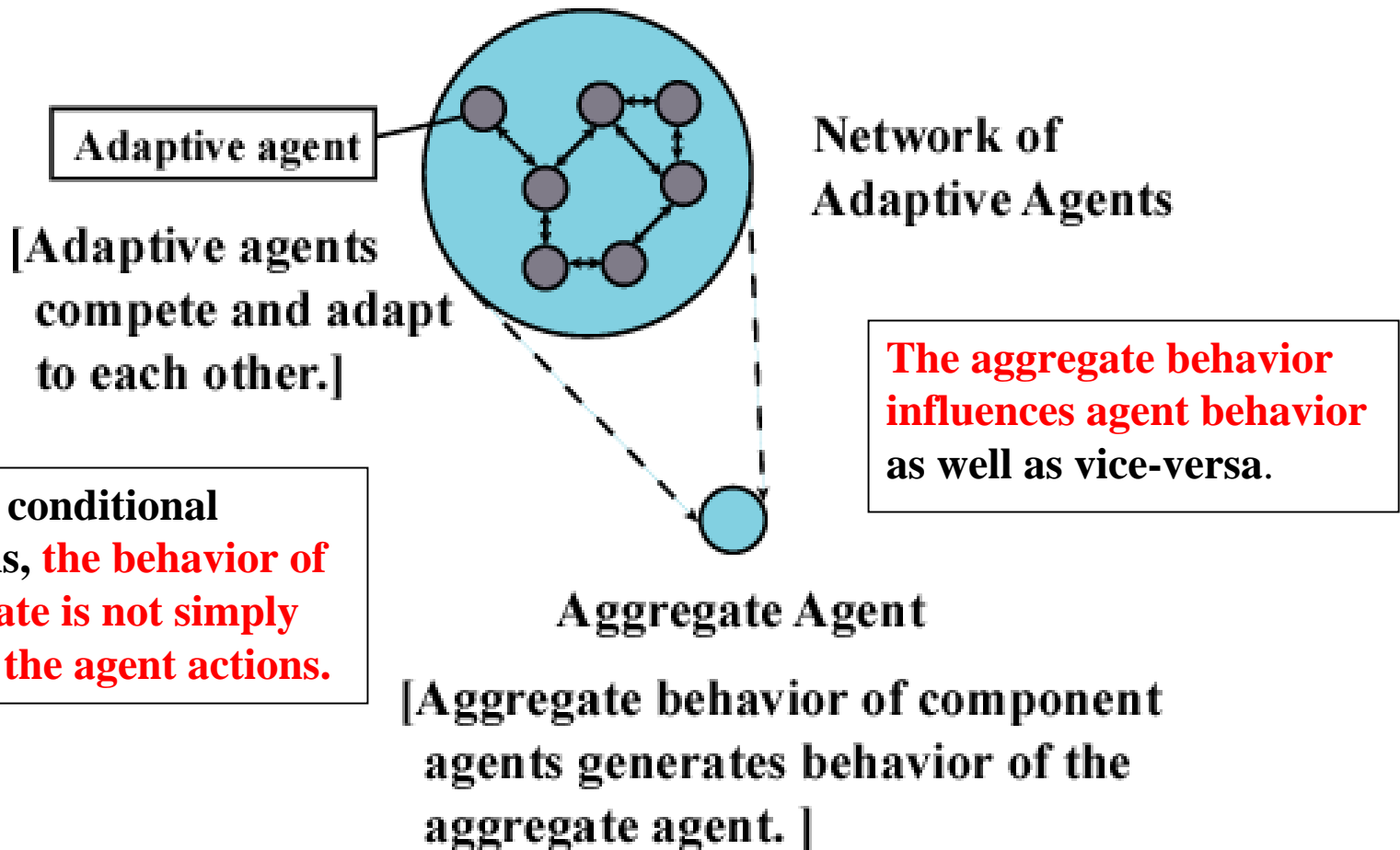


**Innovation  
in  
Complex Adaptive Systems**

# Cross-disciplinary Similarities

<u>Control theory</u>	<u>Economics</u>	<u>Biological cells</u>	<u>Games</u>
process variables	activities	phenotypic features	board configurations
operating costs	activity costs	metabolic costs	board evaluation
objective function	profit	fitness	payoff
<b>control policy</b>	<b>plan</b>	<b>reaction net</b>	<b>strategy</b>

# A Complex Adaptive System [*cas*]



# Problems Involving Complex Adaptive Systems

Some **difficult** problems:

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**.

