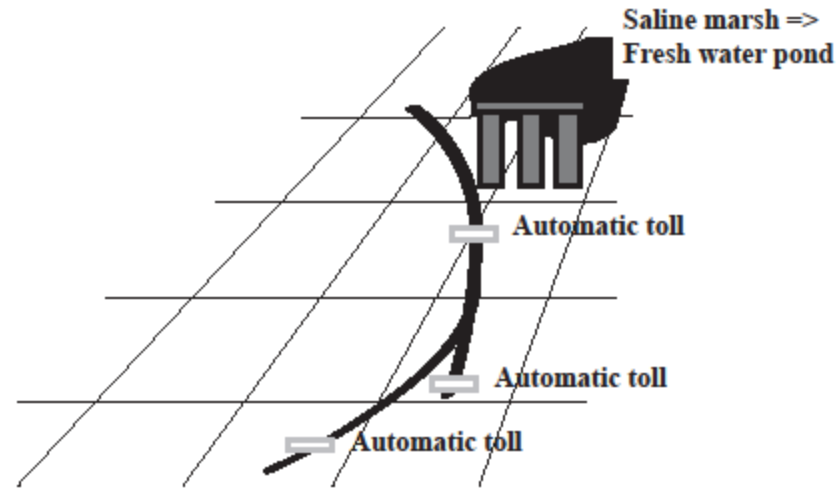


Signals and Boundaries

**Gated-Urn Models
for a
Crude Look at the Whole**

John H. Holland

Two Semi-permeable Boundaries

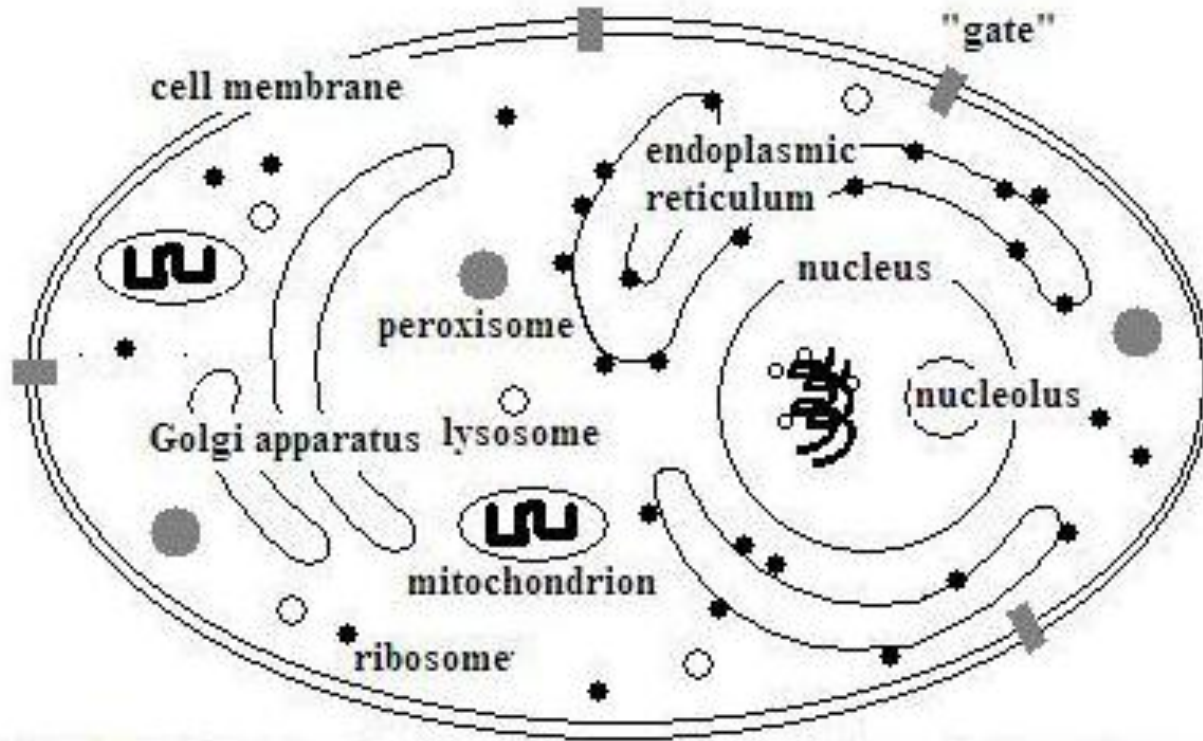


- 1) **FRESH WATER:** Prepared soil filters salt water.
- 2) **TRAFFIC:** Tolls reduce number of cars in inner city.

Results are **automatic** once an appropriate **boundary** is in place.

Typical Signal/Boundary Hierarchy for a Cell

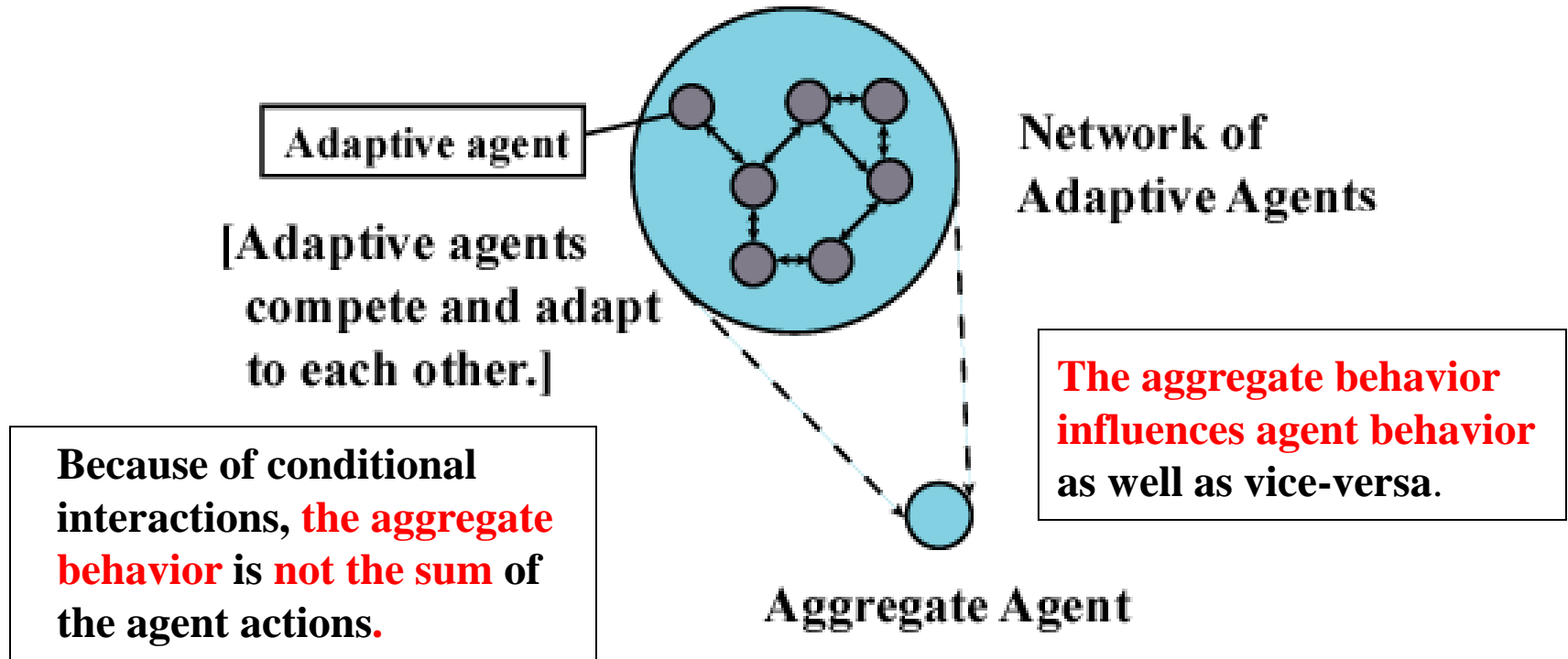
[Specialists]



Semi-permeable Boundaries

Define

Complex Adaptive Systems [*cas*]



Hierarchies of semi-permeable boundaries are present in all *cas*.

Problems Involving Complex Adaptive Systems

Encouraging **innovation** in dynamic economies.

Controlling the **internet** (e.g. controlling viruses and spam).

Predicting changes in **global trade**.

Understanding **markets**.

Providing for **sustainable human growth**.

Preserving **ecosystems**.

Strengthening the **immune system**.

Each problem involves many **interacting agents** (components) that **learn or adapt**.

Semi-permeable **boundaries set limits on the interactions**.

