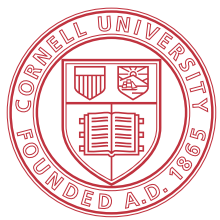
ROSCoq: Robots powered by Constructive Reals

Abhishek Anand
(joint work with Ross Knepper)



Cornell University

ITP, 27-Aug-2015, Nanjing

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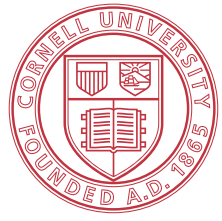

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[1] The symbol ⇑ occurs at many places in this PDF. On a modern PDF reader (with support for OCG) such as Adobe Reader, Evince (Linux), Foxit Reader (Windows), PDF XChange viewer clicking such a symbol will open/close a popup containing extra explanation, e.g. what I said while describing that slide)

Motivation

Collaborating Robots[2] ⇑
Keyboard finding robot[3] ⇑

[2] Mehmet Dogar, Ross A. Knepper, Andrew Spielberg, Changhyun Choi, Henrik I. Christensen, and Daniela Rus. "Towards Coordinated Precision Assembly with Robot Teams". In: *ISER*. 2014.

[3] Abhishek Anand, Hema Swetha Koppula, Thorsten Joachims, and Ashutosh Saxena. "Contextually guided semantic labeling and search for three-dimensional point clouds". In: *IJRR* (2012).

Goals

- Write robotic programs in Coq

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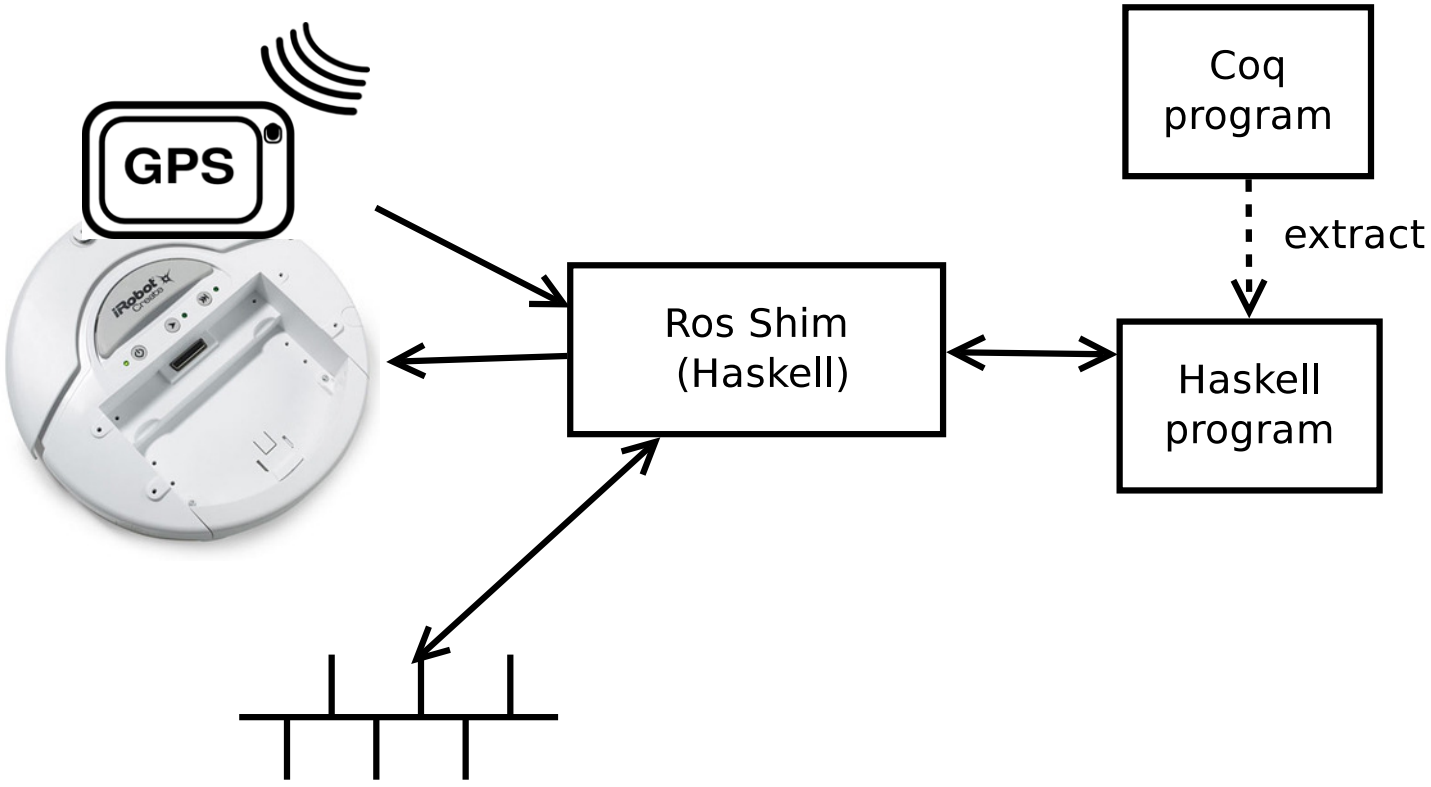


