# Applications of membrane systems in population biology and ecological modelling

Álvaro Romero–Jiménez

romero.alvaro@us.es

Research Group on Natural Computing
Department of Computer Science
University of Seville

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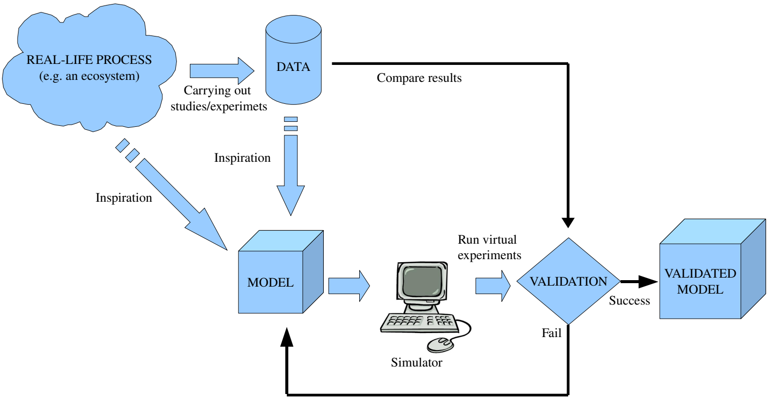
# Modelization

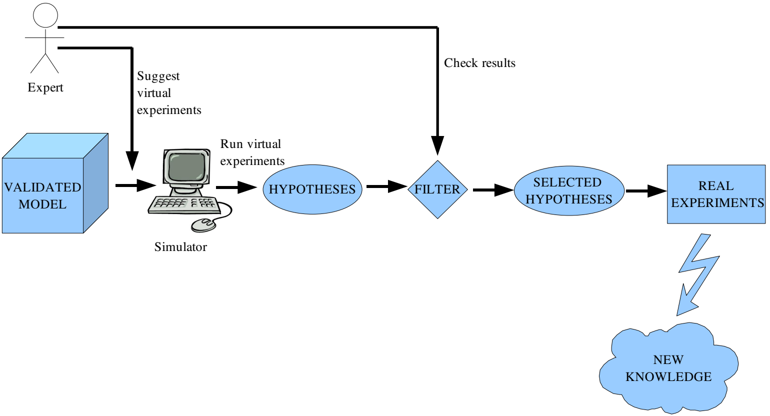
# Modelization

## Protocol for development and validation



# Modelization

## Protocol for virtual experiments



# Framework for ecosystems modelization

Relevant characteristics of ecosystems:

- Discrete components
- Compartmentalization
- Cooperation
- Communication
- Randomness

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- Discrete components
- Compartmentalization
- Cooperation
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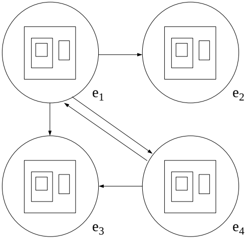
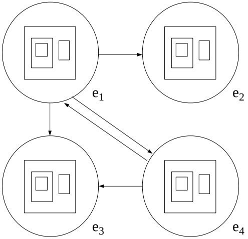
Mathematical models:

- Usual framework: EDOs
- Suitable framework: P systems

# Framework for ecosystems modelization

## A framework based on P systems



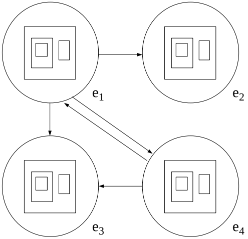



Skeleton of an extended P system with active membranes of degree q $\geq 1$

$$(\Gamma, \mu, R)$$

Evolution rules

$$u[v]_h^{\alpha} \rightarrow u'[v']_h^{\beta}$$

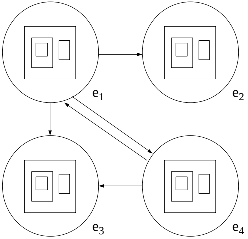



Probabilistic functional extended P system with active membranes of degree q $\geq$ 1, taking T time units

$$\Pi = (\Gamma, \mu, R, T, \{f_r : r \in R\}, M_0, \dots, M_{q-1})$$

Evolution rules

$$u[v]_h^{\alpha} \xrightarrow{f_r} u'[v']_h^{\beta}$$




Multienvironment probabilistic functional extended P system with active membranes of degree $(m, q)$ taking T time units

$$(\Sigma, G, R_E, \Gamma, \mu, R, T, \{f_{r,j} : r \in R_\Pi, 1 \leq j \leq m\}, \{M_{i,j} : 0 \leq i \leq q-1, 1 \leq j \leq m\})$$