What We Don't Know about CAS

(Three Examples)

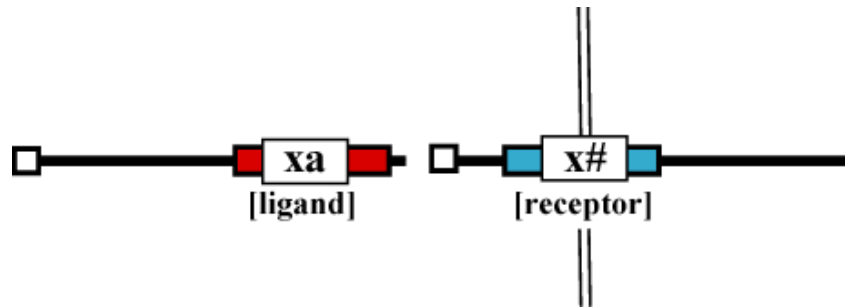
- 1) All *cas* exhibit **lever points** – points where a **simple intervention causes a lasting, directed effect**.
Example: vaccines.
There is no theory that tells us where or **how to look for lever points**.
- 2) **Open-ended evolution** is typical of *cas* – an initially simple system exhibits **increasing diversity of interaction and signaling**.
Example: ecosystems.
There are no models that exhibit **open-ended evolution**.
- 3) All *cas* have a **hierarchical organization** of boundaries enclosing boundaries.
Example: biological cells.
There is no theory or general model that tells us what **mechanisms** cause the **formation of boundaries**.

Some Effects of Semi-permeable Boundaries in *cas*

<u>Boundary</u>	<u>Mechanism</u>	<u>Effect</u>
Markets & Manufacturing	['gate'] “buyers” & “sellers”	increased efficiency
Ecological niche	species interactions (sight, sound, etc.)	recirculation of resources
Cell nucleus (protein-encased chromosome)	conditional gene transcription	chromosome acts like a computer program
Communities (tribes) [national boundary]	utterances [visa]	coordinated activity [“ them ” and “ us ”, selective immigration]

Tags and Semi-permeable Membranes

A **semi-permeable membrane** allows only signals with **specific tags** (acting like addresses) to diffuse from one side of the boundary to another.



[The 'gate' (entry condition) $x\#$ accepts any signal with tag x .]

Tags Mediate Signal/Boundary Interactions

In a typical *cas* there are **spatially distributed sets of interactions** between signals and boundaries. **Tags**, small parts of the signals, typically **direct the interactions**.

Signal-processing system

protein signalling in a **cell**

Food webs in an **ecosystem**

Situated **language** acquisition

Trade in economies.

Central nervous system

Tag

ligands, active sites

images, pheromones

intonation, gesture

'headers' on buy and sell orders.

synapse values in neural network

The Temporal Dimension is Critical

Organization arises from the co-evolution of signals and boundaries.

Darwin's tree of life.

A **'Snapshot'** (such as the current network of agent interactions) **is inadequate**
(Music is meaningless if presented as a series of snapshots.)

It is important to discover the mechanisms of co-evolution.

Steering vs. Optimization

The object is to **constrain changes**, insofar as possible, to plausible **improvements**, rather than attempting optimization.

The **organization** of a living organism is **not optimal**.

Even basins of attraction change as new, different agents arise through co-evolution. (Cf. the effects of an invasive species.)

Metaphor often suggests **mechanisms**, offering an experience-based coarse-graining.

Metaphor transfers knowledge of a well-known *source* to a less-known *target* .

tow lines (**source**) => lines of force (**target**)

-- Maxwell (collected papers)

Tags Provide Steering

By controlling entry and exit, **tags steer signals and resources** through boundary hierarchies.

Examples:

- (i) the **active sites** on catalysts and **gates** on semi-permeable biological membranes concentrate particular reactants;
- (ii) the title '**chief financial officer**' confers a range of powers for controlling a firm's budget.

New tags, by generating new pathways, amount to **hypotheses for ways to steer** signals and resources through the agent's **boundary hierarchy**.

In systems with many agents, **new tags can be tried without seriously disrupting the system**.

New tags only disrupt a small part of the flow, unless they become widespread through adaptation.

Gated-Urn Model of a Semi-permeable Membrane

Each urn is assigned **entry and exit conditions**.

For a ball to enter (exit) an urn under diffusion, its **tags must match** the corresponding condition.



[x# is the entry condition, where # is a 'don't care' symbol
– any signal with tag x matches the entry condition x#.]

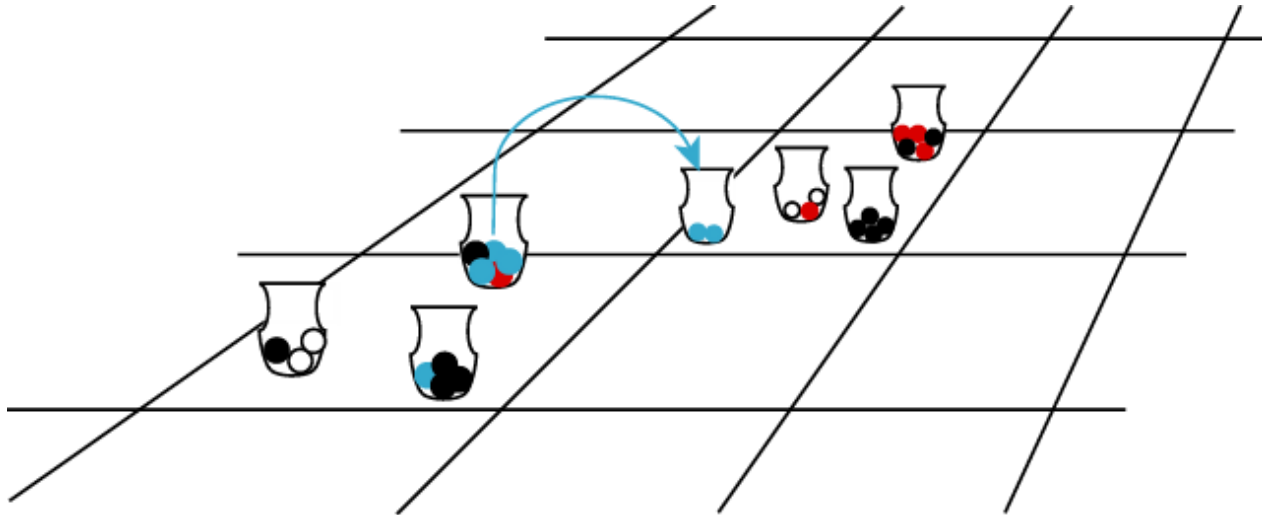
A Spatial Urn Model

Each *site* (square in the array) is assigned a set of urns containing the **reactant species** (e.g. proteins) at that site.

Each **reactant species** is assigned a distinct **color**.

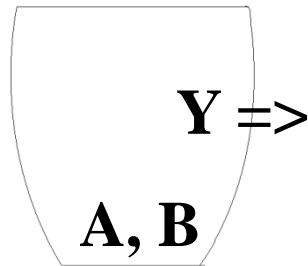
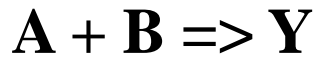
The **number of balls** of each color in each urn gives the **local concentration** of that reactant species.

Diffusion takes place by moving balls at random between adjacent urns.



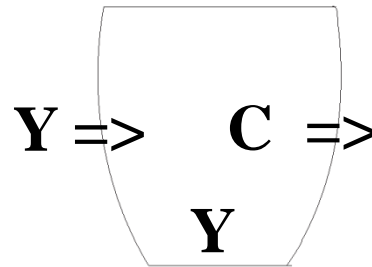
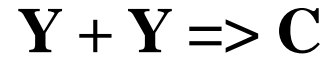
Coupled Gated-Urns

Two irreversible reactions:



$$p(A) = p(B) = 1/2$$

A and B are replenished as soon as used; Y is removed as soon as formed.



$$p(Y) = 1$$

C is removed as soon as formed.

Reactions in Coupled Gated-Urns

[Reactions result from random collisions – the “billiard ball” mechanics of elementary chemistry]

Reactions in the **coupled urns**:

$$p(a) = p(b) = 1/2$$

Production of Y in **urn 1**: $2p(A)p(B) = 1/2$

Production of C in **urn 2**: $P(Y)P(Y) = 1$

Net production of C per time-step: $2p(A)p(B) P(Y)P(Y) = 1/2$

Comparison of Throughput in a Pair of Coupled Urns with Throughput in a Pair of Independent Urns

Throughput (net production of C) in a **single urn**:

$$p(A) = p(B) = p(Y) = 1/3$$

$$\text{Production of Y: } 2p(A)p(B) = 2/9$$

$$\text{Production of C: } P(Y)P(Y) = (1/3)(1/3) = 1/9$$

Production of C per time-step in a **single urn**: $2p(A)p(B)P(Y)P(Y) = 2/81 \sim 1/40$

Production of C per time-step in **two uncoupled urns**: $2/40 \sim 1/20$

[from previous slide]

Production of C per time-step in a **pair of coupled urns**: $1/2$

Speedup (provided by coupling) $(1/2)/(1/20) = 10$.