- Specify the behavior of the shim, physics, and hardware in a *realistic* way

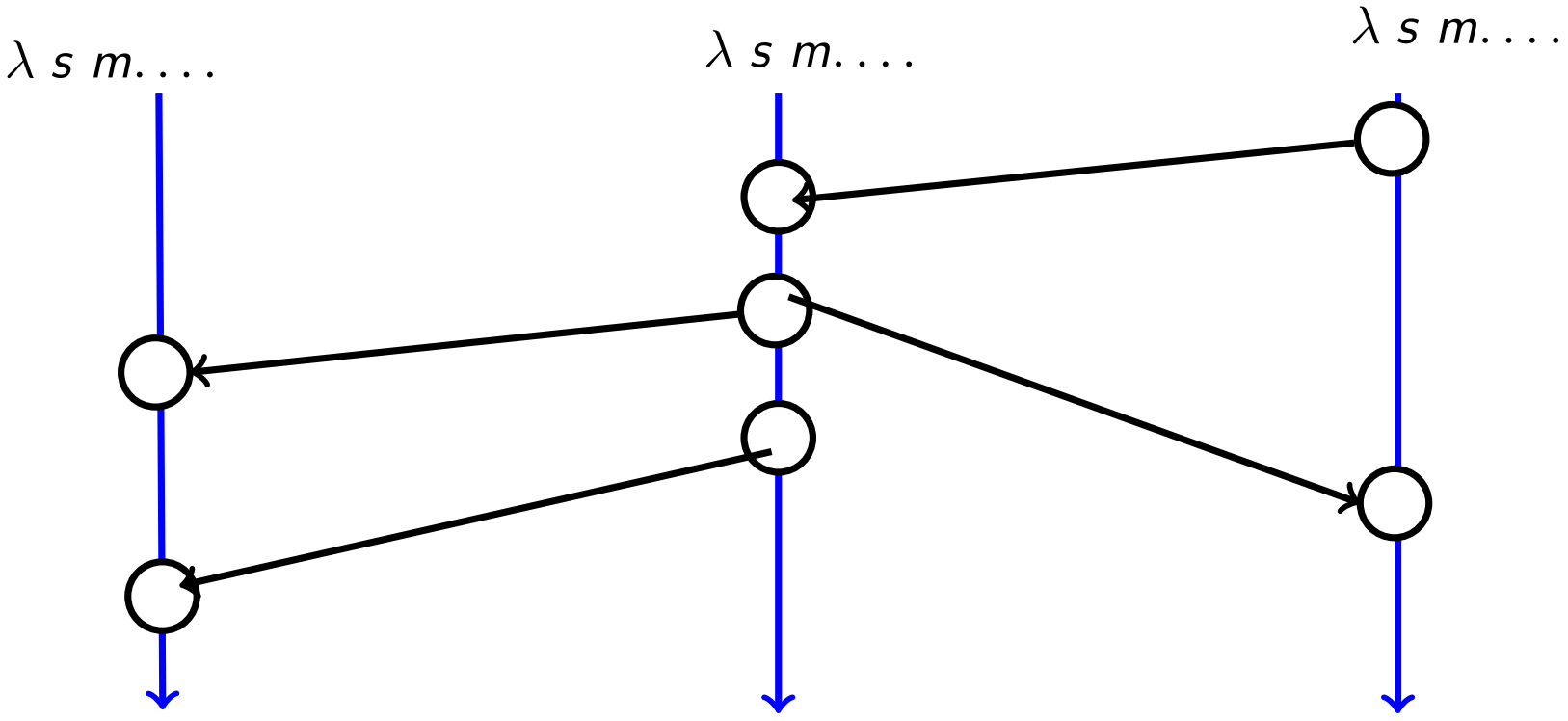
Goals

- Write robotic programs in Coq
- "Run" them on actual robots using a shim:
- Specify the behavior of the shim, physics, and hardware in a *realistic* way
- develop Coq proofs of properties about the overall behavior

The Logic of Events framework

- Cyber Physical systems are distributed systems
- where agents have fancy sensing and/or actuation actuation capabilities.