Evolution rules

$$u[v]_h^\alpha \xrightarrow{f_{r,j}} u'[v']_h^\beta \qquad (x)_{e_j} \xrightarrow{p_{(x,j,j_1,\dots,j_h)}} (y_1)_{e_{j_1}} \dots (y_h)_{e_{j_h}}$$

# Part II

# Ecosystems

# Pyrenean Chamois
## Description

Figure: Rupicapra pyrenaïca, isard des pyrenees bigorre juillet 2003 Bernard-Boehne

Small ungulate living in the Pyrenees:

- Great interest: hunting, naturalistic and touristic
- Good conservation status, but to the edge of extinction in the late 60s
- Suffered from several diseases in recent years, with high ecological, social and economic impact
- Consequences in the ecosystem still unclear

# Pyrenean Chamois

## Population model

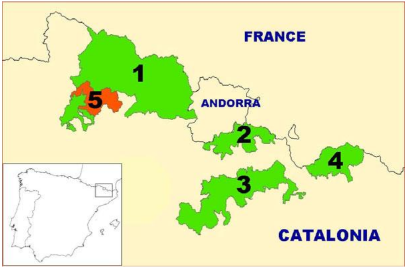
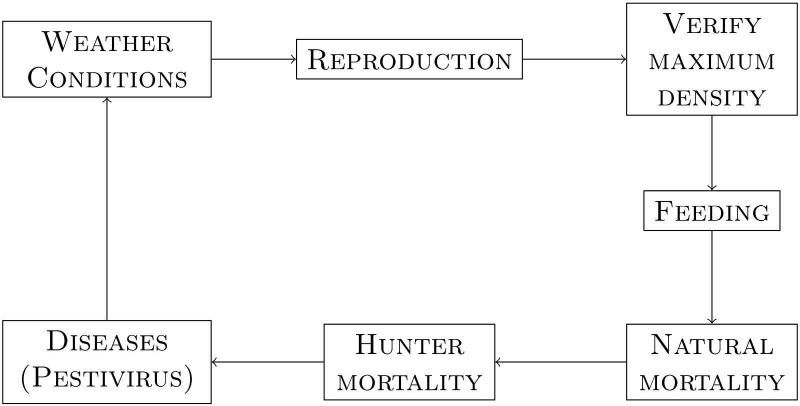



Figure: Study area in the Catalan Pyrenees

- Five main protected areas in the Catalan Pyrenees (area 5 not considered)
- Unlikeliness of movements between areas is assumed
- Weather conditions influence the values of biological parameters
- Causes of death include natural death, hunting and disease



Weather Conditions
Reproduction
Verify maximum density
Feeding
Natural mortality
Hunter mortality
Diseases (Pestivirus)

# Pyrenean Chamois
## Parameters

| Biological parameters | |
|---|---|
| Age at which they are considered adults | $g_0$ |
| Age at which they begin to be fertile | $g_1$ |
| Age at which they cease to be fertile | $g_2$ |
| Life expectancy | $g_3$ |
| Proportion of females in the population (as per 1) | $k_1$ |
| Fertility rate (as per 1) | $k_2$ |
| Number of descendants per female | $k_3$ |
| Rate of natural mortality on young animals (as per 1) | $m_1$ |
| Rate of natural mortality on adult animals (as per 1) | $m_2$ |
| **Geographical parameters** | |
| Amount of grass consumed per month and animal | $\beta_i$ |
| Amount of grass produced per month | $\alpha_{i,\nu}$ |
| Probability of having the disease | $ms_\nu$ |
| Probability of dying from a disease | $md_\nu$ |
| Maximum density of the ecosystem | $d1_\nu$ |
| Number of animals that survive after reaching the maximum density | $d2_\nu$ |
| **Human factors parameters** | |
| Young animals hunted | $h1_\nu$ |
| Adult animals hunted | $h2_\nu$ |

