Natural Computation

Transforming Tools of NBIC: Complex Adaptive Systems

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NBIC Convergence 2004

Converging Technologies for Improving Human Performance

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Agenda

- Victims of Success:

  Instrumentation and Computing
- Pattern Discovery
- Intrinsic Computation
- Distributed Emergent Computation in Plants
- Biological Information Processing

Success in Instrumentation: Data Explosion

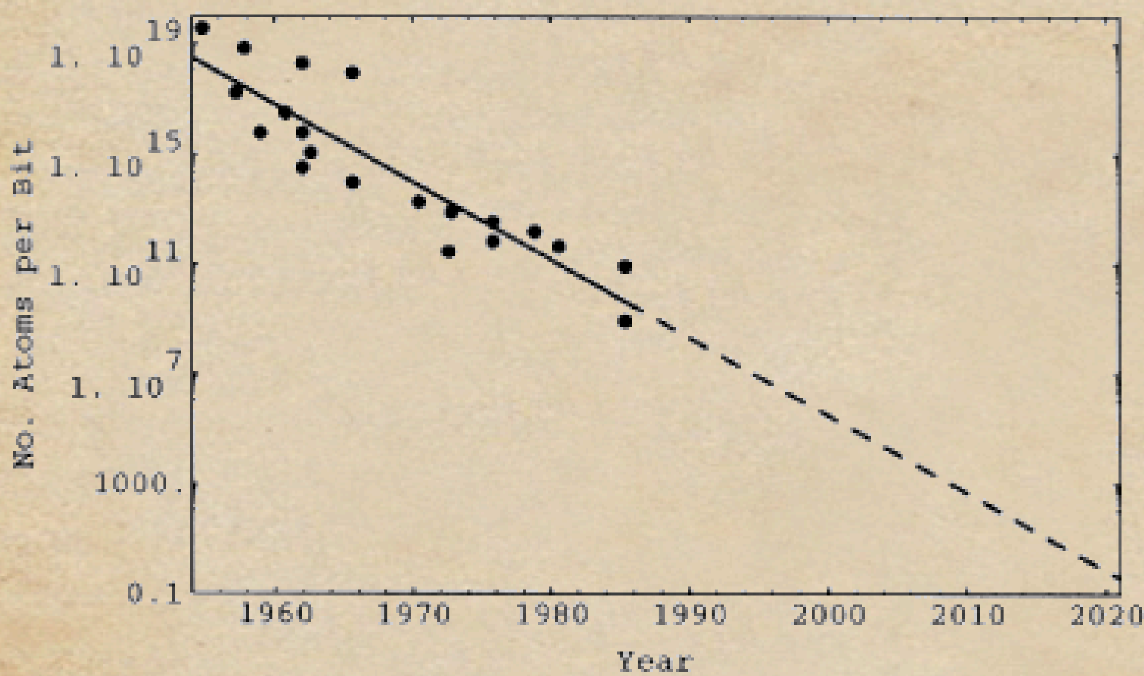
- Neurophysiology: multiple neuron recordings (> 100 neurons @ 1kHz)
- Web Data-Mining: 10-100 GB/day, multi-terabyte databases
- Astrophysical data: Hubble, EUV, Sky Survey, ...
- Neuroimaging: MEG 100-300 Squids (x 16 bits@ 1 kHz)
- Geophysics: Earthquake monitoring with 1000s sensors, of different kinds
- BioInformatics: Genome projects, microarray sequencing, ...
- Searchable Video Databases
- Very large-scale simulations: weather, hydrodynamics, reaction kinetics, ...