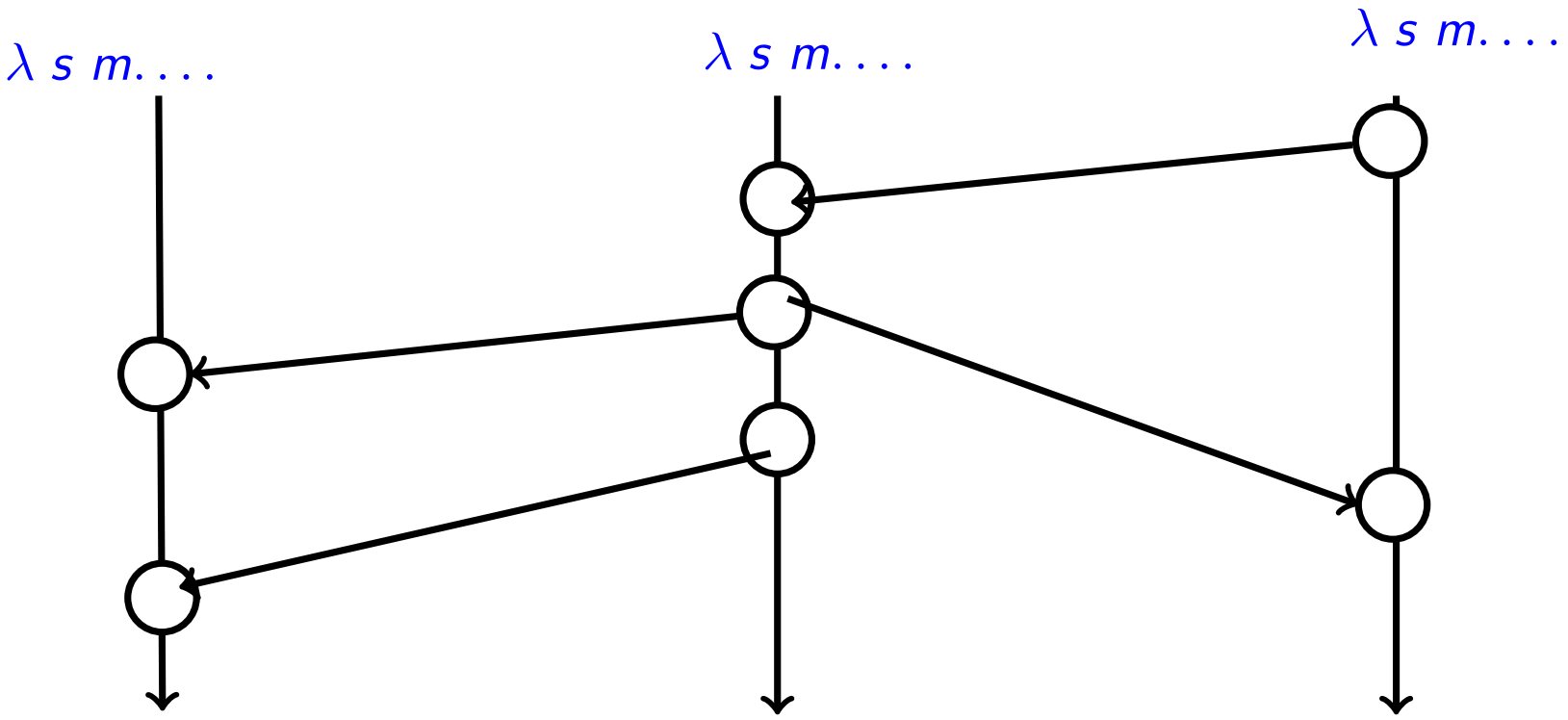
The Logic of Events framework



Nicolas Schiper, Vincent Rahli, Robbert Van Renesse, Marck Bickford, and Robert L. Constable. "Developing correctly replicated databases using formal tools". In: *DSN*. IEEE, 2014, pp. 395–406 ⇑

The Logic of Events framework

$\Uparrow$



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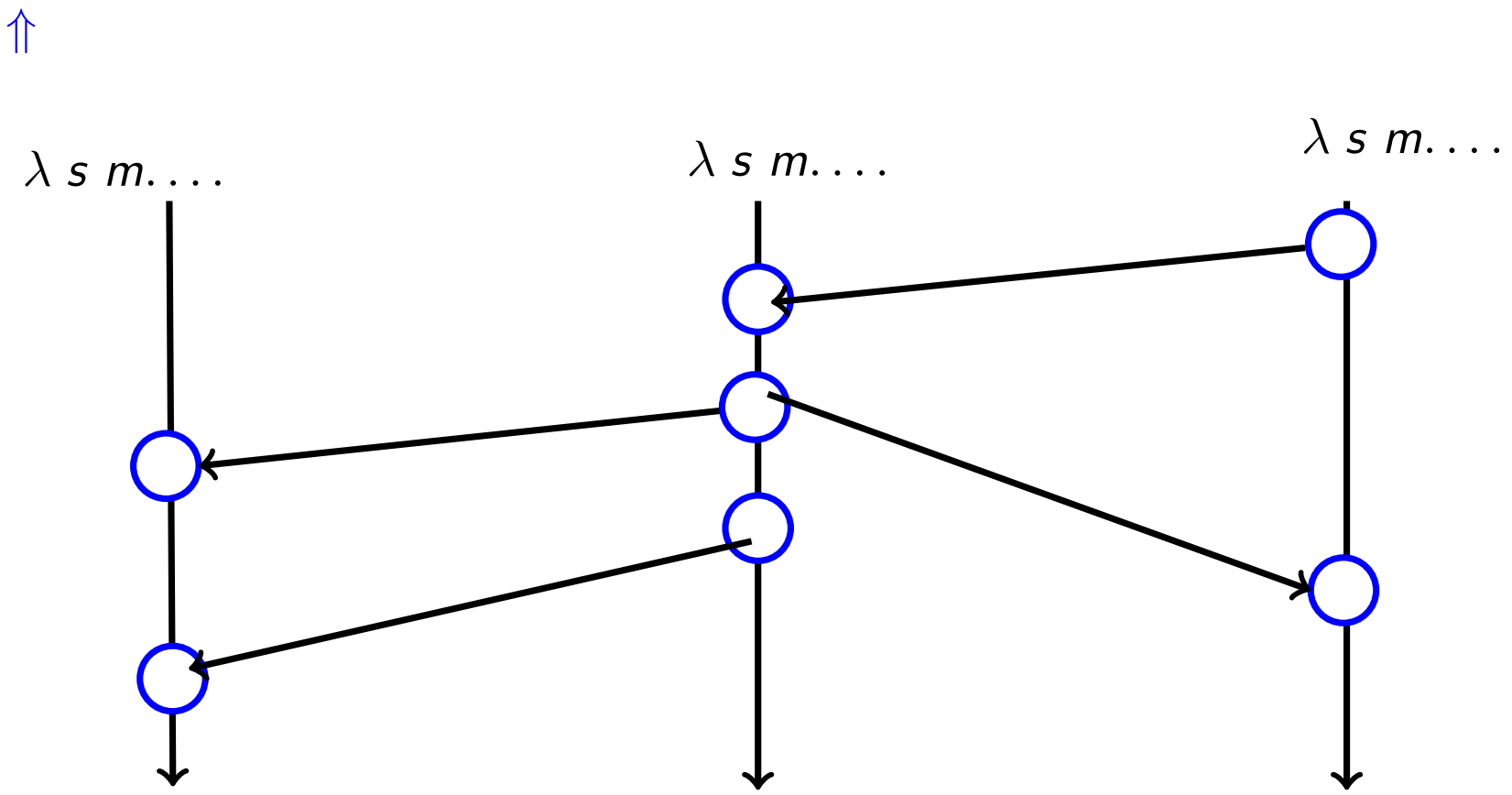

