The Problem of Coordination in Self-Organizing Systems

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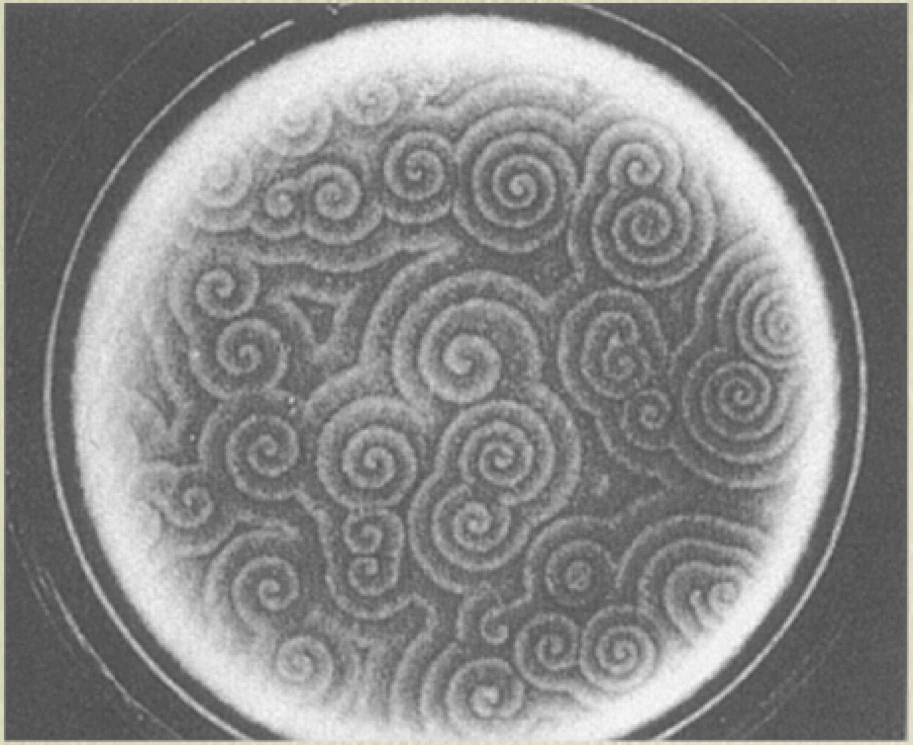
Self-organization

Spontaneous appearance of order or organization

Global **order from** ***local*** **interactions**

Organization ***distributed*** **over all the components**

- collective
- Robust



Agent

Elementary system component

- E.g. molecule, ant, person, robot, sensor, module

Acts on environment

- In response to experienced conditions

Goal-directed

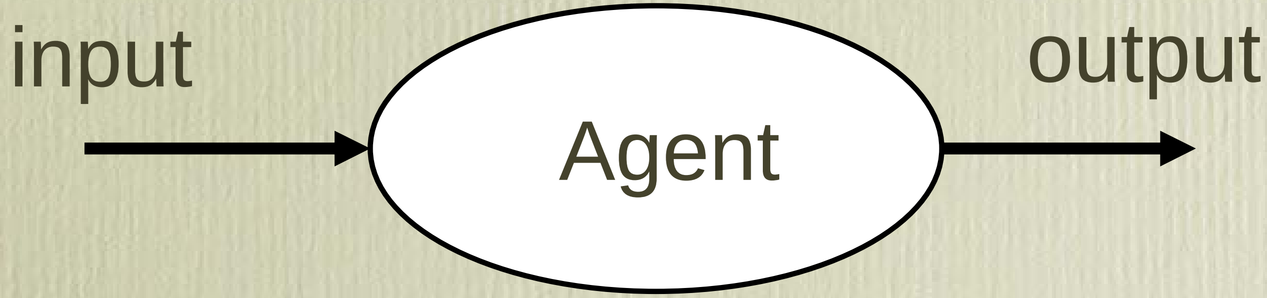
- Actions lead to an attractor or “high fitness” state

Agent as input-output system

Input: sensed state of the environment

Output: new state of environment resulting from action

Agent: “black box” transforming input into output



Self-Organizing System

Collection of many interacting agents

Interaction:

- action by agent A triggers action by B
- Which triggers new action by A, C, D…etc.

Interactions propagate throughout the system

- Local action may have global effects

Goal of System = Attractor of global dynamics

Function of a System

Function = what the system (robustly) does

- System itself determines its purpose

“Does” = transforms input into output

- Represented by input output-function
- f: I → O: i → f(i)

“robustly” = in a stable, invariant matter

- Invariant under further evolution or most perturbations
- The “attractor” of the system’s dynamics is the implicit goal of the system

Controlling Emergent Function

How can we make sure that the global function is as desired?

Input = problem or query

- initial information or situation to be dealt with by the system

Output = solution

- processed information or changed situation that answers the query

Example: neural network

- input = pixels to be recognized
- output= recognized character

Engineering SOS

Design a system consisting of interacting agents

- overall function specified by the designer
- agents initially specified by the designer
- interactions patterns *not* specified

How can the system self-organize to achieve the function?

