

Models and Mechanisms for Artificial Morphogenesis

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Long-Range Challenge

- How can we (re)configure systems that have complex hierarchical structures from microscale to macroscale?
- Examples:
 - reconfigurable robots
 - other computational systems with reconfigurable sensors, actuators, and computational resources
 - brain-scale neurocomputers
 - noncomputational systems and devices that would be infeasible to fabricate or manufacture in other ways
 - systems organized from nanoscale up to macroscale

Embodied Computation

Motivation for Embodied Computing

- Post-Moore's Law computing
- Computation for free
- Noise, defects, errors, indeterminacy
- Massive parallelism
 - E.g. diffusion
 - E.g., cell sorting by differential adhesion
- Exploration vs. exploitation
- Representation for free
- Self-making (the computation creates the computational medium)
- Adaptation and reconfiguration
- Self-repair
- Self-destruction

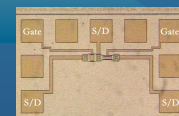
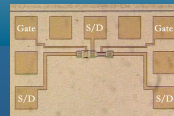
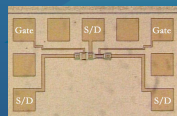
Post-Moore's Law Computation

- The end of Moore's Law is in sight!
- Physical limits to:
 - density of binary logic devices
 - speed of operation
- Requires a new approach to computation
- Significant challenges
- Will broaden & deepen concept of computation in natural & artificial systems

Differences in Spatial Scale

2.71828

0 0 1 0 1 1 1 0 0 1 1 0 0 0 1 0 1 0 0



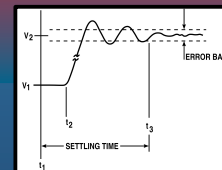
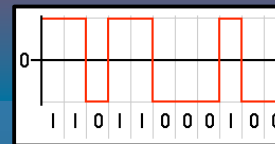
Differences in Time Scale

$$X := Y / Z$$

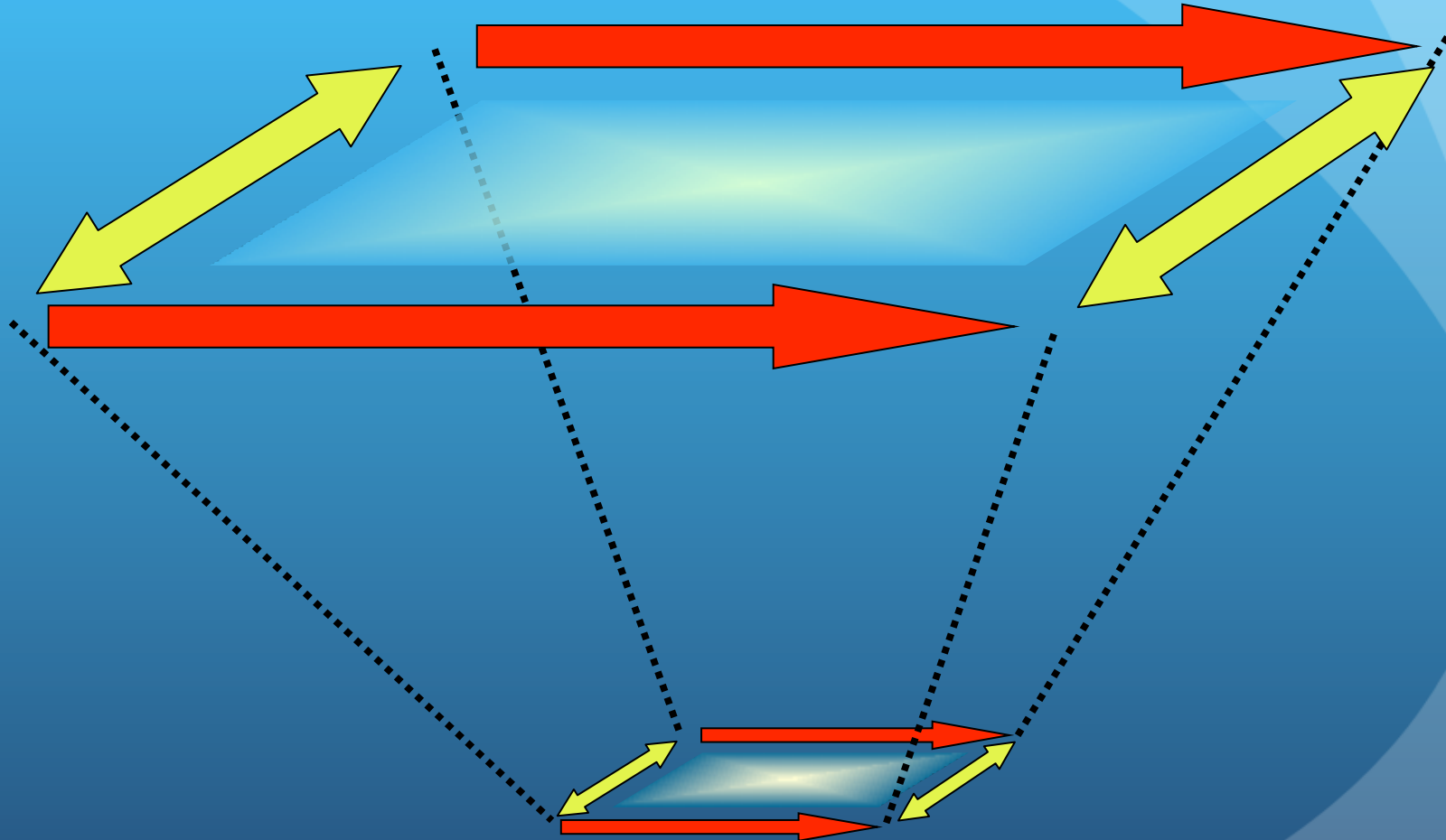
```

P[0] := N
i := 0
while i < n do
  if P[i] >= 0 then
    q[n-(i+1)] := 1
    P[i+1] := 2*P[i] - D
  else
    q[n-(i+1)] := -1
    P[i+1] := 2*P[i] + D
  end if
  i := i + 1
end while

```



Convergence of Scales



Implications of Convergence

- Computation on scale of physical processes
- Fewer levels between computation & realization
- Less time for implementation of operations
- Computation will be more like underlying physical processes
- Post-Moore's Law computing \Rightarrow greater assimilation of computation to physics

Computation is Physical

“Computation is physical; it is necessarily embodied in a device whose behaviour is guided by the laws of physics and cannot be completely captured by a closed mathematical model. This fact of embodiment is becoming ever more apparent as we push the bounds of those physical laws.”

— Susan Stepney (2004)

Cartesian Dualism in Computer Science

- Programs as idealized mathematical objects
- Software treated independently of hardware
- Focus on *formal* rather than *material*
- Post-Moore's Law computing:
 - less idealized
 - more dependent on physical realization
- More difficult
- But also presents opportunities...