These problems center on systems with many **interacting agents** (components) that **learn or adapt**.

## Characteristics of a *cas*

A complex adaptive system, **cas**, is an evolving, perpetually novel set of interacting agents where

- 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

# Adaptation

Adaptation occurs when **agents learn** from each other or **change strategies** as they gain experience.

**Evolving economies** and **ecosystems** are much-studied examples of adaptation.

# What is an Adaptive Agent?

## *System*

**Ecosystem**

**Economy**

**Immune System**

**Market**

...

## *Agent*

**Organism**

**Firm**

**Antibody**

**Trader**

...

# Agent Based Models

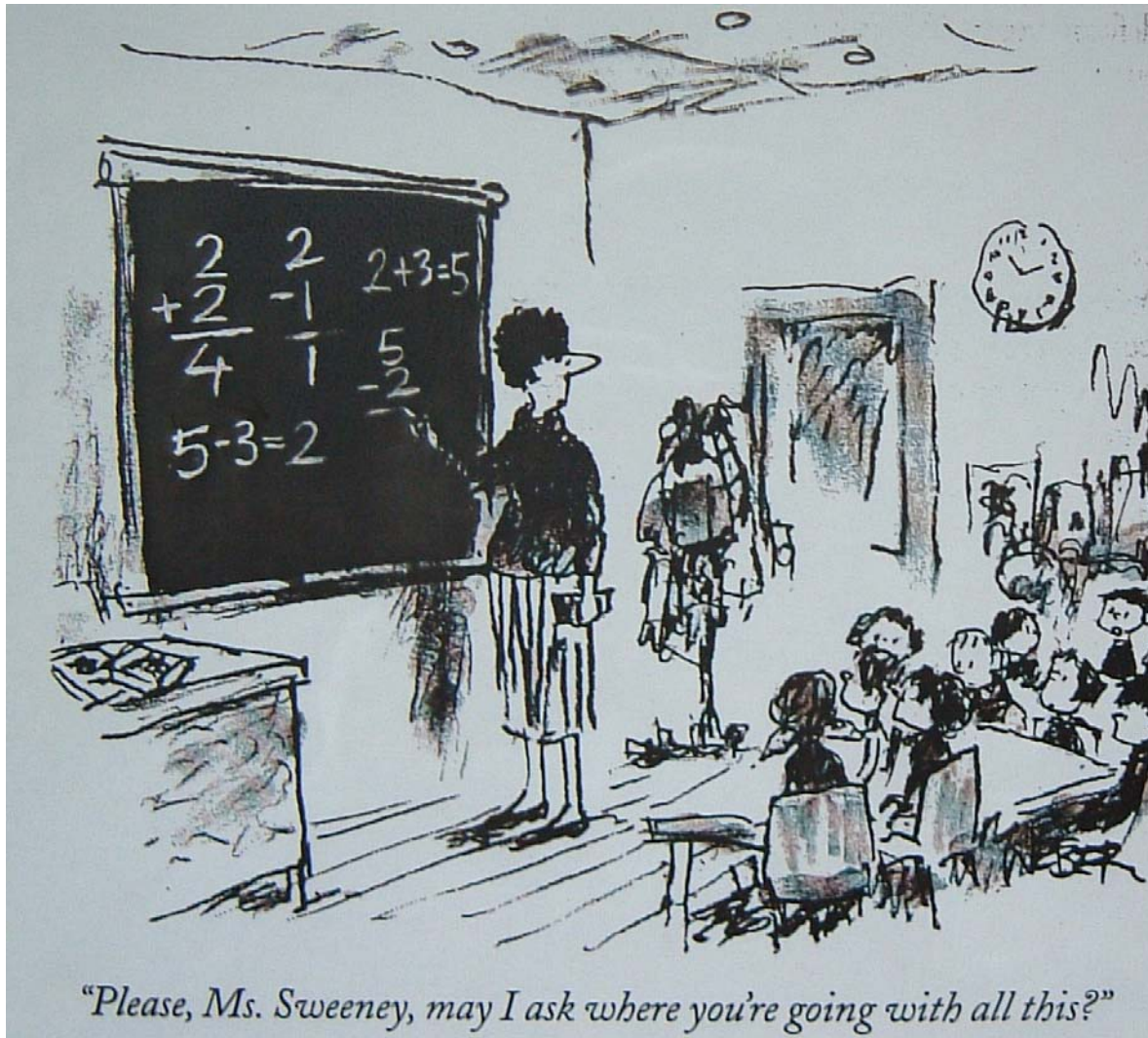
A direct way to implement a *cas agent* in a computer is to provide the agent with a set of **rules** that determine its actions and strategy.