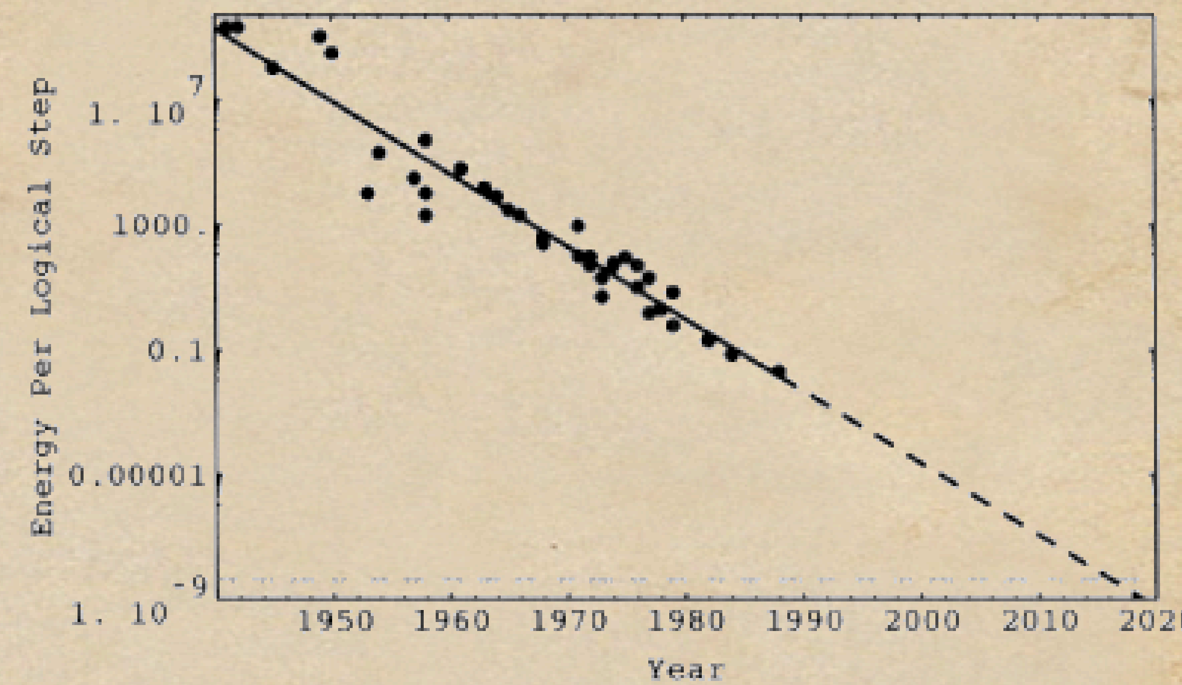
Pattern Discovery

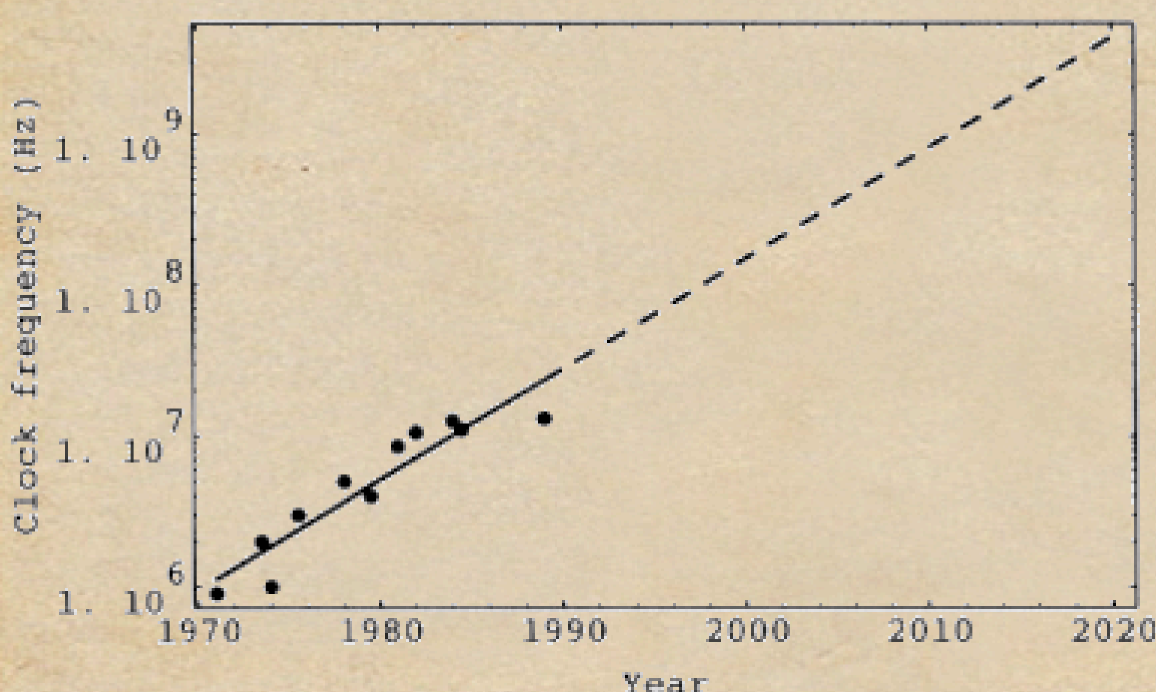
- Machines must help
- Understand “structure”, “pattern”, “regularity”, ...
- Well enough to teach machines
- Beyond Pattern Recognition

J. P. Crutchfield. Is Anything Ever New? Considering Emergence. In *Complexity: Metaphors, Models, and Reality*, G. Cowan, D. Pines, and D. Melzner, editors, *Santa Fe Institute Studies in the Sciences of Complexity* **XIX** Addison-Wesley, Reading, Massachusetts (1994) 479--497.

