Configuration and Reconfiguration of Complex Systems by Artificial Morphogenesis

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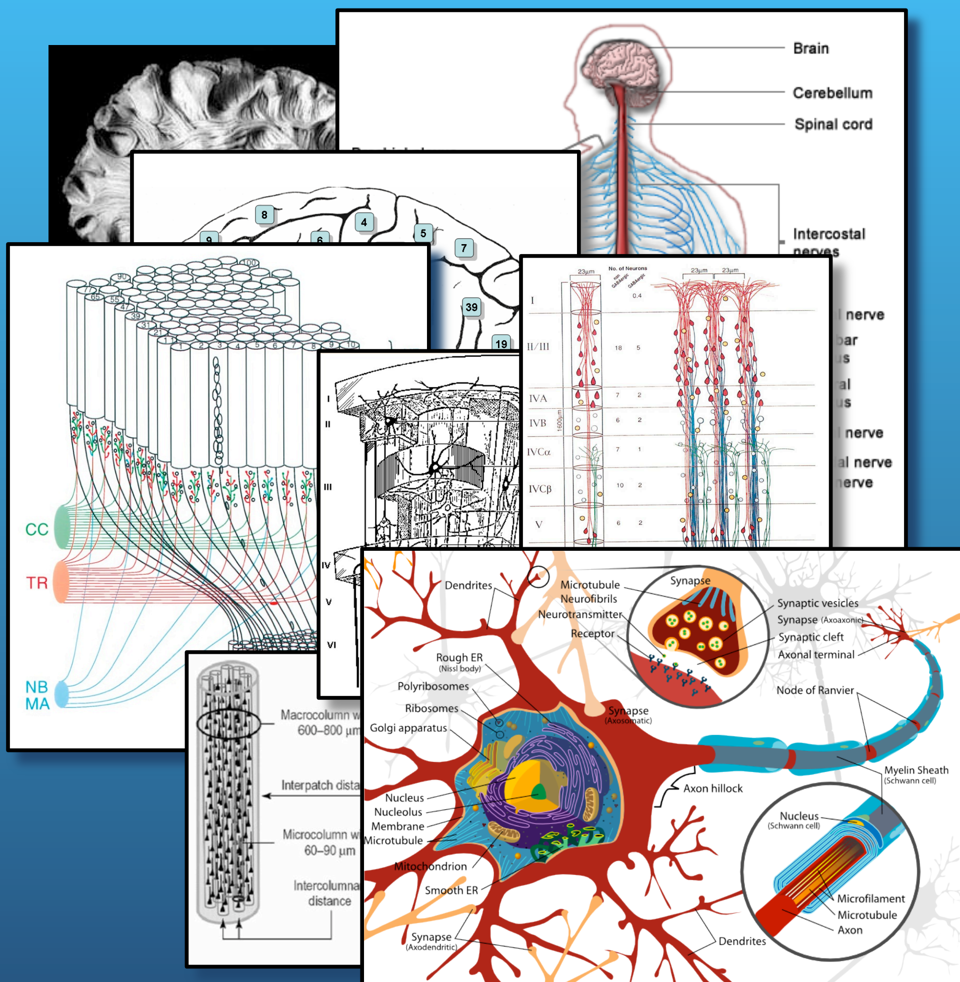
Long-Range Challenge

- 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

Motivation for Artificial Morphogenesis

- Embryological morphogenesis shows how to organize millions of relatively simple units to self-assemble into complex, hierarchical structures
- Morphogenesis: creation of 3D pattern & form in matter
- Characteristics:
  - structure implements function
  - function creates structure
  - no fixed coordinate frame
  - soft matter
  - sequential (overlapping) phases
  - temporal structure creates spatial structure