- 1) impose global function from the outside:
  - **Problem of training**
- 2) let agents discover effective pattern of interaction
  - **Problem of coordination**

Problem of Training

Approach in Evolutionary Algorithms

- Define fitness function
- Let agents and interactions undergo variations
- Retain and multiply fittest ones
- Eliminate least fit ones

Approach in Neural Networks/Reinforcement learning

- Reward /reinforce “good” connections/behavior
- Punish/suppress “bad” connections/behavior

Problem of Credit Allocation

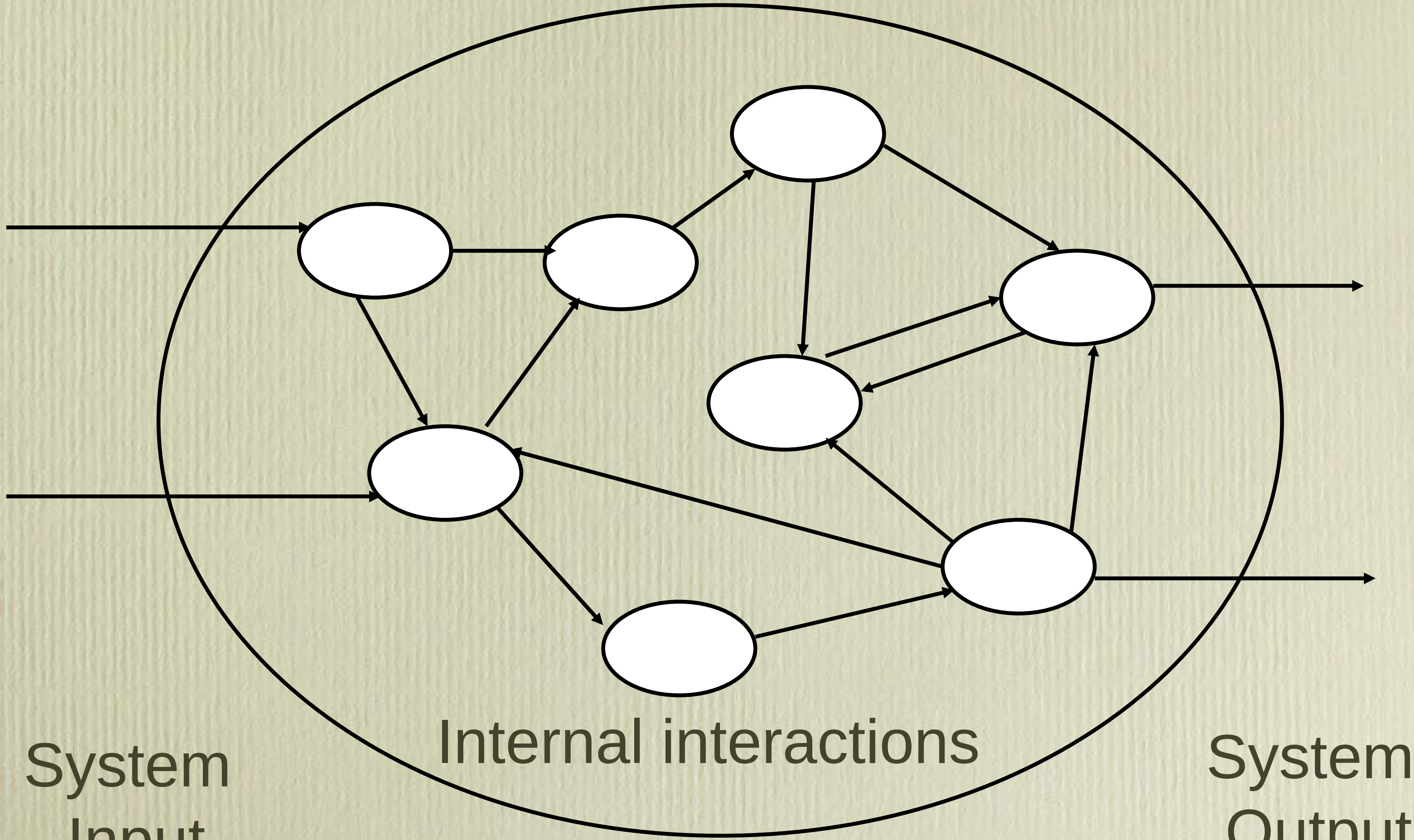
When several agents together perform the function, who should get which reward?

General method: **backpropagation**

- Last agent to deliver solution gets reward
- That agent passes on part of the reward to previous agent(s)
- Which in turn pass on reward to their suppliers, etc.