Success in Computation







Roadblock in 2020:

- 1 bit per atom
- 1 kT per logical operation
- 40 GHz, 4 billion gates, 200 GB RAM
- Dev Cost: 50% of GDP
- Energy: 5% US total power

Keyes 1988, Malone 1995, Hutcheson 1996

Intrinsic Computation

- How much stored historical information?
- How is that information stored?
- How is it processed to produce future behavior?

The Theory of Computational Mechanics:

J. P. Crutchfield and K. Young. Inferring Statistical Complexity. *Physical Review Letters* **63** (1989) 105-108.

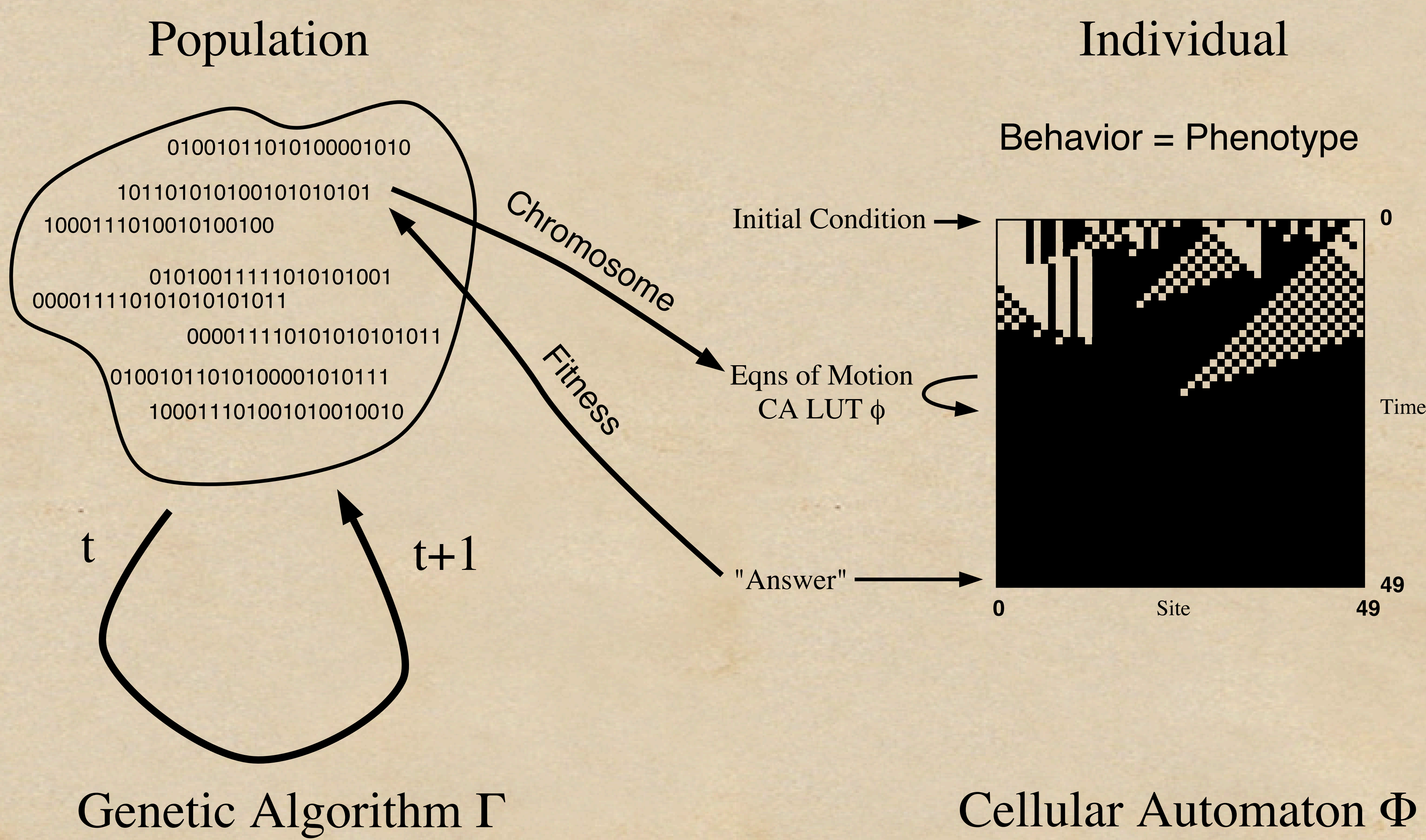
Success into Success?