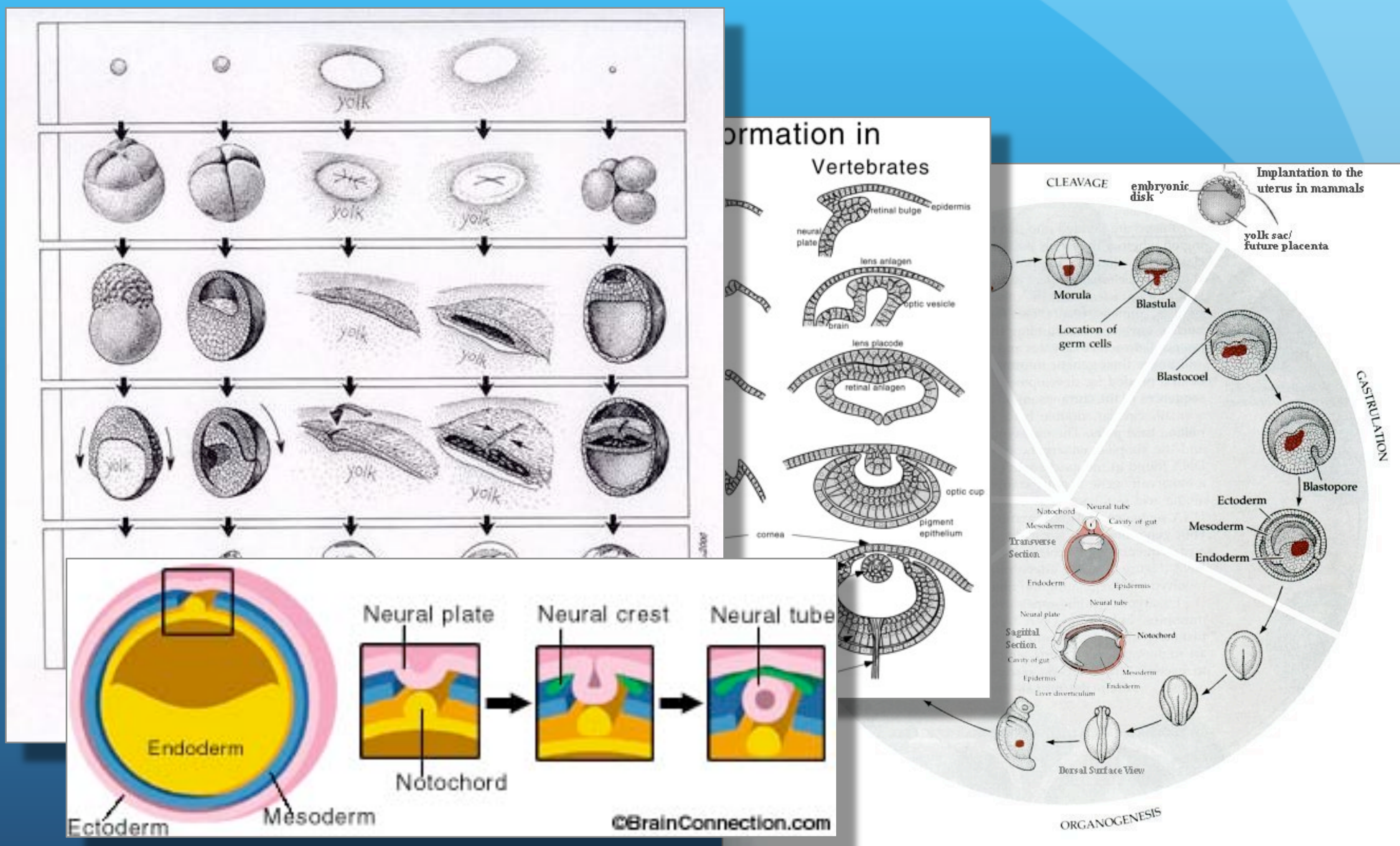
Artificial Morphogenesis



(Images from internet)