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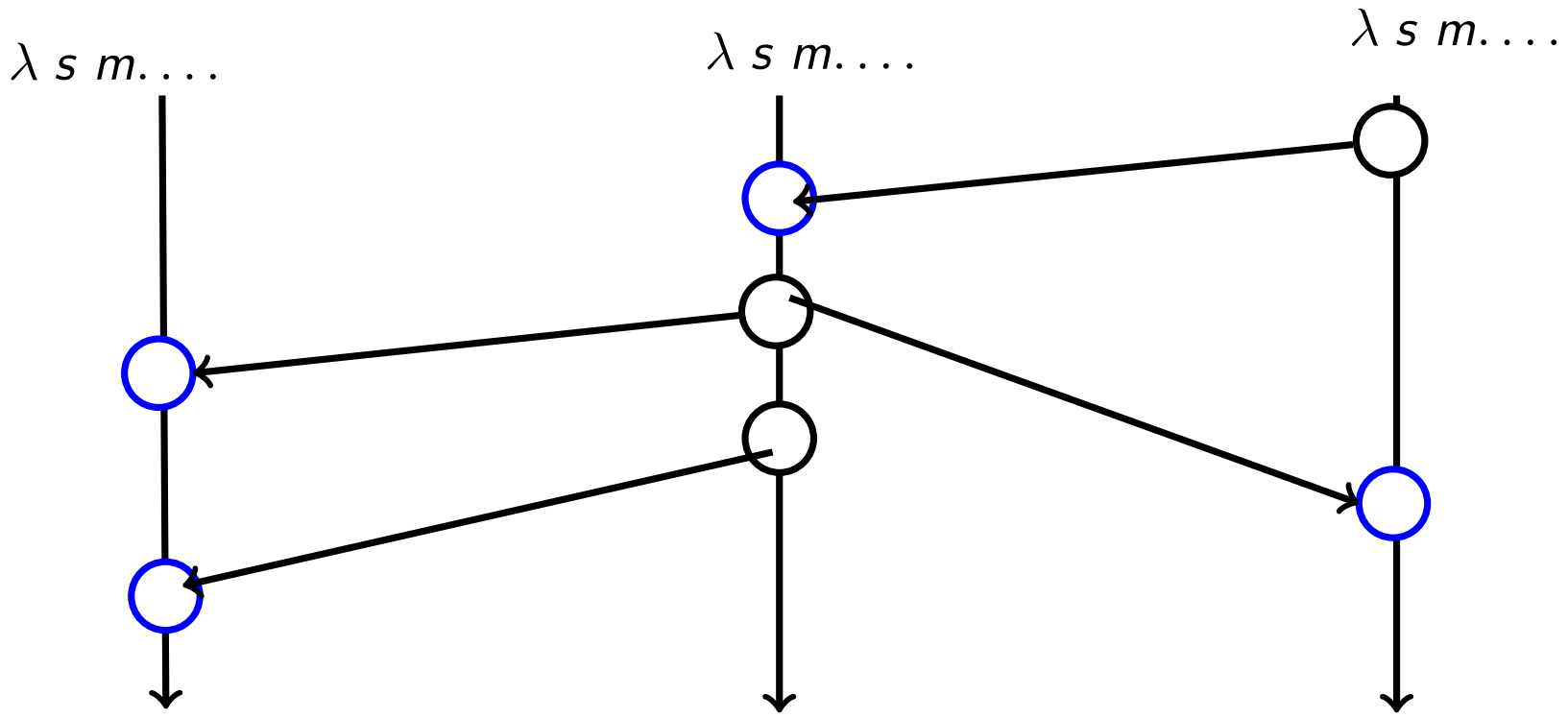

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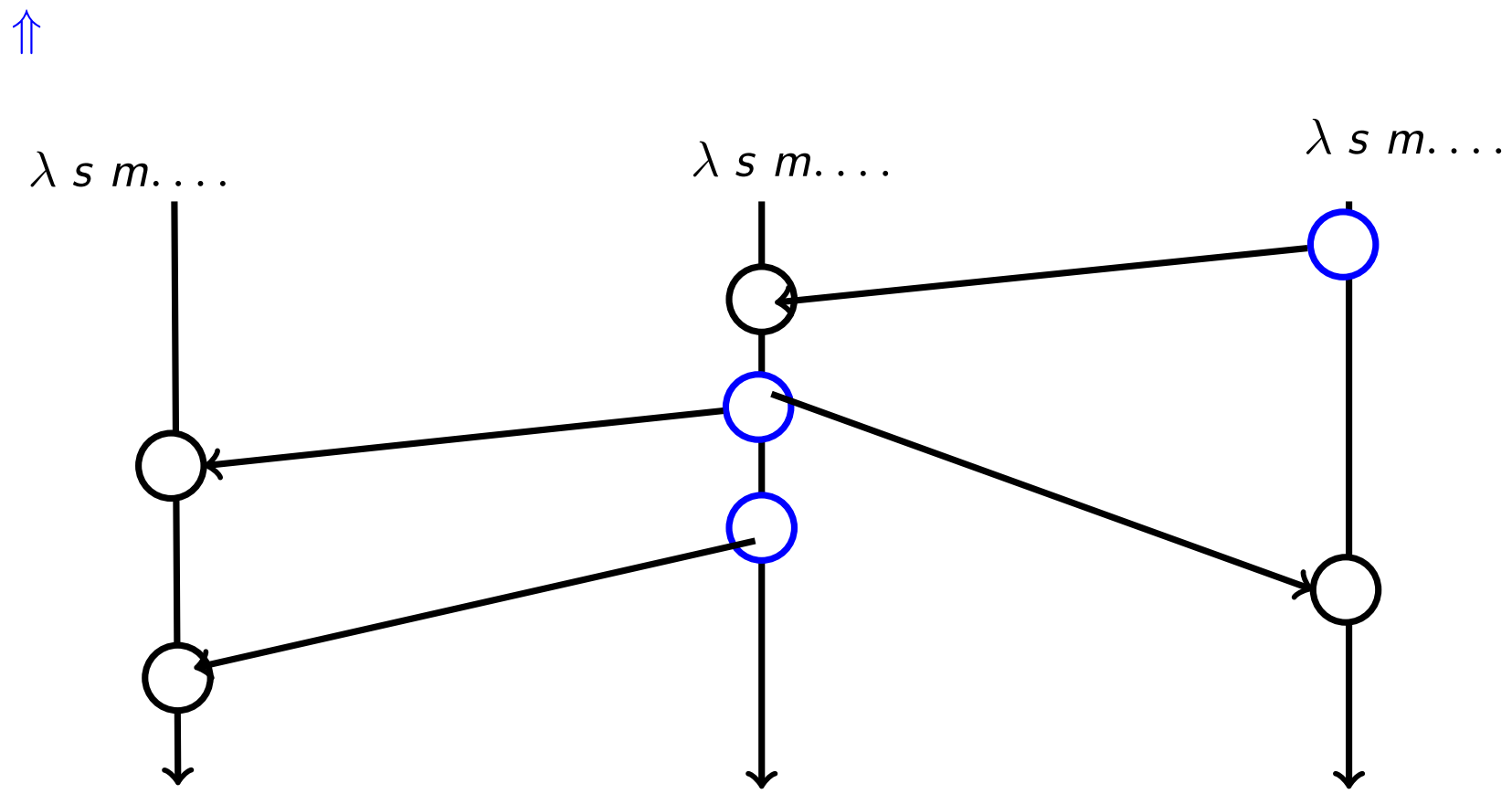