A **GA** modifies the rules as the agent accumulates experience.

**Classifier Systems** offer a well-studied formalism for building such models.

[Artificial Stock Market]

## A New Formalism Often Raises Questions.



**Please, Ms. Sweeney, may I ask where you're going with all this?**

## Computer-based Models of *cas*

The interactions in *cas* are usually **conditional and nonlinear** rather than additive.

The usual technique of reduction – studying the parts and then **adding the behaviors** of the parts – **does not work**.

**The interactions as well as the parts must be studied.**

Computer-based **models** are a crucial tool for exploring the interactions.

# Model & Hypothesis

**A model, like a hypothesis, suggests where to look.**

**There are three basic kinds of model:**

- 1) Data-driven** [e.g., weather prediction models]
- 2) Existence-proof** [e.g., von Neumann's self-reproducing automaton]
- 3) Exploratory** [e.g., artificial life]

**The contemplation in natural science of a wider domain than the actual leads to a far better understanding of the actual**

**– A. S. Eddington**

# Building Blocks and Innovation

We understand the world around us - **proteins, spacecraft, or languages** - by discovering the relevant building blocks

**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.

# Well-known Building Blocks (1)

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

## System

nucleon (proton, neutron)

atom

gas or fluid

    confined (e.g., a boiler)

    free (e.g., weather)

molecule

organelle

...

ecosystem

## Mechanism

quarks, gluons

protons, neutrons, electrons

    PVT equations, flows

    circulation (e.g., fronts), turbulence

mass action, bonds, active sites

membranes, transport, enzymes

...

predation, symbiosis, mimicry

## Well-known Building Blocks (2)

### Phoneme

[elemental sound or gesture]

### Letters

{a, b, c, ... }

### Morpheme

[meaningful combination of  
phonemes]