Used in

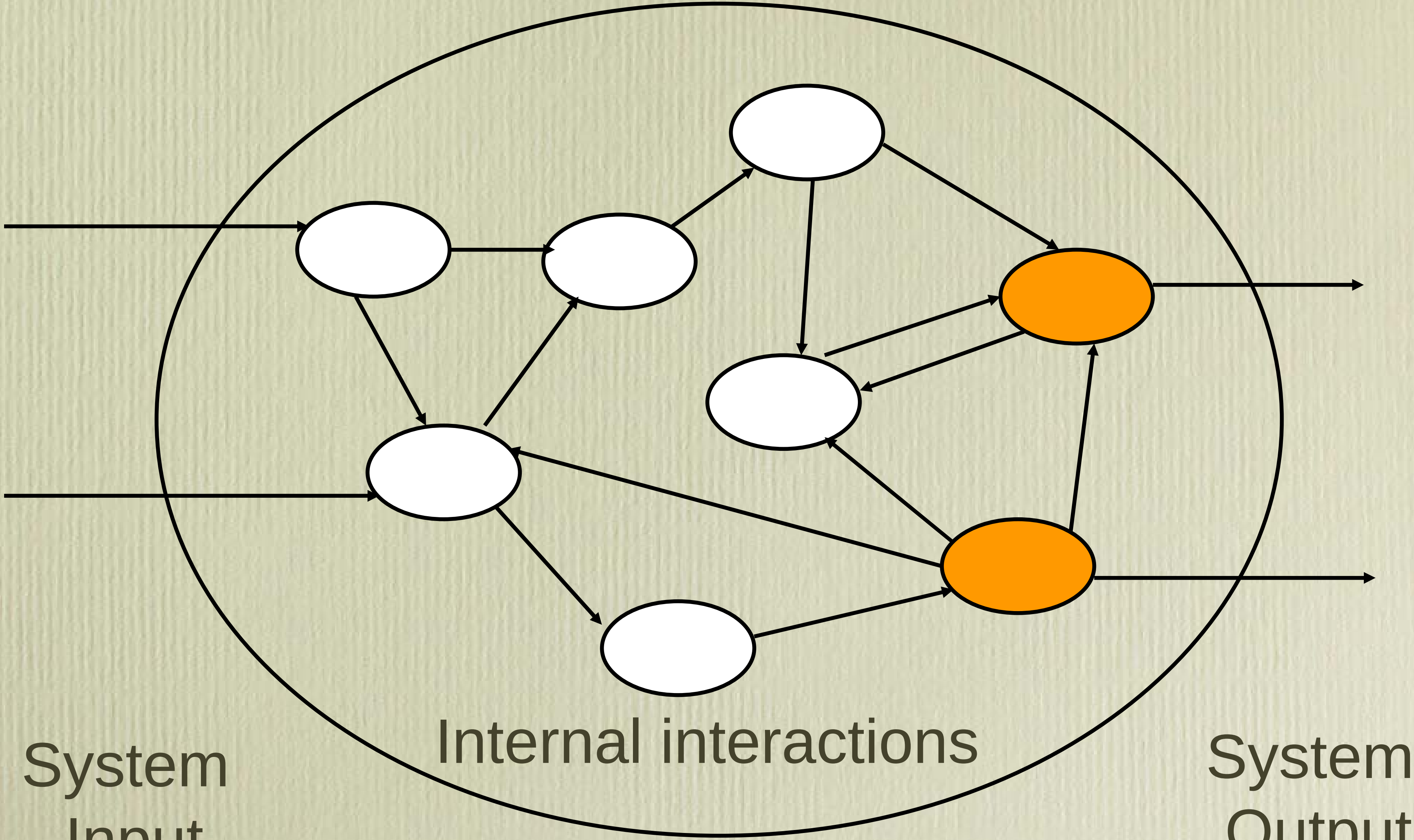
- neural networks
- Classifier Systems (agents undergoing evolutionary algorithms)
- Jack-in-the-Net SO agent service



Internal interactions

System Input

System Output



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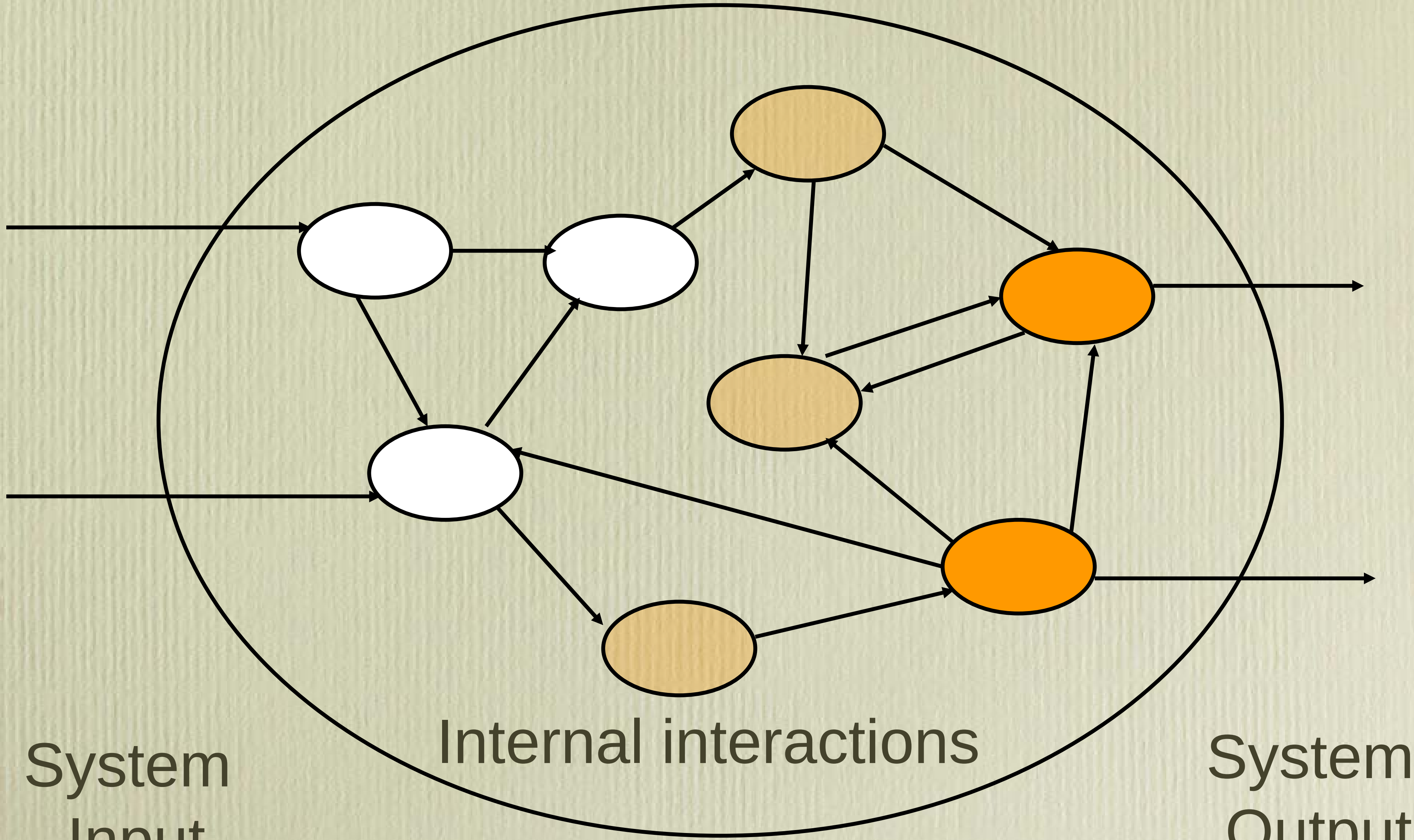