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

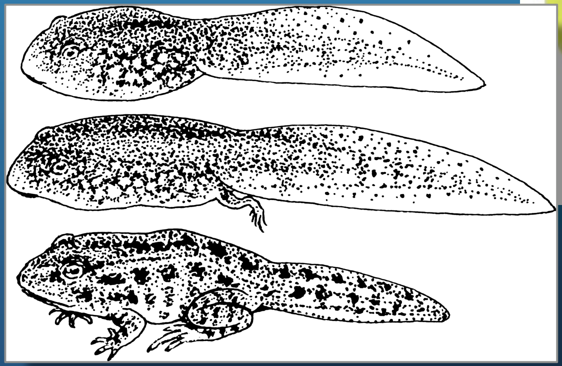
Self-Organization of Physical Pattern and 3D Form



(Images from Wikipedia)

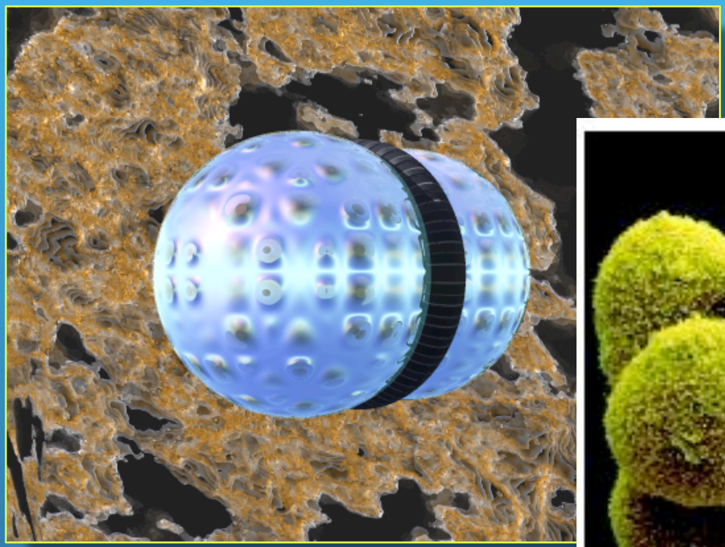
Reconfiguration & Metamorphosis

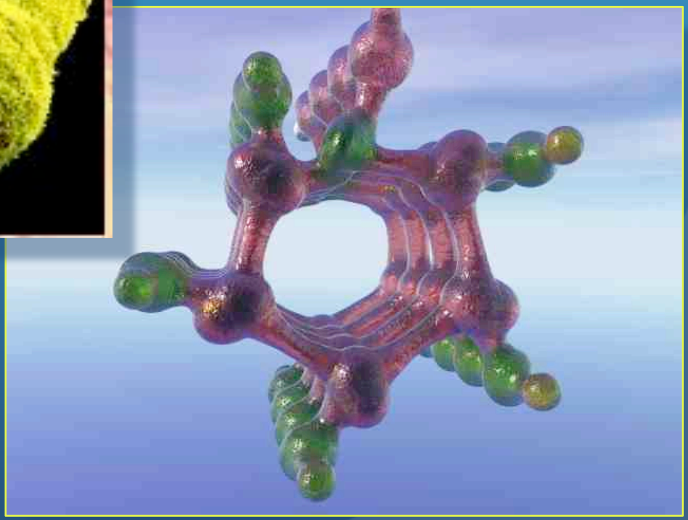
- Degrees of metamorphosis:
  - incomplete
  - complete
- Phase 1: partial or complete dissolution
- Phase 2: morphogenetic reconfiguration



(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

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

* Salazar-Ciudad, Jernvall, & Newman (2003)

Embodied Computing

- Embodiment: "the interplay of information and physical processes." — Pfeifer, Lungarella, & Iida (2007)
- Cf. embodied cognition, embodied AI
- Embodied computation = computation whose physical realization is directly involved in computational process or its goals
- 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

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

Disadvantages

- 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

A preliminary model for morphogenesis

as an 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
- Embodied computation in solids, liquids, gases — especially soft matter
- Active and passive elements
- Energetic issues
- Coordinate-independent behavioral description
- Mathematical interpre-tation
- Operational interpretation
- Influence models
- Multiple space & time scales
- Stochastic

