A Model of Embodied Computation Oriented Toward Artificial Morphogenesis

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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

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:
  - no fixed framework
  - soft matter
  - sequential (overlapping) phases
  - temporal structure creates spatial structure

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)
- Many specific morphogenetic models
- Field Computation (MacLennan, 1987-)

A preliminary model for embodied computing

oriented toward artificial morphogenesis

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 interpre-tation
- Operational interpretation
- Influence models
- Multiple space & time scales
- Stochastic

Substances

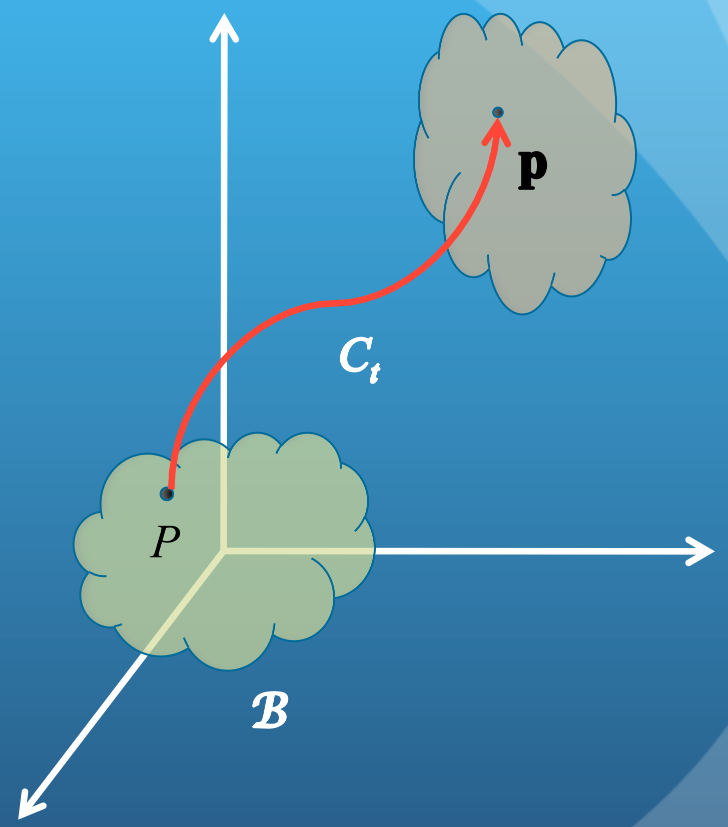
- Complemenarity
  - physical continua
  - phenomenological continua
- Substance = class of continua with similar properties
- Examples: solid, liquid, gas, incompressible, viscous, elastic, viscoelastic, physical fields, …
- Multiple realizations as physical substances
- Organized into a class hierarchy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

- 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

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

- Conversion:

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

- All derivatives are assumed to be relative to their body

Change Equations

- Want to maintain complementarity between discrete and continuous descriptions:

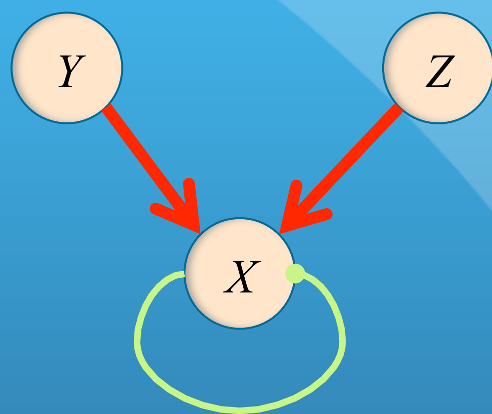
$$\begin{aligned} \mathrm{D}_t X &= F(X,Y) \\ \Delta_t X &= F(X,Y) \end{aligned}$$

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

- 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 medium: …

substance morphogen is
medium with:

scalar field C // concentration

order-2 field $\mathbf{D}$ // diffusion tensor

behavior:

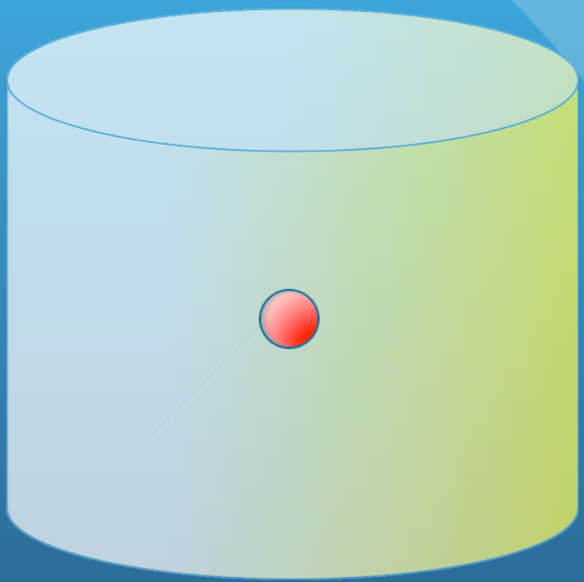
$$\text{Đ}C = \nabla \cdot (\mathbf{D} \cdot \nabla C)$$ // anisotropic diffusion

