IMT SCHOOL FOR ADVANCED STUDIES LUCCA

Open Problems in Concurrency Theory

Bertinoro (Italy), 26-30 June 2023

Open Problems in Concurrency Theory

MODELING FLOCKS AND THEIR EMERGENT BEHAVIORS

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OPCT – Bertinoro June 26 – 30, 2023

Flocking behaviour

- Decentralized system of autonomous components
- Emergent patterns of collective behaviour
  - Coherent movements
  - Cohesion

(video: https://www.quantamagazine.org/smarter-parts-make-collective-systems-too-stubborn-20190226/?mc_cid=1e132cc211&mc_eid=9307f60615)

- https://www.youtube.com/watch?v=3w90X92pDSs

Language-based methodology

Languages play a key role in the engineering of systems

- Systems must be specified as naturally as possible
- Distinctive aspects of the domain need to be first-class citizens
- Intuitive/concise specifications can avoid encodings

Models need to be strictly related to languages for effective analysis

- high-level abstract models guarantee feasible investigations
- scrutiny of results (e.g., counterexample) based on system features, rather than on their low-level representation, guarantees better feedback

Systems Modelling and Analysis

Big challenge: devise appropriate abstractions and linguistic primitives to deal with the specificities of the systems under consideration while relying on an appropriate semantic model.

A possible approach: Combined use of formal methods with model-driven software engineering.

Key ingredients:

1. A specification language equipped with a formal semantics
2. A programming framework with associated runtime environment
3. A number of verification techniques and associated tools

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Our Contributions: A timeline

Languages and tools for different classes of distributed systems

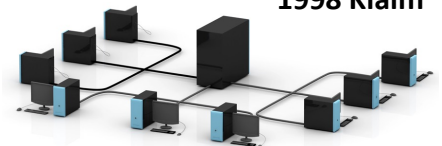
Service-oriented computing
- services composition
- heterogeneous components
- code reuse, interoperability

2006-2009 SCC, COWS, CASPIS

Collective adaptive systems progr.
- large number of components
- decentralised control
- unpredictable environment
- emergent behaviour

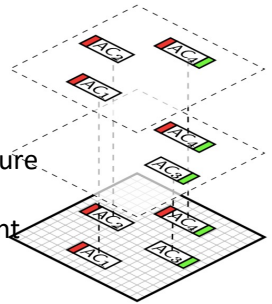
2016 AbC

1998 Klaim



Network-aware programming
- awareness of the network infrastructure
- asynchronous interactions
- open-ended non-determ. environment
- computation mobility

2014 SCEL



Autonomic computing
- reduced maintenance cost
- no human intervention
- continuous monitoring
- adaptation

2020 LAbS

Agent based models
- high-level primitives
- indirect/stigmergic interaction

In this talk

Here, we shall consider:

- AbC: A calculus for Attribute based Programming
  - Modelling Collective Adaptive Systems
- LAbS: A Language with Attribute-based Stigmergies
  - Engineering Agent Based Systems

AbC: A calculus distilled from SCEL

- Components are equipped with attributes whose values can be modified by internal actions and are exposed in their interface .
- Communication actions (send and receive) are decorated with predicates over attributes that partners have to satisfy to make the interaction possible.
- Communication takes place in an implicit multicast fashion: partners are selected via predicates over the attributes exposed in the interfaces.
- Components can offer different views of themselves and can communicate with different partners according to different criteria.
- Semantics for output actions is non-blocking while input actions are blocking and can take place through synchronization with an available sent message.

