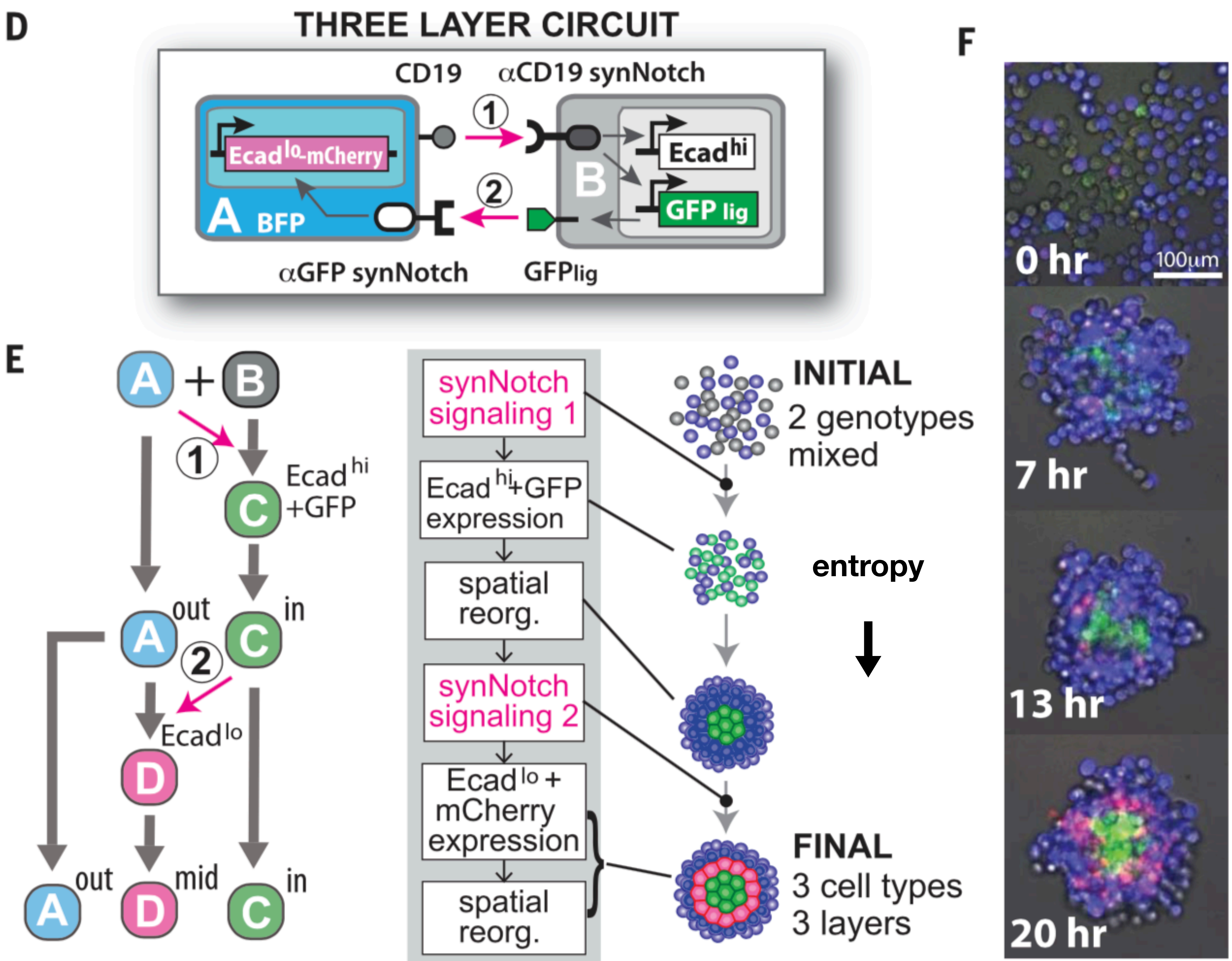


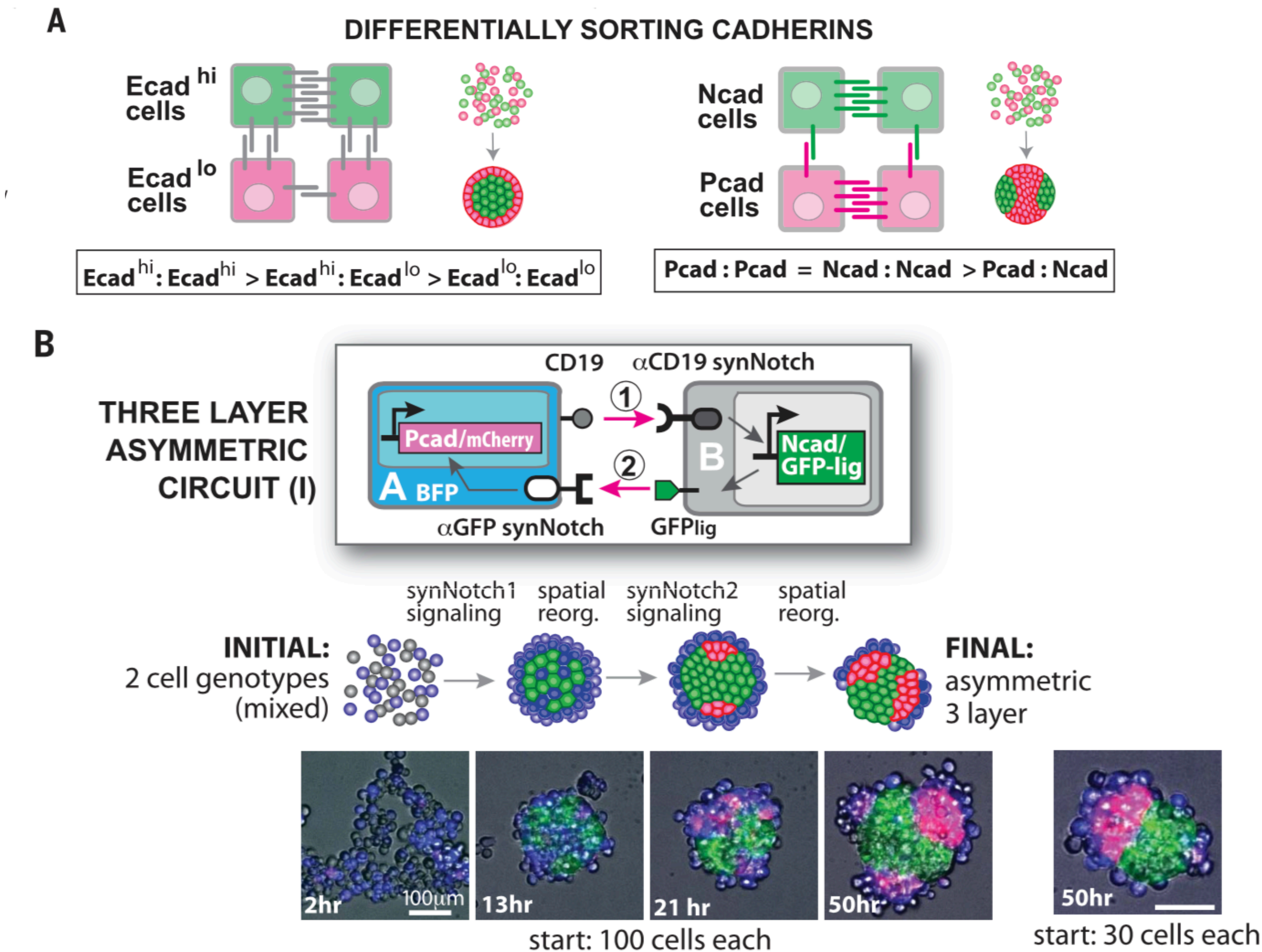




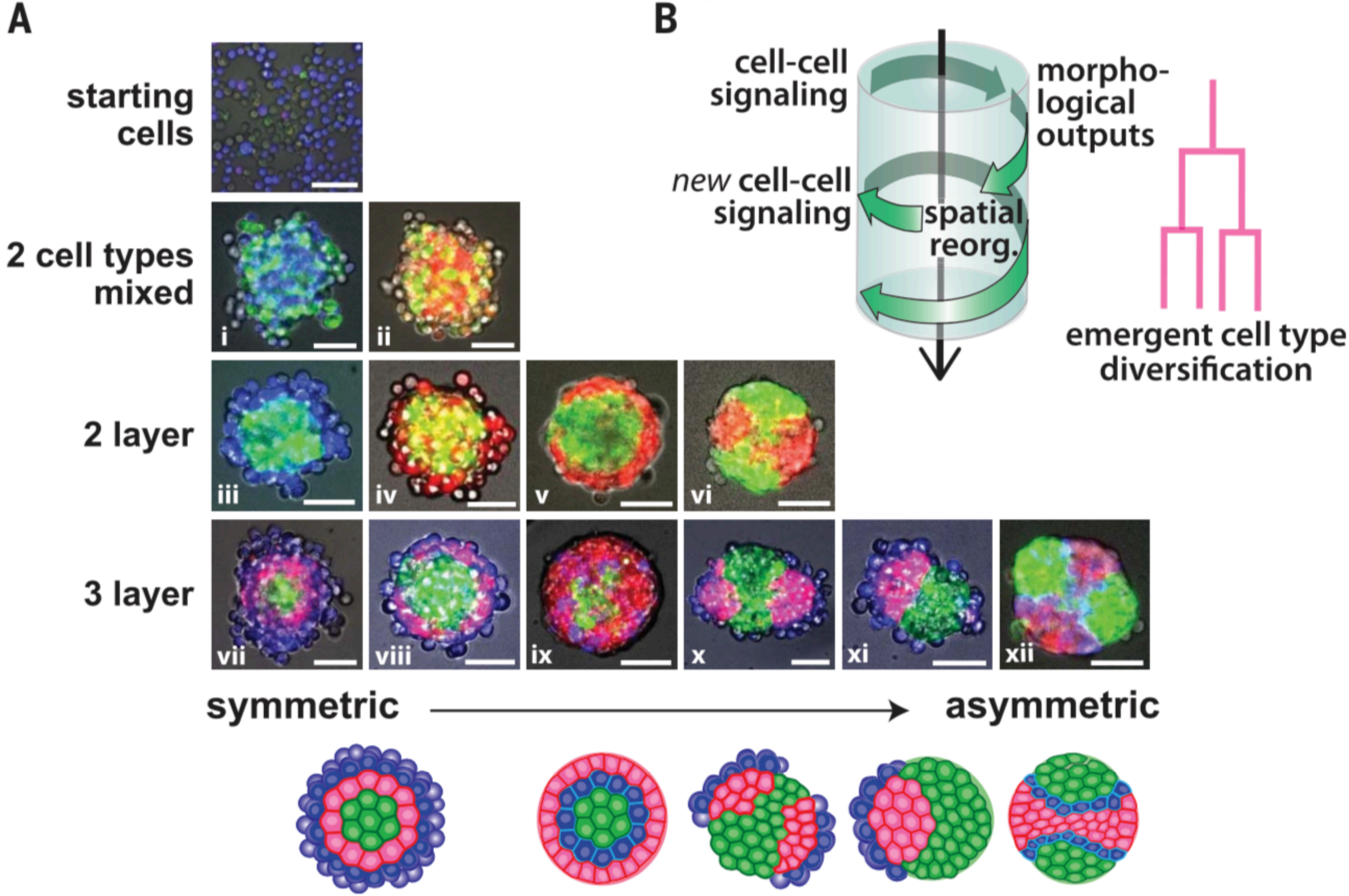
Three-layer circuit

[cell A: CD19; αGFP synNotch]
→ **[cell B:** αCD19 synNotch → $Ecad^{hi}$ + GFP_{lig}]
→ **[cell A:** αGFP synNotch → $Ecad^{lo}$ + mCherry]





A
DIFFERENTIALLY SORTING CADHERINS
Ecad hi cells
Ecad lo cells
Ecad hi : Ecad hi > Ecad hi : Ecad lo > Ecad lo : Ecad lo
Ncad cells
Pcad cells
Pcad : Pcad = Ncad : Ncad > Pcad : Ncad
B
THREE LAYER ASYMMETRIC CIRCUIT (I)
CD19
αCD19 synNotch
1
2
Pcad/mCherry
A BFP
B
Ncad/ GFP-lig
αGFP synNotch
GFPlig
synNotch1 signaling
spatial reorg.
synNotch2 signaling
spatial reorg.
INITIAL: 2 cell genotypes (mixed)
FINAL: asymmetric 3 layer
2hr
100µm
13hr
21 hr
50hr
start: 100 cells each
50hr
start: 30 cells each