Substances

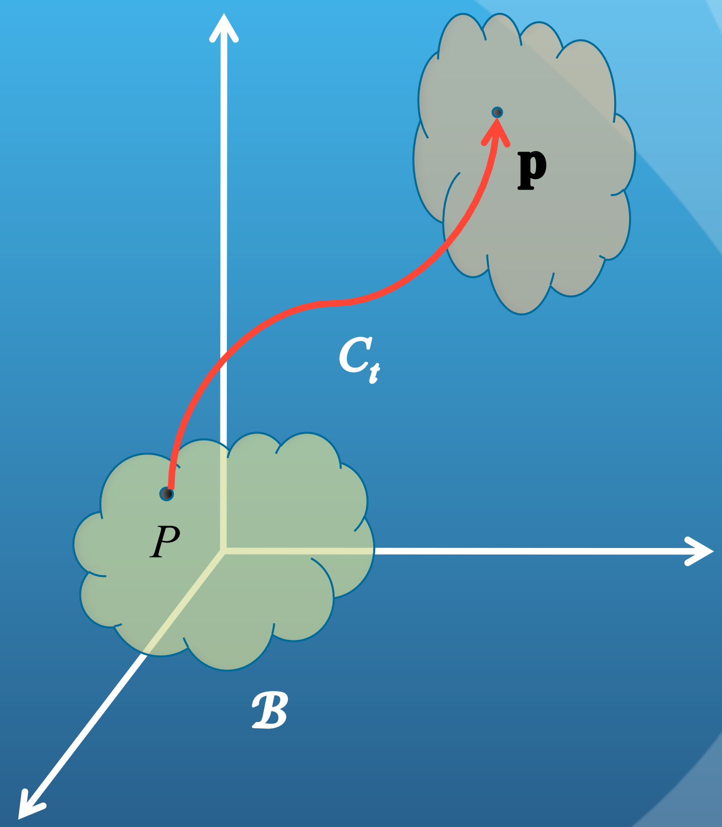
- Complemenarity
  - physical continua
  - phenomenological continua
- Substance = class of continua with similar properties
- Examples: solid, liquid, gas, incompressible, viscous, elastic, viscoelastic, physical fields, …
- Multiple realizations as physical substances
- Organized into a class hierarchy
- 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 for Morphogenesis

- An embodied computation system for morphogenesis 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

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

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

- Conversion:

$$\mathrm{D}_t X = \dot{X} + \mathbf{v} \cdot \nabla X$$

- All derivatives are assumed to be relative to their body

Change Equations

- Want to maintain complementarity between discrete and continuous descriptions:

$$\begin{aligned} \mathrm{D}_t X &= F(X,Y) \\ \Delta_t X &= F(X,Y) \end{aligned}$$

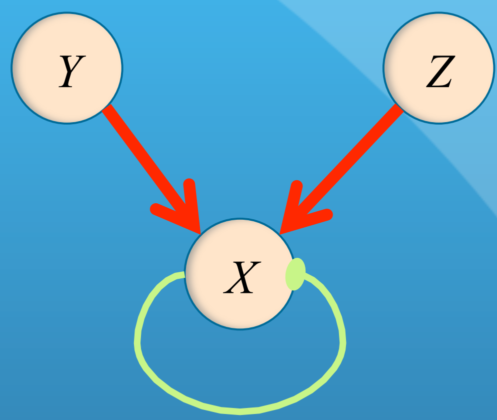
$$\text{where } \Delta_t X = \frac{\Delta X(t)}{\Delta t} = \frac{X(t+\Delta t) - X(t)}{\Delta t}$$

- Neutral "change equation":

$$\text{Đ}X = F(X,Y)$$

Qualitative "Regulations"

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



- We write as "regulations": $\text{Đ}X \sim -X, Y, Z$
- Meaning: $\text{Đ}X = F(-X, Y, Z)$

  where F is monotonically non-decreasing
- Relative magnitudes: $\text{Đ}X \sim Y, Z; -X$