$1 \leq i \leq 10$

$1 \leq \nu \leq 4$

$$(G, \Gamma, \Sigma, R_E, \Pi, \{f_{r,\nu} : r \in R_\Pi, 1 \leq \nu \leq 4\}, \{M_{i,\nu} : 0 \leq i \leq 10, 1 \leq \nu \leq 4\})$$

$$(G, \Gamma, \Sigma, R_E, \Pi, \{f_{r,\nu} : r \in R_\Pi, 1 \le \nu \le 4\}, \{M_{i,\nu} : 0 \le i \le 10, 1 \le \nu \le 4\})$$

Four environments representing each zone

$$G = (V, S) \quad V = \{e_1, \dots, e_4\} \quad S = \{(e_i, e_i), (e_1, e_i) : 1 \le i \le 4\}$$

# Pyrenean Chamois

## P system model

$$(G, \Gamma, \Sigma, R_E, \Pi, \{f_{r,\nu} : r \in R_\Pi, 1 \le \nu \le 4\}, \{M_{i,\nu} : 0 \le i \le 10, 1 \le \nu \le 4\})$$

Four environments representing each zone

The working alphabet contains objects: representing animals in different states, ages and years; associated with the production of grass; controlling the density of population; setting the state of disease

$$\begin{aligned}\Gamma = & \{X_{j,y}, Y_{j,y}, Y'_{j,y}, Y''_{j,y}, Z_{j,y}, V_{j,y}, W_{j,y} : 0 \le j \le g_3, 1 \le y \le T\} \cup \\ & \{a, c, d, e, t, h, d_1, F, D, S, N\} \cup \{t_i : 1 \le i \le 3\} \cup \\ & \{G_i : 4 \le i \le 10\} \cup \{R_i : 0 \le i \le 7\}\end{aligned}$$

$$(G, \Gamma, \Sigma, R_E, \Pi, \{f_{r,\nu} : r \in R_\Pi, 1 \leq \nu \leq 4\}, \{M_{i,\nu} : 0 \leq i \leq 10, 1 \leq \nu \leq 4\})$$

Four environments representing each zone

The working alphabet contains objects: representing animals in different states, ages and years; associated with the production of grass; controlling the density of population; setting the state of disease

The environment alphabet contains objects representing each possible snow thickness

$$\Sigma = \{t\} \cup \{t_i : 1 \leq i \leq 10\}$$

$$(G, \Gamma, \Sigma, R_E, \Pi, \{f_{r,\nu} : r \in R_\Pi, 1 \leq \nu \leq 4\}, \{M_{i,\nu} : 0 \leq i \leq 10, 1 \leq \nu \leq 4\})$$

Four environments representing each zone

The working alphabet contains objects: representing animals in different states, ages and years; associated with the production of grass; controlling the density of population; setting the state of disease

The environment alphabet contains objects representing each possible snow thickness

The skeleton contains membranes associated with each possible climatic scenario

$$\mu = [[\,]_1[\,]_2 \ldots [\,]_{10}]_0$$

1. Weather conditions
2. Initialization
3. Reproduction
4. Density verification
5. Feeding
6. Natural mortality
7. Hunting mortality
8. Disease mortality
9. Finalization

$$(t)_{e_1} \xrightarrow{1/10} (t_i)_{e_1}(t_i)_{e_2}(t_i)_{e_3}(t_i)_{e_4}$$
$$(t)_{e_k} \rightarrow (\#)_{e_k}, 1 < k \leq 4$$

1. Weather conditions
2. Initialization
3. Reproduction
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9. Finalization

$$t_i[\,]_0^0 \rightarrow [t_i]_0^0$$

$$t_i[\,]_i^0 \rightarrow [t]_i^-$$

$$X_{j,y}[\,]_k^- \rightarrow [X_{j,y}]_k^0$$

$$(F[\,]_k^- \rightarrow [G_4^{\alpha_4(\nu)} \dots G_{10}^{\alpha_{10}(\nu)}]_k^0)_{e_\nu}$$