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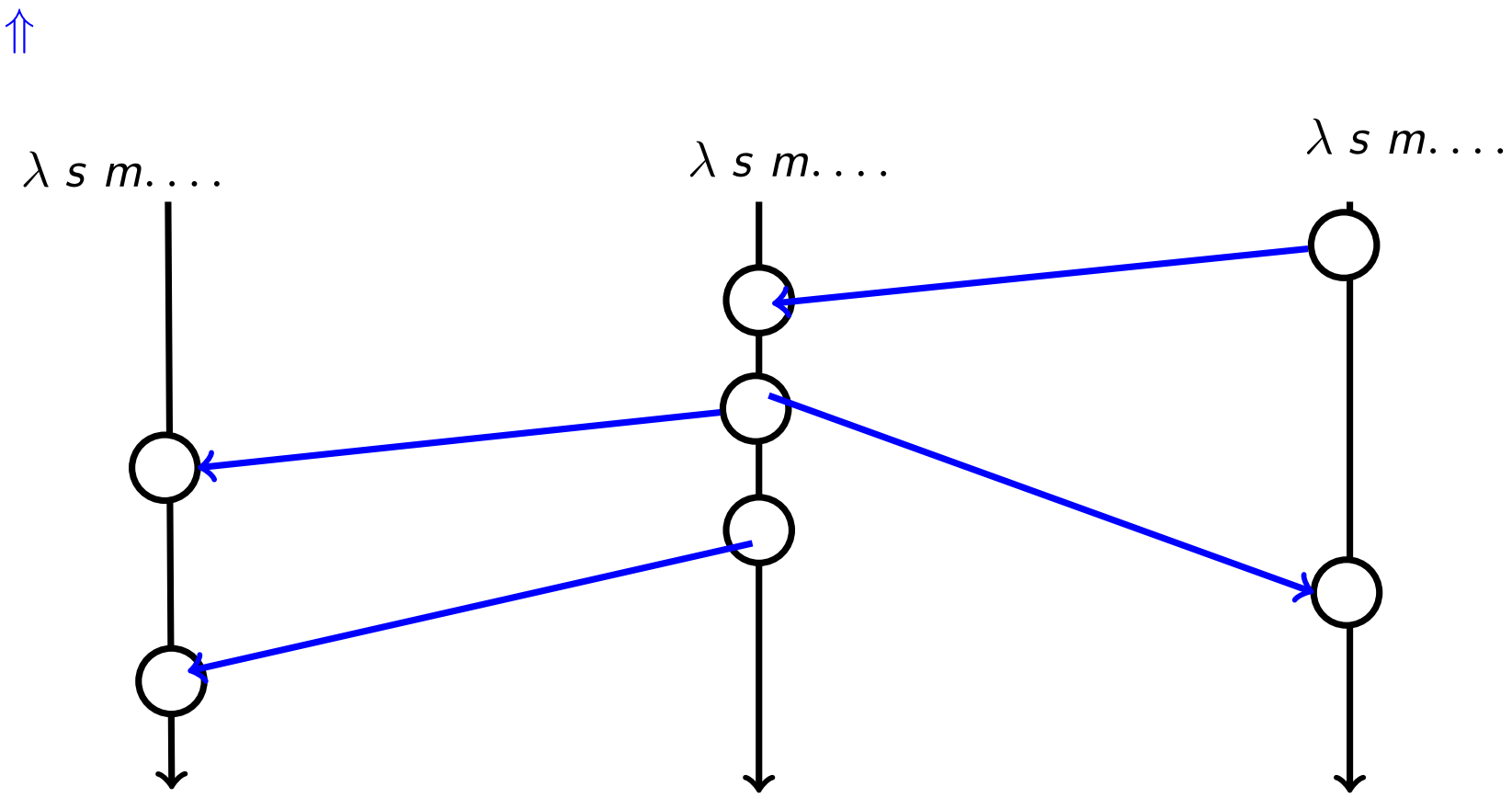
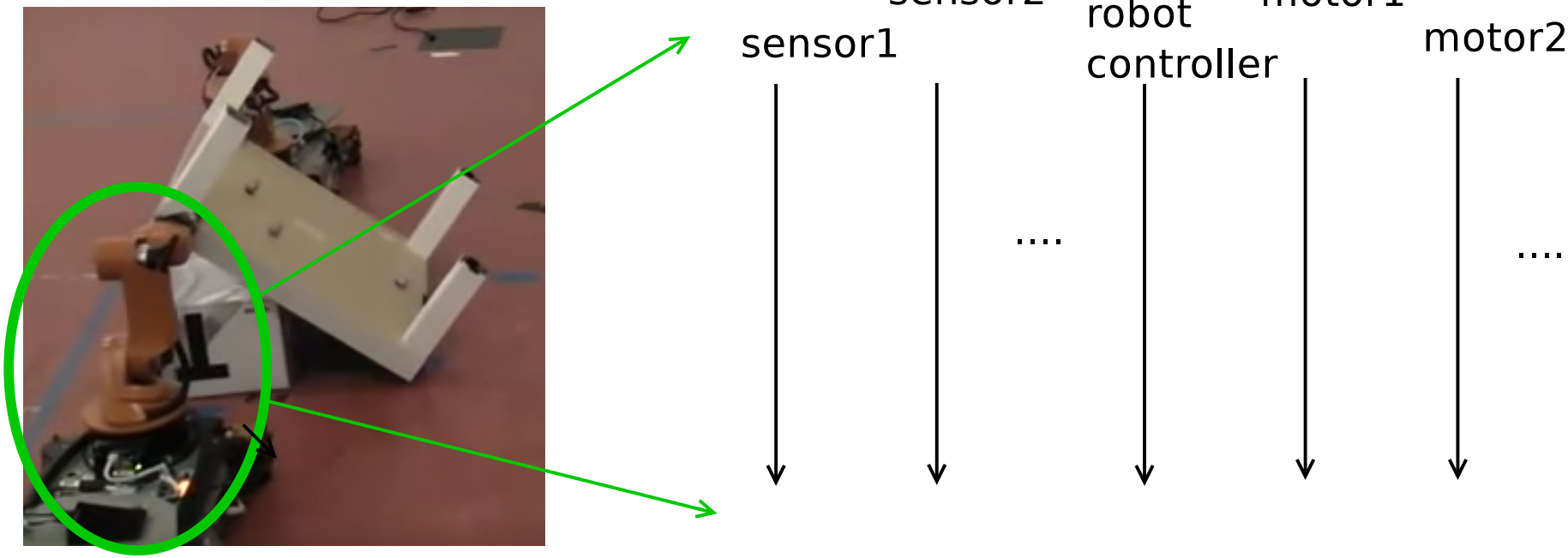