Internal interactions

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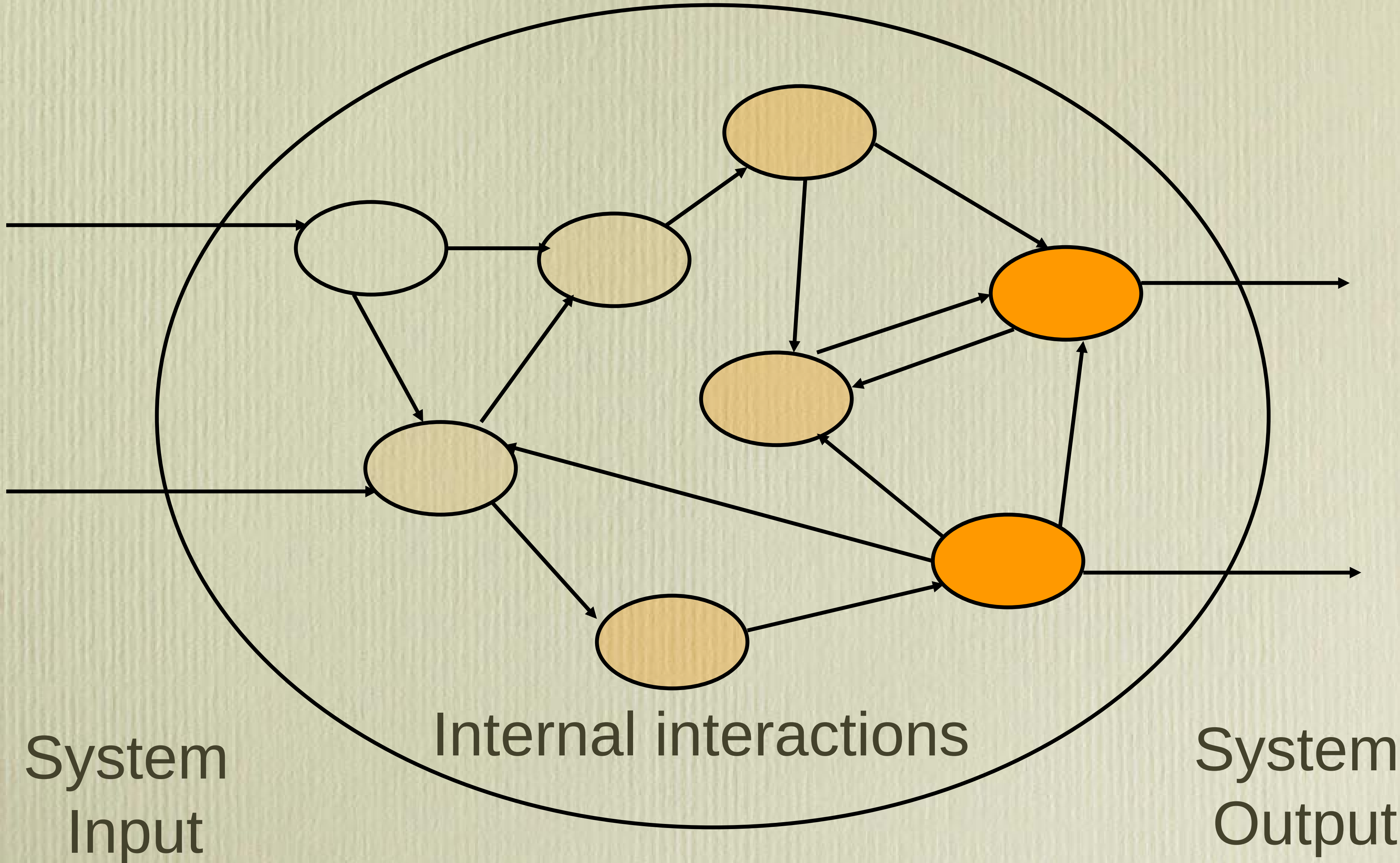


Internal interactions

System Input

System Output

Problem of Coordination

Credit allocation is non-trivial when “geometry” is variable

- Different agent perform different functions at different times and places

“Intelligent” self-organization implies specialization/division of labor among agents