$$h[\,]_k^- \rightarrow [h]_k^0$$

$$(c[\,]_k^- \rightarrow [a^{0.9d1_\nu} e^{0.2d1_\nu}]_k^0)_{e_\nu}$$

$$d[\,]_k^- \rightarrow [d]_k^0$$

$$[dh \rightarrow d_1]_k^0$$

$$([d_1 \xrightarrow{ms_\nu} S]_k^0)e_\nu$$

$$([d_1 \xrightarrow{1-ms_\nu} N]_k^0)e_\nu$$

$$R_0[\,]_k^- \rightarrow [R_0]_k^0$$

$$[R_i \rightarrow R_{i+1}]_k^0$$

$$[e \xrightarrow{0.5} a]_k^0$$

$$[e \xrightarrow{0.5} \#]_k^0$$

1. Weather conditions
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$$[X_{j,y} \xrightarrow{k1k2_l} Y_{j,y} Y_{0,y}^{k_3} D^{k_3+1}]_k^0, g_1 \leq j < g_2$$

$$[X_{j,y} \xrightarrow{k1(1-k2_l)} Y_{j,y} D]_k^0, g_1 \leq j < g_2$$

$$[X_{j,y} \rightarrow Y_{j,y} D]_k^0, g_2 \leq j \leq g_3$$

$$[X_{j,y} \rightarrow Y_{j,y} D]_k^0, 1 \leq j < g_2$$

# Pyrenean Chamois

## Rules

1. Weather conditions
2. Initialization
3. Reproduction
4. Density verification
5. Feeding
6. Natural mortality
7. Hunting mortality
8. Disease mortality
9. Finalization

$$([D^{d1_\nu} a^{d1_\nu - d2_\nu}]_k^0 \to [h_0]_k^0)_{e_\nu}$$

$$[dh_0]_k^0 \to [d_0]_k^0$$

$$[Y_{j,y} \to Y'_{j,y}]_k^0$$

1. Weather conditions
2. Initialization
3. Reproduction
4. Density verification
5. Feeding
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7. Hunting mortality
8. Disease mortality
9. Finalization

$$[Y'_{j,y} a G_4^{\beta_4} G_5^{\beta_5} G_6^{\beta_6} G_7^{\beta_7} G_8^{\beta_8} G_9^{\beta_9} G_{10}^{\beta_{10}} \rightarrow Z_{j,y}]_k^0$$

1. Weather conditions
2. Initialization
3. Reproduction
4. Density verification
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8. Disease mortality
9. Finalization

$$([Z_{j,y} \xrightarrow{1-m1_{k,\nu}} V_{j,y}]_k^0)_{e_\nu}, 0 \le j < g_0$$

$$([Z_{j,y} \xrightarrow{m1_{k,\nu}} \#]_k^0)_{e_\nu}, 0 \le j < g_0$$

$$[Z_{j,y} \xrightarrow{1-m2} V_{j,y}]_k^0, g_0 \le j < g_3$$

$$[Z_{j,y} \xrightarrow{m2} \#]_k^0, g_0 \le j < g_3$$

$$[Y_{g_3,y} \rightarrow \#]_k^0$$

1. Weather conditions
2. Initialization
3. Reproduction
4. Density verification
5. Feeding
6. Natural mortality
7. Hunting mortality
8. Disease mortality
9. Finalization

$$([V_{j,y} \xrightarrow{1-h1_{\nu}} W_{j,y}]_k^0)_{e_\nu}, 0 \leq j < g_0$$

$$([V_{j,y} \xrightarrow{h1_{\nu}} \#]_k^0)_{e_\nu}, 0 \leq j < g_0$$

$$([V_{j,y} \xrightarrow{1-h2_{\nu}} W_{j,y}]_k^0)_{e_\nu}, g_0 \leq j < g_3$$

$$([V_{j,y} \xrightarrow{h2_{\nu}} \#]_k^0)_{e_\nu}, g_0 \leq j < g_3$$

1. Weather conditions
2. Initialization
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7. Hunting mortality
8. Disease mortality
9. Finalization

$$[R_5 S]_k^0 \rightarrow [R_6 h]_k^-$$
$$[R_5 N \rightarrow R_6 h]_k^0$$
$$[R_5 d_0 \rightarrow R_6 h]_k^0$$
$$[R_5 d \rightarrow R_6]_k^0$$
$$[R_6]_k^- \rightarrow [\#]_k^+$$
$$[R_6]_k^0 \rightarrow [\#]_k^+$$
$$([W_{j,y}]_k^- \xrightarrow{md_\nu} [\#]_k^+)_{e_\nu}$$
$$([W_{j,y}]_k^- \xrightarrow{1-md_\nu} [W_{j,y}]_k^+)_{e_\nu}$$

