Biological Computing Ideas

Eric Mjolsness
Computer Science Department
UC Irvine

Calit2 June 2009
Principles shared in biology and computing

with focus on architecture

• Principle of regeneration
• Multilevel network dynamics
  – Computational networks
  – Biological networks
  – Fixed vs. variable-structure networks
  – Evolution
Principle of regeneration

• At all scales, regeneration of subunits confers robustness against coevolved challenges.
• Regeneration in turn implies an information bottleneck.
  – Biological examples
    Bottlenecks: genotype, cultural transmission, ...
  – Computational examples
Multilevel networks

• 1985-1995:
    • RGNN:
      • Eg. scalable continuous codes => Gray codes, etc.
      • Eg. evolution of reproducing “metazoan” lineage tree
  – neural networks/cognitive networks
Transcriptional Gene Regulation Networks

- Gene Regulation Network (GRN) model

\[ \tau_i \dot{v}_i = g \left( \sum_j T_{ij} v_j + h_i \right) - \lambda_i v_i \]


Single slot organism

Fig. 3. An evolved lineage tree for a single-slot organism (no reproduction required). Cells are labelled by their scoring function cell type. The desired numbers of cells of each type are attained: there are 12 terminal cells of type 2, eight of type 3 and four of type 4.
“Frameville” cognitive/neural network architecture

Main problem: crossbar communications
Multilevel networks (cont)

• 2000- ?:
  – biological realism
    • ==> variable-structure network dynamics
  – metabolism/gene regulation+signaling/
    multicellular/spatial network models
  – large-scale dynamics
    • stochastic dynamics
    • morphodynamics
Amino Acid Syntheses

Kmech and (Val, Leu, Ile) biosynthesis:
[Yang, Shapiro, Hung, Mjolsness, and Hatfield, *Journal of Biological Chemistry*, 280(12):11224-32, 2005]
[Yang, Shapiro, Hung, Mjolsness *Bioinformatics* 21: 774-780, 2005.]

Thr biosynthesis from Asp:
ES cell switch


Chickarmane et al 2009:

\[
\frac{d[O]}{dt} = \frac{a_0 + a_1[A] + a_2[O][S] + a_3[O][S][N]}{1 + b_0[A] + b_1[O] + b_2[O][S] + b_3[O][S][N] + b_4[C][O] + b_5[GC]} - \gamma_1[O]
\]

\[
\frac{d[S]}{dt} = \frac{c_0 + c_1[O][S] + c_2[O][S][N]}{1 + d_0[O] + d_1[O][S] + d_2[O][S][N]} - \gamma_2[S]
\]

\[
\frac{d[N]}{dt} = \frac{e_0 + e_1[O][S] + e_2[O][S][N]}{1 + f_0[O] + f_1[O][S] + f_2[O][S][N] + f_3[O][G]} - \gamma_3[N]
\]
Wall spring model

Henrik Jönsson 2008

Calit2 June 2009
“Cell complex” framework:
Plant cell mechanical model

(a) 3D polyhedral model of plant cell. Expanded view shows separate walls (yellow) and cytoplasm (green). (b) FEM simulation of model cell deformation. Original cell was held at the bottom, stretched and twisted by 30\degree. Resulting shape and mesh shown in red. Original cell given as the green outline. (c) The same cell expanding under uniform turgor pressure. Result of simulation shown in red; original cell in green.

(d): Arabidipsis embryo FEM grid.

[Figures courtesy Pawel Krupinski, UCI/Lund, Computable Plant project . ICSB 2007]
Multilevel networks (cont)

• 2010 - ?
  + Metadynamics
    • evolution of dynamics by dynamics
    • networks of rule-like process models (eg. Dynamical Grammars) that specify dynamics, and also evolve by self-application
    • Evolution and evolvability
Dynamical Grammar / Epithelium

```plaintext
grammar Epithelial[
    (*replication*)
    Cell(τ, x, r, g) → {Cell(τ, x - r/2, r/2, g), Cell(τ, x + r/2, r/2, g)}
    with ρ₁(τ,r,g)
    (*differentiation*)
    Cell(τ, x, r, g) → {Cell(τ + 1, x - r/2, r/2, g), Cell(τ + 1, x + r/2, r/2, g)}
    with ρ₂(τ,r,g)
    (*death*)
    Cell(τ, x, r, g) → { }
    with ρ₃(τ,r,g)
    (*growth*)
    Cell(τ, x, r, g) → Cell(τ, x, r, g)
    solving \[ \frac{dx}{dt} = k \]
    (*motion*)
    \{Cell(τ₁, x₁, r₁, g₁), Cell(τ₂, x₂, r₂, g₂)\} → \{Cell(τ₁, x₁, r₁, g₁), Cell(τ₂, x₂, r₂, g₂)\}
    solving \[ \frac{dx₁}{dt} = m(x₁, r₁, x₂, r₂) \]
    (*protein concentration*)
    \{Cell(τ₁, x₁, r₁, g₁), Cell(τ₂ = 4, x₂, r₂, g₂)\} → \{Cell(τ₁, x₁, r₁, g₁), Cell(τ₂ = 4, x₂, r₂, g₂)\}
    solving \[ g₁ = f(x₁, x₂, r₂) \]
]
```

Guy Yosiphon, UCI
DG Self-applicability for Metadynamics

-Eg. genetic algorithm in DG’s
  - mutation, crossover processes
  - development, selection processes
  - alternatively: differential evolution, etc.

-Arrow mutation operator
  - Arrow reversal graph grammar exercise
  - Machine learning by statistical inference
    - e.g. hierarchical clustering (reported)
  - Equilibrium reaction networks for MRF’s
What could be done jointly?

• Artificial life simulations
  – Herbivorous vision
    • Realistic plant growth and imagery
    • Insect brain simulation

• multilevel network dynamics
  • General model language
  • Scale up metadynamics eg. via dynamical grammars

• Anza-Borrego sensor network, a la UCR James Reserve