### Words

{ball, cookie, give, ... }

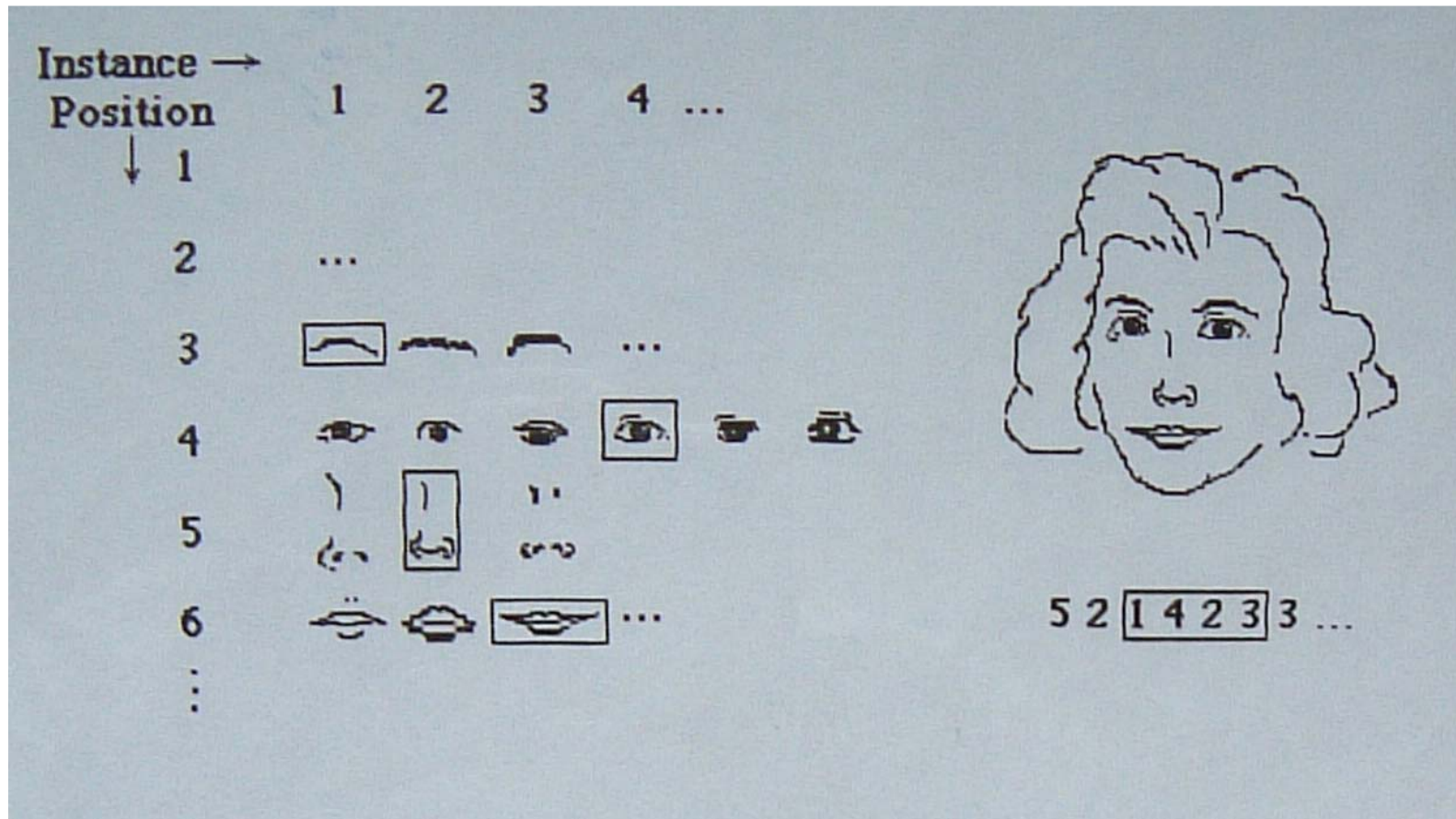
### Sentence

[meaningful combination of  
morphemes]

