Formal Proofs for Mobile Robot Swarms

Lionel Rieg

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Inspiration: Swarms of Mobile Robots

- Swarms?

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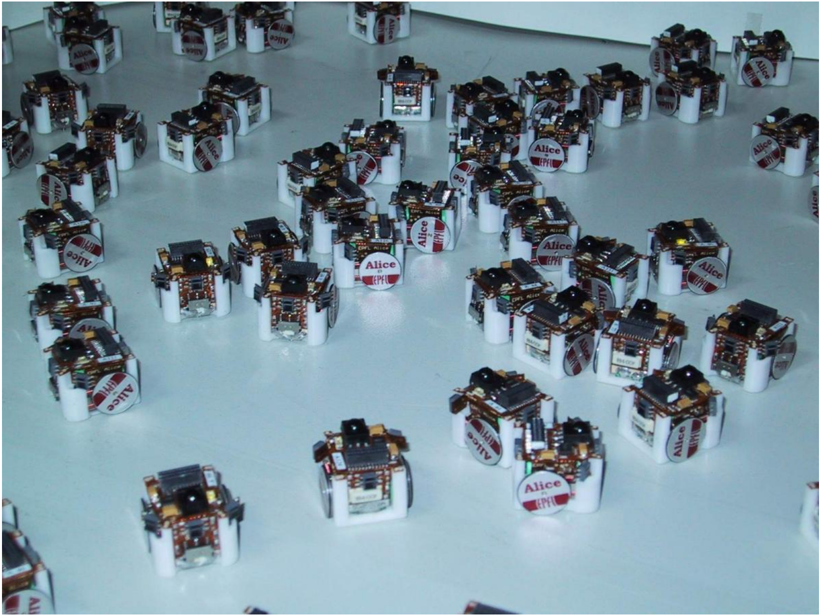

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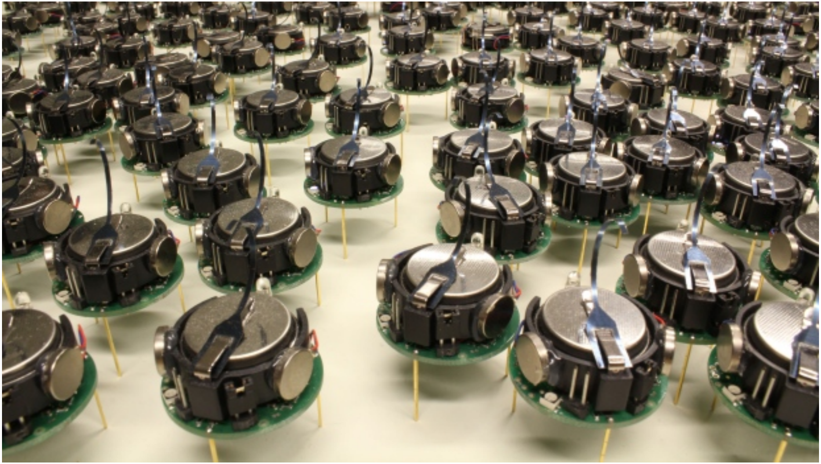

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  - rescue
  - exploration
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  - lots of (small) identical robots
- Where?
  - entertainment
  - rescue
  - exploration
  - ...
- Opportunities?
  - cooperative behavior (swarm intelligence)
  - resilience
- Main challenge?
  - Understand what happens!

Why Formal Methods for Mobile Robots Swarms?

Many mobile robots swarm models:

- Space — discrete/continuous, bounded/unbounded, topology, ...
- Sensors — multiplicity, range, accuracy, orientation, ...
- Faults — none, crash, Byzantine, ...
- Execution — synchronous/asynchronous, fairness, interruption, ...