- Theory of pattern
- Theory of intrinsic computation
- These, it turns out, are the same:

How nature "computes" is how nature is "structured"

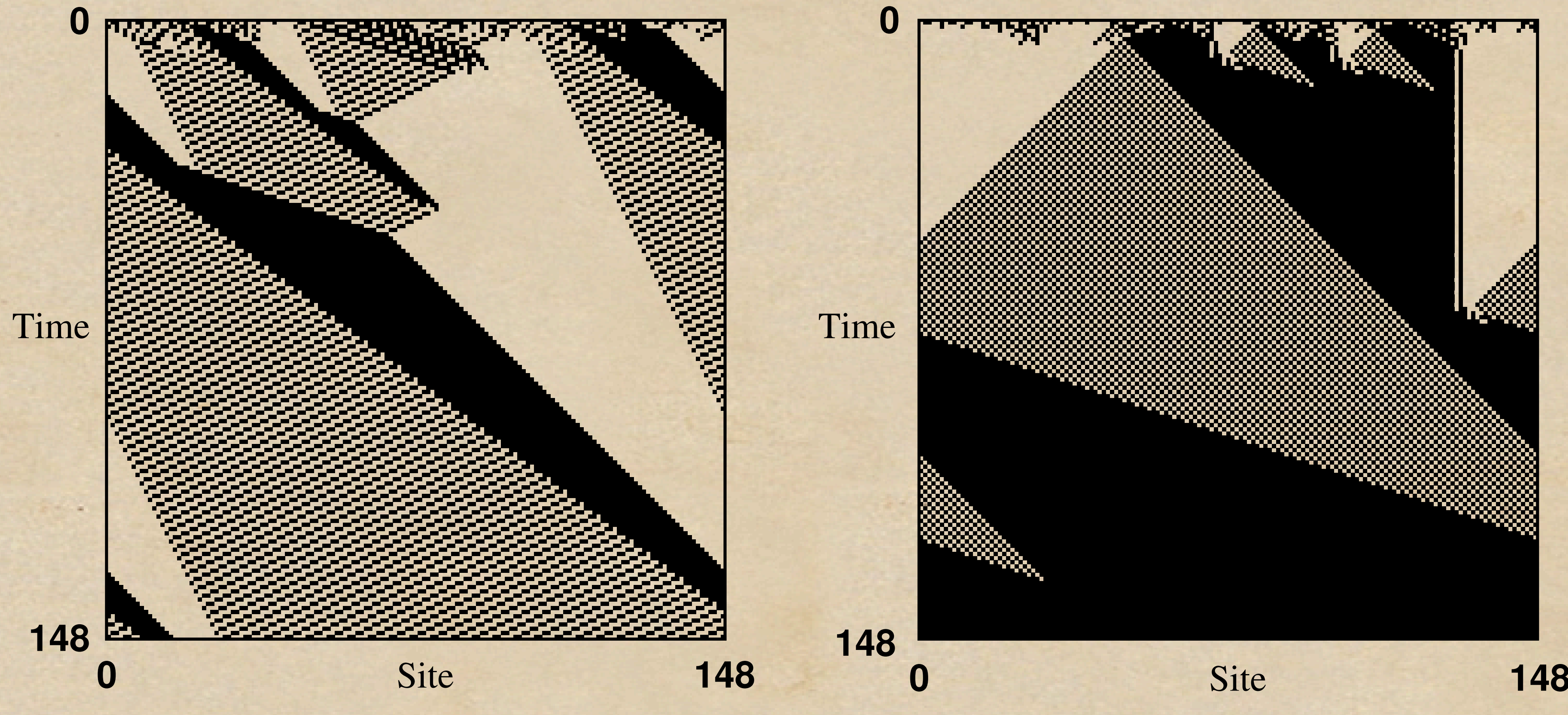
Distributed Emergent Computation