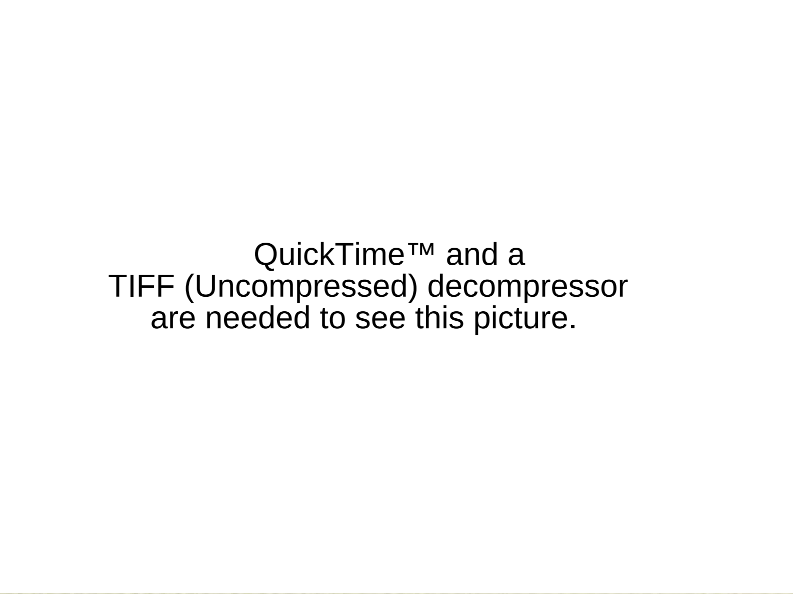
- Different agents have different abilities / experiences
- Together they can be smarter than alone

But how do we achieve such collective intelligence?

Collective Intelligence

Together we can be more intelligent than individually

- E.g. ants, bees, termites
- group can solve more problems than its members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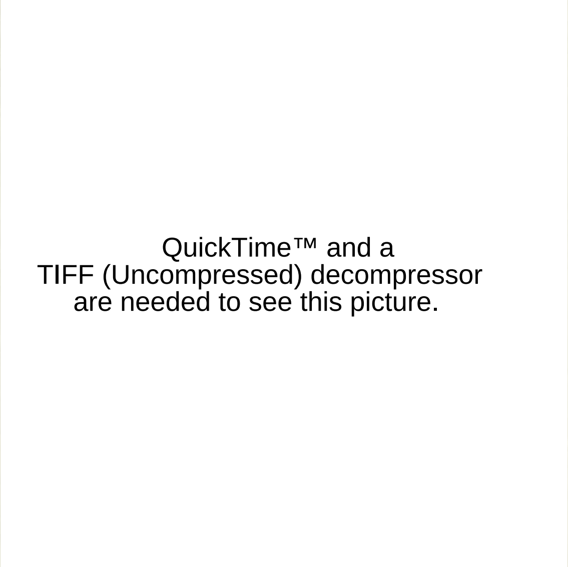
James Surowiecki:

- "The Wisdom of Crowds”
- Summary of requirements for collective intelligence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Requirements for Collective Intelligence

Diversity

- the more varied the individual expertise, the more comprehensive the collective knowledge

Aggregation

- individual contributions must be synthesized into global solution

Independence

- no individuals or subgroups should be able to bias the result

Decentralization (distribution)

- Different individuals should be able to work on different parts of the problem

Intelligent SOS

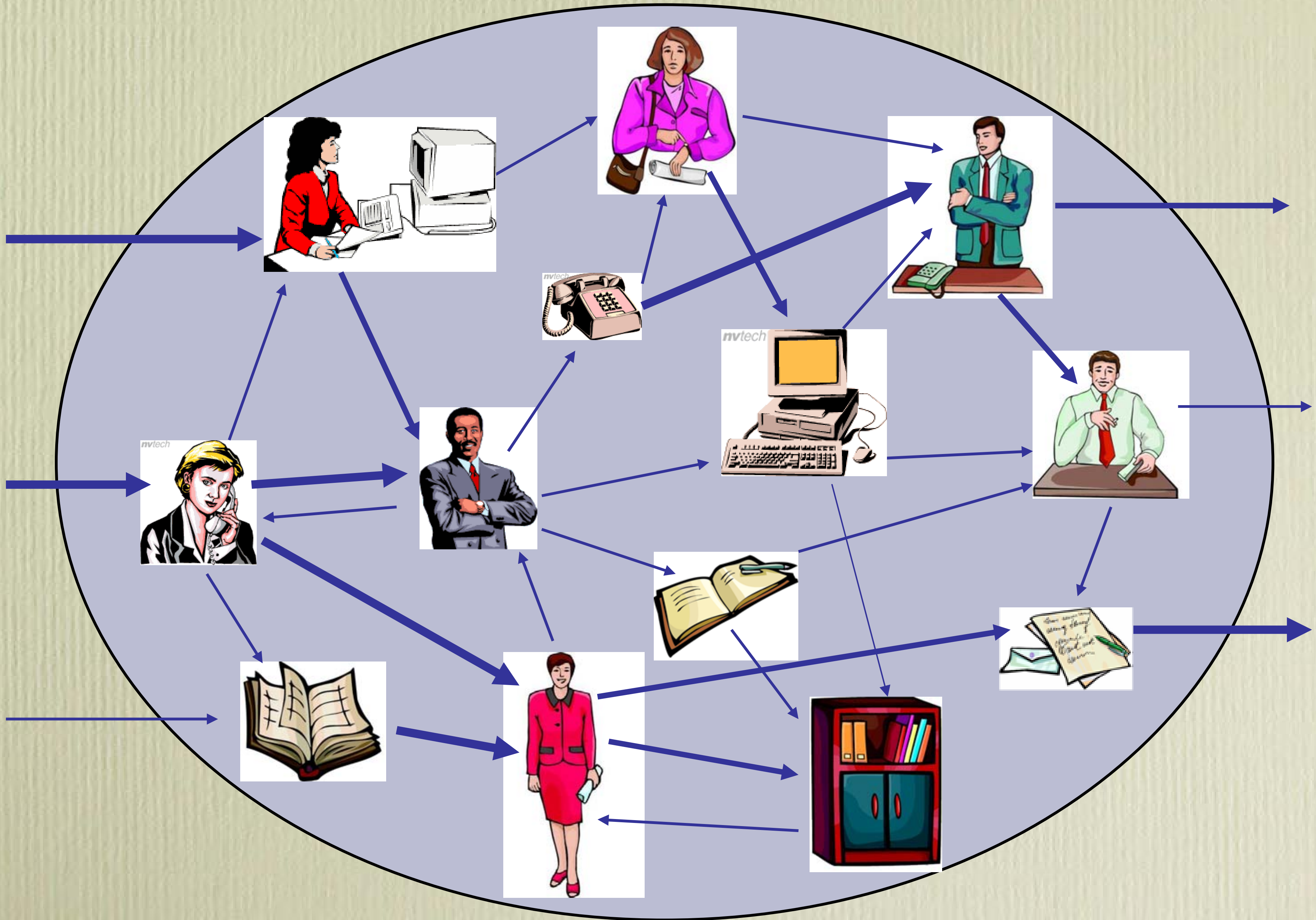
Emergence of a "superagent"