[Cf. Adam Smith's 'pin factory']

Co-evolution in Gated-Urn Models

- (1) A **population** of tagged urns generates a **directed interaction network**.
- (2) **Changes in the tags** used by the urns' entry/exit conditions **change the network** of interactions.
- (3) **Recombination** of entry/exit conditions (using, say, a genetic algorithm) modifies the network by recombining parts of extant tags to generate new conditions.
New urns can **establish new niches**, or enlarge existing niches.

Co-evolution in Gated-Urn Models

mediated by

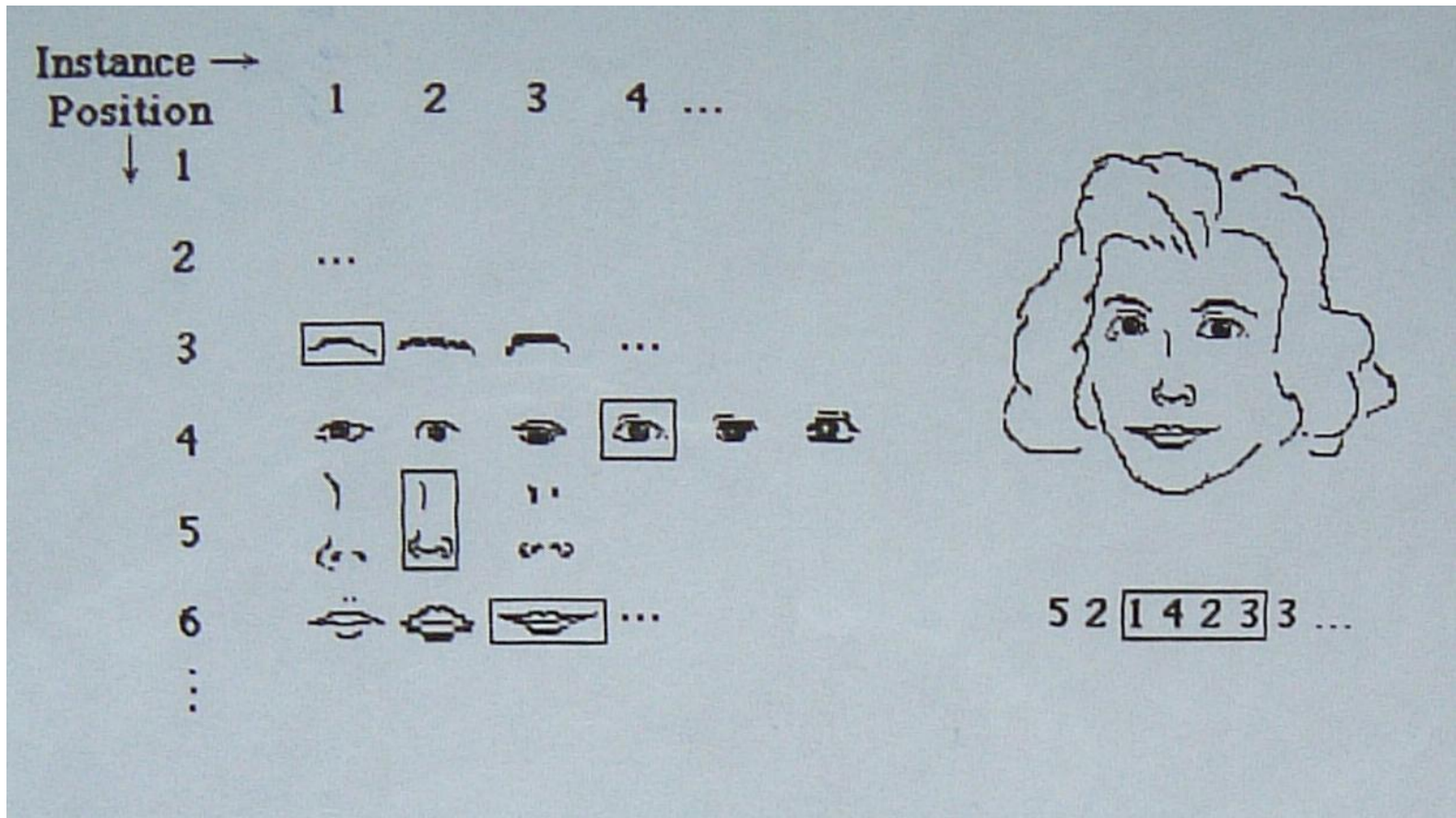
Building Blocks

As the entry/exit conditions are recombined, **parts** of the conditions serve as **building blocks** for new tags.

As agents (urns) replicate, **building blocks** for tags that route important signals tend to **appear in more combinations**.

Tags with similar building blocks often mediate similar functions (cf. **motifs** in genomics) .

The Importance of Building Blocks



Emergent Phenomena in Tag-Based *cas*

Semi-permeable boundaries provide **locally increased concentrations** of reactants
– **niches** – that offer new possibilities for interaction.

Through the ‘**layered**’ use of **boundaries and tags**, **agents become building blocks**
for still more complex agents,
as in the membrane=>organelle=>cell=>organ=>... hierarchy of biological cells.

Co-evolution of tags, under genetic operators (e.g. recombination), provides
increasing diversity of signals and agents.

Summarizing: Reactions, Conditions, & Tags

- 1) A **reaction** requires a given **combination of tags** (active sites) for **each reactant** involved.
- 2) An entry/exit **condition**, using 'don't care' (#) symbols, specifies the particular **combination** of tags required for balls (reactants and signals) **to enter or exit a gated urn**.
- 3) Accordingly, when an urn admits balls with **tags required for a given reaction**, the concentrations of the reactants will usually be substantially increased, **increasing the reaction rate**.

Semi-permeable boundaries act much like catalysts.

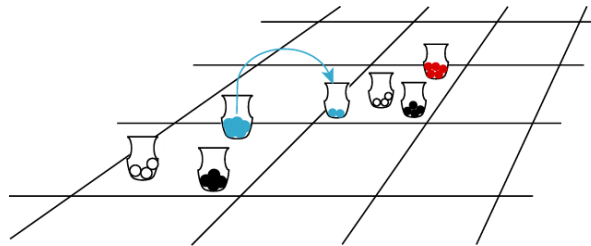
Formalisms for Signal/Boundary Hierarchies

Difference Equations

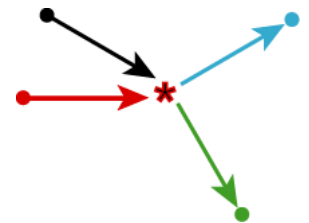
$$x(t+1) = x(t) - rx(t)y(t) + r^*u(t)v(t),$$

where x, y, \dots are concentrations and r, r^*, \dots are reaction rates.

Urn Model



Billiard Ball [撞球] Mechanics (Markov Process)



Rule-based Signal Processing

$$a_1 a_2 a_3 \dots a_k \ \& \ b_1 b_2 \dots b_k \Rightarrow a_1 \dots a_k b_1 \dots b_k$$

Quick Summary

- 1) The **co-evolution of signals and tags** can provide the hierarchical organization typical of *cas*.
- 2) **Exploratory gated-urn models** allow us to explore these possibilities.

[The **emergence of language** from pre-primate abilities provides a good test of these ideas.]

Hypotheses to be Tested

Local concentrations of resources induced by feedback and recycling provide opportunities for the **formation and adaptive radiation of agents**.

This process of **agent formation** leads to increasing diversity of agents and progressively **larger amounts of resource “tied up” in agents**.

Under **‘tranquil’ conditions**, increasing **agent specialization** should be observed.

Two BIG Problems

- 1) There is no comprehensive theory of the **signal-modulated behavior in niches** and autonomous systems.

For example, a **theory of mind** requires **internal models for anticipation** of future actions of other agents within the physical world.

- 2) There is no over-arching theory of the **co-evolution** of agent **interaction networks** and **the flow of resources and signals** over those networks.

For example, an **increasingly diverse range of carbon exchanges and recycling** produces the **complex hierarchies** of an ecosystem or a biological cell.

A Crude Look Claim

Even a crude look at a complex adaptive system must be **layered** because of the **increasingly diverse communities** (niches) that emerge as *cas* agents co-adapt.