1. Weather conditions
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$$[W_{j,y}]_k^+ \rightarrow X_{j+1,y+1}[\,]_k^0$$

$$[Y'_{j,y}]_k^+ \rightarrow [\#]_k^0$$

$$[t]_k^+ \rightarrow R_0 Ftcd[\,]_k^0$$

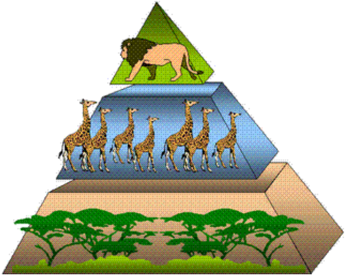
$$[h]_k^+ \rightarrow h[\,]_k^0$$

$$[a]_k^+ \rightarrow [\#]_k^0$$

$$[G_i]_k^+ \rightarrow [\#]_k^0$$

$$[t]_0^0 \rightarrow t[\,]_0^0$$

# Tritrophic



Simplification of a real ecosystem:

- Suitable for performance tests
- Three trophic levels: carnivores, herbivores, grass
- Ecosystem model: 5 modules, 10 areas

# Scavenger Birds

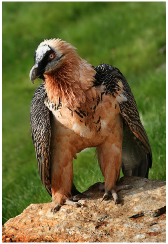


Figure: Bearded Vulture *Gypaetus barbatus* 2007 Richard Bartz

Figure: Eurasian Griffon Vulture *Gyps fulvus* 2008 Ingrid Taylar

Figure: Egyptian Vulture *Neophron percnopterus* 2005 Kousik Nandy

Endangered species in the Catalan Pyrenees:

- Purpose: study the evolution of the ecosystem under different scenarios
- 3 predator species, 13 prey species
- Ecosystem model: 4 modules

# Zebra Mussel

Figure: Zebra Mussel *Dreissena polymorpha* 2004 GerardM

Small freshwater mussel:

- Invasive species in Ribarroja reservoir (Northeast of Spain)
- Purpose: learn how to reduce mussel population
- Ecosystem model: many variables involved

# Part III

# Software

Implementation vs Simulation:

- No implementation of P systems yet, neither *in vivo* nor *in vitro*
- Software/hardware is necessary for simulating P system computations

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Applications of simulators:

- Pedagogical tools
- Support research within Membrane Computing
- Simulation, validation and virtual experimentation over models of real-life phenomena

# Simulators for P systems

## General structure

- Many simulators available
- Ad hoc development
- Similar structure

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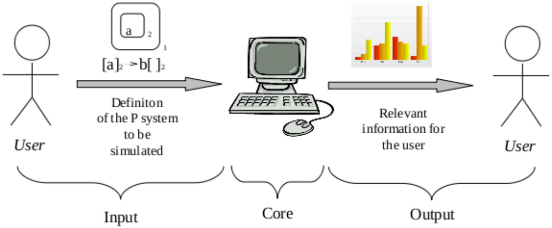
- Similar structure



Each simulator implements its own method for providing the input

Proposed solution: a specification language

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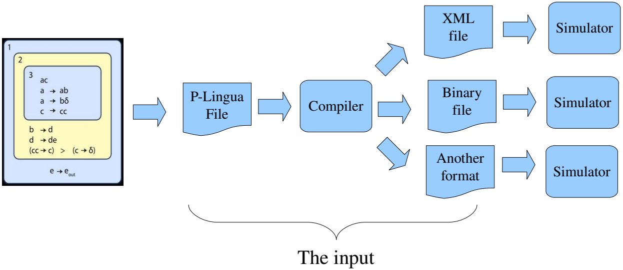
Proposed solution: a specification language

Main features:

- Syntax close to scientific notation
- Modular
- Parametric
- Decoupled from its applications
- Extensible

# P-Lingua

## Diagram of use



First line: P system model

Supported models:

- Transition P systems
- Active membranes with division rules
- Active membranes with creation rules
- Symport/antiport P systems
- Stochastic P systems
- Probabilistic P systems
- Tissue-like P systems with communication and division rules

First line: P system model

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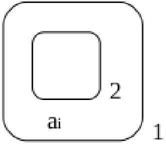
Definition of modules