Embodied Cognition

- Rooted in pragmatism of James & Dewey
- Dewey's *Principle of Continuity*:
 - no break from most abstract cognitive activities
 - down thru sensory/motor engagement with physical world
 - to foundation in biological & physical processes
- Cognition: emergent pattern of purposeful interactions between organism & environment
- Cf. also Piaget, Gibson, Heidegger, Merleau-Ponty

Embodiment, AI & Robotics

- Dreyfus & al.:
 - embodiment essential to cognition,
 - not incidental to cognition (& info. processing)
- Brooks & al.: increasing understanding of value & exploitation of embodiment in AI & robotics
 - intelligence without representation

Embodiment & Computation

- Embodiment = “the interplay of information and physical processes”
 - Pfeifer, Lungarella & Iida (2007)
- *Embodied computation* = information processing in which physical realization & physical environment play unavoidable & essential role

Embodied Computing

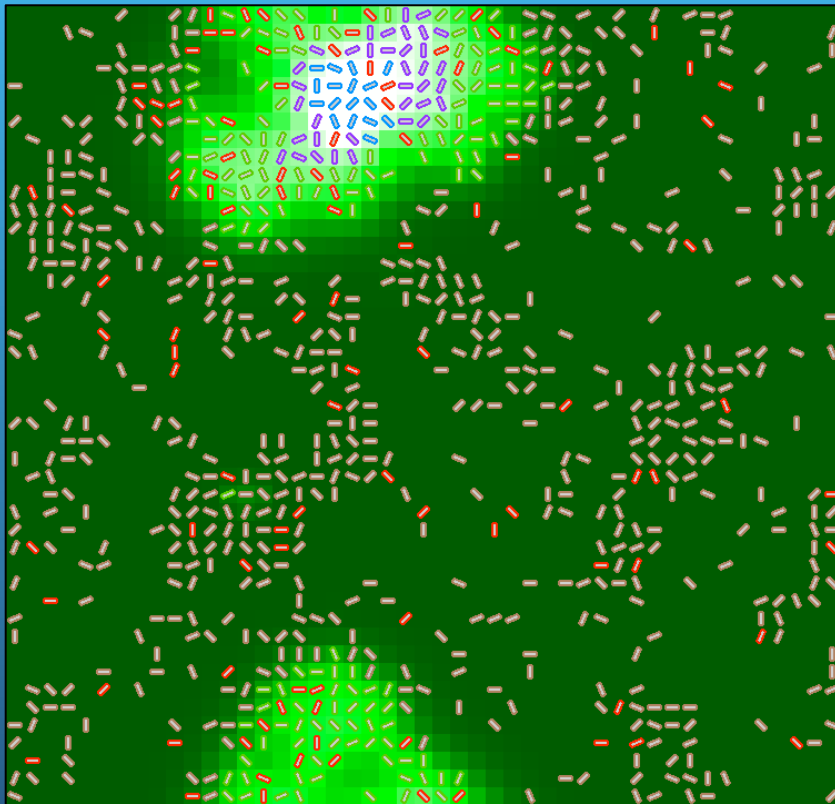
Includes computational processes:

- that directly exploit physical processes for computational ends
- in which information representations and processes are implicit in physics of system and environment
- in which intended effects of computation include growth, assembly, development, transformation, reconfiguration, or disassembly of the physical system embodying the computation

Strengths of Embodied Computation

- Information often implicit in:
 - its physical realization
 - its physical environment
- Many computations performed “for free” by physical substrate
- Representation & info. processing emerge as regularities in dynamics of physical system

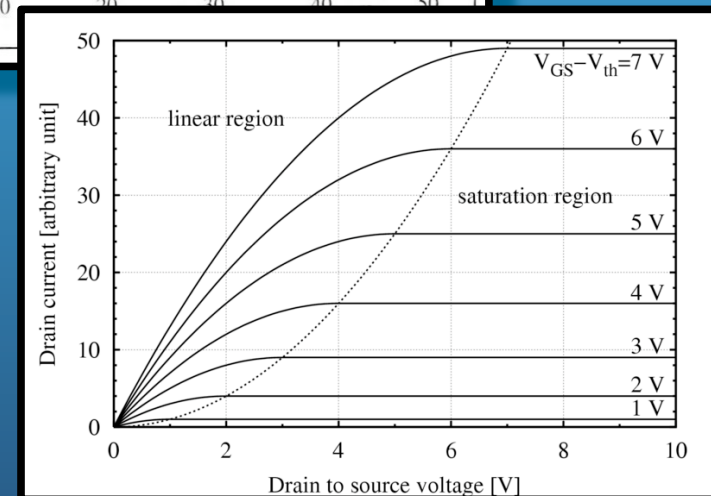
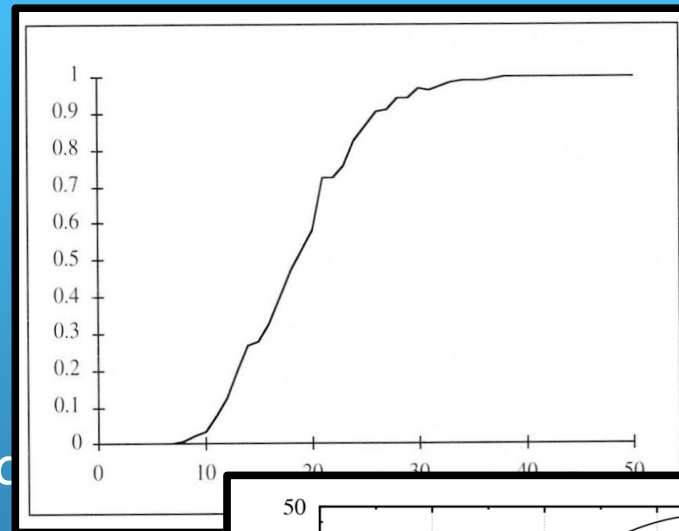
Example: Diffusion



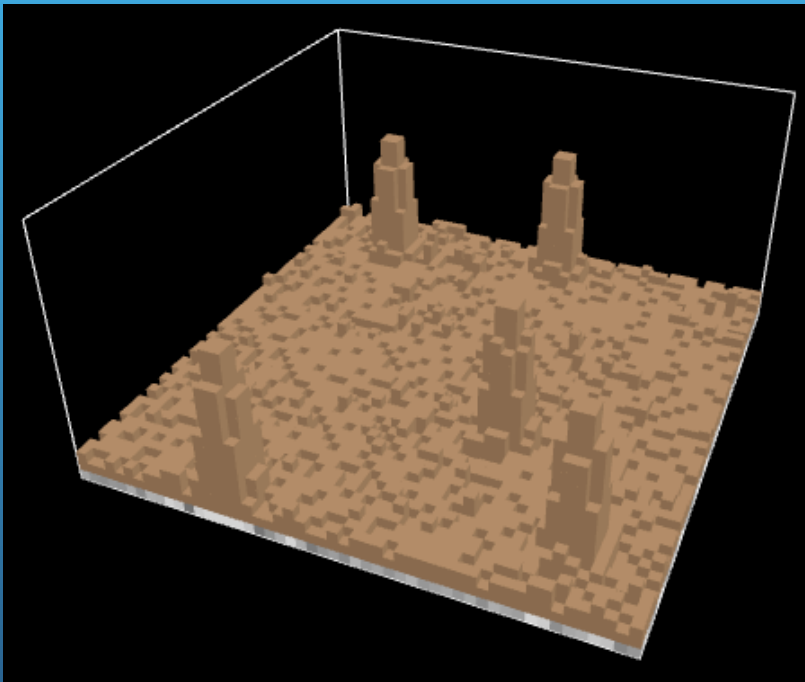
- Occurs naturally in many fluids
- Can be used for many computational tasks
 - broadcasting info.
 - massively parallel search
- Expensive with conventional computation
- Free in many physical systems

Example: Saturation

- Sigmoids in ANNs & universal approx.
- Many physical sys. have sigmoidal behavior
 - Growth process saturates
 - Resources become saturated or depleted
- EC uses free sigmoidal behavior