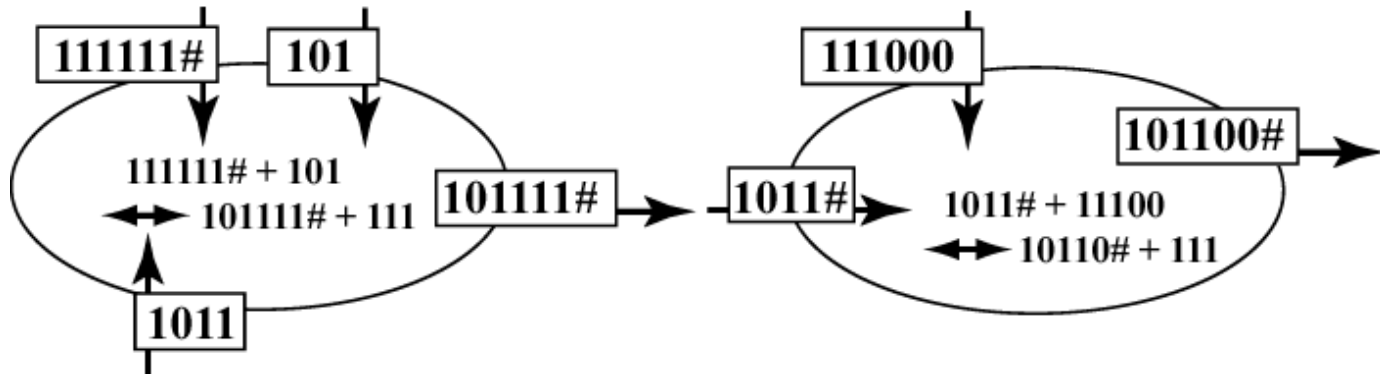
For example, new technologies rapidly create **new markets**, as well as **new threats** to the environment and governments.

To **assess** these risks and **steer** through their impact, even a crude model must provide for the **co-evolution of signals and boundaries**.

Gated urns offer one way of constructing and evaluating such models.

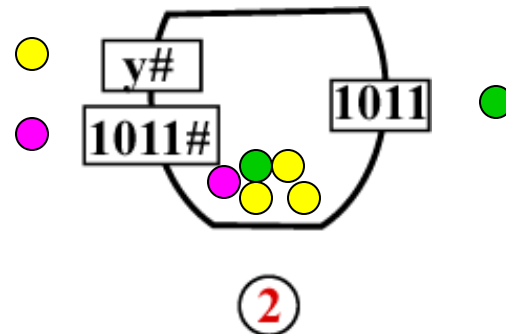
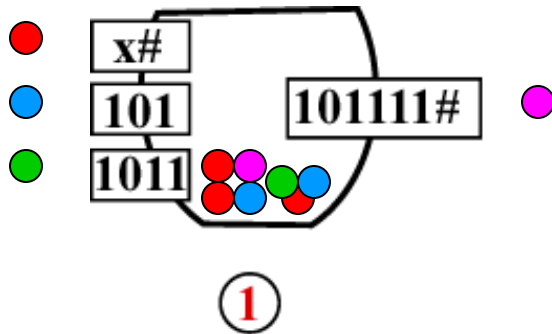
Additional details

Urn Model of Interactions

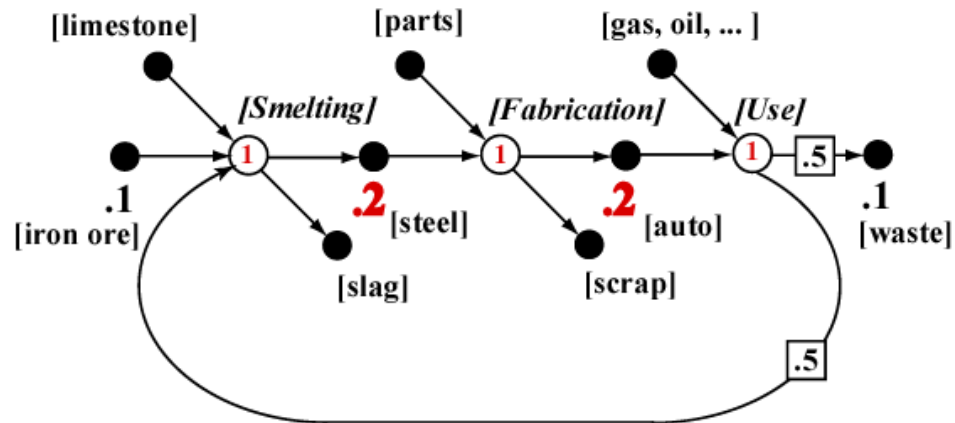
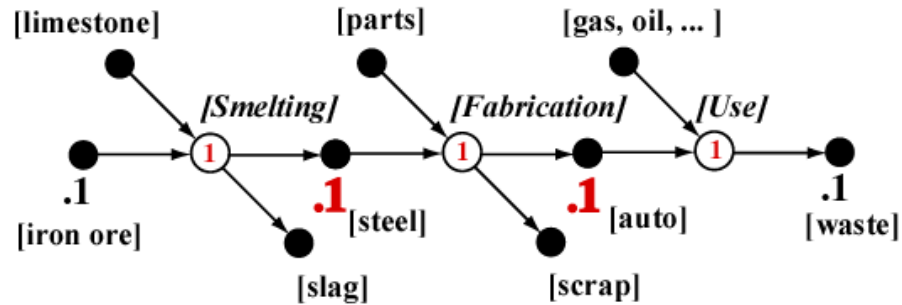


● $x = 111111$

● $y = 111000$



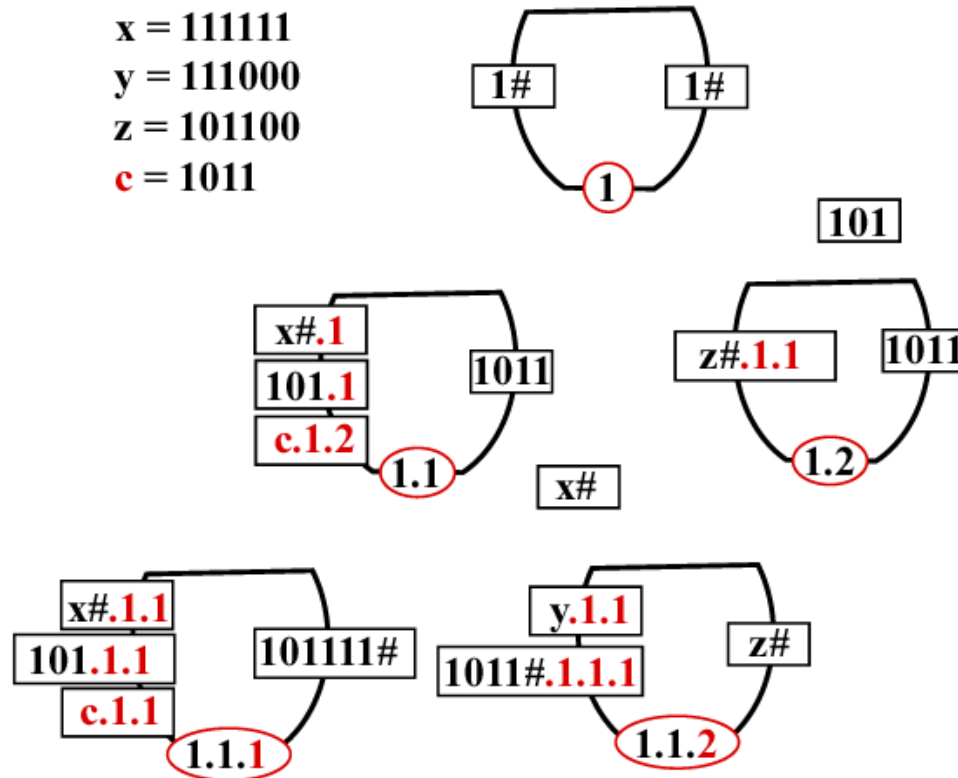
The Effect of Recycling



Note the increased concentration in the interior of the loop.

A Hierarchical Urn Model

Urn do **not** have to be placed inside urns to provide a hierarchy.



The **suffix** on the each urn entry tag **specifies the urn(s) from which incoming balls may be drawn.**

A Sequence of Markov Matrices describes Co-evolution

Each change in a tag results in a new Markov matrix for describing the dynamics of the s/b system.