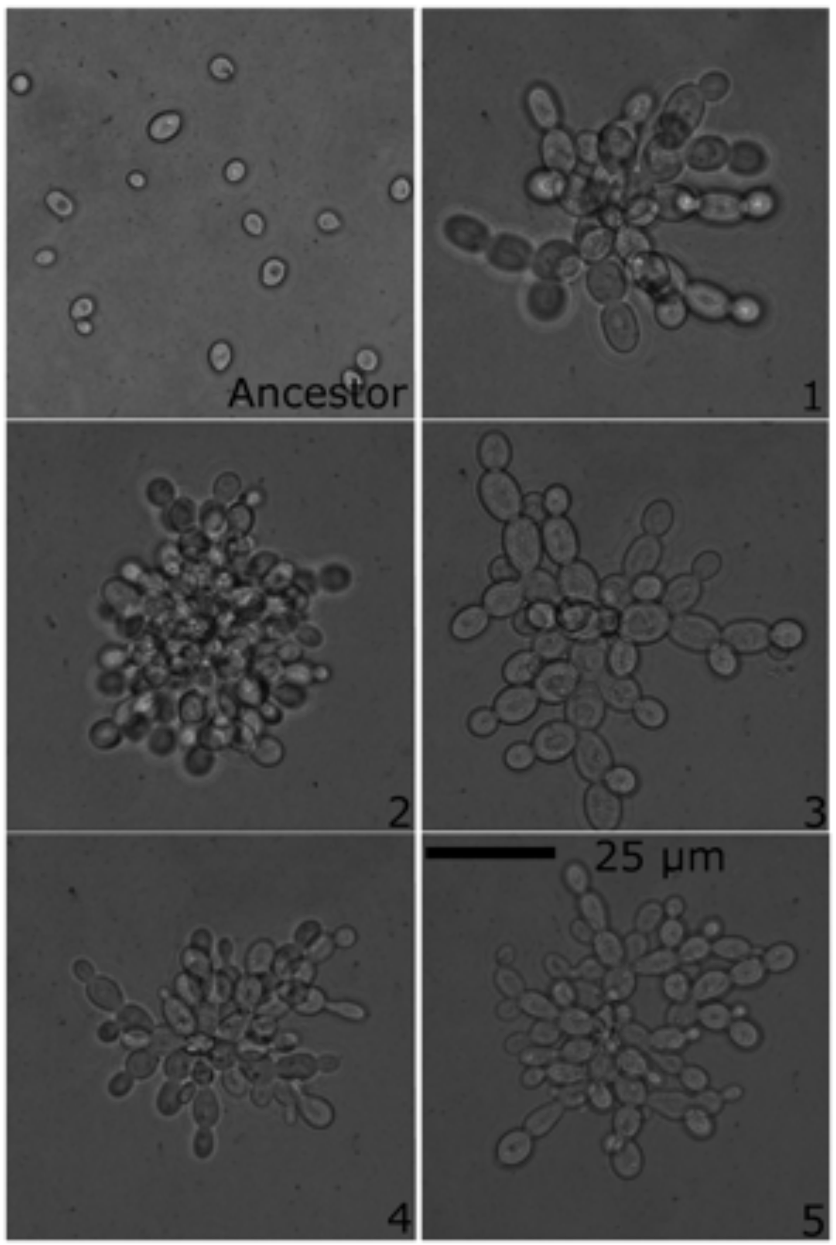


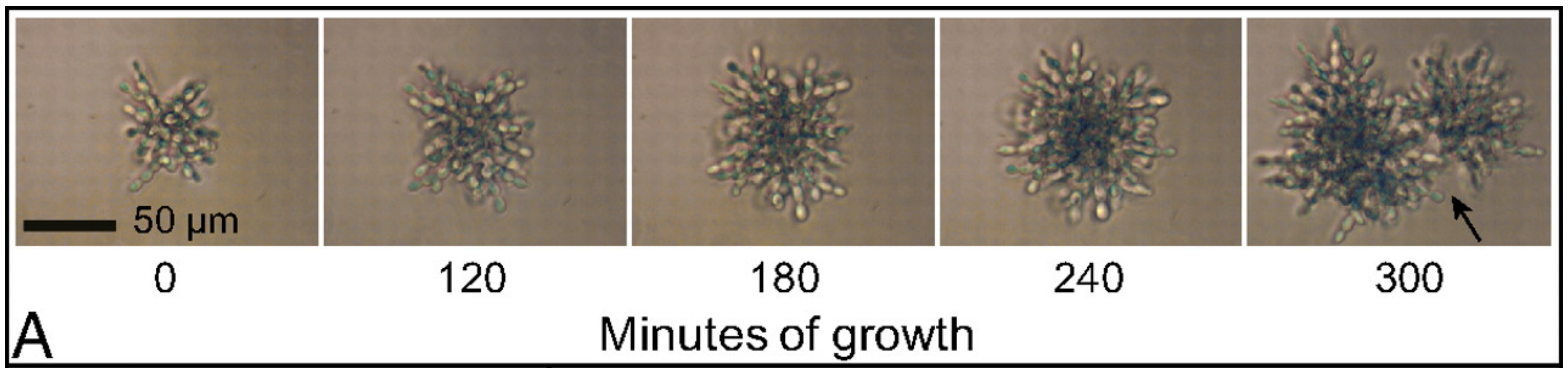
A
starting cells
2 cell types mixed
i
ii
2 layer
iii
iv
v
vi
3 layer
vii
viii
ix
x
xi
xii
symmetric
asymmetric
B
cell-cell signaling
morpho-logical outputs
new cell-cell signaling
spatial reorg.
emergent cell type diversification

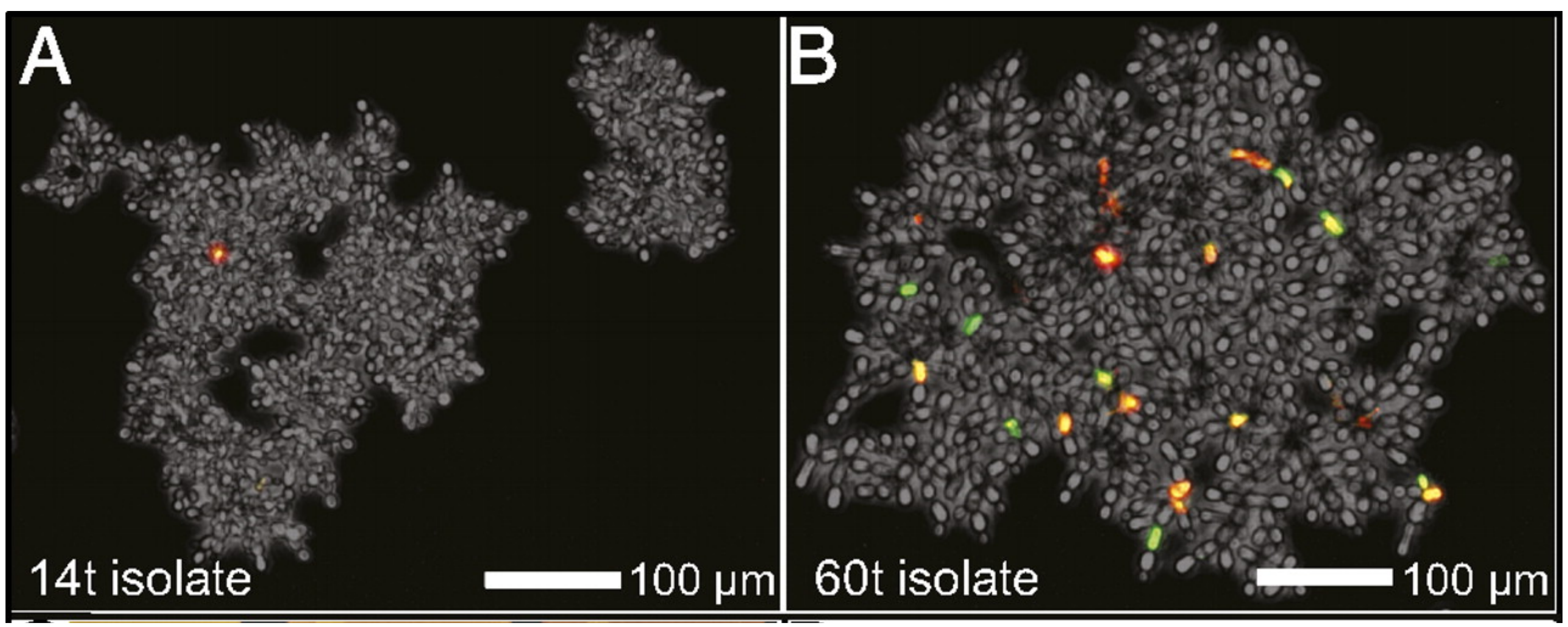
Experimental evolution of multicellularity