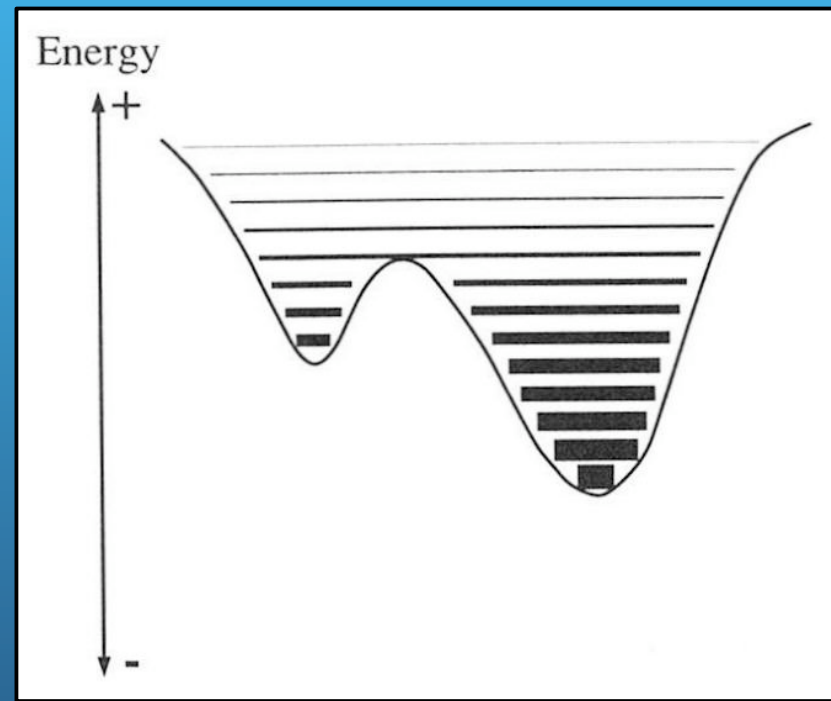
Example: Negative Feedback



- Positive feedback for growth & extension
- Negative feedback for:
 - stabilization
 - delimitation
 - separation
 - creation of structure
- Free from
 - evaporation
 - dispersion
 - degradation

Example: Randomness

- Many algorithms use randomness
 - escape from local optima
 - symmetry breaking
 - deadlock avoidance
 - exploration
- For free from:
 - noise
 - uncertainty
 - imprecision
 - defects
 - faults



Example: Balancing Exploration and Exploitation

- How do we balance
 - the gathering of information (*exploration*)
 - with the use of the information we have already gathered (*exploitation*)
- E.g., ant foraging
- Random wandering leads to exploration
- Positive feedback biases toward exploitation
- Negative feedback biases toward exploration

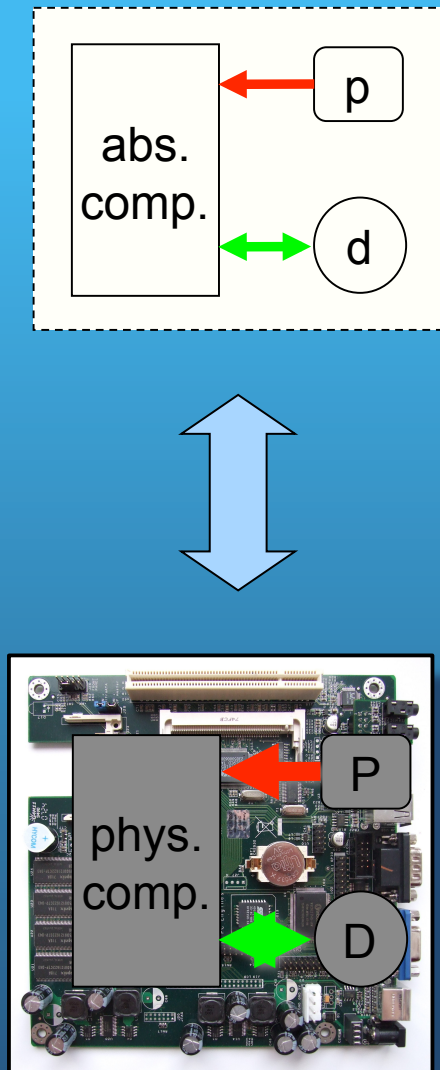
“Respect the Medium”

- Conventional computer technology “tortures the medium” to implement computation
- Embodied computation “respects the medium”
- Goal of embodied computation:

Exploit the physics, don't circumvent it

Computation for Physical Purposes

Embodied Comp. for Action



- EC uses physics for information processing
- Information system governs matter & energy in physical computer
- EC uses information processes to govern physical processes

Embodied Computation for Physical Effect

- Natural EC:
 - governs physical processes in organism's body
 - physical interactions with other organisms & environment
- Often, result of EC is not *information*, but *action*, including:
 - self-action
 - self-transformation
 - self-construction
 - self-repair
 - self-reconfiguration

Disadvantages of Embodied Computation

- Less idealized
- Energy issues
- Lack of commonly accepted and widely applicable models of computation
- But nature provides good examples of how:
 - computation can exploit physics without opposing it
 - information processing systems can interact fruitfully with physical embodiment of selves & other systems

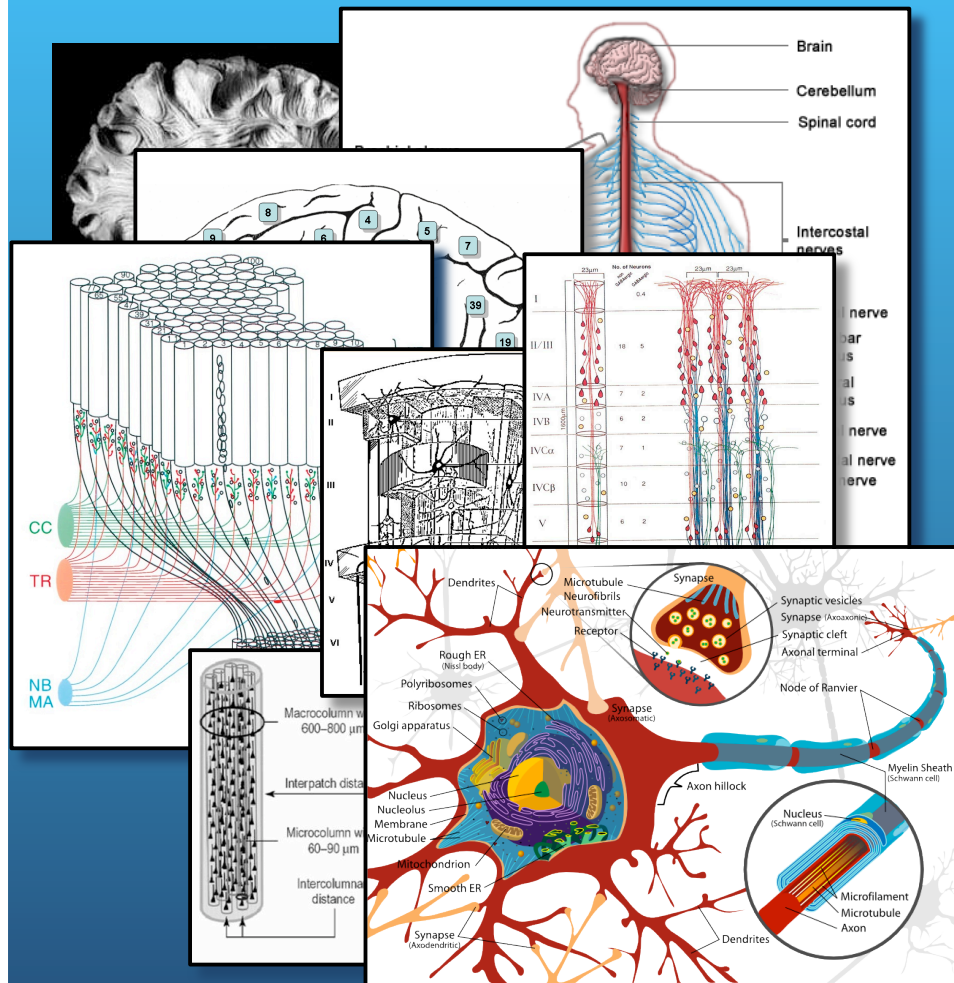
Artificial Morphogenesis

The creation of three-dimensional pattern and form in matter

Motivation for Artificial Morphogenesis

- Nanotechnology challenge: how to organize millions of relatively simple units to self-assemble into complex, hierarchical structures
- It can be done: embryological development
- Morphogenesis: creation of 3D form
- Characteristics:
 - structure implements function – function creates structure
 - no fixed coordinate framework
 - soft matter
 - sequential (overlapping) phases
 - temporal structure creates spatial structure