ROS : Even single robots are distributed systems

- Based on asynchronous message passing[4]
- Very popular, drivers (as DS agents) available for many robots [5]



[4] Morgan Quigley, Ken Conley, Brian Gerkey, Josh Faust, Tully Foote, Jeremy Leibs, Rob Wheeler, and Andrew Y. Ng. "ROS: an open-source Robot Operating System". In: *ICRA workshop on open source software*. Vol. 3. 2009, p. 5.

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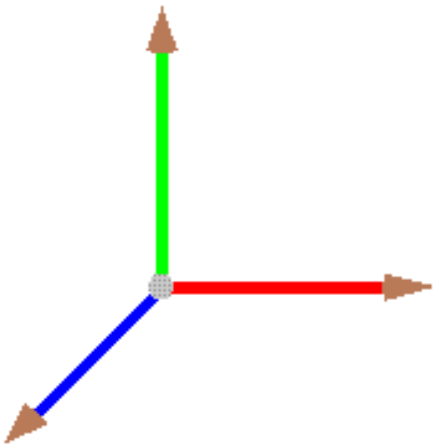

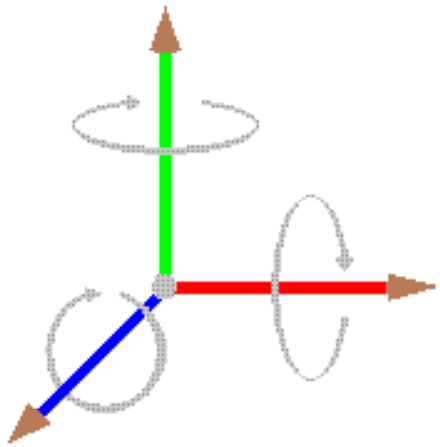

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- Running Example