A GA Evolves CAs



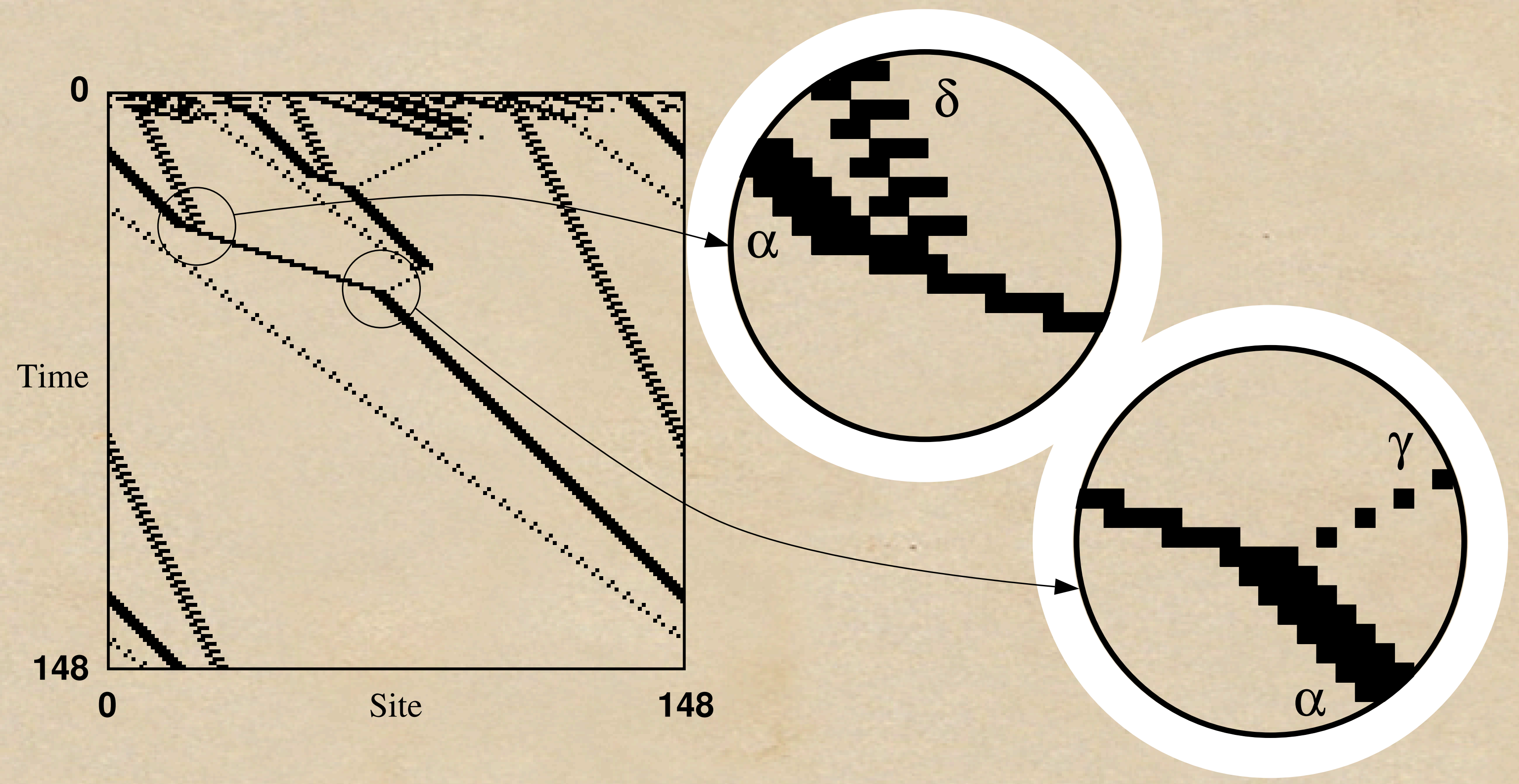
J. P. Crutchfield and M. Mitchell, The Evolution of Emergent Computation, *Proceedings of the National Academy of Sciences USA* **92** (1995) 10742-10746.