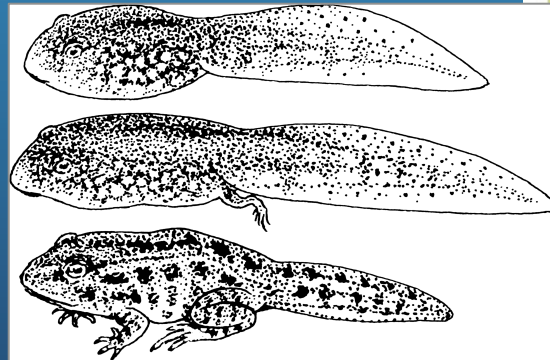
Artificial Morphogenesis



- Morphogenesis can coordinate:
 - proliferation
 - movement
 - disassembly
- to produce complex, hierarchical systems
- Future nanotech.: use AM for multiphase self-organization of complex, functional, active hierarchical systems

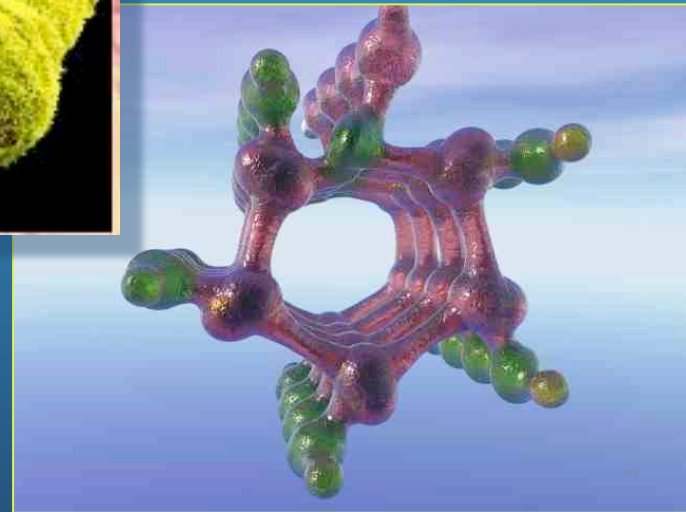
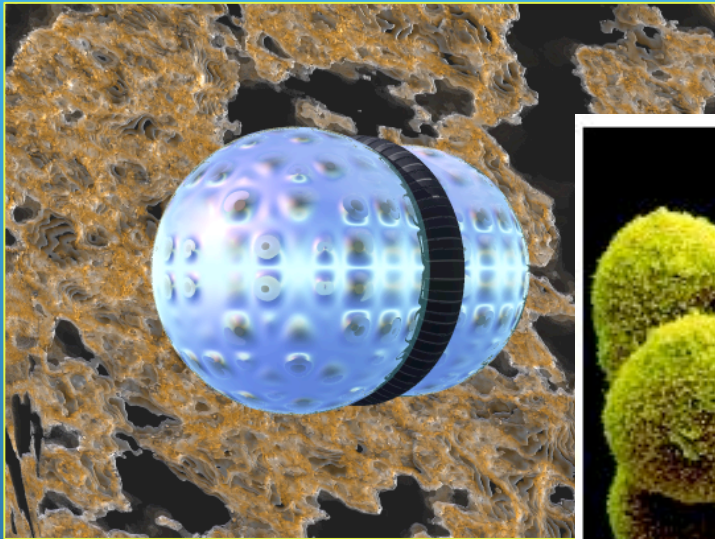
Reconfiguration & Metamorphosis

- Degrees of metamorphosis:
 - incomplete
 - complete
- Phase 1: partial or complete dissolution
- Phase 2: morphogenetic reconfiguration



(Images from Wikipedia)

Microrobots, Cells, and Macromolecules



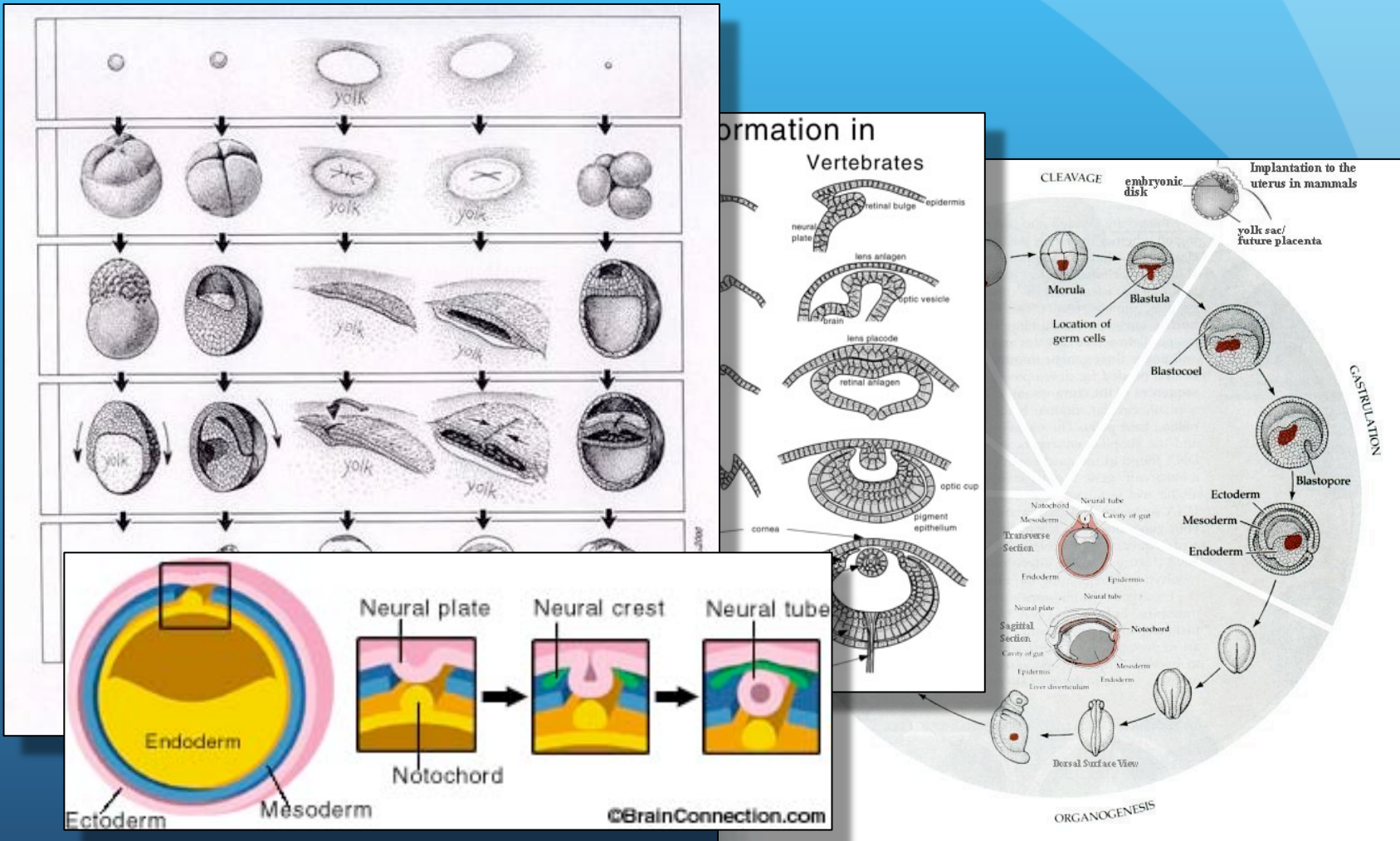
Components

- Both active and passive
- Simple, local sensors (chemical, etc.)
- Simple effectors
 - local action (motion, shape, adhesion)
 - signal production (chemical, etc.)
- Simple regulatory circuits (need not be electrical)
- Self-reproducing or not
- Ambient energy and/or fuel