AbC: Primitives

- Attribute updates $[a := e, \dots]$
  - (Optionally) change values of own attributes
  - Atomically happen after an input/output interaction

- Attribute-based output $(\vec{e})@\Pi[a := e, \dots]$
  - Evaluate expressions $\vec{e}$
  - Send values to all components matching Π

- Attribute-based input $\Pi(\vec{x})[a := e, \dots]$
  - Receive values from any component matching Π
  - Bind values to variables $\vec{x}$

LAbS in few lines

- AbC does not rely on explicit peers identifiers
- Can we also do without explicit send actions?
- In LAbS, agents use stigmergic interaction, i.e. they "drop" bits of information that can be retrieved by others.
- Inspired by biological systems where this form of communication is commonplace
- How?
  - Distributed data structures (*virtual stigmergies*)
  - Shared variables (*environment*)
  - Local information (*attributes*)

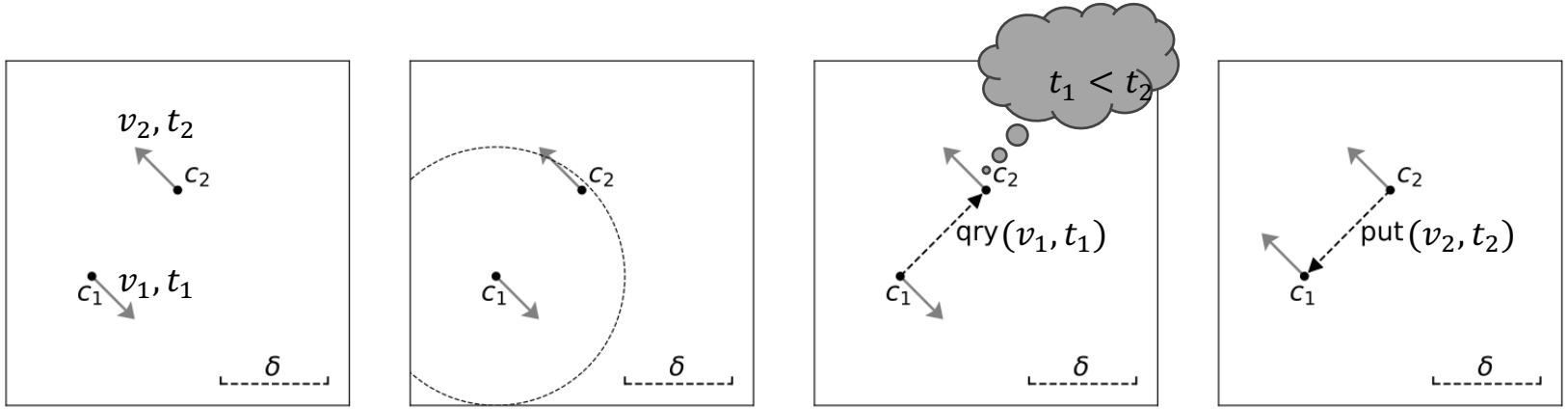
LAbS: Syntax overview

- $P, Q \ ::= \alpha \mid \{B\} \mid P; Q \mid P + Q \mid g \rightarrow P \mid K$ (Process - Componens)
- $\alpha ::= v \leftarrow q \mid v \rightsquigarrow q \mid v \Leftarrow q$ (Statement)
- $\beta ::= \alpha \mid t \ := q \mid p \ := \mathbf{pick}\ n \langle type \rangle \langle \mathbf{where}\ \varphi \rangle$ (Block Statement)
- $B \ ::= \beta \mid \beta\ ; B$ (Block)
- $e \ ::= \kappa \mid v_e \mid e \diamond e \mid \neg e \mid e \wedge e \mid \ e\ \mathbf{if}\ e\ \mathbf{else}\ e$ (Expression)
- $q \ ::= e \mid \mathbf{forall}\ type\ x, q(x) \mid \mathbf{exists}\ type\ x, q(x)$ (Quant. Expression)

- This is the basic syntax of LAbS agents
- Additional rules are needed to describe systems, declare variables, …
- $\leftarrow, \rightsquigarrow, \Leftarrow$ are used to update information about attributes, stigmergy, and environment, respectively.