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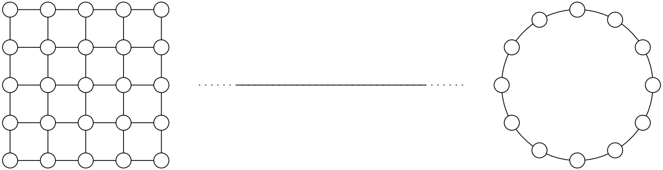

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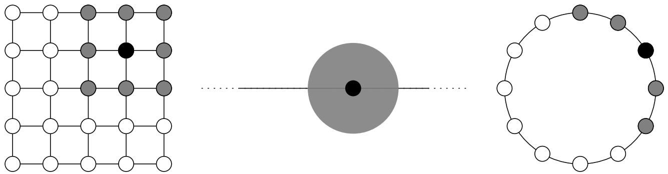

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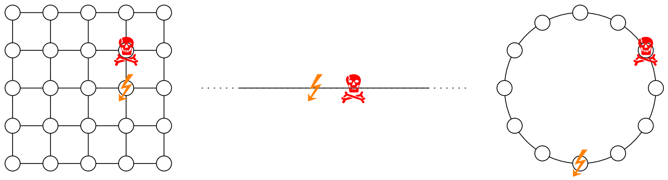

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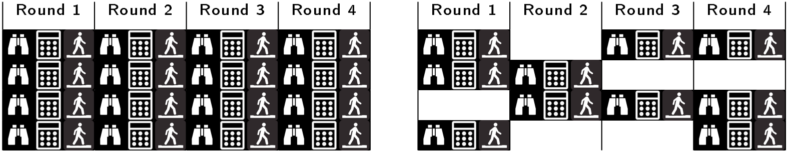

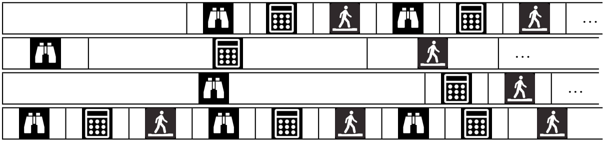

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- Careful of mismatch spec/proof!
- Lots of proof cases

$\Rightarrow$ Formal methods can help

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$\Rightarrow$ Formal methods can help

Which model? (process algebra, TLA, ...)
Which tool? (model checking, proof assistant, ...)

We need a suitable framework — What are the requirements?

Robot Model

[Suzuki, Yamashita 99]

Robot Model

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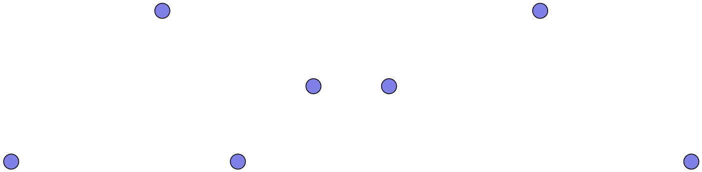
- Points



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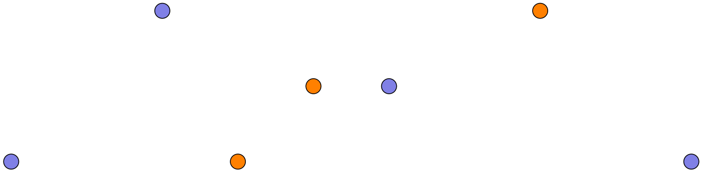

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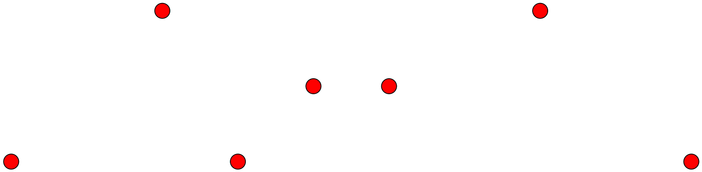

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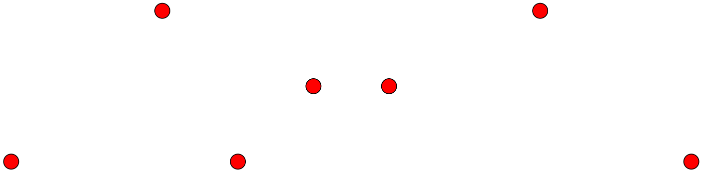

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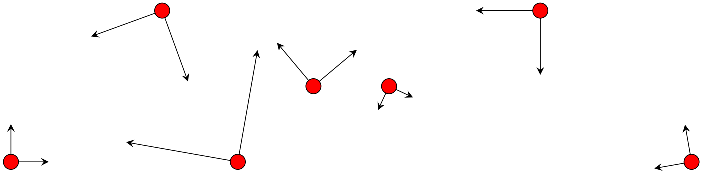