Metaphors for Morphogenesis

- Donna Haraway: *Crystals, Fabrics, and Fields: Metaphors that Shape Embryos* (1976) – a history of embryology
- The fourth metaphor is soft matter:
 1. crystals
 2. fabrics
 3. fields
 4. soft matter

Self-Organization of Physical Pattern and 3D Form



Fundamental Processes*

- directed mitosis
- differential growth
- apoptosis
- differential adhesion
- condensation
- contraction
- matrix modification
- migration
 - diffusion
 - chemokinesis
 - chemotaxis
 - haptotaxis
- cell-autonomous modification of cell state
 - asymmetric mitosis
 - temporal dynamics
- inductive modif. of state
 - hierarchic
 - emergent

A preliminary model for morphogenesis

as a nature-inspired approach to the configuration and reconfiguration of physical systems

Some Prior Work

- Plant morphogenesis (Prusinkiewicz, 1988-)
- Evolvable Development Model (Dellaert & Beer, 1994)
- Fleischer Model (1995-6)
- CompuCell3D (Cickovski, Izaguirre, et al., 2003-)
- CPL (Cell Programming Language, Agarwal, 1995)
- Morphogenesis as Amorphous Computation (Bhattacharyya, 2006)
- Many specific morphogenetic models
- Field Computation (MacLennan, 1987-)

Goals & Requirements

- Continuous processes
- Complementarity
- Intensive quantities
- Embodies computation in solids, liquids, gases – especially soft matter
- Active and passive elements
- Energetic issues
- Coordinate-independent behavioral description
- Mathematical interpretation
- Operational interpretation
- Influence models
- Multiple space & time scales
- Stochastic

Substances

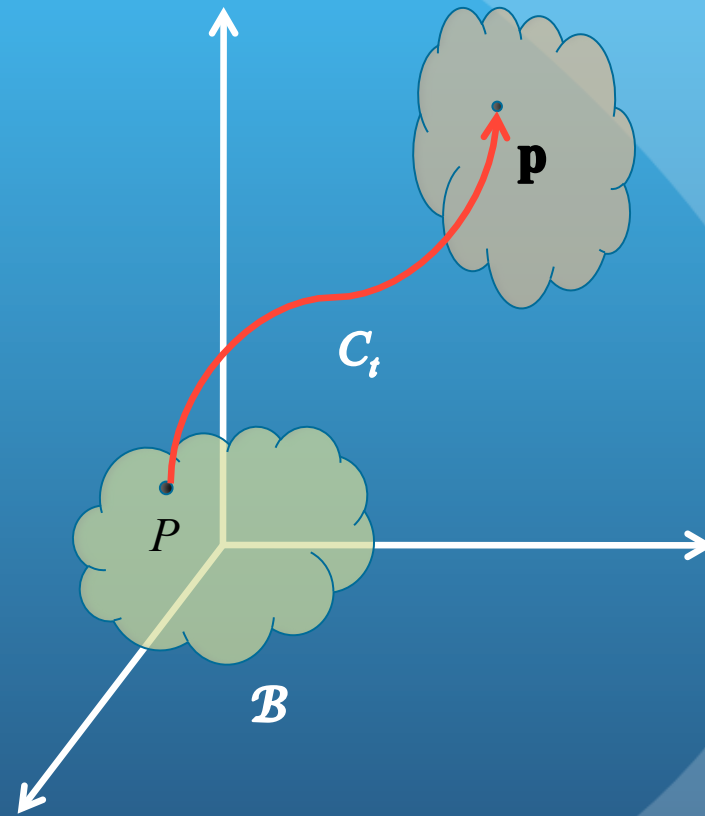
- Complementary
 - physical continua
 - phenomenological continua
- Substance = class of continua with similar properties
- Examples: solid, liquid, gas, incompressible, viscous, elastic, viscoelastic, physical fields, ...
- Multiple realizations as physical substances
- Organized into a class hierarchy
- Similarities and differences to class hierarchies in OOP

Bodies (Tissues)

- Composed of substances
- Deform according to their dynamical laws
- May be able to interpenetrate and interact with other bodies

Mathematical Definition

- A body is a set \mathcal{B} of particles P
- At time t , $\mathbf{p} = C_t(P)$ is position of particle P
- C_t defines the configuration of \mathcal{B} at time t
- Reflects the deformation of the body
- C is a diffeomorphism



Embodied Computation System

- An embodied computation system comprises a finite number of bodies of specified substances
- Each body is prepared in an initial state
 - specify region initially occupied by body
 - specify initial values of variables
 - should be physically feasible
- System proceeds to compute, according to its dynamical laws in interaction with its environment

Elements

(Particles or material points)

Material vs. Spatial Description

- *Material (Lagrangian) vs. spatial (Eulerian) reference frame*
- Physical property Q considered a function $Q(P, t)$ of fixed particle P as it moves through space
- rather than a function $q(\mathbf{p}, t)$ of fixed location \mathbf{p} through which particles move
- Reference frames are related by configuration function $\mathbf{p} = C_t(P)$
- Example: velocity

Intensive vs. Extensive Quantities

- Want independence from size of elements
- Use intensive quantities so far as possible
- Examples:
 - mass density vs. mass
 - number density vs. particle number
- Continuum mechanics vs. statistical mechanics
- Issue: small sample effects

Mass Quantities

- Elements may correspond to masses of elementary units with diverse property values
- Examples: orientation, shape
- Sometimes can treat as an average vector or tensor
- Sometimes better to treat as a random variable with associated probability distribution

Free Extensive Variables

- When extensive quantities are unavoidable
- May make use of several built in free extensive variables
 - $\delta V, \delta A, \delta L$
 - perhaps free scale factors to account for element shape
- Experimental feature

Behavior

Particle-Oriented Description

- Often convenient to think of behavior from particle's perspective
- Coordinate-independent quantities: vectors and higher-order tensors
- Mass quantities as random variables

Material Derivatives

- For particle-oriented description: take time derivatives with respect to fixed particle as opposed to fixed location in space

$$D_t X = \partial X / \partial t |_{P \text{ fixed}} \quad \text{vs.} \quad \dot{X} = \partial X / \partial t |_{\mathbf{p} \text{ fixed}}$$

- Conversion:

$$D_t X = \dot{X} + \mathbf{v} \cdot \nabla X$$

- All derivatives are assumed to be relative to their body

Change Equations

- Want to maintain complementarity between discrete and continuous descriptions:

$$D_t X = F(X, Y)$$

$$\Delta_t X = F(X, Y)$$

$$\text{where } \Delta_t X = \frac{\Delta X(t)}{\Delta t} = \frac{X(t + \Delta t) - X(t)}{\Delta t}$$