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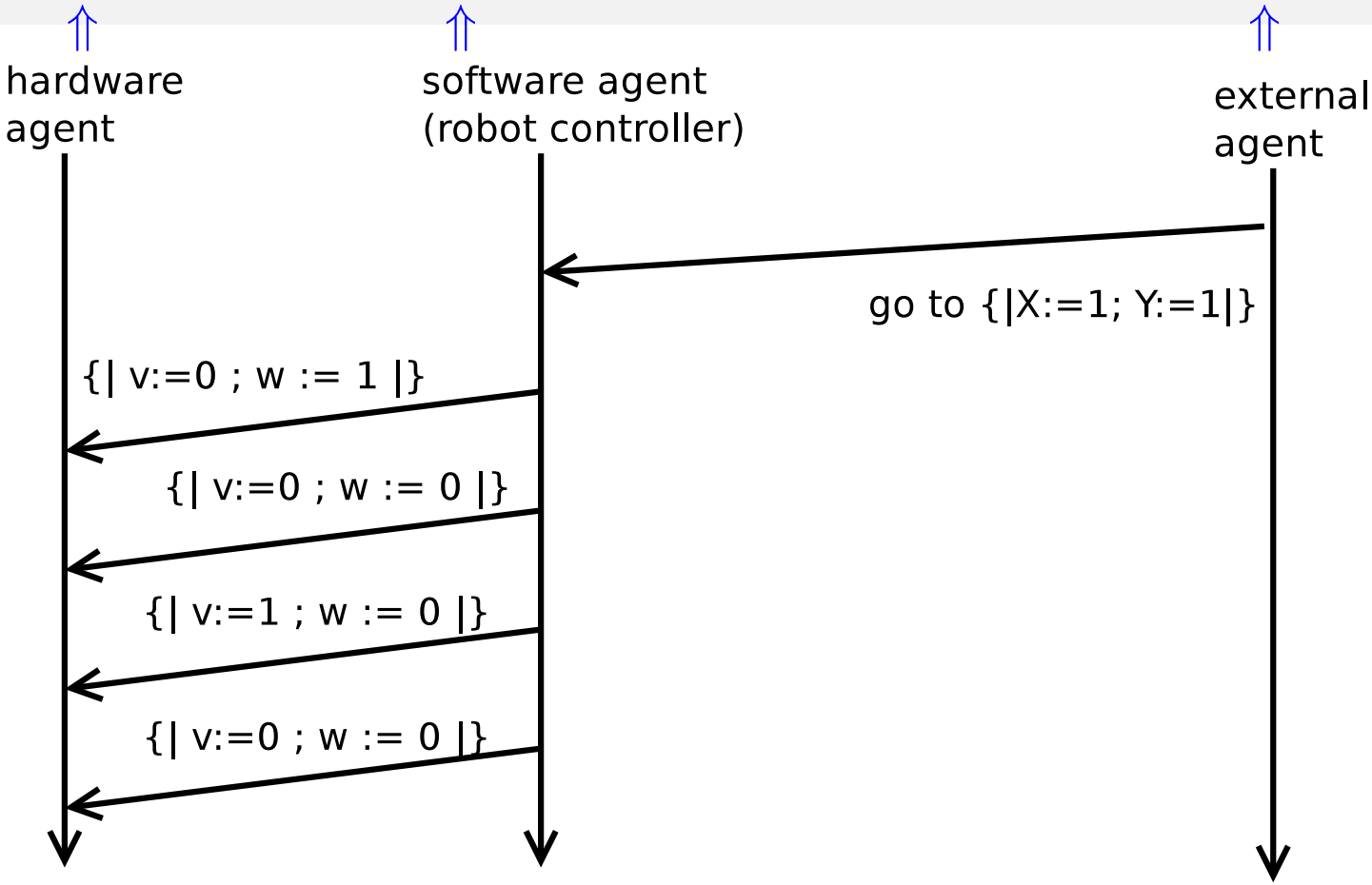
[5] http://wiki.ros.org/Robots

Running Example



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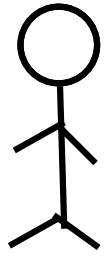
```

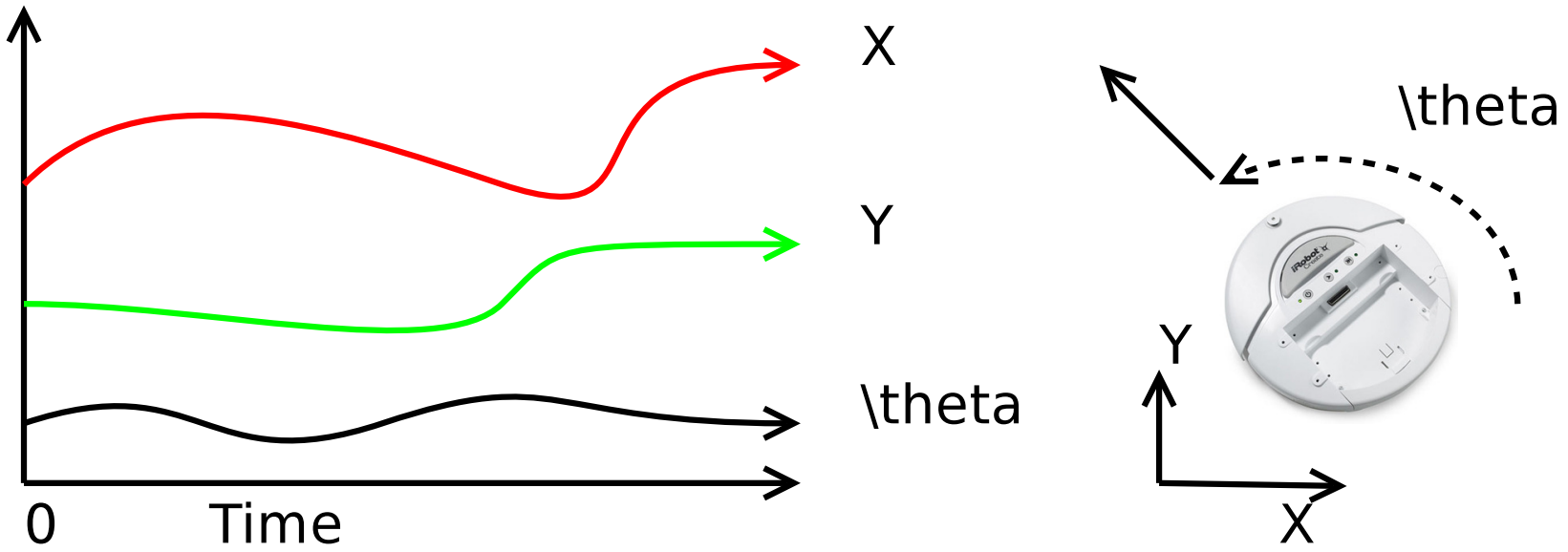


How to Specify a CPS in ROSCoq

- Define the physical model as a Coq type
- Define the collection of agents
- Specify the behavior of each agent
  - S/w agent : Coq program
  - H/w agent : ...

Physical Model of a CPS

Describes how the relevant physical quantities evolve over time



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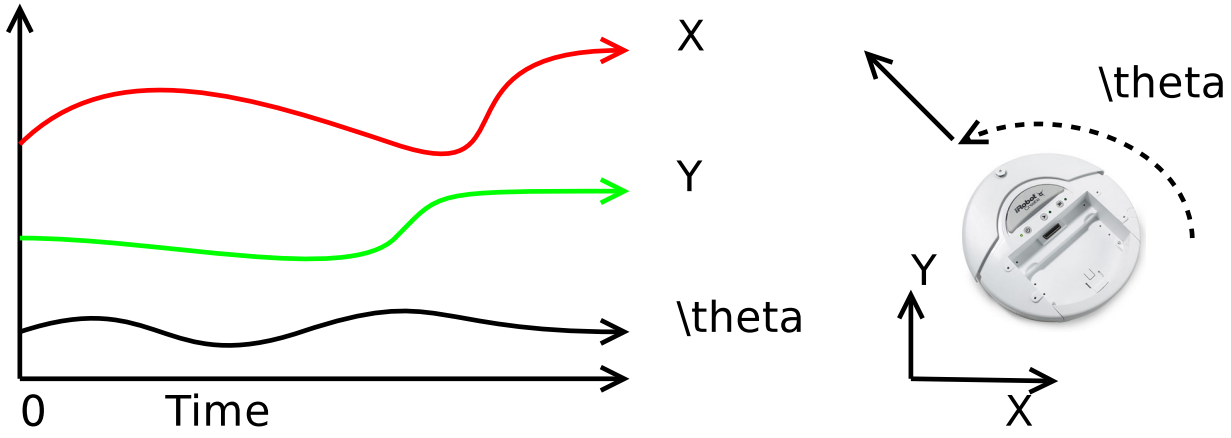