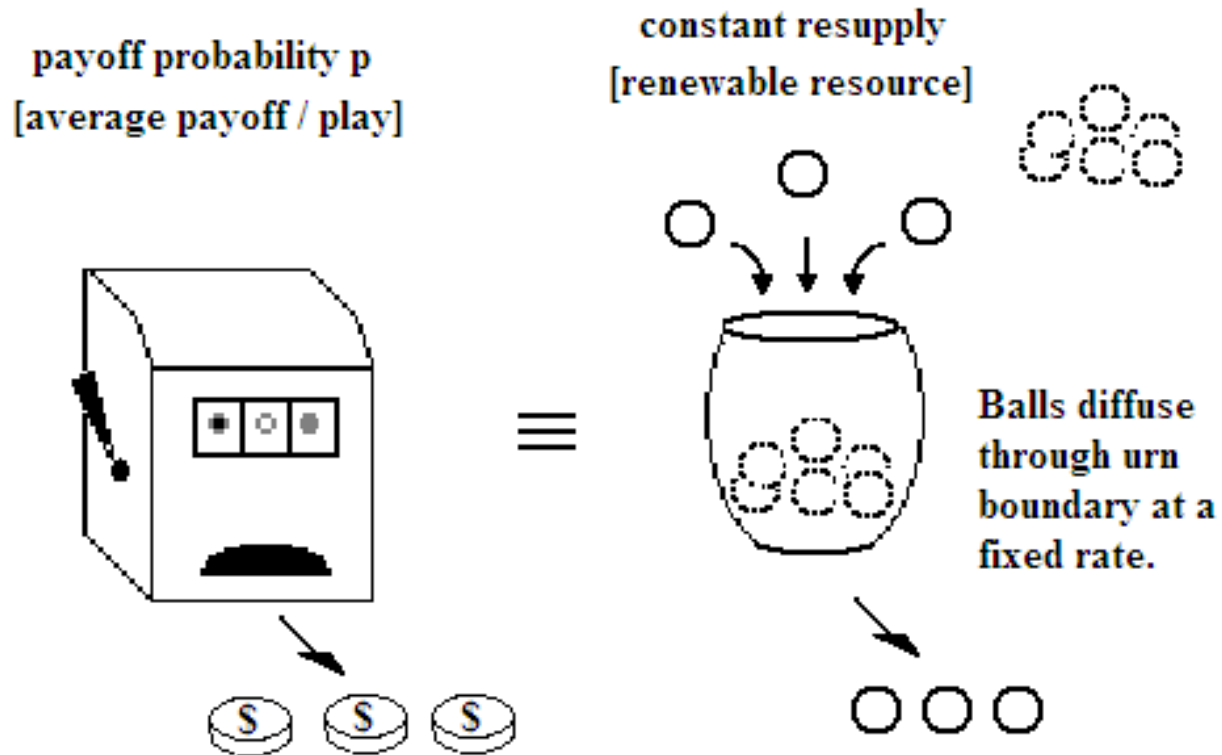
The changes in the matrix are often restricted to a small part of the matrix, making it relatively easy to predict the effects on the system.

A co-evolutionary sequence is described by the sequence of Markov matrices that correspond to the changes.

The evolution of the s/b interaction network is accordingly so-described

Modeling Niches with One-armed Bandits and Tagged Urns

Using a **one-armed bandit** (a slot machine with a fixed payoff probability) as a **starting point**, a mathematics for studying niches can be developed.

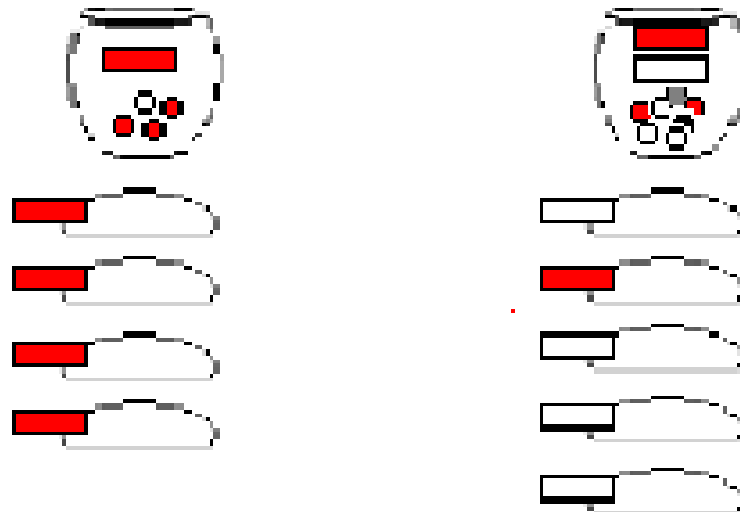


Tagged Urns with Queues

Payoff / time-step

1 ◻ / 3 ●

8 ◻ / 1 ●



Agents in a queue share resources that match their tag.

payoff ◻ / agent ◻

2.0 ◻ / time-step

payoff ● / agent ●

0.75 ● / time-step

1.0 ● / time-step

2(n)-armed Bandits are Equivalent to 2(n) Tagged Urns with Queues

A **two-armed bandit**, is a slot machine with two levers, each with a different payoff probability; it offers **two 'niches' for a player**.

To find the arm (niche) that **maximizes long-term payoff**, both arms must be sampled continually, allocating **exponentially more samples to the observed best arm**.

The **mathematics of 2(n)-armed bandits is well-developed**, and can be adapted to the study of tagged urns with queues.

Key point: An agent that best uses resources supplied by a niche **replicates exponentially** more rapidly than other agents in the niche -- that is, **the agent increases its sampling rate exponentially** as required by n-armed bandit theory.

Some Complex Outcomes of Signal/Boundary Co-evolution

The “devil’s” garden

Octopus “joints” and convergent evolution

Octopus mimicry of snakes and fish

The signals and boundaries induced by **averaging** of environmental changes in a *cas* (“riding it out” – e.g. **spores**) are quite different from those induced by **tracking** (e.g. the **immune system**).

Outline

- 1) **Complex Adaptive Systems (cas).**
- 2) **Signal-processing.**
- 3) **Tags.**
- 4) **Boundaries.**
- 5) **Gated urns.**

Characteristics of a *cas*

- There is **no universal competitor** or global optimum.
- There is great **diversity**, as in a tropical forest, with many **niches** occupied by different kinds of agents.
- **Innovation is a regular feature** – equilibrium is rare and temporary
- **Anticipations** change the course of the system.

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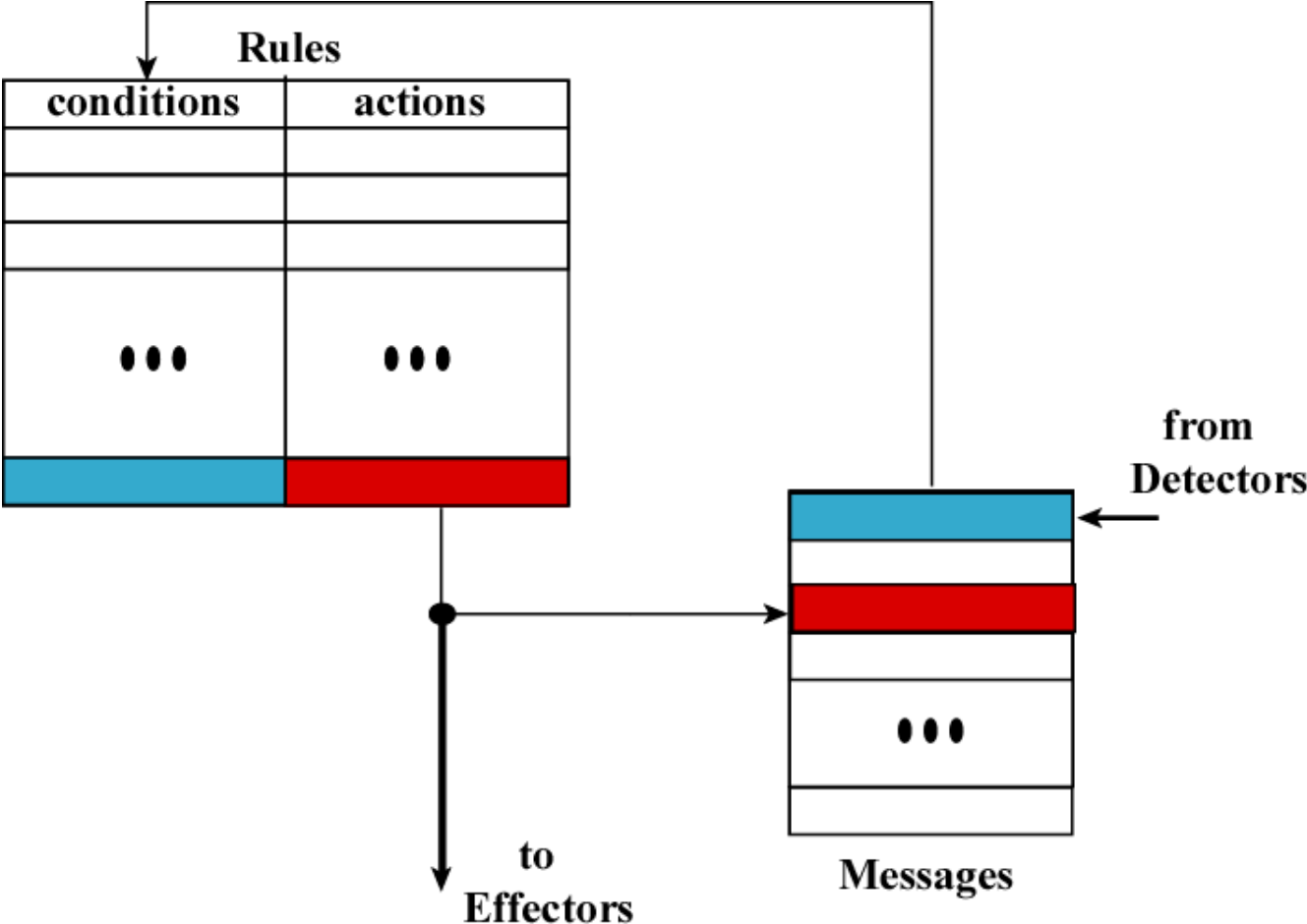
Rule-based models