Virtual stigmergy

- A virtual stigmergy is a store of variables
- At assignment time, a stigmergy variable receives a timestamp
- Agents exchange messages about local values and timestamps after write and read actions; newer values replace older ones
- Messages' exchange is constrained by predicates



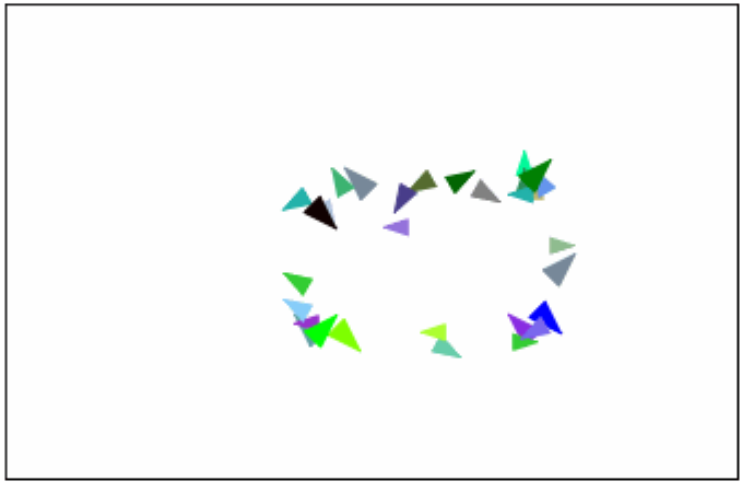
Modelling flocks our way

- High-level language to specify individual behaviours
- Bottom-up, incremental modelling
- Automated encoding into sequential imperative programs
  - For properties verification to exploit existing tools offering different techniques
  - For simulation

Baseline model of a flock of birds

Every agent goes its own way

```
1  agent Bird {
2      Interface =
3          x: 0..G;
4          y: 0..G;
5          dirx: −D..D + 1;
6          diry: −D..D + 1
7
8      Behaviour = Move; Behaviour
9      Move = {
10         x ← x + dirx;
11         y ← y + diry
12     }
13 }
```



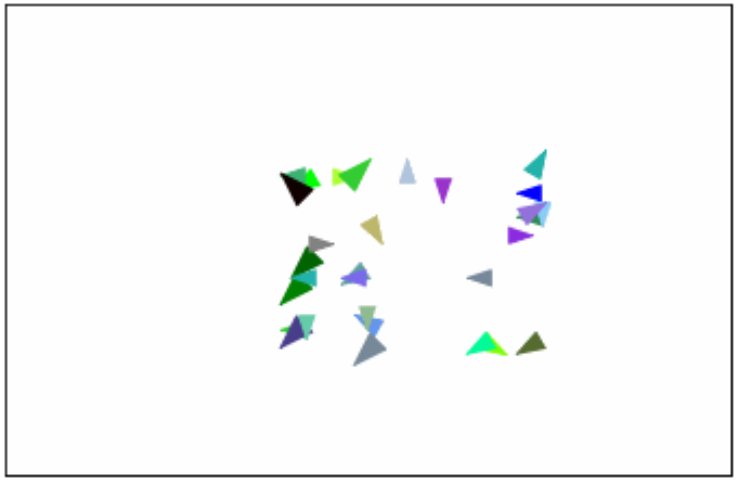
- Attributes of a Bird:
  position (x,y) heading vector (dirx, diry)
- {…} = notation for an atomic block

- $A..B$ = nondeterministic initialization from $[A, B[$
- G, D = external parameters

Alignment: taking the same direction

- Look at another agent and follow its direction

```
1  agent Bird
2      Interface = ...
3
4      Behaviour = Move; Behaviour
5      Move = {
6          p := pick 1;
7          dirx ← dirx_p;
8          diry ← diry_p;
9          x ← x + dirx;
10         y ← y + diry
11     }
12 }
```