- coordinated, goal-directed collective
- characterized by *collective intelligence*

Distributed cognition

- different agents contribute different results at different times and places
- results are integrated
- together, they solve the global problem

Distributed Cognition



Distributed Cognition

Complex problems must be decomposed into a network of subproblems

- With each subproblem tackled by the appropriate agent
- The different contributions must be integrated into a coherent whole

This requires coordinated action

- *Alignment*
- *Division of labor*
- *Workflow*
- *Aggregation*

Alignment

Simplest case of coordination

Agents should not obstruct or hinder each other

They should act with a common “intention”

- work towards the same goal
- Speak same “language”
- Refer to the same things

Functions of Alignment

Development of shared standards

- agents must agree about doing things the same way
- so as to avoid confusion, friction or conflict

Examples

- *Synchronization*: agreeing about the time to do something
- driving on the same side of the road
- using compatible technological formats

SO of Alignment

Via trial-and-error two agents discover how to act synergetically:

- 1-1 alignment

Basic mechanism

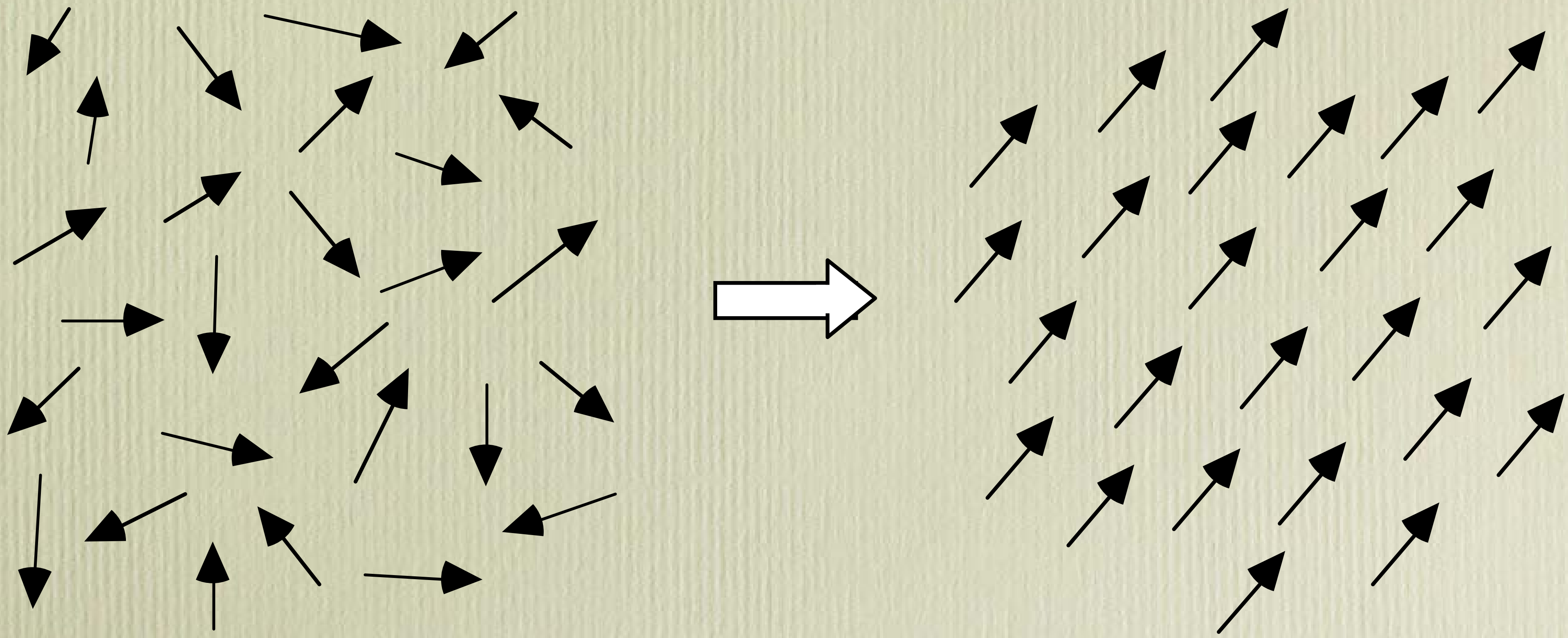
- reinforcement of synergetic interactions
- suppression of frictional interactions

