Recent Research in Bio-inspired Computation

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Why Bio-inspired Computation?

- Natural systems solve many important problems efficiently and robustly.
- They are typically:
  - intelligent
  - adaptive
- **Basic research**: What are the principles of computation and control used by natural systems?
- **Applied research**: How can these principles be applied in artificial systems?
Why Bio-inspired Computation?

- Biological systems are:
  - efficient
  - robust
  - adaptive
  - flexible
  - parallel
  - decentralized
  - self-organizing
  - self-repairing
  - self-optimizing
  - self-protecting
  - self-*
  - etc.
Some Specific Research Areas

- Field Computation
- Adaptive Self-Organizing Systems
- Embodied Computation
- Algorithmic Assembly
- Artificial Morphogenesis
Field Computation

- Field computation = computation on continuous distributions of continuous data
- Inspired by massively-parallel analog processing in cerebral cortex
- Examples:
  - optical computers
  - Kirkhoff machines
  - coupled-map lattice computers
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

(Images from Wikipedia)
Differences in Time Scale

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

\[X := Y / Z\]
Convergence of Scales
Implications of Convergence

- Computation on scale of physical processes
- Fewer levels between computation & physical realization
- Less time for implementation of operations
- Computation will be more like underlying physical processes
- Post-Moore’s Law computing →
greater assimilation of computation to physics
- Biology shows us some ways to do it
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 in AI & Robotics

- Hubert Dreyfus & al.:  
  - embodiment essential to cognition,
  - not incidental to cognition (& info. processing)

- Rodney 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
Embodied Computation

- Embodied (vs embedded) computation:
  - little or no abstract computation
  - computation as physical process in continuing interaction with other physical processes

(Images from Wikipedia)
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 approximation
- Many physical systems have sigmoidal behavior
  - Growth process saturates
  - Resources become saturated or depleted
- EC uses free sigmoidal behavior

(Images from Bar-Yam & Wikipedia)
Example: Negative Feedback

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

- Many algorithms use randomness
  - escape from local optima
  - symmetry breaking
  - deadlock avoidance
  - exploration

- Comes for free from:
  - noise
  - uncertainty
  - imprecision
  - defects
  - faults

(Image from Anderson)
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 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
EC Controlling Matter & Energy

- May want to move more rather than less
- Physical effects may be direct results of computation
- No clear distinction between processors & actuators
- Examples:
  - Algorithmic assembly by DNA computation (Winfree)
  - Nanostructure synthesis & control by molecular combinator reduction (MacLennan)
Natural Computation

- Challenge of EC: little experience with it
- Nature provides many examples of effective EC
- Nature shows how computation can
  - exploit physics
  - without fighting it
- Shows how 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

- Approach: use AM for multiphase self-organization of complex, functional, active hierarchical systems
Self-Organization of Physical Pattern and 3D Form
Reconfiguration & Metamorphosis

- Degrees of metamorphosis:
  - incomplete
  - complete

- Phase 1: partial or complete dissolution

- Phase 2: morphogenetic reconfiguration

(Images from Wikipedia)
Microrobots, Cells, and Macromolecules
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

Morphogenesis
examples
Simple Diffusion

**substance morphogen:**

- **scalar field** $\phi$  | concentration
- **vector fields:**
  - $j$  | flux
  - $\mu$  | drift vector
- **order-2 field** $\sigma$  | diffusion tensor

**behavior:**

\[
\begin{align*}
  j &= \mu \phi - \nabla \cdot (\sigma \sigma^T \phi)/2 \quad | \quad \text{flux} \\
  \Delta \phi &= -\nabla \cdot j \quad | \quad \text{change in conc.}
\end{align*}
\]
Activator-Inhibitor System

substance activator-inhibitor:

scalar fields:
\[ A \] || activator concentration
\[ I \] || inhibitor concentration

order-2 fields:
\[ \sigma_A \] || activator diffusion tensor
\[ \sigma_I \] || inhibitor diffusion tensor

behavior:

\[ \mathcal{D} A = f_A(A, I) + \Delta(\sigma_A \sigma_A^T A) \]
\[ \mathcal{D} I = f_I(A, I) + \Delta(\sigma_I \sigma_I^T I) \]
Vasculogenesis* (Morphogen)

Substance morphogen is medium with:

Scalar fields:
- $C'$ || concentration
- $S'$ || source

Order-2 field $D$ || diffusion tensor

Scalar $\tau$ || degradation time constant

Behavior:

$$D C' = \Delta(D C') + S - C'/\tau$$ || 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
- $\phi$ | cell compression force
- $v$ | cell velocity

**vector field** $v$

**scalars:**
- $n_0$ | maximum cell density
- $\alpha$ | rate of morphogenesis release
- $\beta$ | strength of morphogen attraction

**order-2 field** $\gamma$ | dissipative interaction

**behavior:** ...
Vasculogenesis  
(Cell-Mass Behavior)

behavior:

\[ S = \alpha n \quad || \text{production of morphogen} \]

\[ \text{|| follow morphogen gradient, subject to drag and compression:} \]

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

\[ \text{|| change of density in material frame:} \]

\[ \mathbf{D} n = -\nabla \cdot (n \cdot \mathbf{v}) + \mathbf{v} \cdot \nabla n \]

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

8/30/10
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)
- 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

- Biological systems embody novel approaches to computation and control that are intelligent and adaptive
- We can discover the principles of natural computation and apply them in artificial systems
  - Biological systems exploit their embodiment
  - Computational and physical processes each regulate the other
- There will be a fruitful interaction between investigations of embodiment in computation, cognition, biology, and philosophy