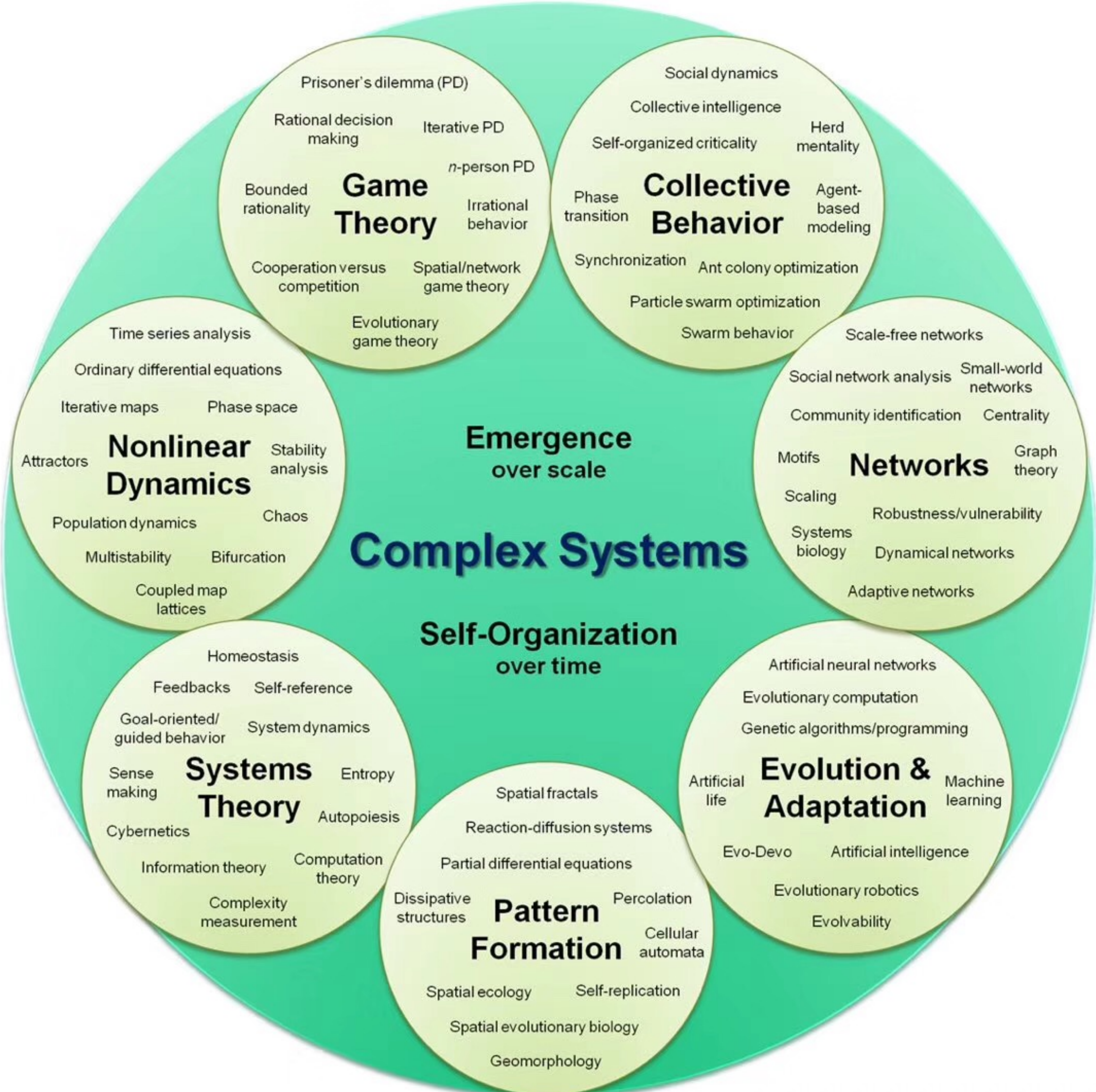
William C. Ratcliff, R. Ford Denison, Mark Borrello, and Michael Travisano