pick K returns K agent's identifiers excluding the one of the acting agent

v_p = value of v for agent p

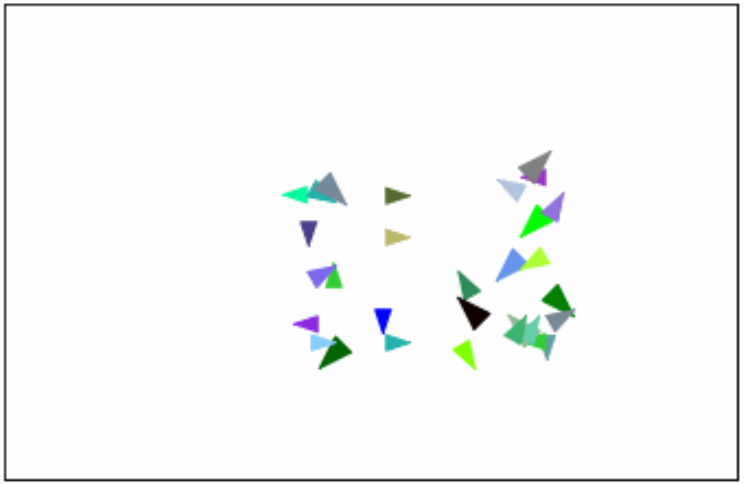
Cohesion: getting as close as possible

Estimate p's position ω steps in the future and aim there; average with current heading for inertia

Move = {
    p := **pick** 1;

    a_x := $x_p + \omega \cdot dirx_p$;
    a_y := $y_p + \omega \cdot diry_p$;
    sgn_x := 0 **if** x = a_x **else** (-1 **if** x > a_x **else** 1);
    diff_x := $d((x, 0), (a\_x, 0))$;
    ... *(Same for* sgn_y, diff_y*)*
    a_dirx := sgn_x $\cdot$ (D:2 **if** diff_y > diff_x **else** D);
    a_diry := sgn_y $\cdot$ (D:2 **if** diff_y < diff_x **else** D);

    dirx $\leftarrow$ (dirx + a_dirx) : 2;
    x $\leftarrow$ x + dirx
    ... *(Same for* diry, y*)*
}



- a **if** c **else** b is the ternary conditional operator
- $x : y$ is real division plus rounding
- $d(a, b)$ is the Manhattan distance $(|x_a - x_b| + |y_a - y_b|)$

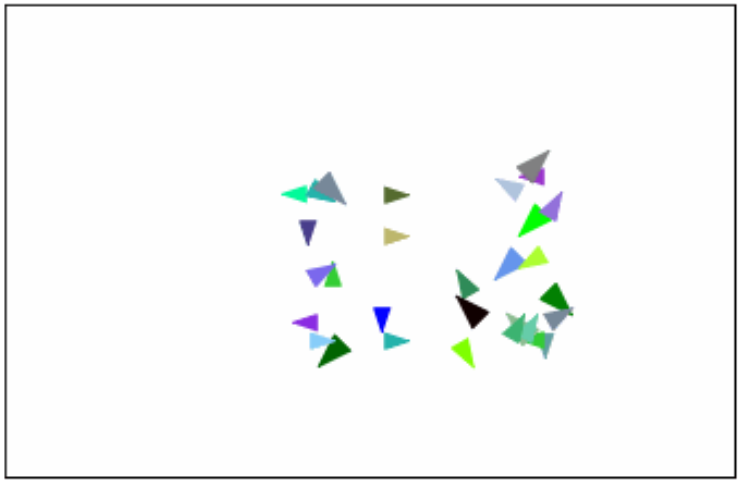
Additional constraints

- Ignore p if it is isolated
- Do not move if destination is already occupied by another bird