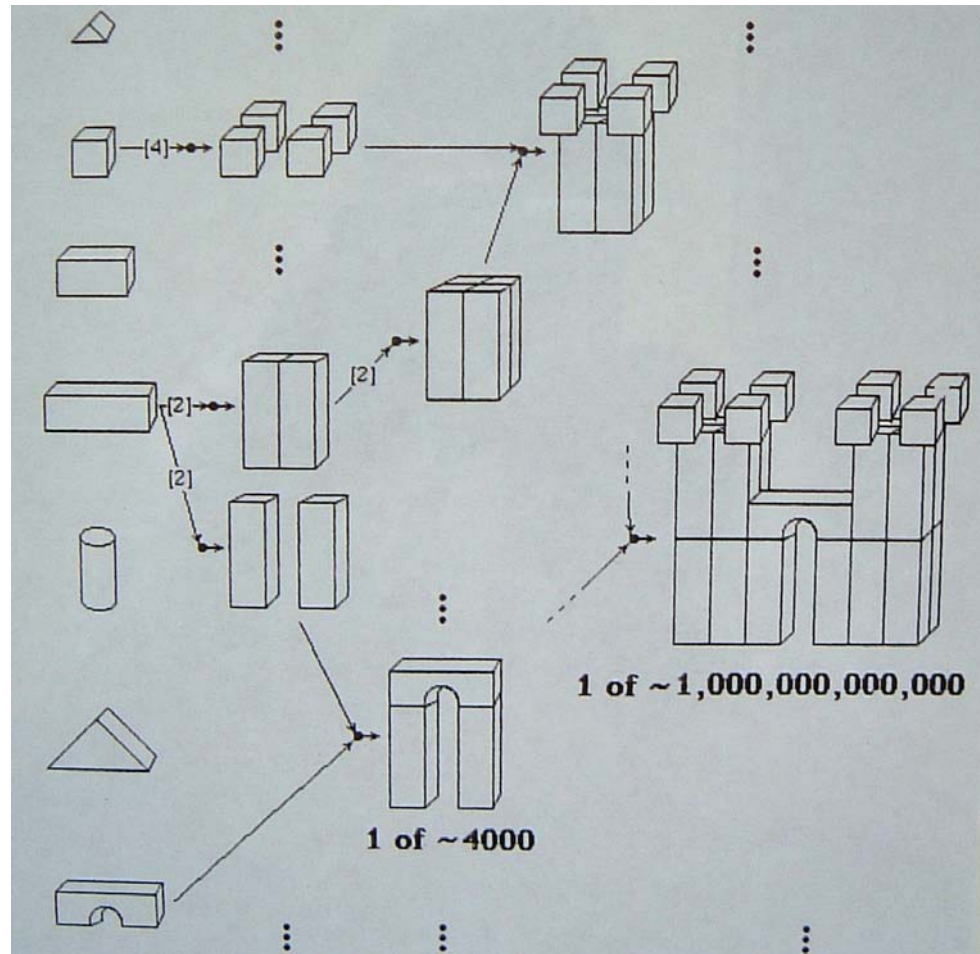
### Sentence

{Give the ball to me. }

# Building Blocks for a Face

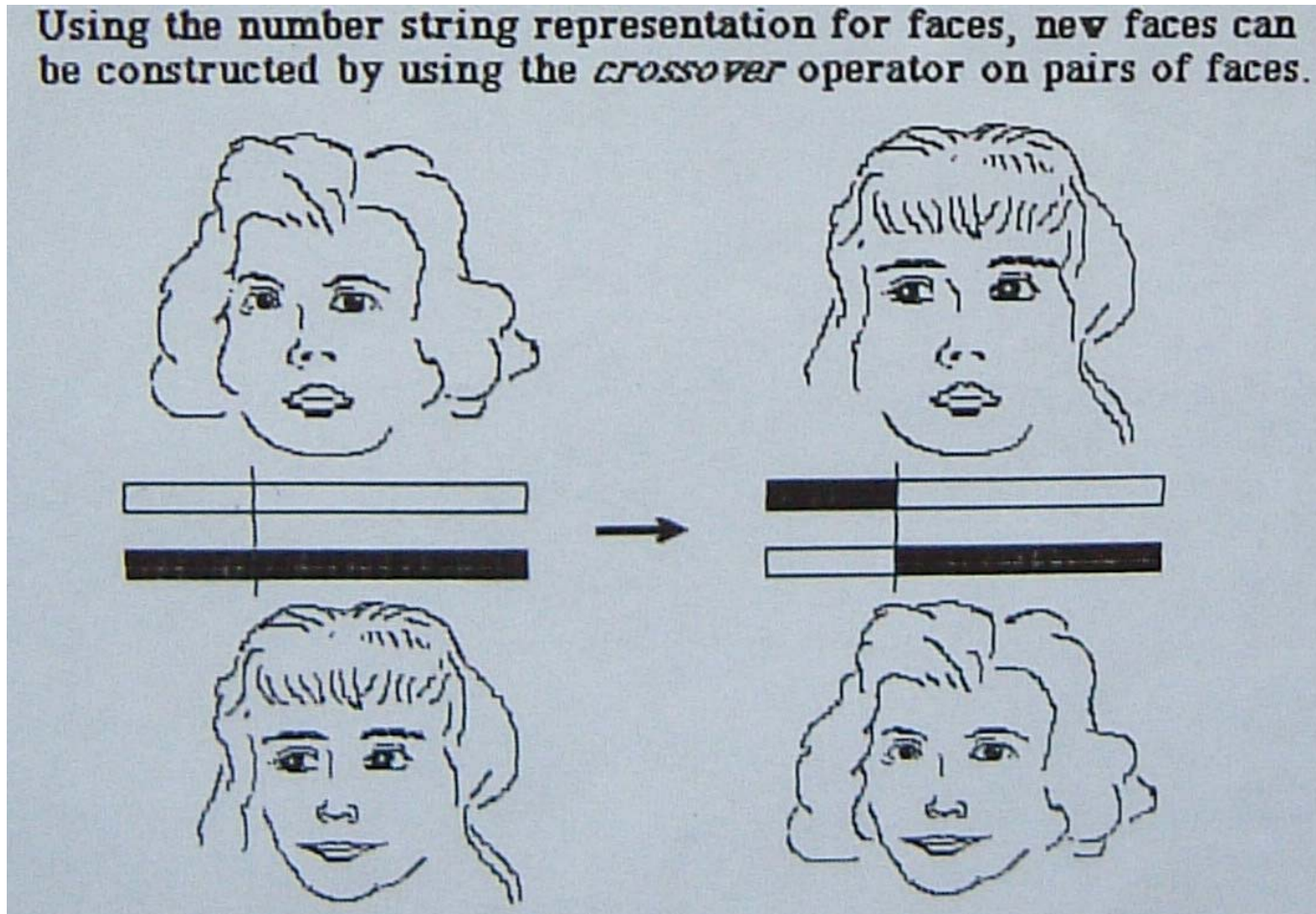


# The Combinatorics of Building Blocks



# Innovation by Recombination

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



# Adaptation and Building Blocks

To understand **innovation** in cas we must understand the relations  
between **adaptation** and **building blocks**.