PNAS January 31, 2012 109 (5) 1595-1600; https://doi.org/10.1073/pnas.1115323109

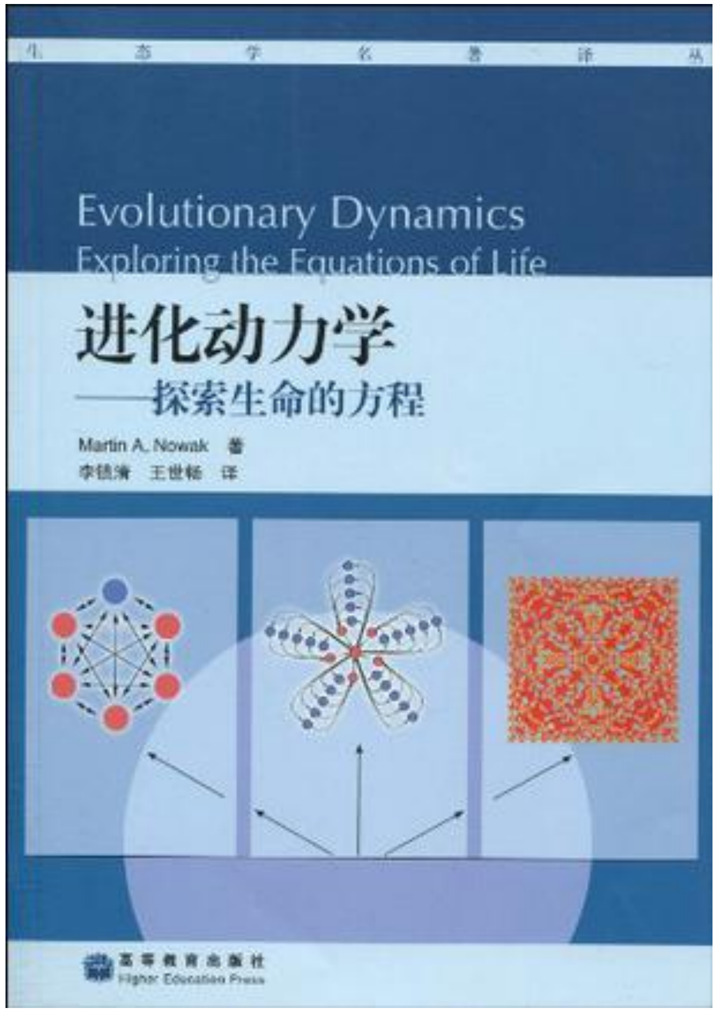








Complex Systems
Emergence over scale
Self-Organization over time
Game Theory
Prisoner's dilemma (PD)
Rational decision making
Iterative PD
n-person PD
Bounded rationality
Irrational behavior
Cooperation versus competition
Spatial/network game theory
Evolutionary game theory
Collective Behavior
Social dynamics
Collective intelligence
Herd mentality
Self-organized criticality
Phase transition
Agent-based modeling
Synchronization
Ant colony optimization
Particle swarm optimization
Swarm behavior
Networks
Scale-free networks
Social network analysis
Small-world networks
Community identification
Centrality
Motifs
Graph theory
Scaling
Robustness/vulnerability
Systems biology
Dynamical networks
Adaptive networks
Nonlinear Dynamics
Time series analysis