Evolutionary Stages

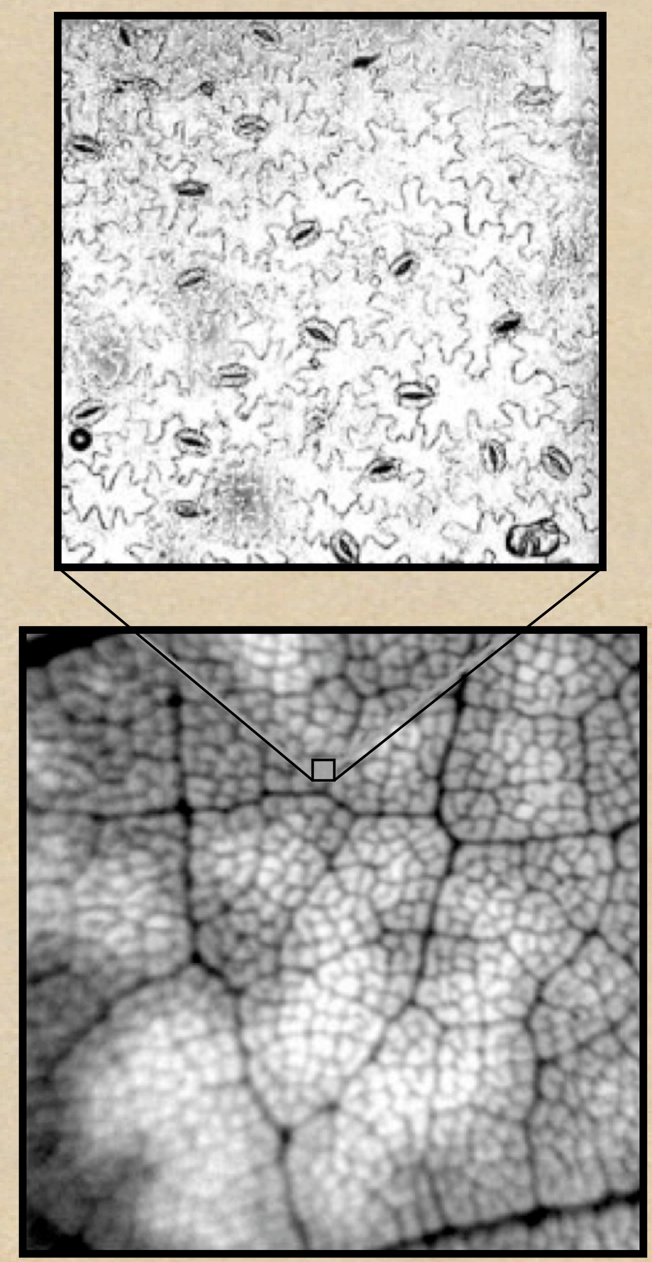


(a) (b)

Particle Analysis



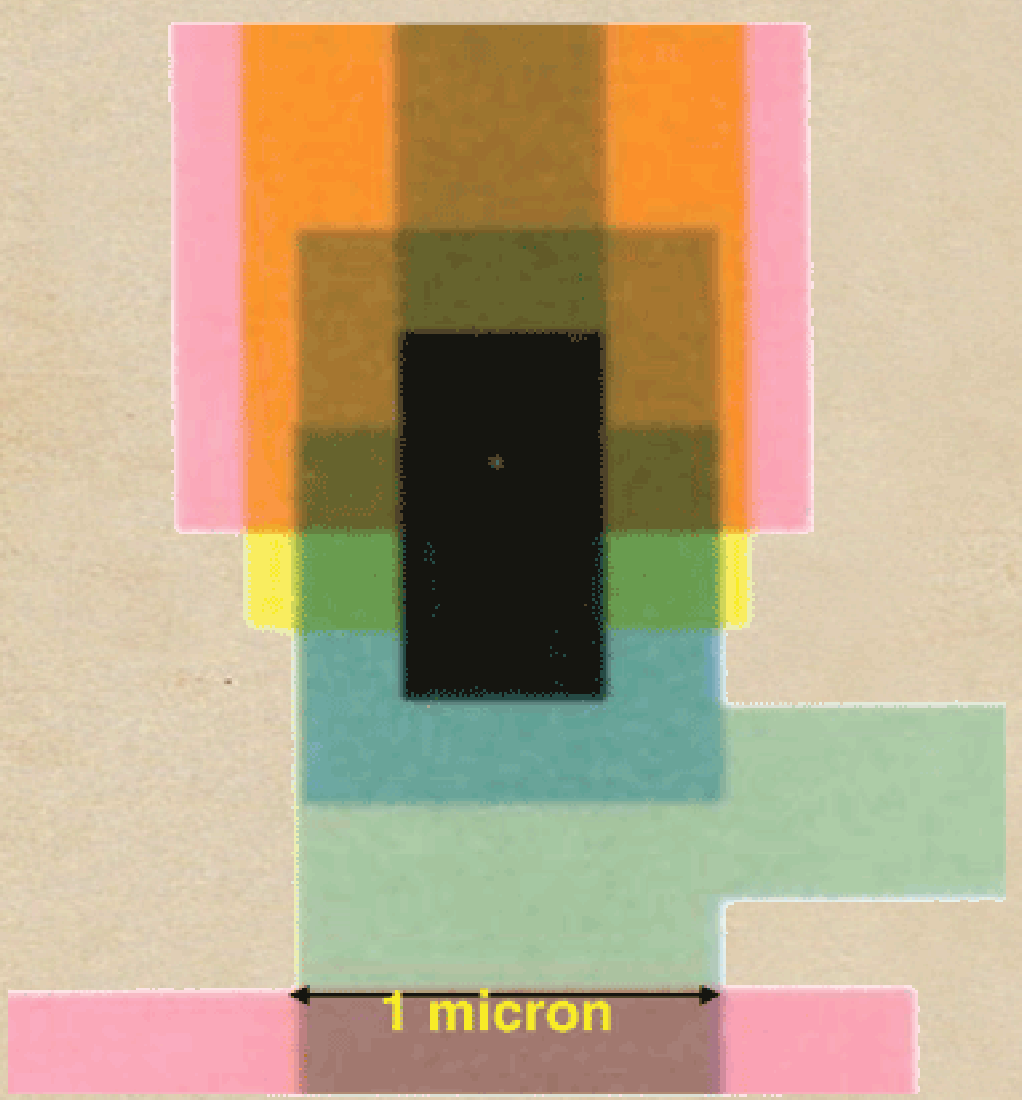
Stomataputers:
Intrinsic Computation in Plant Respiration