Move $= \{$
  p $\coloneqq$ **pick** 1;
  pIsIsolated $\coloneqq$ **forall** Bird b, (b $=$ p) **or** $d((x_p, y_p), (x_b, y_b)) > \delta$;
  appId $\coloneqq$ id **if** pIsIsolated **else** p;

  a_x $\coloneqq x_{appId} + \omega \cdot dirx_{appId}$;
  sgn_x $\coloneqq$ 0 **if** x $=$ a_x **else** (-1 **if** x $>$ a_x, **else** 1);
  diff_x $\coloneqq d((x, 0), (a\_x, 0))$;
  ... *(Same for* a_y, sgn_y, diff_y*)*
  a_dirx $\coloneqq$ sgn_x $\cdot$ (D:2 **if** diff_y $>$ diff_x **else** D);
  a_diry $\coloneqq$ sgn_y $\cdot$ (D:2 **if** diff_y $<$ diff_x **else** D);

  dirx $\leftarrow$ (dirx + a_dirx) : 2;
  diry $\leftarrow$ (diry + a_diry) : 2;
  posFree $\coloneqq$ **forall** Bird b, ($x_b \neq x +$ dirx) **or** ($y_b \neq y +$ diry);
  x $\leftarrow$ x + dirx **if** posFree **else** x
  y $\leftarrow$ y + diry **if** posFree **else** y
$\}$



Decision are taken by evaluating predicates over agents' state

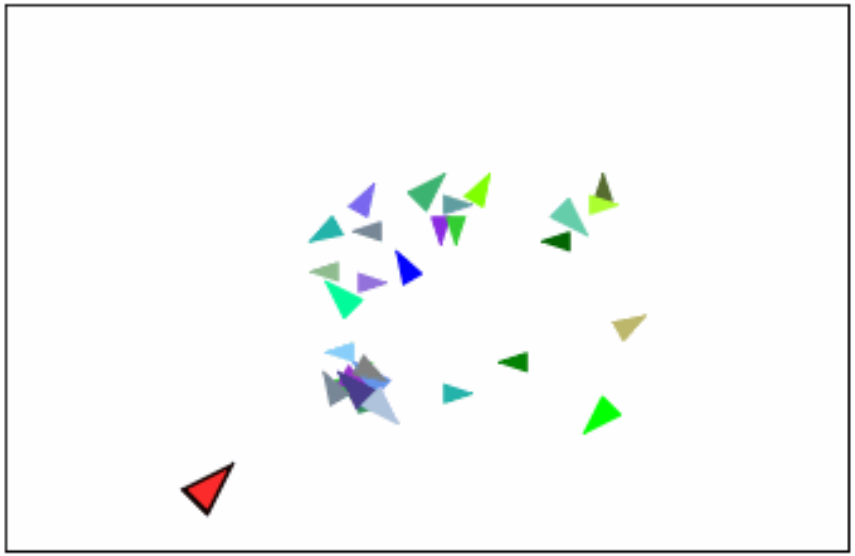
Avoiding predators

- A predator P moving in a straight line is added
- If P is closer than λ, agents move away from it

```
Move = {
    p := pick 1 Bird;
    ...
    a_diry := sgn_y · (D:2 if diff_y < diff_x else D);

    e := pick 1 Predator;
    e_x := x_e + ν · dirx_e;
    esgn_x := 1 if x ≥ e_x else −1;
    ediff_x := d((x, 0), (e_x, 0));
    ... (Same for e_y, esgn_y, ediff_y)
    e_dirx := esgn_x · (D:2 if ediff_y > ediff_x else D);
    e_diry := esgn_y · (D:2 if ediff_y < ediff_x else D);

    e_dist := d((x, y), (e_x, e_y));
    f_dirx := e_dirx if e_dist < λ else a_dirx;
    dirx ← (dirx + f_dirx) : 2;
    ... (Same for f_diry, diry)
    posFree := forall Bird b, (x_b ≠ x + dirx) or (y_b ≠ y + diry);
    x ← x + dirx if posFree else x
}
```



