Biology and Networks:

Bio Inspired Networks and Network Inspired Bio

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Outline

• Bio Inspired Networks (applying bio concepts/mechanisms to nets)
  – Bio Networking Architecture
• Network Inspired Bio (applying insights from nets to create a new bio net systems)
  – Molecular communication
• Bio and Grid

Part 1: Bio Inspired Networks

Bio-Net:
An Evolvable Architecture for Adaptive Network Services

Motivation

• Network services/applications need to be
  – scalable, adaptable, survivable/available, simple to design/maintain
• Observation:
  – large scale biological systems have desirable features
• So, apply biological concepts/mechanisms
Emergent Behavior

- Biological systems
  - (useful) group behavior emerges from local interaction of individuals with simple behaviors

- In Bio Net
  - Application emerges from local interaction of cyber-entities with simple behaviors

Emergent Behavior in Bio-Net

- individuals = cyber-entities (agents/objects) in Bio-Net
  - abstraction of various system components
    - service components (e.g., program code, flight reservation service component), resource, user
  - autonomous with simple behaviors
    - replication, reproduction, migration, death, etc.
    - makes its own decision, according to its own behavioral policy

Evolution and Adaptation

- CE behavior: energy exchange
  - gain energy from a cyber-entity (e.g., a user) in exchange for performing a service
  - expend energy to receive service from other cyber-entities (e.g., to use network/computing resources)
  - can be used as a natural selection mechanism
    - death from energy starvation
    - tendency to replicate/reproduce from energy abundance

- Biological systems
  - individuals adjust their behaviors to environmental changes
  - key components
    - diversity from mutations and crossovers during replication/reproduction
    - natural selection keeps entities with beneficial features alive and increase reproduction probability
Evolution and Adaptation in Bio-Net

- **Bio Net**
  - cyber-entities (CEs) adjust their behaviors to environmental changes

- **Key components**
  - diversity
    - A CE behavior is implemented by different policies
      - human designers can introduce diversity in CE behaviors
      - CEs replicate/reproduce with mutation/crossover in behavior policies
  - natural selection (using energy)
    - death from energy starvation
    - tendency to replicate/reproduce from energy abundance

Adaptation at CE Level

- Cyber-entity behaviors implemented
  - Replication
    - If current energy level > threshold, then create a new entity of same type
  - Death
    - if current energy level = 0, then, die
  - Migration
    - migrate towards source of energy (user requesting service)
    - avoid coexisting on a node with same entity

**Energy Seeking Entity (Simulation 1)**

- Entity 1: \( w_1 = 0.5, w_2 = 0.5, \text{agress} = 4 \)
- Entity 2: \( w_1 = 0.425, w_2 = 0.575, \text{agress} = 2.25 \)
- Entity 3: \( w_1 = 0.575, w_2 = 0.45, \text{agress} = 4.5 \)
Entity 1: $w_1 = 0.5$, $w_2 = 0.5$, aggress = 4
Entity 2: $w_1 = 0.425$, $w_2 = 0.575$, aggress = 2.25
Entity 3: $w_1 = 0.575$, $w_2 = 0.45$, aggress = 4.5
Vision

- No central or coordinating entity exists.
- A large number of CEs (created by millions of millions of Internet users), autonomously moving/replicating,
- CEs making relationships with other CEs providing related services,
- diverse behavior policies getting created, good behaviors survive, bad ones die, making system flexible, adaptable and evolvable
- Let the Internet live its own life.

Some Thought on Bio Inspired Nets

- A large number of bio inspired network research
  - Ant routing
    - Ants find a route following strength of pheromone
  - Immune system based intruder detection
    - Immune system finds shapes that are not similar to self
  - Etc, etc

- “Bio inspired nets” at this point seems to be just an analogy between bio world and nets

- No systematic approach to decide at level analogy should be made
  - Molecular level
  - Protein level
  - Single cell organism level
  - Multi-cell organism level
  - Insect level
  - Human level
  - Human society level
• No systematic approach to decide at level analogy should be made
  – Molecular level
  – Protein level
  – Single cell organism level (immune system)
  – Multi-cell organism level
  – Insect level (ant routing)
  – Human level
  – Human society level (bio net)

• No systematic approach to decide how accurate analogy need to be
  – Ants emit different types of pheromone
  – Queen ants, regular ants; being ignored
  – Bio systems are usually more complex than analogy that has been applied in networks

• Our approaches in bio inspired net seem to be ad hoc

• We need to be clear on
  – what our “target” system is
    • A network?
    • A router?
    • ?
  – what features we want a “target” system to have?
    • Robustness?
    • Scalability?
    • ?