# CAS and the Conduct of Science

Observing *cas* that regularly produce innovations, e.g. evolving ecosystems, suggests changes in the way we usually conduct research:

- 1) **Risk-taking.** Allow for high failure rates in funding. Because of the exponential growth of the successes and their “spin-offs”, the return from “home-runs” greatly exceeds the losses incurred by the failures.  
[The current bottom line is a poor measure of long-term success.]
- 2) **Diversity and Parallelism.** Follow several paths simultaneously in exploring a given question.  
[Avoid a single “game plan”.]
- 3) **Credit assignment.** Provide ways of rewarding stage-setting activities.  
[“Greedy algorithms” rarely work for *cas*.]

# Stage-Setting

**Credit assignment** is the most difficult activity in the conduct of science or business.

In cas it is usually the **early, less obvious, sometimes costly, activities** that make possible **later, obviously good, courses of action.**

Consider the *gambit* in chess.

Real option theory gives a better approach to these questions than standard decision theory.

[*Real Option Theory* Trigeorgis MIT Press]

# Controlling *cas* – a Simple Example (1)



**Flocking rules:**

- 1) **Be near**, but not too near, **at least one** other bird.
- 2) **The more** birds you are near, **the better**.
- 3) **Follow** the average direction of the birds ahead of you.

# Controlling *cas* – a Simple Example (2)

**Shill**



The **shill's** movement is controlled externally.

The **shill** biases the movement of the flock by taking advantage of the flocking rules; it does **NOT** change the flocking rules.

Professor Han Jing, at the Chinese Academy of Sciences, Beijing, is studying this model of "distributed control" using elaborations of adaptive control theory.

Soft Control on Collective Behavior of a Group of Autonomous Agents by a Shill Agent. Han Jing, Ming Li and Lei Guo. *Journal of Systems Science and Complexity*, 2006(19):54-62.

## Controlling *cas* – a Simple Example (3)



Professor Han's model and analysis show that distributed control is possible and effective.

# The Importance of Theory

**Theory is not a pejorative!**

**Newton's laws are "just a theory", but we could not design a skyscraper or find trajectories for a space probe without them.**

**Theory tells you where to look.**

**Without theory everything would be trial and error.**

# What Is to Come

- **Flight simulators** for organizations

Gell-Mann's dim flashlight: provides insight into options and possible disasters.

Allows testing and verification by experts who are not programmers.

- **Exploitation of cas lever points**

Principled discovery of targeted interventions similar to vaccines

- **Allocation of credit** for exploratory research

Depreciation-like accounting principles that allow costs of exploratory research to be spread over future income

# Challenges

## Autonomous formation of **agent hierarchies**

[seed machines – cf. the development of multi-celled organisms]

## Evolution of **reaction networks**

[From partial information about reactions and reactant concentrations produce candidate reaction networks – e.g. models of phenotypic plasticity and cancerous cell transitions]

## Origins of **symbolic signaling**

[Model situated, structured grammar acquisition using pre-linguistic cognitive abilities]

## **Open-ended evolution**

[Produce a computer-based system that exhibits the increasingly complex niches and exchanges exhibited by an evolving ecosystem]

# Summary

**Complex adaptive systems** are the central element of some of our most important and difficult problems:

**Innovation, the internet, global trade, markets, sustainability, ecosystems, the immune system.**

**We are just beginning to develop a useful theory of such systems.**

**As Stephen Hawking says, “Complexity is the science of the 21<sup>st</sup> century.”**

# Details

# Controlling *cas*

Lever points

Real options [Black-Scholes]

# Overview

Studying *cas*

dynamic structures

flows of resources and information

formation of boundaries; diversity

subsystems, niches, and indirect effects

What persists?

building blocks (cf. instructions for a computer)

What is the structure

*programs*

# A Classifier System