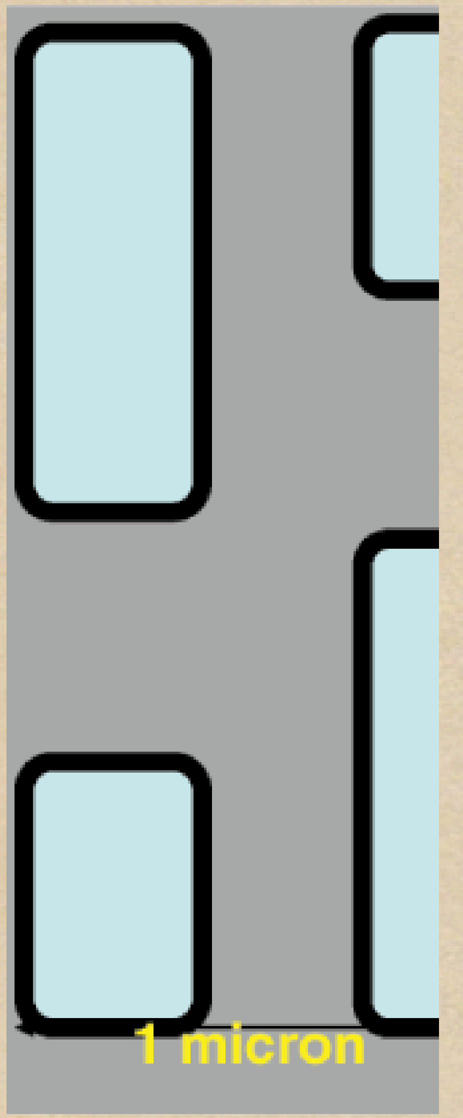
Peak, D. . . . and K. A. Mott. Evidence for complex, collective dynamics and emergent, distributed computation in plants. *Proceedings of the National Academy of Sciences* **101** (2004) 918-922.

Intrinsic Computation in Molecular Biology

Pentium II



DVD



E. Coli

Biological Information Processing

(w/ Walter Fontana & David Krakauer, SFI)

Component turn-over:
- Persistence of identity
- Memory of state via structure & form

Stochasticity (in number and recognition):
- Error-correction

Massive concurrency:
- Emergence of determinism
- Coordination & conflicts

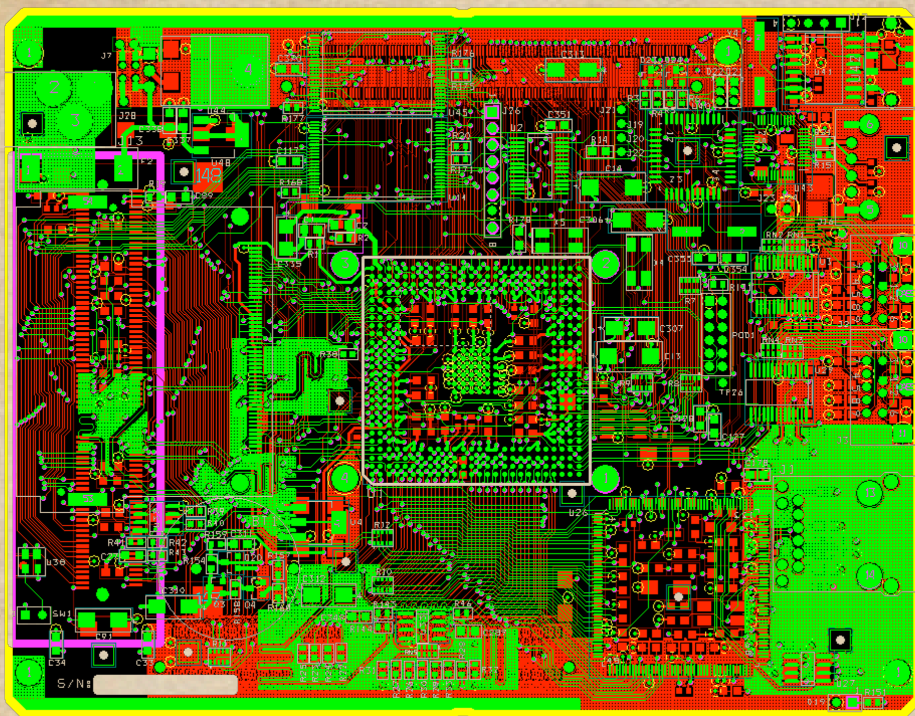
Communication by contact:
- Energy transport
- Control of space

Function:
- Driven by energy, but
- Supported by transformation of stored information

Biological architectures emphasize systemic capacities:

- Plasticity
- Reconfigurability
- Compressibility
- Evolvability (neutrality, modularity)
- Autonomy
- Self
- Robustness