• We need to consider multilevel analogy
  – Human society ------ ???
  – Individuals ------------ ???
  – Organs ---------------- ???
  – Cells ------------------ ???
  – Proteins ---------------- ???
  – Atoms ------------------ ???

• Bio inspired mechanism at one level will lead to some behavior at a higher level
• We need to consider multilevel analogy
  – Human society ------ network applications (bio net)
  – Individuals --------- cyber entities (bio net)
  – Organs -------------- ???
  – Cells ---------------- ???
  – Proteins -------------- ???
  – Atoms ---------------- ???

• Bio inspired mechanism at one level will lead to some behavior at a higher level

• We need to consider multilevel analogy
  – Human society ------ ???
  – Individuals ----------- ant routing
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    • Robustness?
    • Scalability?
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Part 2: Net Inspired Bio

Molecular Communication: A New Paradigm for Communication among Biological Nanomachines

- Biological nanomachines
  - nano-scale or molecular scale objects that are capable of performing simple tasks

Communication among Biological Nanomachines

- A new paradigm for nano scale communication
  - Among biological nanomachines

Figure: “Protonic Nanomachin Project”, Prof. Namba at Osaka University: http://www.npn.jst.go.jp/index.html

- Biological nanomachines (in bio world)
  - Cells
  - Bacteria
  - Molecular Motors

All figures: Alberts, Molecular Biology of the Cell
 Biological nanomachines (artificially created)  
- logic gates made of biological components  
  - If both substrate and effector exist, product produced  
  - If no effector or no substrate, substrate remains unchanged

Nano-Scale Communication in Bio World

- Nano/micro-scale communication in biological systems  
  - Within a cell (vesicles transported by molecular motors)

Microtubule Rails
- Polymer on which motors walk  
- Formed through dynamic Instability  
  - Polymerize and depolymerize relative to tubulin concentration

Molecular Motors
- Kinesin  
  - Consumes ATP energy to move along microtubule  
  - Binds cargo according to tail domain
• Nano/micro-scale communication in biological systems
  – Within a cell (vesicles transported by molecular motors)
    - A vesicle transported by a kinesin motor toward the periphery of the cell
    - A vesicle transported by a dynein motor toward the center of the cell

• Nano/micro-scale communication in biological systems
  – Between cells (Cells coordinate through calcium signaling)
    - Gap junction channel
      - Intracellular signals (e.g., IP₃)
      - Extracellular signals (e.g., ATP)

Stimuli

Gap junction channel
Intracellular signals (e.g., IP$_3$)

Extracellular signals (e.g., ATP)

Gap junction channel

• How do biological nanomachines communicate in the bio world?
  – Using molecules (ions, proteins, etc)
• So, let’s have our biological nanomachines communicate using molecules

Molecular Communication

• As the first step, we are researching
• Goal
  – Achieve communication between biological nanomachines
  – Over communication distance of nano/micro scale
• How
  – By sending and receiving molecules (such as proteins, ions, DNAs) as an information carrier

• A receiver biochemically reacts to incoming molecules
  – Bio-chemical reaction, state = information
    • Nanomachines cannot “interpret” abstract information
Simplest Molecular Communication System: An Example

1. **Encoding**
   - Senders (nanomachines)
   - Information Source
     - Information molecules (Proteins, ions, DNAs, etc)

2. **Sending**
   - Information molecules

3. **Propagation (directional)**

4. **Receiving (selective)**
Simplest Molecular Communication System: An Example

1. **Encoding**
   - Information molecules (Proteins, ions, DNAs, etc)

2. **Sending (selective)**
   - Senders (nanomachines)

3. **Propagation (directional)**

4. **Receiving (selective)**
   - Receivers (nanomachines)

5. **Decoding**

An Example System Component: A Sender

- Artificially synthesized cell

- Genetically altered mutant cell

- Encoding by controlling density of emitting molecules

- Non-spontaneous reaction
  - Sender nanomachine
  - Stable: Concentration LOW

- Spontaneous reaction
  - Sender nanomachine
  - Instable: Concentration HIGH

- Spontaneous reaction
  - Sender nanomachine
  - Stable: Concentration LOW

Decomposition
An Example System Component: Free Diffusion based Propagation Direction Control

1. **Encoding**

2. **Sending**

3. **Propagation (directional)**

Information Source

- Information molecules (Proteins, ions, DNAs, etc)