Self-reinforcing growth of the synergetic assembly

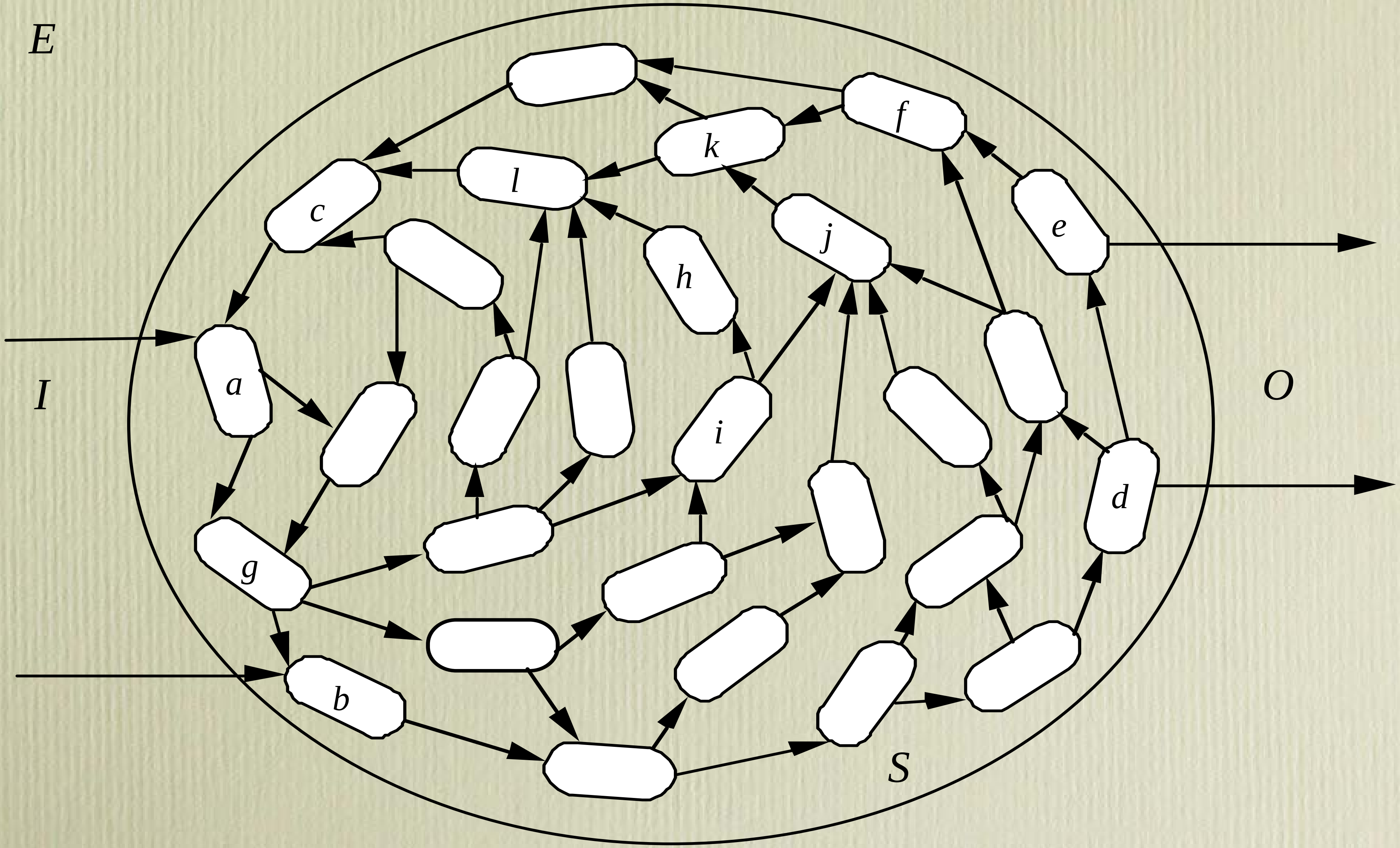
- speeds up process

Eventually, the whole system become “aligned” or “coordinated”