Using binary strings, a *cas* agent can be modelled with **string-processing rules**:

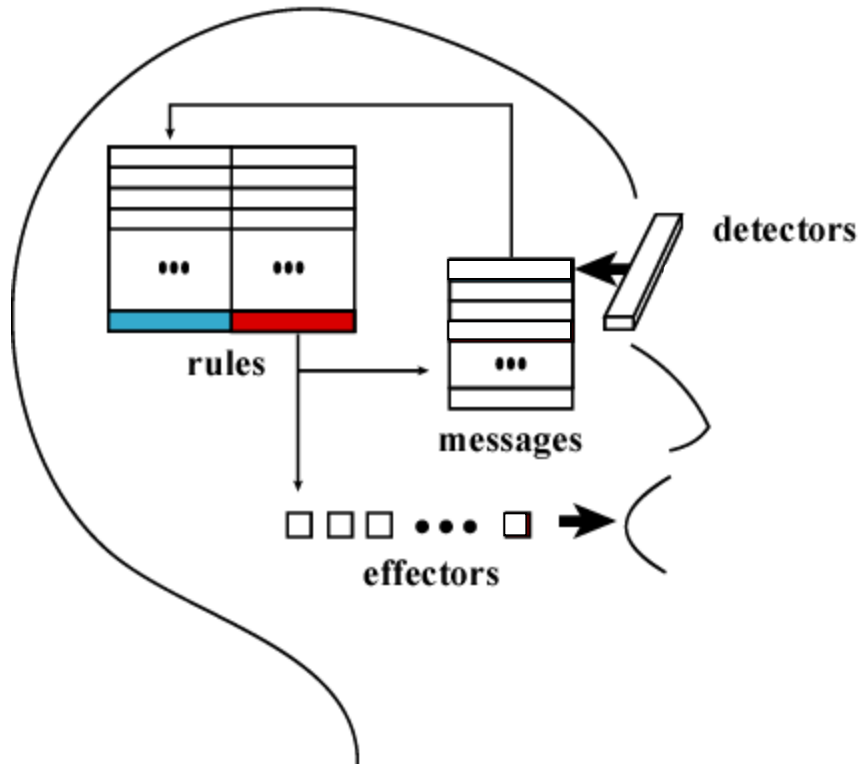
**IF (signal 100110 present) & (signal 1110 present)
THEN (send signal 00111).**

These string-processing rules can be combined to simulate **any computer-executable model** -- this rule system is *computationally complete*.

A Classifier System



A Language-oriented Agent



Outline

- 1) **Complex Adaptive Systems (cas).**
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- 4) **Boundaries.**
- 5) **Gated urns.**

Tag-sensitive rules

Tag-sensitive rule conditions can be specified using a three letter alphabet {1,0,#}, where the # is a 'don't care' symbol.

For example:

The condition **100#** accepts any signal string that has the prefix 100, and the rule

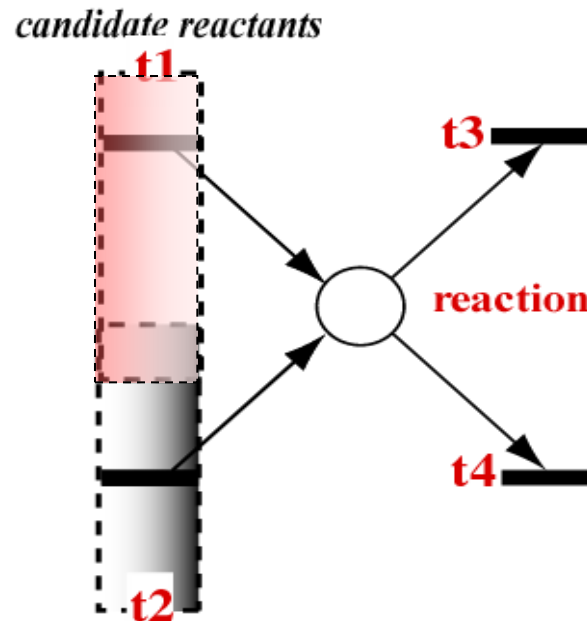
IF(100#) & (#110#) THEN (00111)

if presented, say, with the signals **100110** and **0111011** would send the signal **00111**.

Billiard Ball Mechanics

A Rule-based Version of Signal Processing (similar to a chemical reaction)

IF [**t1**#...#] & [**t2**#...#] THEN [**t3**a1...1k] & [**t4**b1...bk]



t1, t2, t3, and t4 are tags (ligands, receptors, active sites).

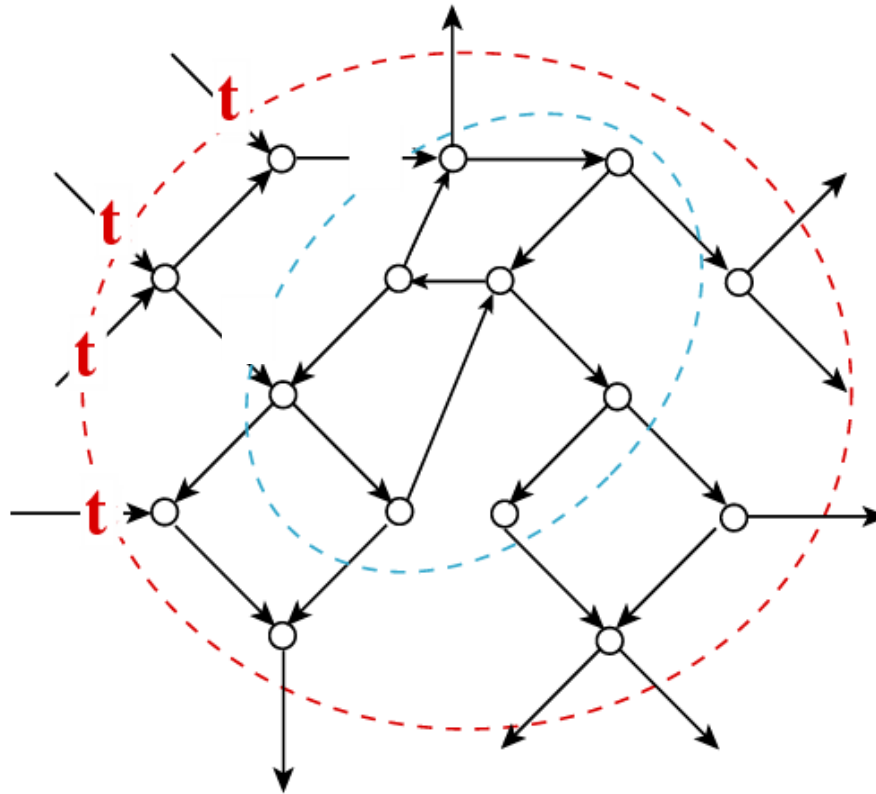
— is a particular string; if it has the tag prefix **t1** it is a candidate reactant (for the first reactant of the binary reaction)

Outline

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Tag-based Boundaries

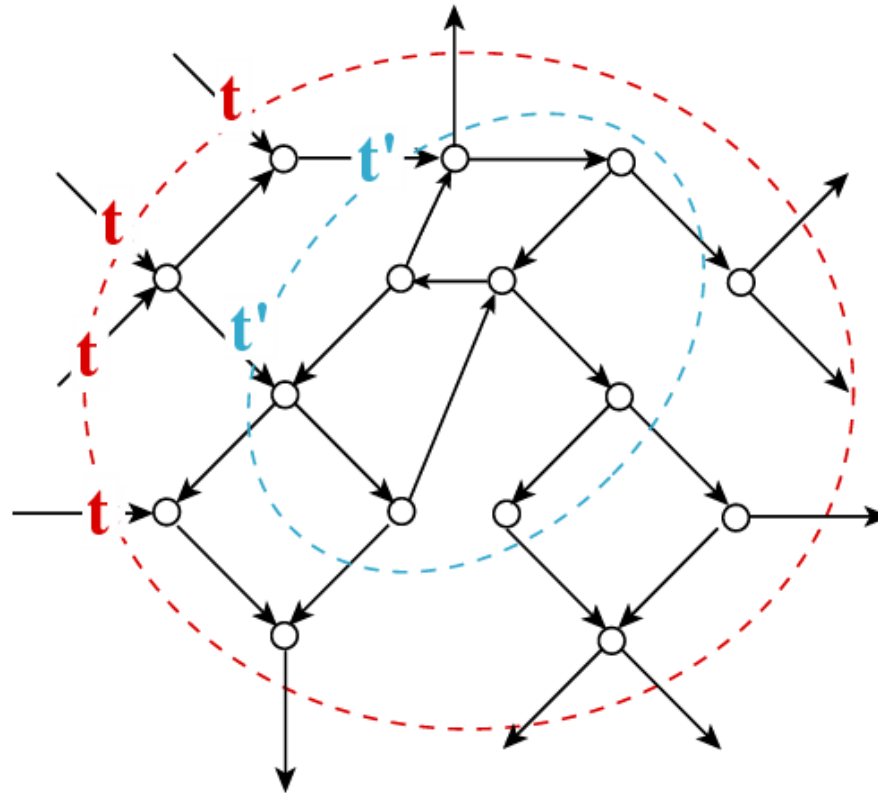
A reaction network with 4 inputs and 7 outputs



Only reactants with the tag **t** can enter the network.