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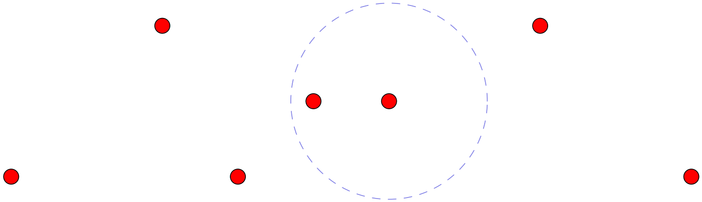

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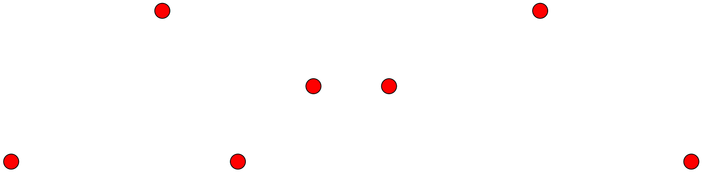
- Limited/unlimited vision? multiplicity?
- Same (deterministic) program everywhere



Execution Models (1)

[Suzuki, Yamashita 99]

3 phases for each robot:

1. Look: observe its surrounding
   - indirect communication
   - depends on sensor capabilities
2. Compute: choose what to do
   - choose an objective
   - depends on observation, program
3. Move: do it (or try to)
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and repeat

Execution Models (2): Scheduling [Suzuki, Yamashita 99]

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Either ASYNC: full interleaving

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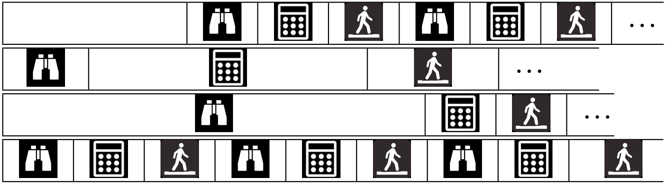

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or Same phase for all active robots

- Time split into rounds

Round 1	Round 2	Round 3	Round 4	Round 5

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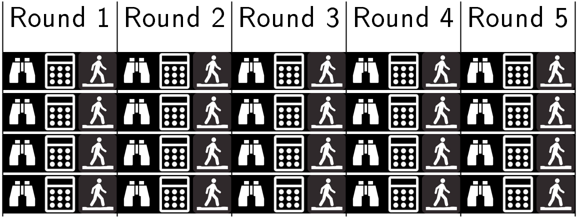

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Scheduling of robots is

Either ASYNC: full interleaving

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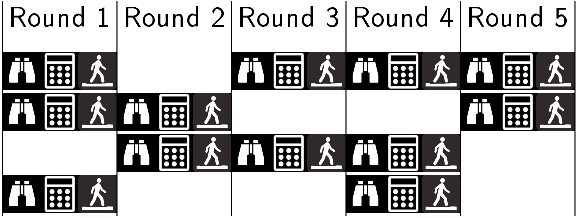
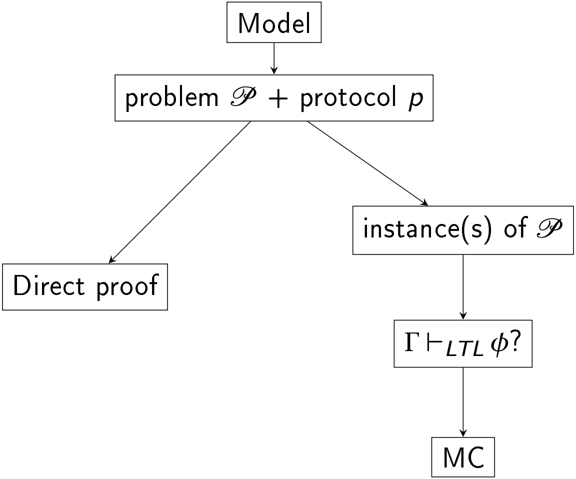
- Time split into rounds
- FSYNC: all robots are activated each round
- SSYNC: only a subset is activated

  $\rightsquigarrow$ Fairness assumptions on the scheduling (demon)