Desirable but absent in today's computer architectures



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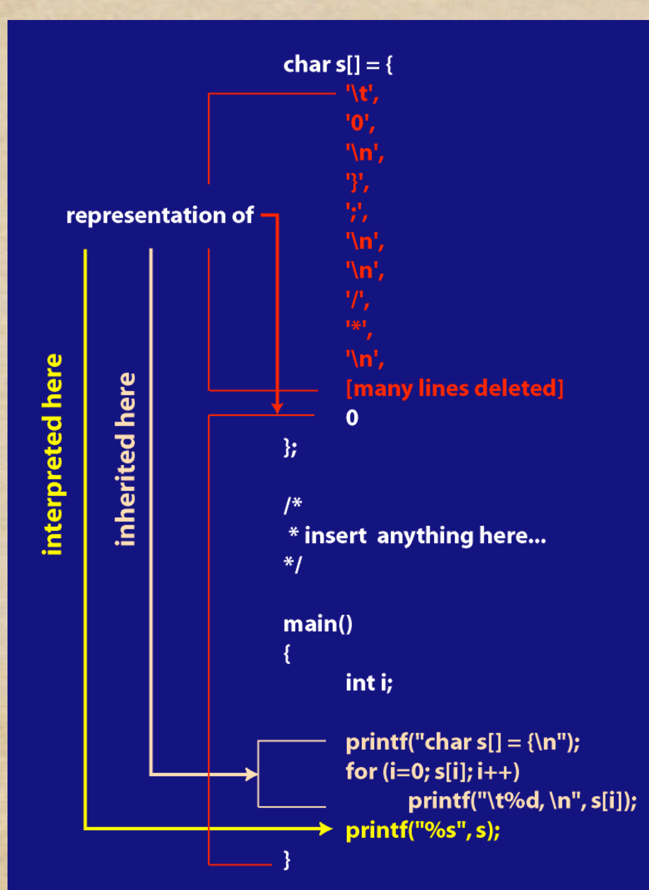

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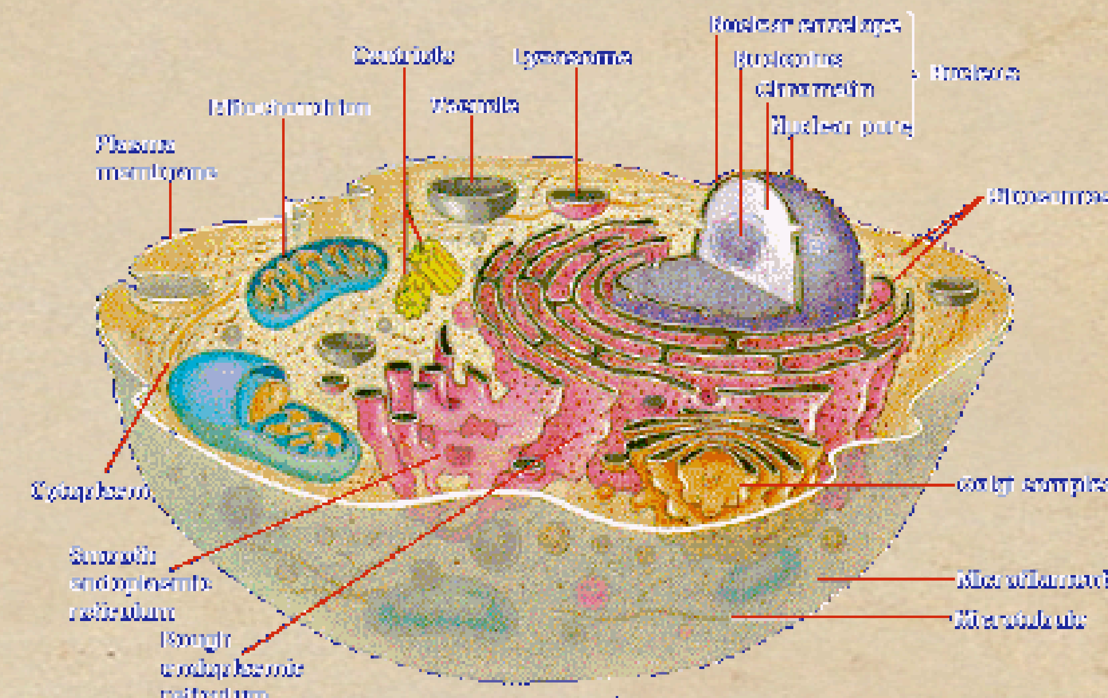

In biological systems there is no software running on hardware.

Novel Forms of Information Processing: Natural Computation

- Tech: Information storage and processing in new substrates, at new scales and speeds (nano/bio)
- Science: New View of how Nature organizes and computes (info/cogno)

Toward a Thermodynamics for the Information Age

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www.santafe.edu/projects/CompMech