This time **pick** is typed

Concerns about global information

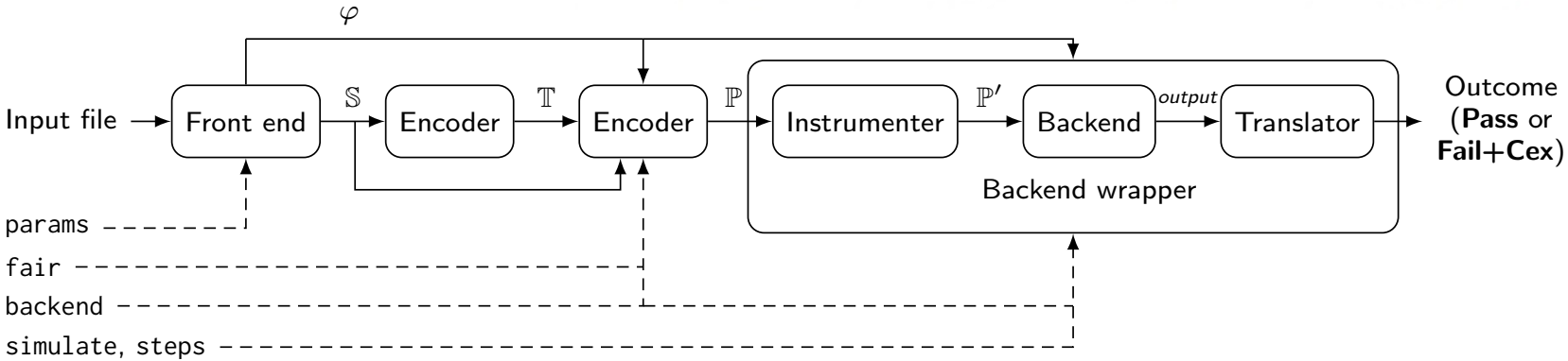
- Formally, pick, forall, exists, v_p rely on a global knowledge of the system

- However, they can be evaluated "locally" by a given agent
  - "pick 1 agent randomly" -→ a form of neighbor discovery
  - "check that no agent is at position (x, y)" -→ look at (x, y)
  - $dirx_p$ -→ look at agent p
  - "check that agent p is isolated" -→ look around agent p

Additional details

- For this model we assumed round-robin scheduling, allowing the execution of an instruction (or an atomic block) by each agent at each round
- We can set up initial constraints in an **assume** { … } section, e.g., to state that:
  - Birds start at the center of the arena
  - Birds have different initial positions
  - Birds have non-null initial directions
- For simulation, some nondeterminism is resolved upfront by fixing initial states and outcomes of **pick** statements

SLiVER: Verification/Simulation of LAbS models



- 𝕊 Syntax tree of model
- 𝕋 Intermediate representation (a set of triples: activation condition, statement, program counter update)
- ℙ Emulation program (here a C program; we also support LNT)

The back end currently used is CBMC (SAT-based bounded model checking)

Verifying cohesion

In the model without the predator, we want to check that the distance between all birds gets smaller than k after B steps:

$$\textbf{after } B \textbf{ forall } \text{Bird } a, \textbf{forall } \text{Bird } b, d(a,b) < k$$

Indeed: If initially all birds are "close" they keep close.

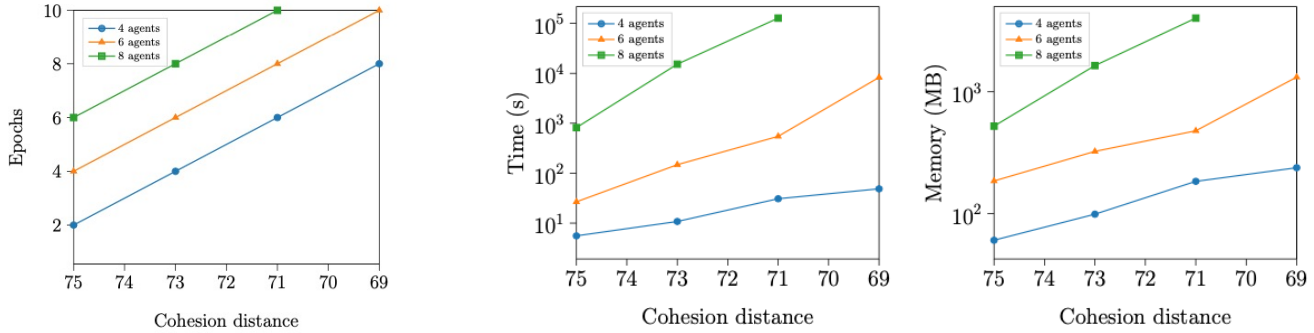
But: With two groups at distance $k_0 > k$, the property may not hold.