Boundaries in a Interaction Network

A reaction network with 4 inputs and 7 outputs



Only reactants with the tag **t** can enter the network.
Only reactants with tag **t'** can enter the interior network
which has **2 linked feedback loops**.
The two tags designate nested boundaries that constrain
flows within the network.

Outline

- 1) **Complex Adaptive Systems (cas).**
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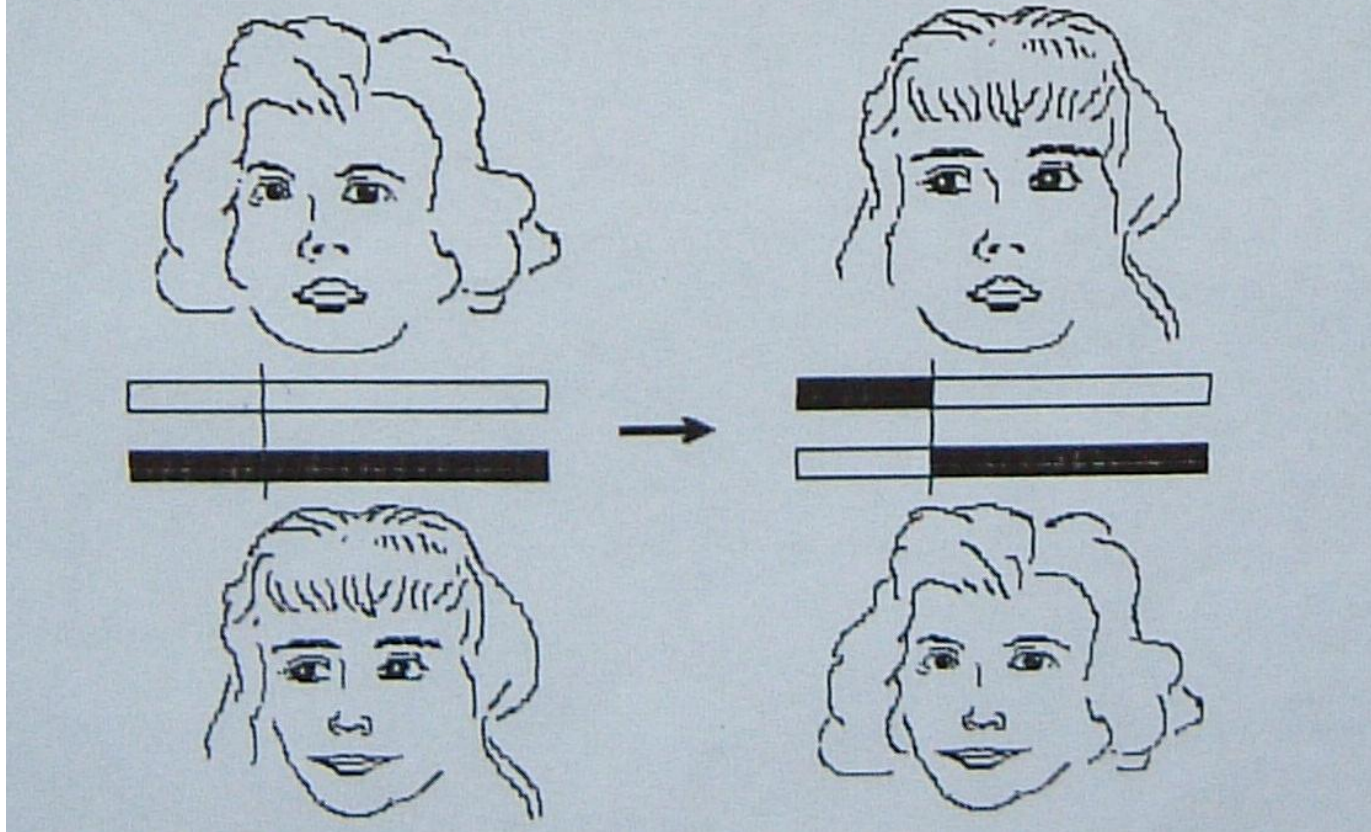
Gated Urn Dynamics

- 1) The **state s** of a collection of tagged urns is given by the **distribution** of colored balls in the urns.
- 2) **Diffusion and interactions change this state** time-step by time-step.
- 3) When the tags and conditions remain constant, the **change in ball distribution** can be described by a **Markov matrix M**
$$s(t+1) = Ms(t).$$
- 4) Under typical conditions, the **probability** of finding a given color of ball in a given urn becomes a **constant as time elapses**.
$$Ms = s.$$

Tags and Co-evolution

Innovation by Recombination

Using the number string representation for faces, new faces can be constructed by using the *crossover* operator on pairs of faces.



Faces, in turn, become building blocks for social recognition and interaction.

Reactants

The form of an s/b interaction typically depends upon a **tag**, a small segment of the reactant, e.g. the **active site** of a protein.



In a **spatially distributed reaction system** reactants typically undergo a mass action chemistry – a **'billiard ball' mechanics** – diffusing and colliding at random.

Colliding reactants react with a probability determined by the **reaction rate**.

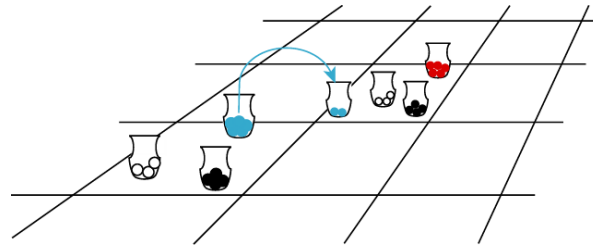
Formalisms for Reaction Nets

Difference Equations

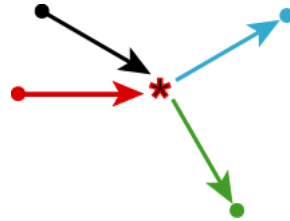
$$\mathbf{x}(t+1) = \mathbf{x}(t) - r\mathbf{x}(t)\mathbf{y}(t) + r^*\mathbf{u}(t)\mathbf{v}(t),$$

where x, y, \dots are concentrations and r, r^*, \dots are reaction rates.

Urn Models



Billiard Ball Mechanics (Markov Process)



Rule-based Signal Processing

$$a_1 a_2 a_3 \dots a_k \ \& \ b_1 b_2 \dots b_k \ \Rightarrow \ a_1 \dots a_k \ b_1 \dots b_k$$

Outline

- 1) **Complex Adaptive Systems (cas).**
- 2) **Main components: Signals and Boundaries.**
- 3) **Generated systems, Strings, and Tags.**
- 4) **Co-adaptation and Niches.**
- 5) **Dynamics and Steering.**

Well-known Building Blocks in Science

A typical hierarchy of mechanisms (building blocks) in science:

<u>Level</u>	<u>Building Block</u>
nucleon (proton, neutron)	quarks, gluons
atom	protons, neutrons, electrons
gas or fluid	
confined (e.g., a boiler)	PVT equations, flows
free (e.g., weather)	circulation (e.g., fronts), turbulence
molecule	mass action, bonds, active sites
organelle	membranes, transport, enzymes
...	...
ecosystem	predation, symbiosis, mimicry

Building Blocks and Innovation

Most **innovation** comes from **combining well-known building blocks** in new ways.

For example, the **internal combustion engine** combined well-known parts in a new way:

gears for mechanical advantage,
pumps for fuel distribution,
Volta's sparking device for ignition,
Venturi's perfume sprayer for carburetion,
and so on.