Proving Distributed Protocol



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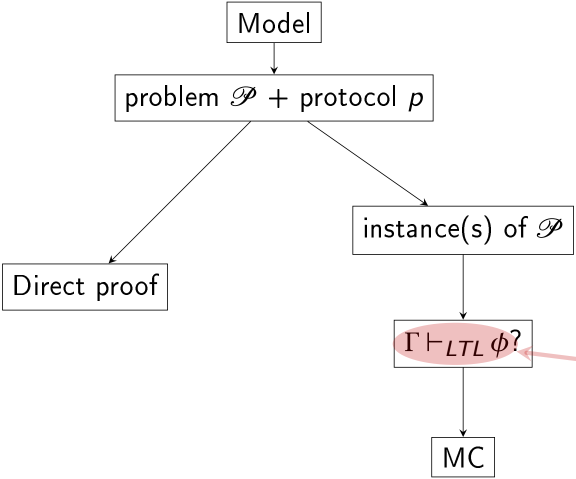
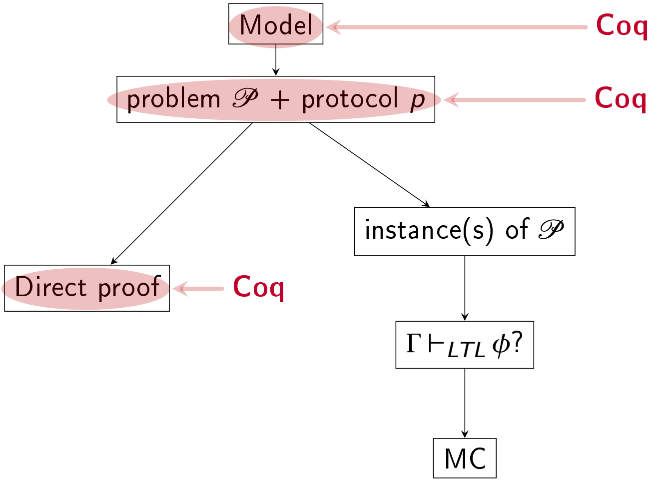


true iff p succeeds on all schedulings

Pactole



Model
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problem $\mathscr{P}$ + protocol p
Coq
instance(s) of $\mathscr{P}$
Direct proof
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$\Gamma \vdash_{LTL} \phi$?
MC

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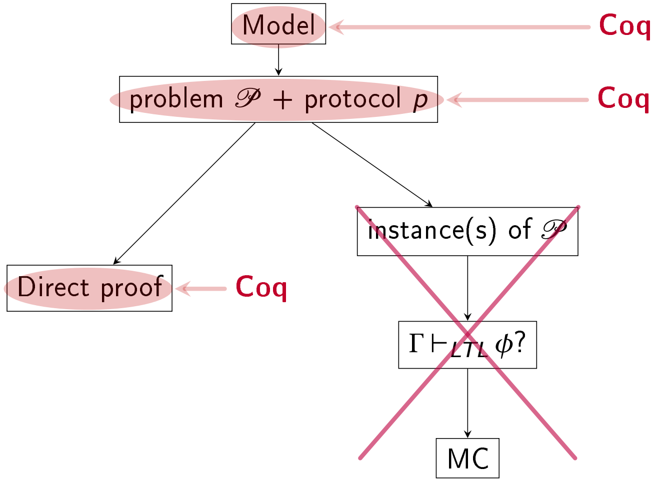

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Pactole: a Coq Framework for Mobile Robots

Very Parametric (but still useful):

- Space
- State of Robots (location, memory, battery level, etc.)
- Sensors
- How states are updated during the move phase

Key Ingredients:

- Configuration — function ident → state
- Spectrum — info on config from sensors
- Robogram — function spectrum → location
- Demon (scheduler) — adversarial environment
- Round — one step of execution

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Robogram: what happens for a robot?

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   a. **Look**: get information from its surrounding
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Demon: what does the environment decide?