*main* module

Configuration:

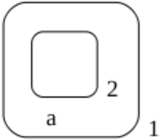



Rules:

$$[a_i[\,]_2]_1 \rightarrow [a_{i+1}[b_i]_2]_1, 1 \leq i \leq 10$$

```
@model<transition>
def main()
{
 @mu = [[]'2]'1;
 @ms(1) = a{1};
 [a{i} []'2]'1 --> [a{i+1} [b{i}]'2]'1 : 1<=i<=10;
}
```

Configuration:




Rules:

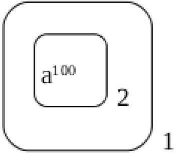
$$[a \to ab]_1$$
$$b[\,]_2 \to [c]_2^+$$
$$[c]_2^+ \to [d]_2[e]_2^-$$

```
@model<membrane_division>
def main()
{
 @mu = [[]'2]'1;
 @ms(1) = a;
 [a --> a,b]'1;
 b[]'2 --> +[c]'2;
 +[c]'2 --> [d]'2 -[e]'2;
}
```

# P-Lingua

## P-Lingua file example: probabilistic P systems

Configuration:




Rules:

$$[a]_2 \xrightarrow{0.4} b[c]_2$$

$$[a]_2 \xrightarrow{0.4} [d]_2$$

$$[a]_2 \xrightarrow{0.2} e[\,]_2$$

```
@model<probabilistic>
def main()
{
 @mu = [[]'2]'1;
 @ms(2) = a*100;
 [a]'2 --> b[c]'2:: 0.4;
 [a]'2 --> [d]'2 :: 0.4;
 [a]'2 --> e[]'2 :: 0.2;
}
```

Translation of P-Lingua files to suitable formats for simulators (currently XML and binary format)

Lexical, syntactic and semantic parsing

Main goals:

- P-Lingua files reusable by different simulators
- Free simulators from checking the correctness of P system definitions

pLinguaCore:

- Programmed in Java
- Implements a parser, a compiler, and a simulator for each supported model
- Pluggable into other applications

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Simulator for probabilistic P systems:

- Binomial block based algorithm
- Direct non-deterministic distribution with probabilities algorithm

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Simulator for active membranes with division rules:

- A parallel implementation using the CUDA technology is available

Two type of users:

- Designer users
- End users

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Designer users:

- Membrane computing experts
- Follows ecology experts guidance
- P systems written in P-Lingua language

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End users:

- No membrane computing knowledge required
- Perform virtual experiment
- GUIs to set virtual experiments parameters

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End users:

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  PROBLEM: ad hoc GUI for each modeled ecosystem

Features for end users:

- Initialization of parameter values of the ecosystem
- Selection of the number of years to simulate
- Selection of the total number of simulations per year
- Saving/loading the values of initial parameters to/from files
- Execution of simulations

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Additional features for designer users:

- Edition and compilation of P-Lingua files
- Step by step simulation
- Setting of number of computational steps per year

Highly customizable generator of ecosystems simulators

Highly customizable generator of ecosystems simulators

Adaptation to each scenario through a configuration file:

- General data about the simulator
- Tabs hierarchy in the main window
- Input tables configuration
- Parameters configuration
- Output elements configuration

Part IV

# Practical demonstration

Part V

# Conclusions and future work

# Conclusions

- P systems as a high-level modeling framework for ecosystems
- Several ecosystems modeled within this framework
  - Pyrenean Chamois in Catalan Pyrenees
  - Tritrophic virtual ecosystem
  - Scavenger Birds in Catalan Pyrenees
  - Zebra Mussel in Ribarroja reservoir
- Software framework for performing virtual experiments over the models
  - P-Lingua
  - MeCoSim

# Future work

- Consider more ecosystems to model
- Model real-life processes apart from ecosystems
- Continue developing the P system framework for modeling
- Extend the software framework to cover more P system variants
- Develop simulators within the High Performance Computing field
- Design a common protocol to communicate simulators and user interfaces
- Design more efficient and standard GUIs for final users

# Links and bibliography

The P systems web page: http://ppage.psystems.eu
The P-Lingua web page: http://www.p-lingua.org
The MeCoSim web page: http://www.p-lingua.org/mecosim


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