Ordinary differential equations
Iterative maps
Phase space
Attractors
Stability analysis
Population dynamics
Chaos
Multistability
Bifurcation
Coupled map lattices
Systems Theory
Homeostasis
Feedbacks
Self-reference
Goal-oriented/ guided behavior
System dynamics
Sense making
Entropy
Autopoiesis
Cybernetics
Information theory
Computation theory
Complexity measurement
Pattern Formation
Spatial fractals
Reaction-diffusion systems
Partial differential equations
Dissipative structures
Percolation
Cellular automata
Spatial ecology
Self-replication
Spatial evolutionary biology
Geomorphology
Evolution & Adaptation
Artificial neural networks
Evolutionary computation
Genetic algorithms/programming
Artificial life
Machine learning
Evo-Devo
Artificial intelligence
Evolutionary robotics
Evolvability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进化动力学
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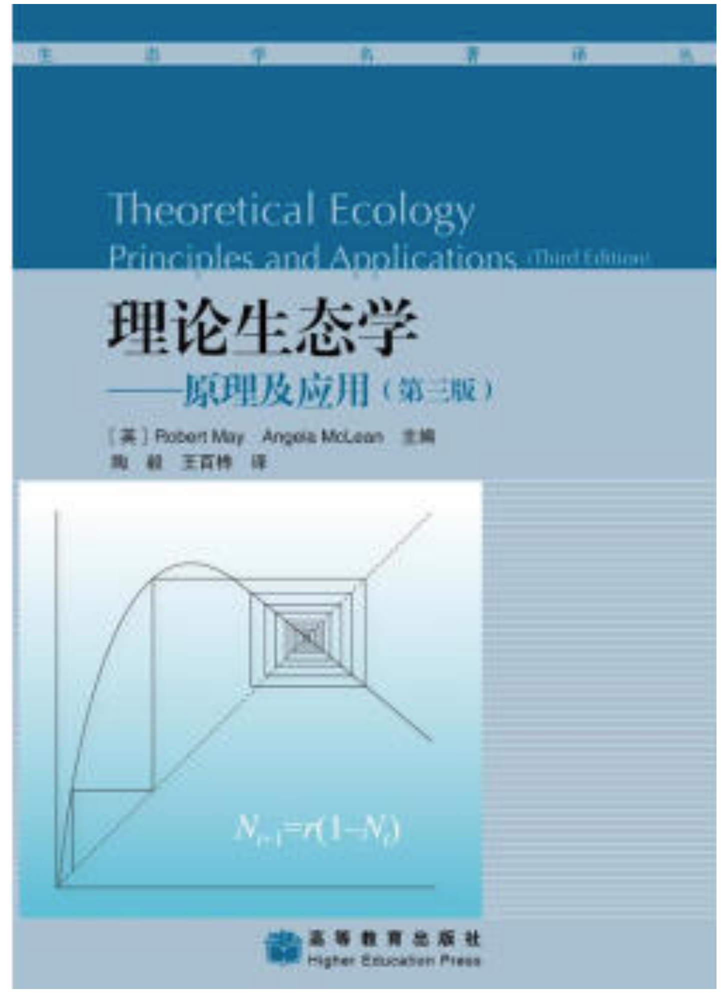
Martin A. Nowak 著
李镇清 王世畅 译
高等教育出版社
Higher Education Press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[英] Robert May Angela McLean 主编
陶毅 王百桦 译
$N_{t+1}=rN_t(1-N_t)$
高等教育出版社
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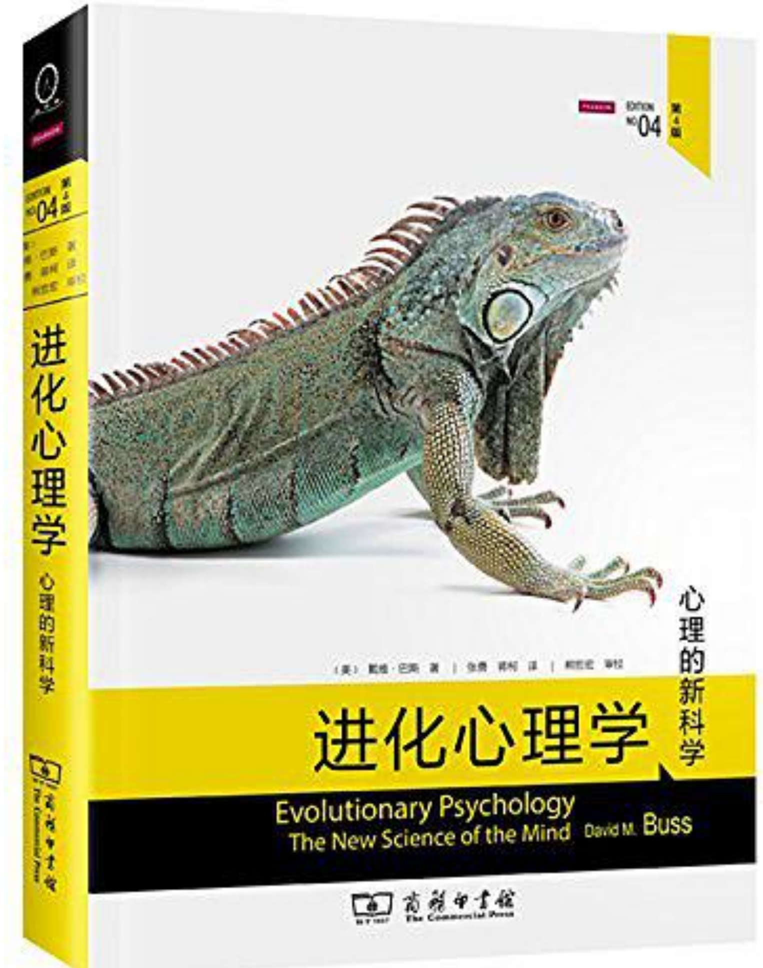
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David M. Buss
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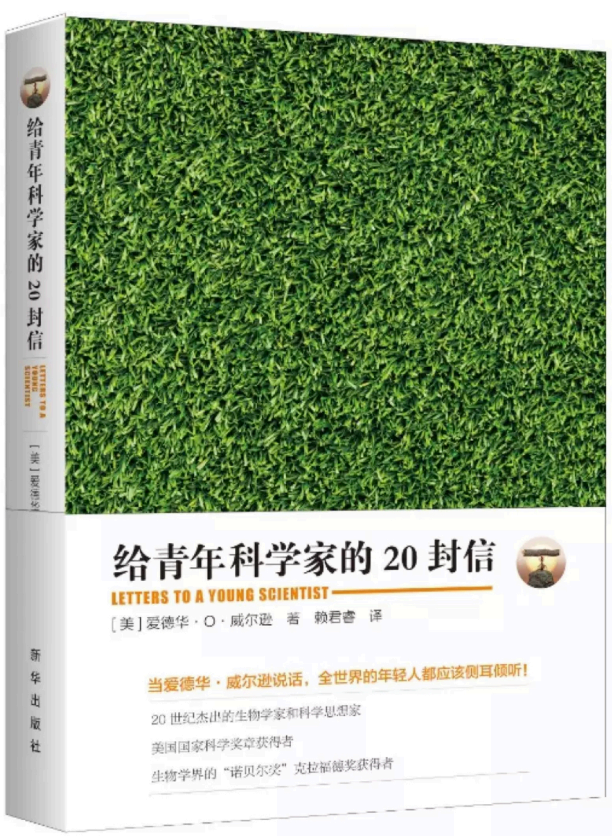
给青年科学家的 20 封信
LETTERS TO A YOUNG SCIENTIST
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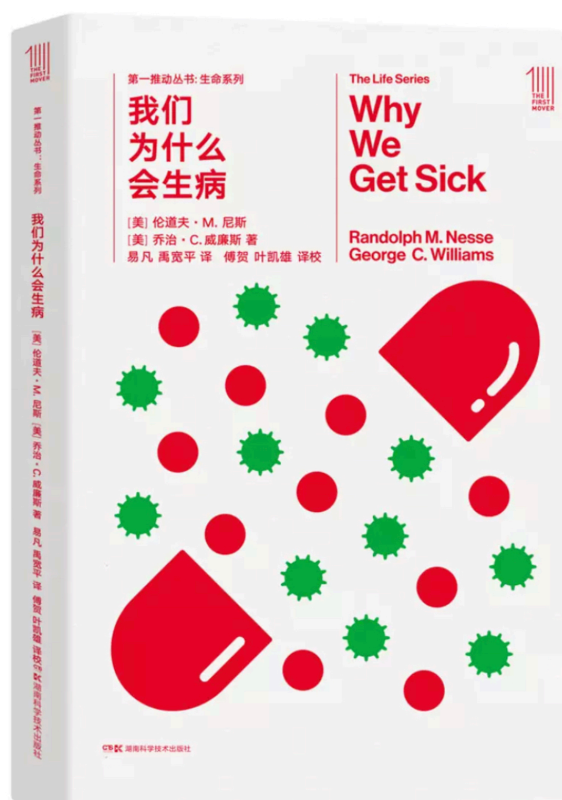
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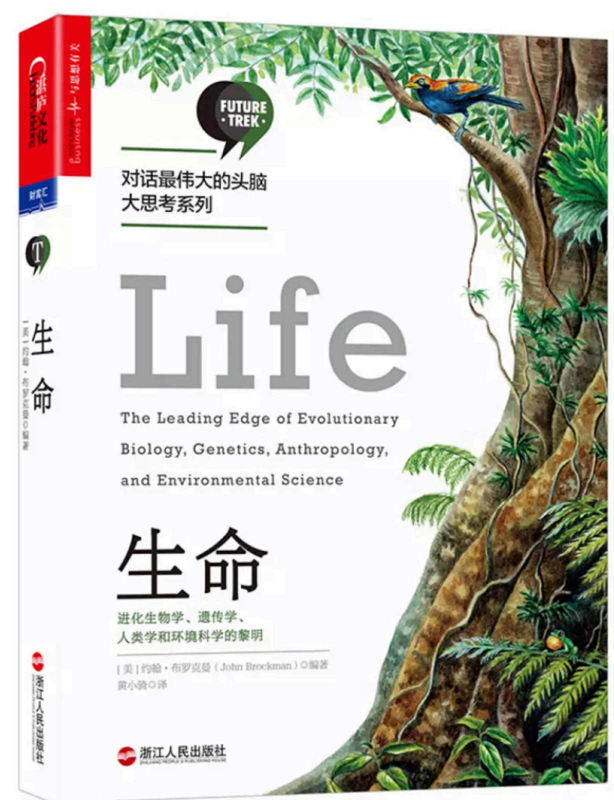
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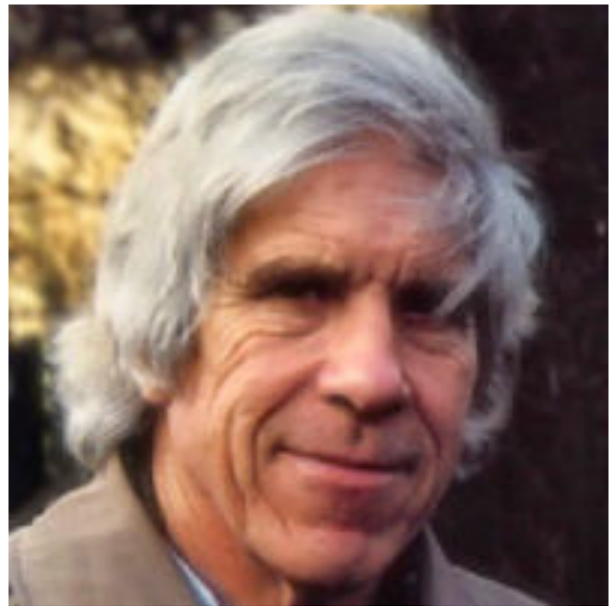
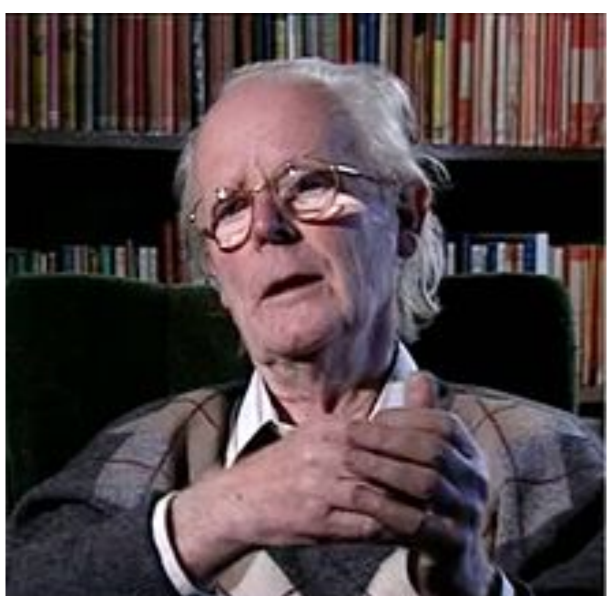
Robert Axelrod
(1943~)