- Neutral “change equation”:

$$\mathfrak{D}X = F(X, Y)$$

Qualitative “Regulations”

- Influence models indicate how one quantity enhances or represses increase of another

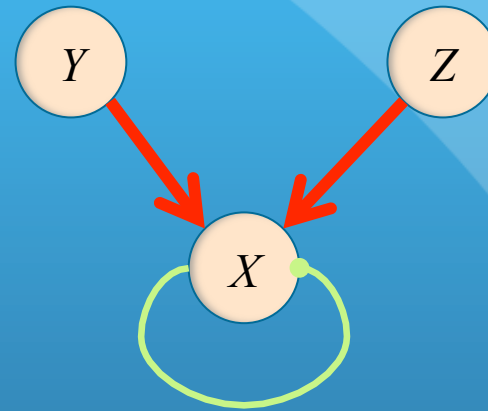
- We write as “regulations”:

$$\exists X \sim -X, Y, Z$$

- Meaning: $\exists X = F(-X, Y, Z)$

where F is monotonically non-decreasing

- Relative magnitudes: $\exists X \sim Y, Z; -X$



Stochastic Change Equations

- Indeterminacy is unavoidable
- W_t is Wiener process
- Complementarity dictates Itô interpretation

$$X_t = \int_0^t H_s dW_s$$

$$dX_t = H_t dW_t$$

$$\Delta X_t = H_t \Delta W_t$$

$$\mathfrak{D}X_t = H_t \mathfrak{D}W_t$$

$$\Delta_t X_t = H_t \Delta_t W_t$$

$$\mathfrak{D}_t X_t = H_t \mathfrak{D}_t W_t$$

Interpretation of Wiener Derivative

- Wiener process is nowhere differentiable
- May be interpreted as random variable
- Multidimensional Wiener processes considered as primitives

$$\begin{aligned}\Delta W_t &= W_{t+\Delta t} - W_t \\ &\sim \mathcal{N}(0, \Delta t)\end{aligned}$$

$$\begin{aligned}\Delta_t W_t &= \Delta W_t / \Delta t \\ &\sim \mathcal{N}(0, 1)\end{aligned}$$

$$\mathbb{D}W_t \sim \mathcal{N}(0, 1)$$

Examples

Simple Diffusion

substance morphogen:

scalar field ϕ	concentration
vector fields:	
\mathbf{j}	flux
$\boldsymbol{\mu}$	drift vector
order-2 field $\boldsymbol{\sigma}$	diffusion tensor

behavior:

$$\begin{aligned}\mathbf{j} &= \boldsymbol{\mu}\phi - \nabla \cdot (\boldsymbol{\sigma}\boldsymbol{\sigma}^T \phi)/2 && \text{|| flux} \\ \mathfrak{D}\phi &= -\nabla \cdot \mathbf{j} && \text{|| change in conc.}\end{aligned}$$

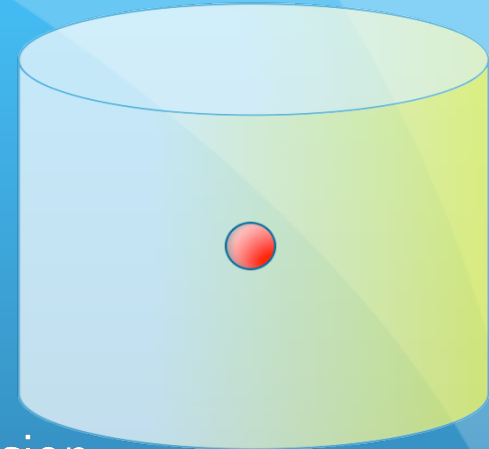
A Simple Diffusion System

body Concentration of morphogen:
for $X^2 + Y^2 \leq 1$ and $-1 \leq Z \leq 1$:

$$\mathbf{j} = 0 \quad || \text{initial 0 flux}$$

$$\boldsymbol{\mu} = 0 \quad || \text{drift vector}$$

$$\boldsymbol{\sigma} = 0.1\mathbf{I} \quad || \text{isotropic diffusion}$$



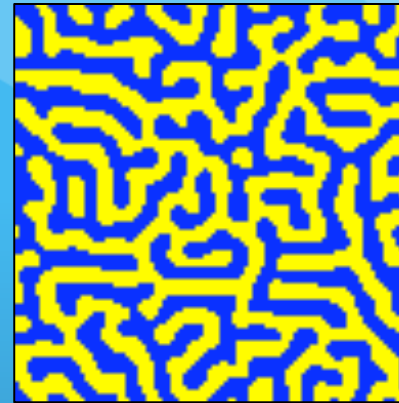
for $X^2 + Y^2 + Z^2 \leq 0.1$:

$$\phi = 100 \quad || \text{initial density inside sphere}$$

for $X^2 + Y^2 + Z^2 > 0.1$:

$$\phi = 0 \quad || \text{zero density outside sphere}$$

Activator-Inhibitor System



substance activator-inhibitor:

scalar fields:

A || activator concentration
 I || inhibitor concentration

order-2 fields:

σ_A || activator diffusion tensor
 σ_I || inhibitor diffusion tensor

behavior:

$$\begin{aligned}\mathbb{D}A &= f_A(A, I) + \Delta(\sigma_A \sigma_A^T A) \\ \mathbb{D}I &= f_I(A, I) + \Delta(\sigma_I \sigma_I^T I)\end{aligned}$$

Activator-Inhibitor System as Regulations

substance activator-inhibitor:

scalar fields:

A || activator concentration

I || inhibitor concentration

order-2 fields:

σ_A || activator diffusion tensor

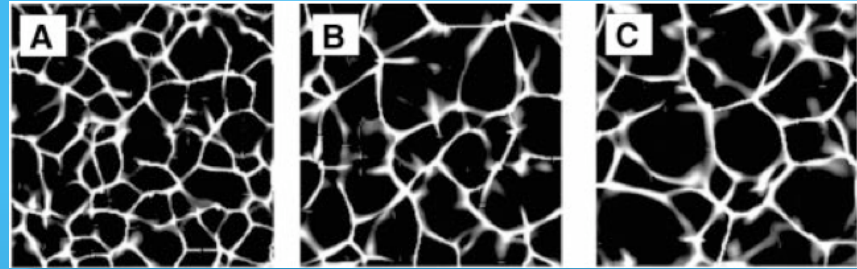
σ_I || inhibitor diffusion tensor

behavior:

$$\mathbb{D}A \sim A, -I, \Delta(\sigma_A \sigma_A^T A)$$

$$\mathbb{D}I \sim A, -I, \Delta(\sigma_I \sigma_I^T I)$$

Vasculogenesis* (Morphogen)



substance morphogen is medium with:

scalar fields:

C

|| concentration

S

|| source

order-2 field \mathbf{D}

|| diffusion tensor

scalar τ

|| degradation time constant

behavior:

$$\mathbb{D}C = \Delta(\mathbf{D}C) + S - C/\tau \quad || \text{diffusion} + \text{release} - \text{degradation}$$

* from Ambrosi, Bussolino, Gamba, Serini & al.

Vasculogenesis (Cell Mass)

substance cell-mass is morphogen with:

scalar fields:

n

|| number density of cell mass

ϕ

|| cell compression force

vector field \mathbf{v}

|| cell velocity

scalars:

n_0

|| maximum cell density

α

|| rate of morphogenesis release

β

|| strength of morphogen attraction

order-2 field γ

|| dissipative interaction

behavior: ...