Senders (nanomachines)

Receivers (nanomachines)

An Example System Component: Cell network based Propagation Direction Control

1. **Encoding**

2. **Sending**

3. **Propagation (directional)**

Information source

- Information molecules (Proteins, ions, DNAs, etc)

Senders (nanomachines)

Receivers (nanomachines)

An Example System Component: Cell network based Propagation Direction Control

1. **Encoding**

2. **Sending**

3. **Propagation (directional)**

Information source

- Information molecules (Proteins, ions, DNAs, etc)

Senders (nanomachines)

Receivers (nanomachines)
- amplifying signals

CICR (Calcium Induced Calcium Release)

- Dynamic switching
  - Apply external signals to phosphorylate connexins.

An Example System Component:
Molecular Motor based Propagation Direction Control

1. Encoding

2. Sending

3. Propagation (directional)

Information source

Information molecules
(Proteins, ions, DNAs, etc)

An Example System Component:
Molecular Motor based Propagation Direction Control

1. Encoding

2. Sending

3. Propagation (directional)

Information source

Information molecules
(Proteins, ions, DNAs, etc)
An Example System Component:
*Molecular Motor based Propagation Direction Control*

1. **Encoding**

2. **Sending**

3. **Propagation (directional)**

Information source

- Information molecules (Proteins, ions, DNAs, etc)

- Senders (nanomachines)

- Receivers (nanomachines)

- Self-organizing creation of a rail molecule network

*Note: The diagrams illustrate the process of encoding, sending, and propagating information molecules in a molecular motor-based system. The self-organizing creation of a rail molecule network is highlighted as a key component.*
An Example System Component: *A Receiver*

- An artificially synthesized cell

  - Reception
    - Using artificial receptors
    - Liposome-liposome merger

- Genetically altered mutant cell

  - Selective reception
    - Only right receivers accept information

Decode information: different biochemical reactions
• Selective reception
  – Only right receivers accept information

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5' 3'

TACTTTATTTTGGTTTTATTTCATTTTGTTTA

ATGAAATAAAACCAAAATAAAGTAAAACAAAT

---

3' 5'

---

5' 3'

TACTTTATTTTG

ATGAAATAAAACCAAAATAAAGTAAAACAAAT

---

3' 5'

Replacement of DNA hybridization

Carrier molecule

Information molecule A

Loading of an Information Molecule

Unloading of an Information Molecule
An Example System Component: 
**Information Encoding**

- Encode information onto
  - Types of molecules
    - Send X (and Y) to cause a bio chemical reaction to recreate the desired state at a receiver
    - Send hormone X to control behavior of receiving cells (e.g., upon receiving insulin, a cell uptakes glucose)
    - Send a DNA (or a artificially created DNA) to create a protein at a receiver

- Frequency/oscillation encapsulated in a vesicle
  - Biological cells generate various types of waves with different frequencies
  - Periodic (unstable) chemical reaction

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Ca2+ Transporter
Belousov-Zhabotinsky Reaction
```
• Encoding of a program

• Encoding of a program

• Encoding of a program

• Encoding of a program
System Characteristics

• A generic transport system
  – A molecule transport system independent of applications

• A communication system that is
  – Autonomous (i.e., no human control)
  – (but may be slow and probabilistic)

Applications

• New Biological Computing (a new approach to problem solving)
  – Program simple behavior rules into biological nanomachines
  – They solve large scale, non-traditional computing problems (e.g., a maze, global weather simulation prediction) through collaboration and communication

• Molecular communication
  – New paradigm
  – New research area
  – A lot to investigate
Part 3: Bio and Grids

- Two ways for Grid and Bio to work together
  - Grid for Bio
    - Grid to support bio research
  - Bio Inspired Grids
    - applying bio concepts/mechanisms to Grid to create Grid with desirable features

Grid for Bio Research

- Grid can support bio research
  - Drug creation/delivery
    - Binding of various types/shapes of proteins
  - Molecular dynamics simulations
    - Multi level simulations (atom, protein, cells, etc)
  - Disease epidemic simulation
    - How disease spread
  - Health monitoring
    - Communicating sensors imbedded in a human body

- By providing
  - High computing power
  - Federated data base and knowledge base
  - Visualization tools
  - A grid of sensors that work as a computer
Bio Inspired Grids

• Bio inspired grid
  – Apply bio concepts/mechanisms to provide desirable features to grids
    • Flexible
    • Robust
    • Scalable

• Bio has a huge implication in Grid and networks
  – Need a lot more research

• Thanks!