1. Pick which robots are activated
2. Decide how to update inactive ones
3. Update Byzantine ones as it wishes
4. Select the new frame of reference for non Byzantine ones
5. Decide how to update them depending on their destination

The Core of Pactole: the Round Function

Coq

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Definition round (r:robogram) (da:demonic_action) cfg
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      (* actual state update performed by the update function *)
      update cfg g global_traj choice
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Proving in Pactole

Correctness proof:

1. Formalize your problem

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3. Express your algorithm in the global frame of reference

Two different points of view

Global View (demon + proof)	**Local View** (robots)
absolute location	local frame of reference
robots: Byzantine or not (B / G)	indistinguishable robots
identifiers ident = $G + B$	
configuration = ident → position	local configuration
	spectrum
	robogram
	: spectrum → location
round r d : config → config	
exec = stream of configurations	

spectrum = degraded local view of a configuration

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Impossibility proof:

1. Formalize your problem
2. Assume given a robogram (a variable) + its properties
3. Prove that the algorithm does not solve the problem
   (`round_simplify` not always needed)

Some results (✓verified in Pactole)

- Convergence $\mathbb{R}^2$, rigid, $\geq 1/3$ Byzantine, SSYNC
  Impossibility [Bouzid et al. TCS'10] [SSS'13] ✓
- Gathering $\mathbb{R}^2$, rigid, no Byzantine, SSYNC
  Impossibility ($2 \times n$ robots) [Suzuki,Yamashita SICOMP'99] [IPL'15] ✓
- Gathering $\mathbb{R}^2$, rigid, no Byzantine, SSYNC, start not bivalent
  Effective (universal) algorithm [DISC'16] ✓
- Gathering $\mathbb{R}^2$, non rigid, no Byzantine, FSYNC, no multiplicity
  Effective (universal) algorithm [SSS'16] ✓
- Exploration $\mathbb{Z}/n\mathbb{Z}$, discrete, k robots, no bizantine, SSYNC
  Impossibility (k divides n) [ICDCN'17] ✓
- Discrete/continuous graphs, non rigid, ASYNC
  Model equivalence [SSS'18] ✓
- Connection $\mathbb{R}^2$, rigid, no bizantine, SSYNC
  Effective (non optimal) algorithm [SSS'21] ✓

Case Study: Gathering

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Let's formalize it!

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Coq

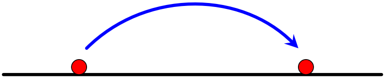
```
(* All good robots are at the same location [pt] (exactly). *)
Definition gathered_at (pt : location) (cfg : configuration) :=
  ∀ g, get_location (cfg (Good g)) ≡pt.

(* At all rounds of [e], robots are gathered at [pt]. *)
Definition Gather (pt : location) (e : execution) : Prop :=
  Stream.forever (Stream.instant (gathered_at pt)) e.

(* The infinite execution [e] is *eventually* [Gather]ed. *)
Definition WillGather (pt : location) (e : execution) : Prop :=
  Stream.eventually (Gather pt) e.
```

Impossibility Proof [Suzuki & Yamashita 99]

By symmetry, both robots act the same.

Two cases:

Impossibility Proof [Suzuki & Yamashita 99]



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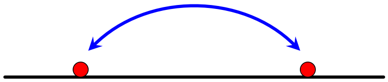

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Generalizations:

- Even number of robots
- Type of line ($\mathbb{Q}$ ou $\mathbb{R}$), higher dimension

Universal Algorithm

Key Ideas:

- Center of the smallest enclosing circle
- Move in stages (not all robots at once)
- Never create the configuraton of the impossibility proof

Hard part of the proof: termination $\leadsto$ termination order

- #robots on the circle decreases
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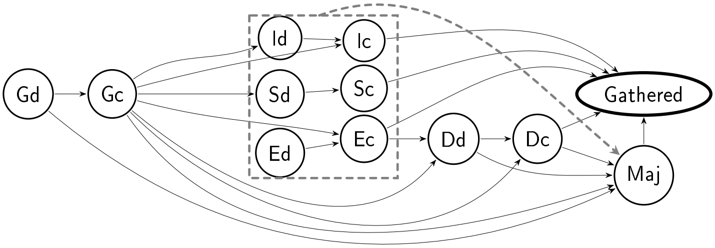

Termination Order in Coq

Coq

```
Definition m_clean s := nG-s[target s].
Definition m_dirty s := nG-SECT_cardinal s.
Function measure (s : observation): nat * nat :=
 match support (max s) with
  | nil ⇒ (0, 0)                                        (* no robot *)
  | pt :: nil ⇒ (0, nG -  s[pt])                        (* majority *)
  | _ :: _ :: _ ⇒
    match on_SEC (support s) with
     | nil | _::nil ⇒ (0,0)                    (* impossible cases *)
     | pt1::pt2::nil ⇒                            (* diameter case *)
       if clean s then (1,m_clean s) else (2,m_dirty s)
     | pt1::pt2::pt3::nil ⇒                       (* triangle case *)
       if clean s then (3,m_clean s) else (4,m_dirty s)
     | _ ⇒                                         (* general case *)
       if clean s then (5,m_clean s) else (6,m_dirty s)
 end
end.

Definition lt_config x y :=
      Lexprod.lexprod lt lt (measure (!! x)) (measure (!! y)).
```