Stochastic Change Equations

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

$$
\begin{aligned}
X_t &= \int_0^t H_s \mathrm{d}W_s \\
\mathrm{d}X_t &= H_t \mathrm{d}W_t \\
\Delta X_t &= H_t \Delta W_t \\
\text{Đ} X_t &= H_t \text{Đ} W_t \\
\Delta_t X_t &= H_t \Delta_t W_t \\
\mathrm{D}_t X_t &= H_t \mathrm{D}_t W_t
\end{aligned}
$$

Interpretation of Wiener Derivative

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

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

Examples

Simple Diffusion

substance morphogen:

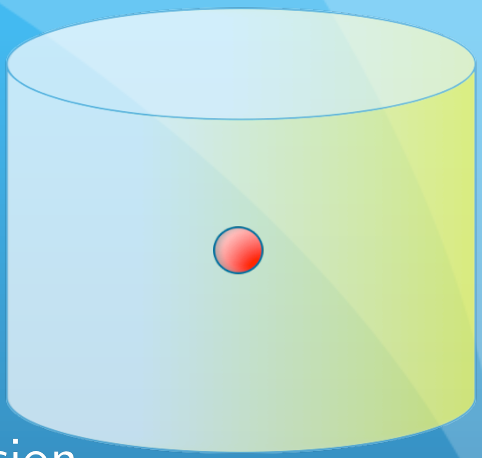
scalar field ϕ	‖ concentration
vector fields:	
$\mathbf{j}$	‖ flux
$\boldsymbol{\mu}$	‖ drift vector
order-2 field $\boldsymbol{\sigma}$	‖ diffusion tensor

behavior:

$$\mathbf{j} = \boldsymbol{\mu}\phi - \nabla \cdot (\boldsymbol{\sigma}\boldsymbol{\sigma}^{\mathrm{T}}\phi)/2 \quad \| \text{ flux}$$

$$\text{Đ}\phi = -\nabla \cdot \mathbf{j} \quad \| \text{ change in conc.}$$

A Simple Diffusion System



body Concentration **of** morphogen:

for $X^2 + Y^2 \leq 1$ **and** $-1 \leq Z \leq 1$:

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

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

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

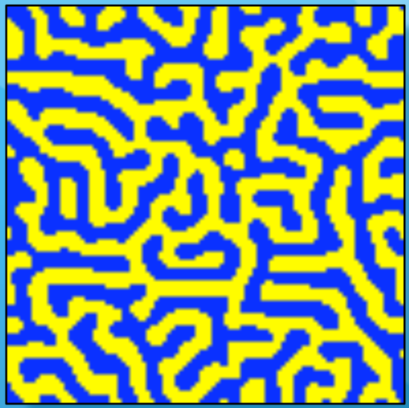
for $X^2 + Y^2 + Z^2 \leq 0.1$:

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

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:

$\boldsymbol{\sigma}_A$	activator diffusion tensor
$\boldsymbol{\sigma}_I$	inhibitor diffusion tensor

behavior:

$$\begin{aligned} \text{Đ}A &= f_A(A, I) + \triangle(\boldsymbol{\sigma}_A \boldsymbol{\sigma}_A^{\mathrm{T}} A) \\ \text{Đ}I &= f_I(A, I) + \triangle(\boldsymbol{\sigma}_I \boldsymbol{\sigma}_I^{\mathrm{T}} I) \end{aligned}$$

Activator-Inhibitor System as Regulations

substance activator-inhibitor:

scalar fields:

A	‖	activator concentration
I	‖	inhibitor concentration

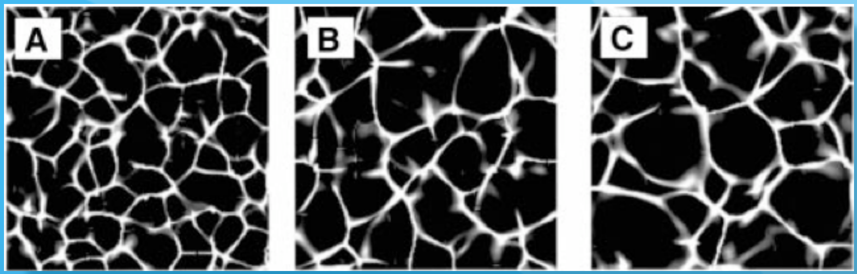
order-2 fields:

$\boldsymbol{\sigma}_A$	‖	activator diffusion tensor
$\boldsymbol{\sigma}_I$	‖	inhibitor diffusion tensor

behavior:

$$\begin{aligned} \text{Đ}A &\sim A, -I, \triangle(\boldsymbol{\sigma}_A \boldsymbol{\sigma}_A^{\mathrm{T}} A) \\ \text{Đ}I &\sim A, -I, \triangle(\boldsymbol{\sigma}_I \boldsymbol{\sigma}_I^{\mathrm{T}} I) \end{aligned}$$

Vasculogenesis* (Morphogen)



substance morphogen **is** medium **with**:

scalar fields:

C	concentration
S	source
order-2 field D	diffusion tensor
scalar τ	degradation time constant

behavior:

$$ÐC = \triangle(\mathbf{D}C) + S - C/\tau$$ || diffusion + release - 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 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:

$$S = \alpha n$$ || production of morphogen

|| follow morphogen gradient, subject to drag and compression:

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

|| change of density in material frame:

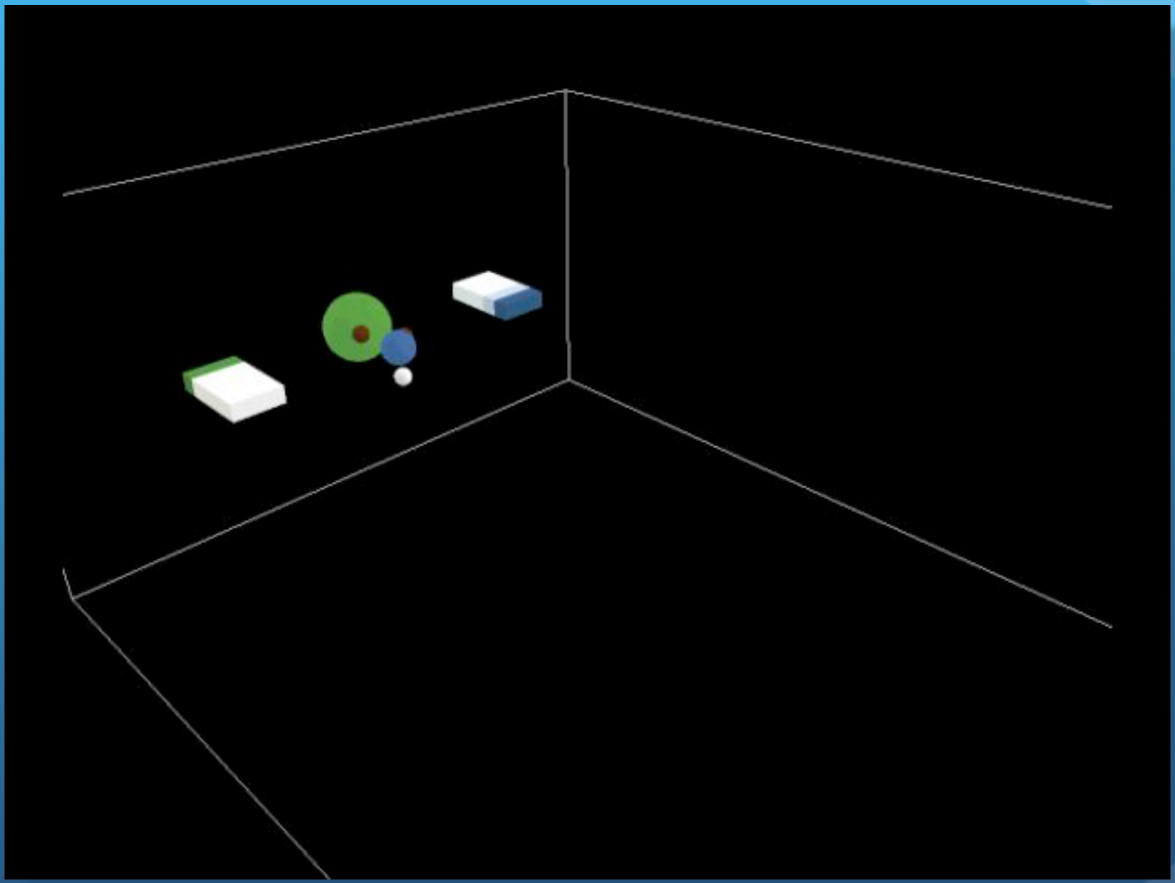
$$Đn = -\nabla \cdot (n \cdot \mathbf{v}) + \mathbf{v} \cdot \nabla n$$