- **pick** might always select bird from the same group.
- To avoid this, we assign Birds a $groupId$ and force them to look at a different group after each step (**pick** … **where** … adds further constraints when choosing agents)

$$p \coloneqq \textbf{pick}\ 1\ \textbf{where}\ (check = 0)\ \textbf{or}\ \left(groupId_p \neq groupId\right);$$

$$check = (check + 1)\textbf{mod}\ 2;$$

- With this fix the property holds for several values of k, B



Conclusion

- Bottom-up modelling with LAbS
  - Compact specifications of individual behaviours
  - No explicit communication primitives
  - Possibility of gradual improvements
- Simulations
  - Some assurance that the desired collective behaviour will emerge
  - Feedback to refine specifications
- Verification
  - Catch subtle bugs
  - Can definitely prove the emergence of desired collective features

Next steps

- Modelling flocks in 3D
- Statistical model checking
- Runtime verification
- Use other verification back ends
- Extend the range of supported properties
- Consider different approaches and compare
  - Discrete-time dynamics (e.g., Boids)
  - Equational modelling (
  - Decentralized control laws

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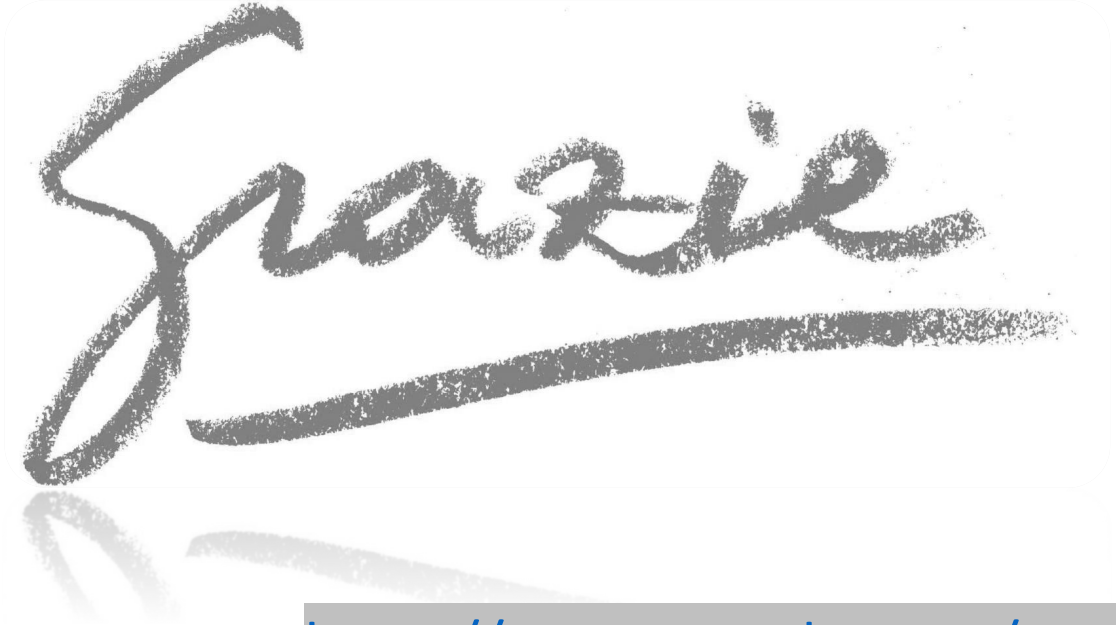
- LAbS code: https://github.com/labs-lang

QUESTIONS?



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