Vasculogenesis (Cell-Mass Behavior)

behavior:

$$S = \alpha n \quad \parallel \text{production of morphogen}$$

\parallel follow morphogen gradient, subject to drag and compression:

$$\mathfrak{D}\mathbf{v} = \beta \nabla C - \gamma \cdot \mathbf{v} - n^{-1} \nabla \phi$$

\parallel change of density in material frame:

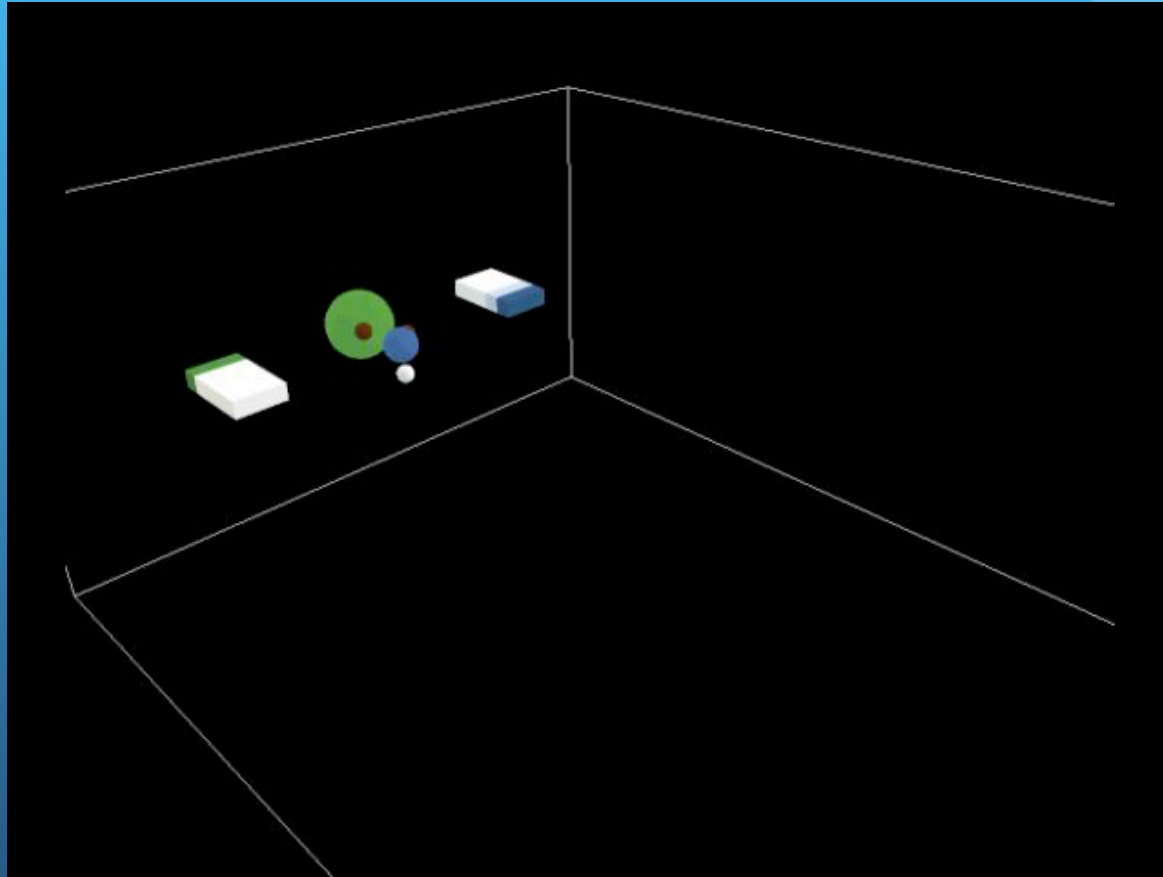
$$\mathfrak{D}n = -\nabla \cdot (n \cdot \mathbf{v}) + \mathbf{v} \cdot \nabla n$$

$$\phi = [(n - n_0)^+]^3 \quad \parallel \text{arbitrary penalty function}$$

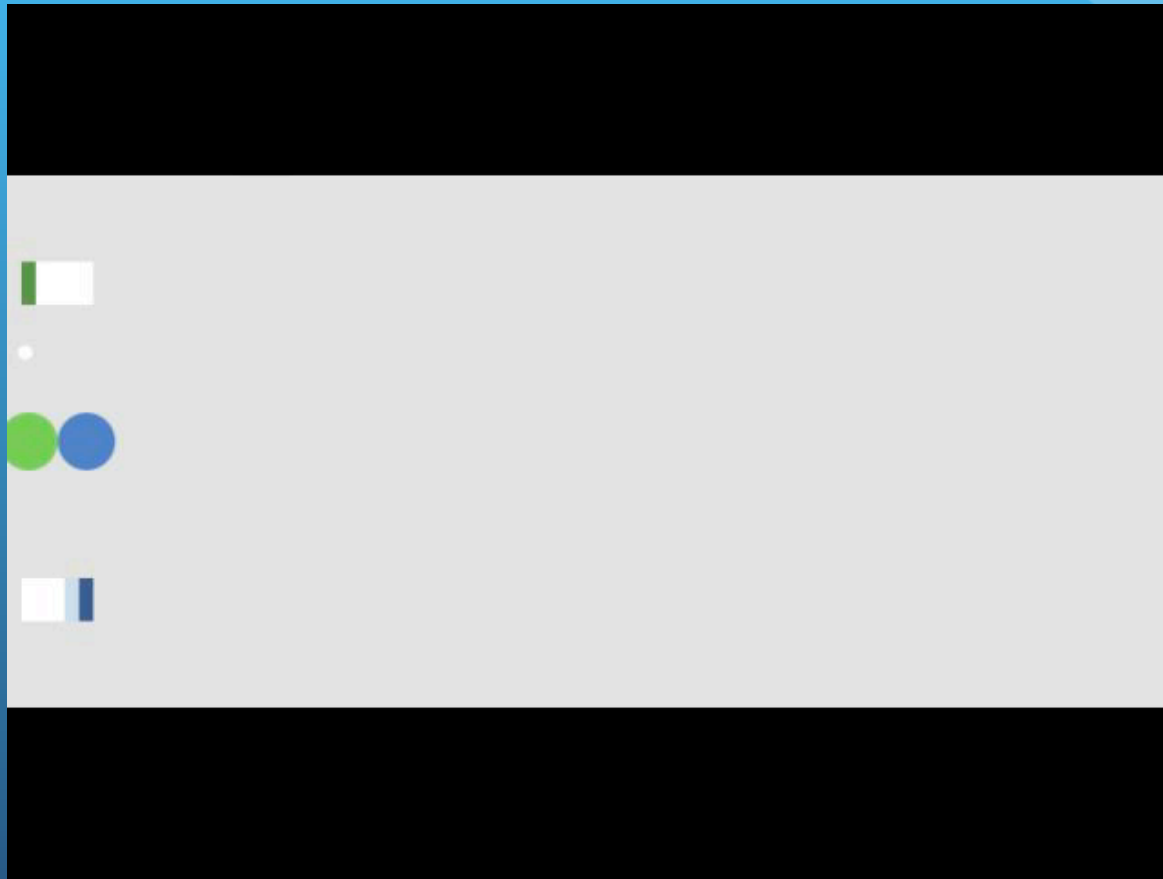
Clock-and-Wavefront Model of Segmentation