$$\phi = [(n - n_0)^+]^3$$ || 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

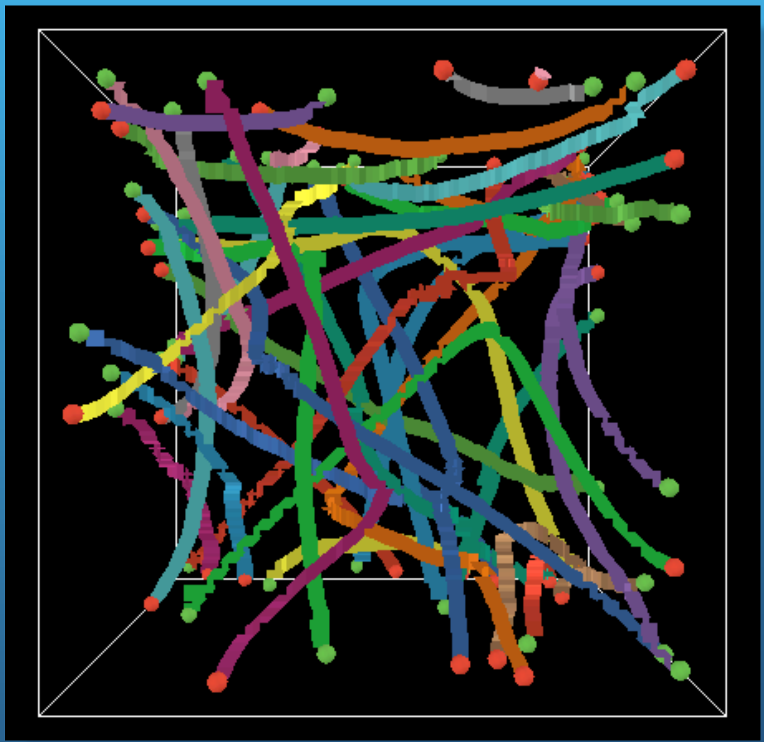
Simulated Segmentation by Clock-and-Wavefront Process