W. D. Hamilton
(1936–2000)

George C. Williams
(1926-2010)

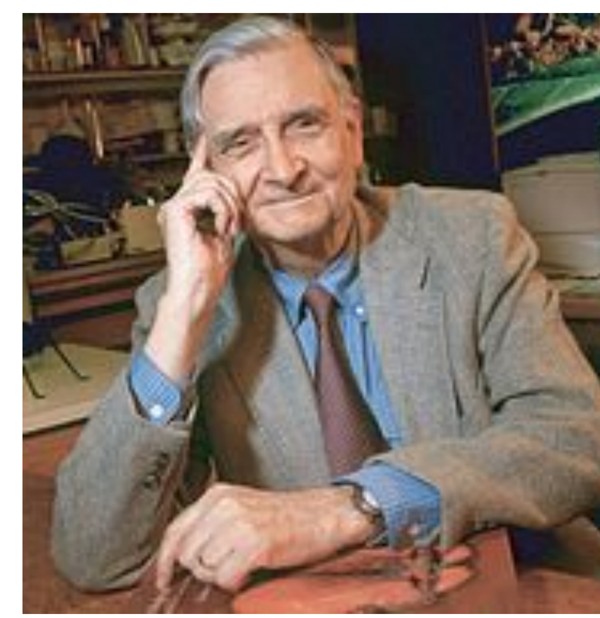
Robert Trivers
(1943~)



J. Maynard Smith
(1920 - 2004)

Karl Sigmund
(1945~)

Martin Nowak
(1965~)



E. O. Wilson
(1929~)