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- ⊕ Ease of use for specification
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- Highly parametric — space, sensors, execution model, ...
- Very expressive
- Common base of definition (no more mismatches)

$\Rightarrow$ A junction point for several formal results?

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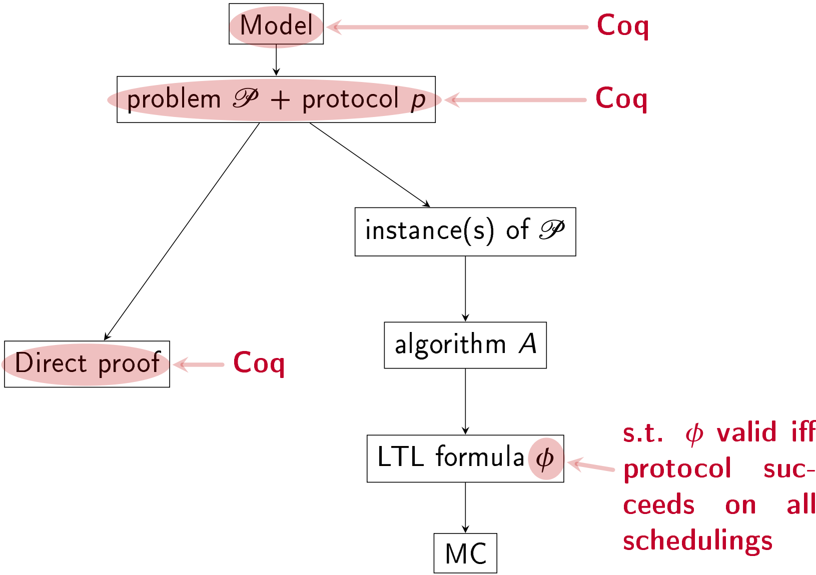
⇒ A junction point for several formal results?

- ⊖ Caveat
  - No fully automated procedure (yet)
  - Building proofs is a lot of work

Future

- ANR SAPPORO (2019-2023):
  - Randomized protocols
  - Automated proofs (graph rewriting)
  - Non euclidean geometry (non-perfect sensors)
  - Luminous robots
- Link with model checkers

Appendix: Link with model checking



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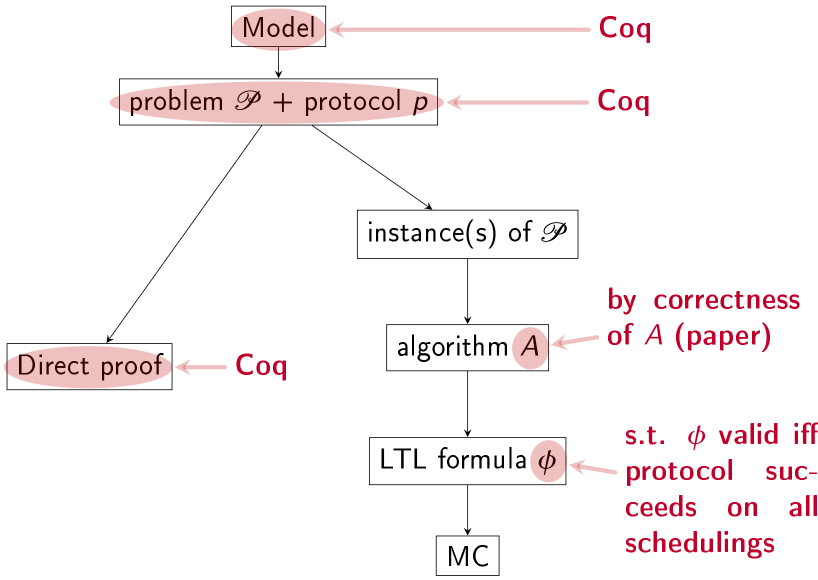

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