2D Simulation of Clock-and-Wavefront Process

Effect of Growth Rate

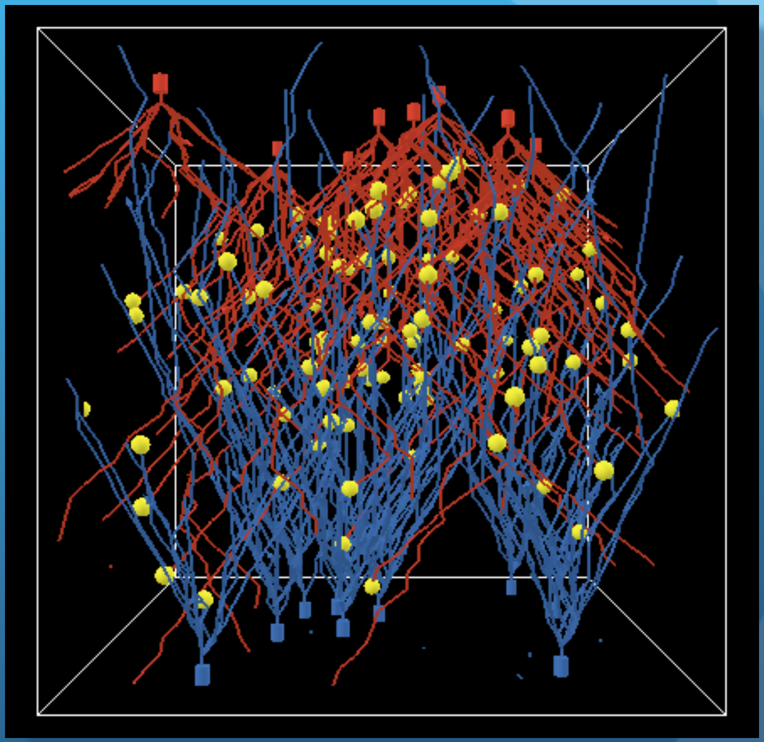
Example of Path Routing



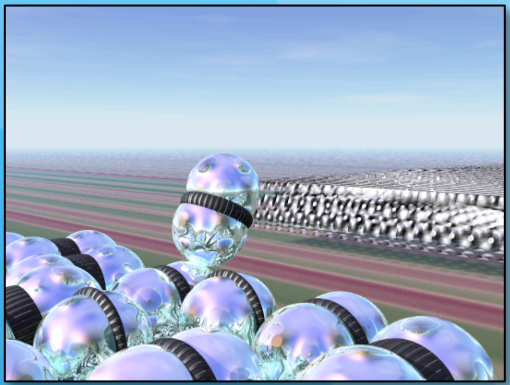
- Agent seeks attractant at destination
- Agent avoids repellant from existing paths
- Quiescent interval (for attractant decay)
- Each path occupies ~0.1% of space
- Total: ~4%

Example of Connection Formation

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



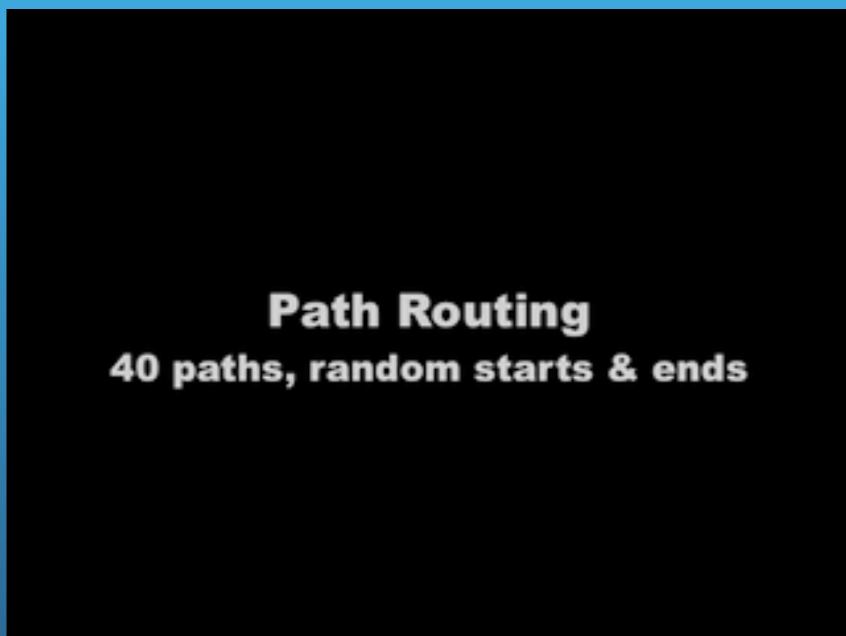
Conclusions & Future Work



- 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

Extra Slides

Example of Path Routing



- 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)
- Simulation stopped after 100 connections (yellow) formed