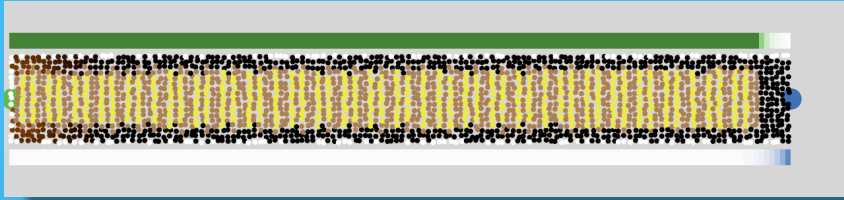
- Vertebrae: humans have 33, chickens 35, mice 65, corn snake 315 – characteristic of species
- How does developing embryo count them?
- Somites also govern development of organs
- Clock-and-wavefront model of Cooke & Zeeman (1976), recently confirmed (2008)
- Depends on clock, excitable medium (cell-to-cell signaling), and diffusion

Simulated Segmentation by Clock-and-Wavefront Process



2D Simulation of Clock-and-Wavefront Process

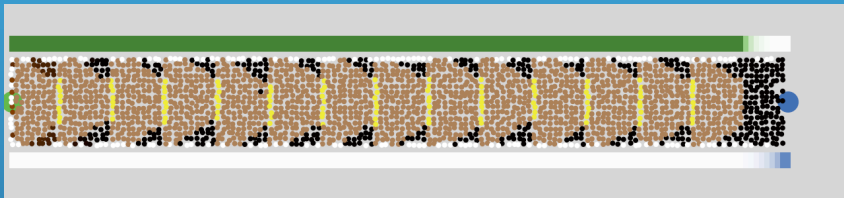




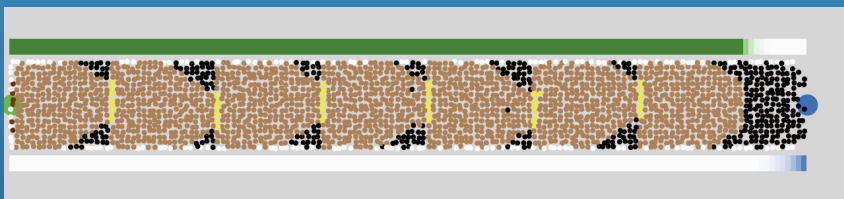
500



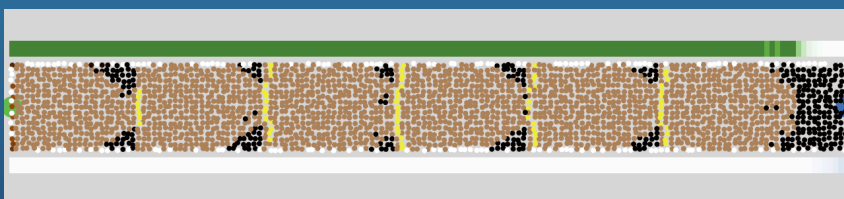
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2000



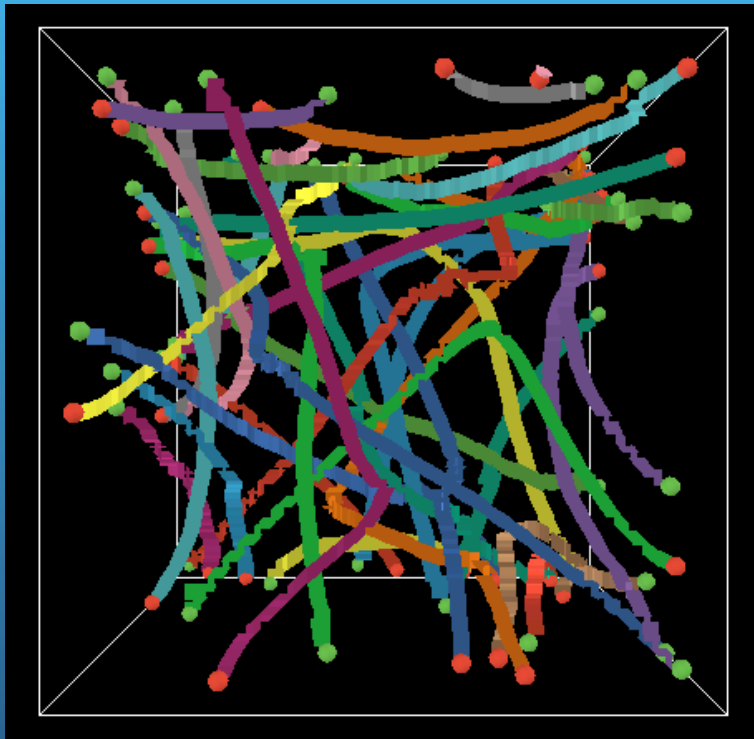
4000



5000

Effect of Growth Rate

Example of Path Routing



- Agent seeks attractant at destination
- Agent avoids repellant from existing paths
- Quiescent interval (for attractant decay)
- Each path occupies ~0.1% of space
- Total: ~4%

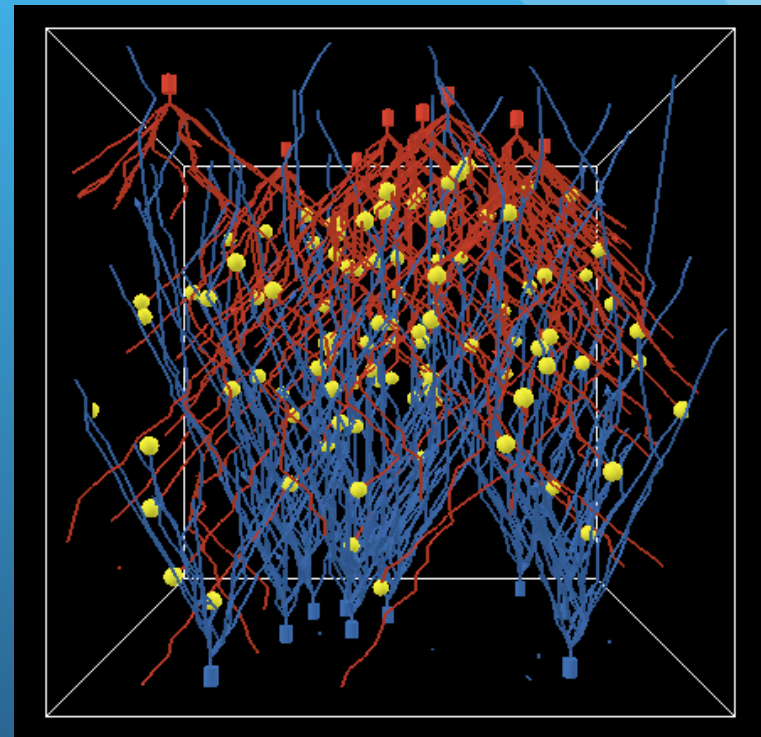
Example of Path Routing

Path Routing
40 paths, random starts & ends

- Starts and ends chosen randomly
- Quiescent interval (for attractant decay) omitted from video
- Each path occupies ~0.1% of space
- Total: ~4%

Example of Connection Formation

- 10 random “axons” (red) and “dendrites” (blue)
- Each repels own kind
- Simulation stopped after 100 connections (yellow) formed



Example of Connection Formation

- 10 random “axons” (red) and “dendrites” (blue)
- Simulation stopped after 100 connections (yellow) formed



Conclusions & Future Work

- Artificial morphogenesis is a promising approach to configuration and reconfiguration of complex hierarchical systems
- Biologists are discovering many morphogenetic processes, which we can apply in a variety of media
- We need new formal tools for expressing and analyzing morphogenesis and other embodied computational processes
- Our work is focused on the development of these tools and their application to artificial morphogenesis