A Simple Diffusion System

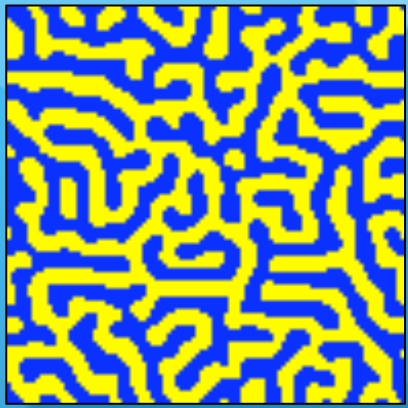
<u>body</u> Substrate <u>of</u> medium
<u>for</u> $X^2 + Y^2 \leq 1$
<u>and</u> $-1 \leq Z \leq 1$:
… initialize variables …

<u>body</u> Signals <u>of</u> morphogen
<u>for</u> $X^2 + Y^2 + Z^2 \leq 0.1$:

$C = 100$
$\mathbf{D} = 0.1\,\mathbf{I}$



Activator-Inhibitor System



substance A-I is medium with:

  scalar fields:

    A // activator concentration

    I // inhibitor concentration

  order-2 fields:

    $\mathbf{D}_A$ // activator diffusion tensor

    $\mathbf{D}_I$ // inhibitor diffusion tensor

behavior:

$$
\begin{aligned}
ĐA &= \nabla \cdot (\mathbf{D}_A \cdot \nabla A) + f_A(A, I) \\
ĐI &= \nabla \cdot (\mathbf{D}_I \cdot \nabla I) + f_I(A, I)
\end{aligned}
$$

Activator-Inhibitor System as Regulations

substance A-I is medium with:

scalar fields:

A // activator concentration

I // inhibitor concentration

order-2 fields:

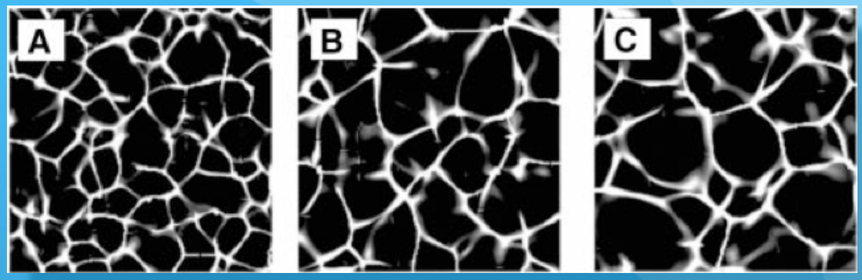
$\mathbf{D}_A$ // activator diffusion tensor

$\mathbf{D}_I$ // inhibitor diffusion tensor

behavior:

$$
\begin{aligned}
ÐA &\sim A, -I, \nabla \cdot (\mathbf{D}_A \cdot \nabla A) \\
ÐI &\sim A, -I, \nabla \cdot (\mathbf{D}_I \cdot \nabla I)
\end{aligned}
$$

Vasculogenesis* (Morphogen)



substance medium: …

substance morphogen is
  medium with:
    scalar fields:
      C // concentration
      S // source
    order-2 field **D** // diffusion tensor
    scalar τ // degradation time const

behavior: // diffusion & degradation

$$ÐC = \nabla \cdot (\mathbf{D} \cdot \nabla C) + S - C/\tau$$

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

Vasculogenesis (Cell Mass)

```
substance cell-mass is morphogen
    with :
    scalar fields:
      n                                  // number density
      φ                                  // cell compression force
    vector field v                       // cell velocity
    order-2 field γ                      // dissipative interaction
    scalars:
      α                                  // rate of morphogen release
      β                                  // strength of morph. attraction
      n0                                 // maximum cell density

behavior: …                              // see next slide
```

Vasculogenesis (Cell-Mass Behavior)

behavior:

$$
\begin{aligned}
S &= \alpha n \\
\text{Đ}\mathbf{v} &= \beta \nabla C - \gamma \cdot \mathbf{v} - n^{-1} \nabla \phi \\
\text{Đ}n &= -\nabla \cdot (n \cdot \mathbf{v}) + \mathbf{v} \cdot \nabla n \\
\phi &= [(n - n_0)^{+}]^3
\end{aligned}
$$

Conclusions

- Embodied computation will be important in post-Moore's Law computing
- But we need new models of computation that:
  - are orthogonal to Church-Turing model
  - and address relevant issues of EC
- Artificial morphogenesis will be important in nanotechnology
- A formalism can be based on continuum mechanics
- There will be a fruitful interaction between investigations of embodiment in computation, cognition, and philosophy