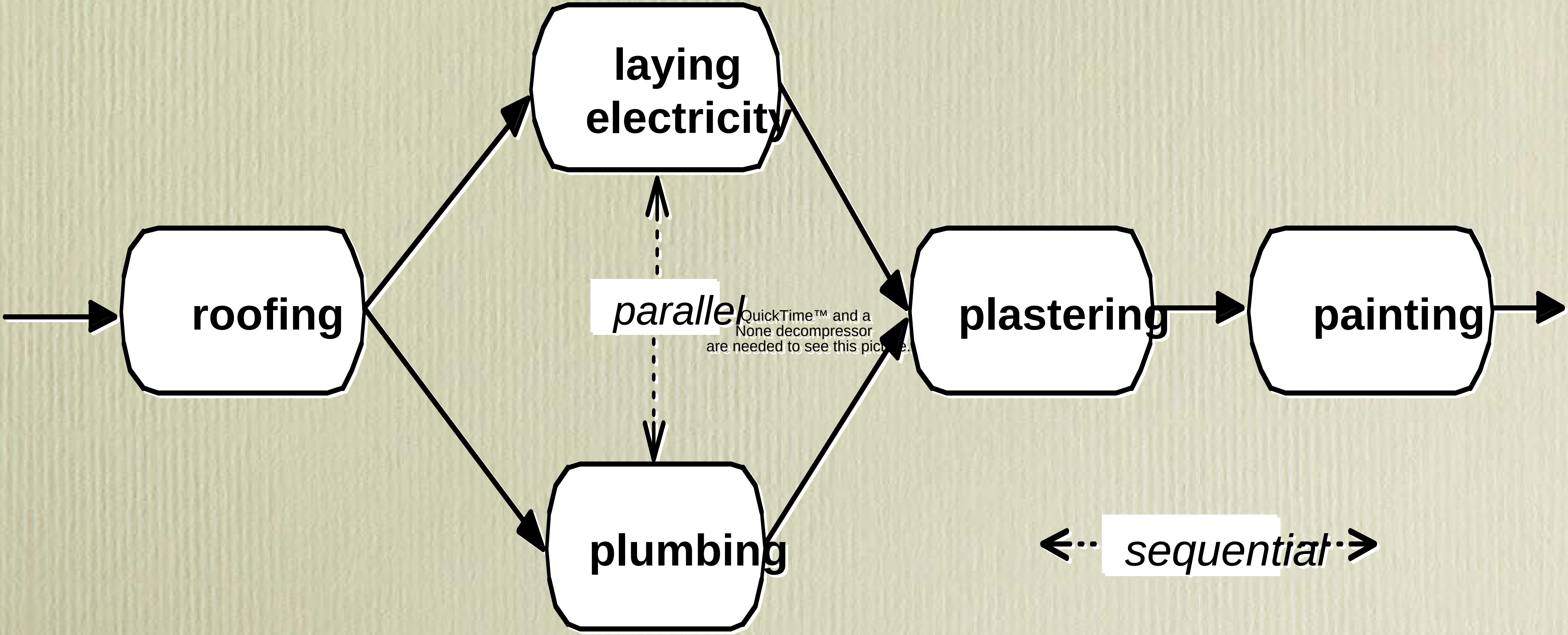
Example: Magnetization



System as Network of Agents

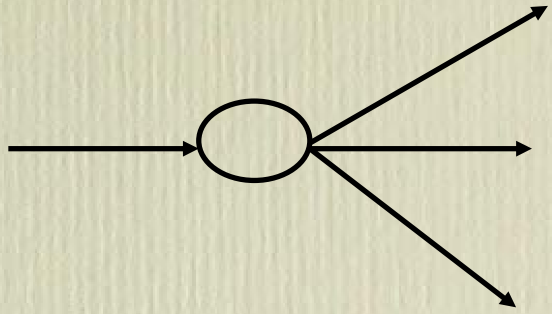


Parallel and Sequential Coordination

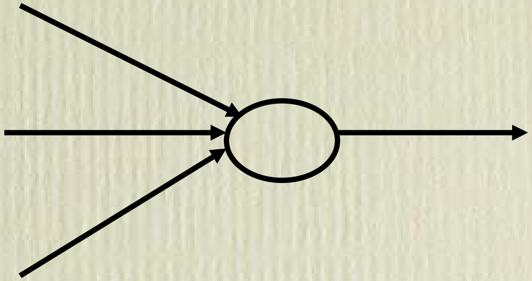


Parallel coordination

Input parallel = division of labor



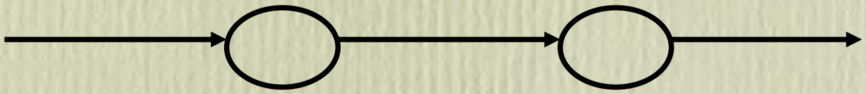
- who does what?
- Different parts of the task allocated to different agents
- allows specialization



Output parallel = aggregation of results

- How are the different results put together again?

Sequential coordination



Ordering of tasks

- second task can only be started when first is finished
- E.g. plasterer -> painter
- together they can do things they cannot do in separation

Workflow

- who does what when?
- How does the “work” move from agent to agent?
- partially solved problem must be passed on to next in line

SO coordination mechanisms

Stigmergy

- Agents deposit partially finished work in shared medium
- Agents pick up tasks from medium

Hebbian learning

- Agents interact preferentially with frequent partner
- Creates links between agents -> “social” network

Backpropagation

- Agents interact with the one that rewarded them

Stigmergy

Division of Labor

- Each agent picks up task it can do best

Workflow

- Partially completed tasks are put back in the medium to be picked up by next agent

Aggregation

- Medium accumulates all results

Examples:

- Wikipedia, ant pheromone traces

Hebbian Learning

Division of Labor

- May require lateral inhibition
    - Active agent suppresses activity in parallel agents
    - Thus forcing them to differentiate in specialization

Workflow

- Agents order themselves in a sequence of activity

Aggregation

- Output agents aggregate output they receive from their input agents

Backpropagation

Division of Labor

- Agents that successfully performed a task will get more of these tasks delegated to them

Workflow

- Agents learn to recognize who is next in line?

Aggregation

- Like in Hebbian learning

Integrated coordination mechanisms

Classifier systems (Holland):

- Stigmergy + Backprop

Jack-in-the-Net agent architecture (Itao et al.):

- Hebbian + Backprop

Ant algorithms:

- Stigmergy + Hebbian

Ideal system?:

- Stigmergy + Hebbian + Backprop?
- Formally represented by hypernetworks?