Specific combinations of building blocks at one level **become building blocks for the next level** of the hierarchy.

Building Blocks and Theory

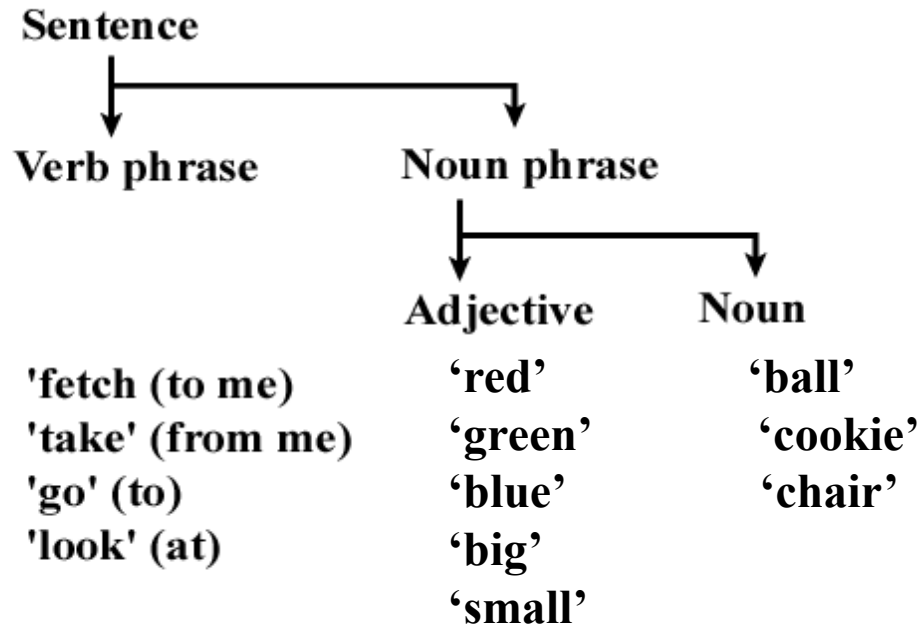
Theory is often advanced by finding a new building block for an old problem.

For example, **Bjerknes**, a scientist from Bergen, Norway introduced the notion of **fronts** as a building block for describing weather patterns.

Using **fronts** to make predictions from familiar data, the accuracy of weather prediction increased from **60% to approximately 75%.**

Grammars

A grammar makes possible the combinatoric use of vocabulary.



60 meaningful triples can be constructed from the 12 utterances shown.

The number of meaningful n-tuples increases factorially with increasing size of the vocabulary of utterances.

E.g. Increasing the number of utterances above to 20+20+20 yields 8,000 triples!

Finitely Generated Systems

A grammar is an example of a finitely generated system.

A *finitely generated system* consists of a finite set of *generators*,

$$G = \{g_1, g_2, \dots, g_n\},$$

and a finite set of *operators*

$$R = \{r_1: G \times G \Rightarrow G, \dots, r_k: G \times G \Rightarrow G\}$$

for assembling the generators into strings.

The *operators are applied repeatedly* to partly assembled structures to produce a *corpus* of strings.

Finitely generated systems can be used to *extend the notion of grammar* and *corpus to any evolving s/b system*.

[In mathematics, a *finitely generated group* is a finitely generated system.]

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- 5) **Dynamics and Steering.**

Outline

- 1) **Complex Adaptive Systems (cas).**
- 2) **Main components: Signals and Boundaries.**
- 3) **Generated systems, Strings, and Tags.**
- 4) **Co-adaptation and Niches**
- 5) **Dynamics and Steering**

Additional Details

Typical Adaptive Agents

System

Ecosystem

Economy

Immune System

Market

...

Agent

Organism

Firm

Antibody

Trader

...

Strings

The building blocks of s/b systems are generated from simple “**alphabets**”.

s/b system

genetics
molecular biology
ecological niches

language communities
music
political units
production lines

signals

chromosomes
proteins
resources

utterances
melodic phrases
memoranda
raw materials

alphabet

nucleotides
amino acids
C, N, O
(and “trace elements”)

phonemes
notes
written alphabet
atoms

Thus, **signals**, **boundary conditions**, and **reactants** in s/b models can be represented as **strings** without loss of generality.

Objectives

Observe the **robustness** and organization of the **generated networks** that result from signal/boundary/reaction arrangements.

Observe the kinds of **agents** (bounded sets of reactions), if any, that form through the **co-evolution of tags**.

Develop a notion of **niche**, based on local resource enrichment, that applies to these **dynamic, perpetually changing networks**.

Niches in S/B Networks

A **niche** is an intense localized **recirculation of resources and signals** flowing over the interaction network of an s/b system.

[A niche is a complex version of the **standing wave** in front of a rock in a whitewater river – dependent on the flow, and self-repairing.]

[Mark Newman's definition of **community** for graphs captures many of the network properties of a niche.]

Niches are ***semi-autonomous***: **input from outside the niche generally just modulates ongoing activity.**

The niche concept is widely used in discussing *cas*, though usually in an intuitive or narrow sense.

ecological niche (for a species)

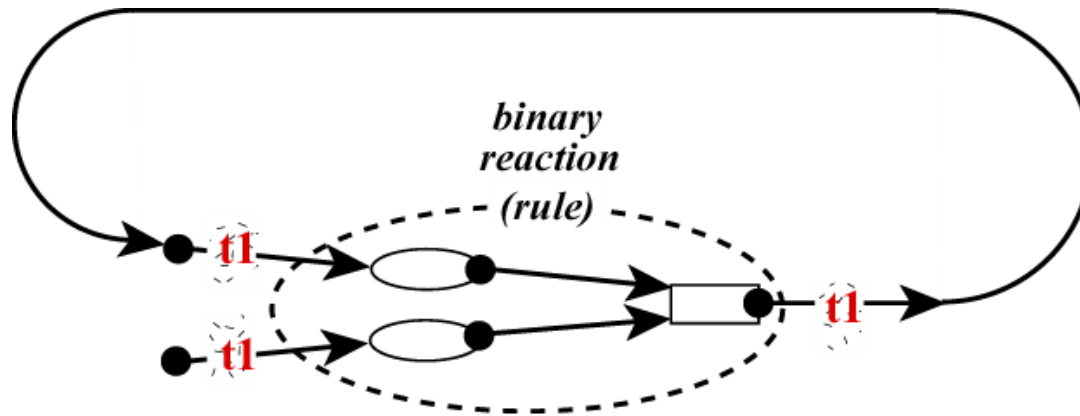
market niche (for a firm)

cell assembly (for a nervous system)

etc.

Building Agents from Reactions (1)

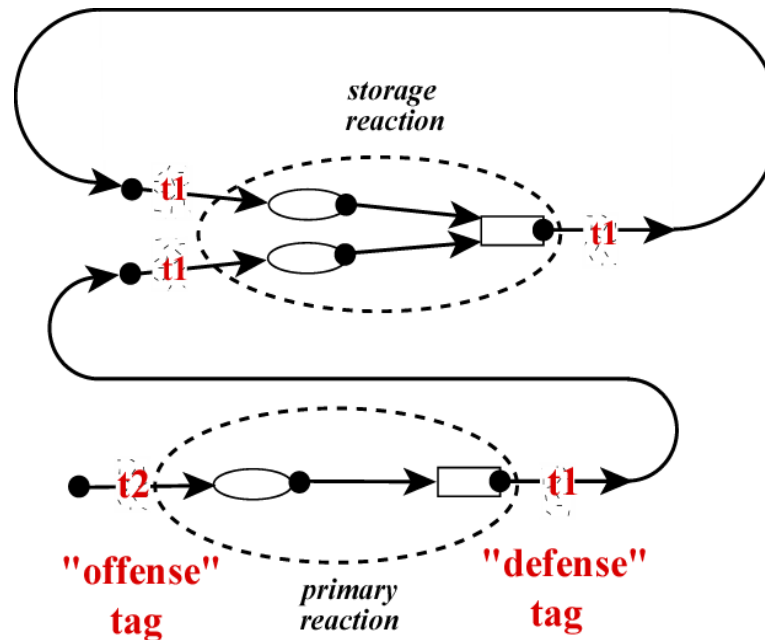
A Reservoir [储蓄器]



The **tag t1** keeps the content of the reservoir **recycling**, while at the same time allowing **additional input** to the reservoir.

The reservoir can only be "tapped" by a reaction that uses tag t1.

Building Agents from Reactions (2)



The **"defense" tag** limits interactions. The tag is **not arbitrary** because it is also used to transport resources to the reservoir reactions.

Reaction Inside a Semi-permeable Membrane

Consider a system that consists of :

(1) the reaction, $x\# + *y \rightleftharpoons xy + \#*$,



(2) a semi-permeable boundary that allows entry of reactants with tags x and y and exit of reactant ab,