```
Record Cart2D (T : Type) : Type := {X : T; Y: T}.

Record iCreate : Type := {
  position : Cart2D (Time →C ℝ);
  theta : (Time →C ℝ);
```

Physical Model of a CPS

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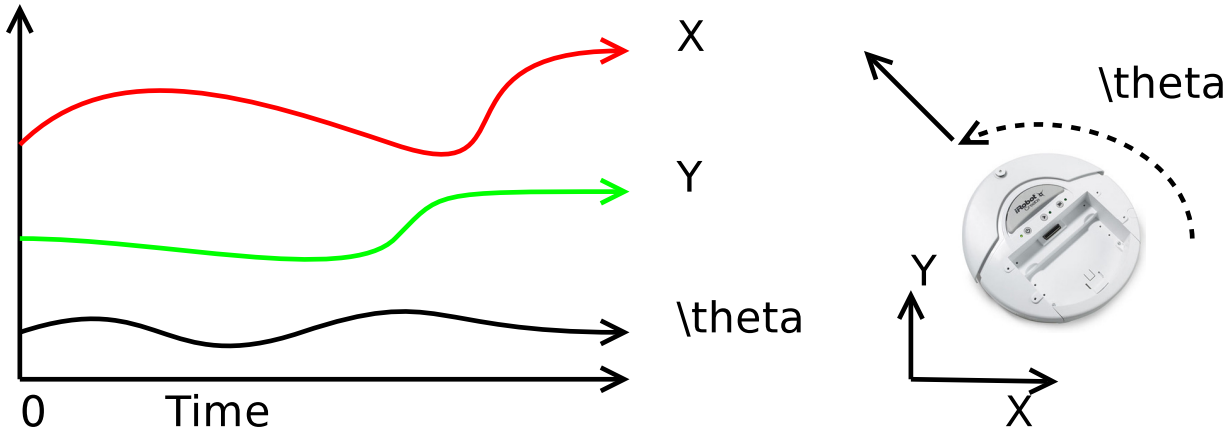
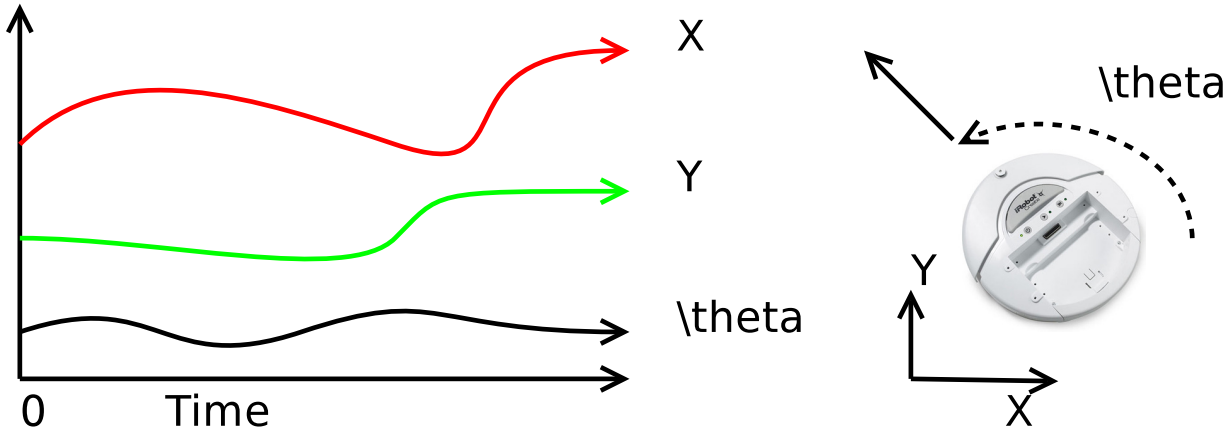



```
Record iCreate : Type := {
  position : Cart2D (Time →C ℝ);
  theta : (Time →C ℝ);
  linVel : (Time →C ℝ);
  omega : (Time →C ℝ);

  derivRot : isDerivativeOf omega theta;
  derivX : isDerivativeOf (linVel * ( FCos theta)) (X position);
  derivY : isDerivativeOf (linVel * ( FSin theta)) (Y position);
```

Physical Model of a CPS

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```
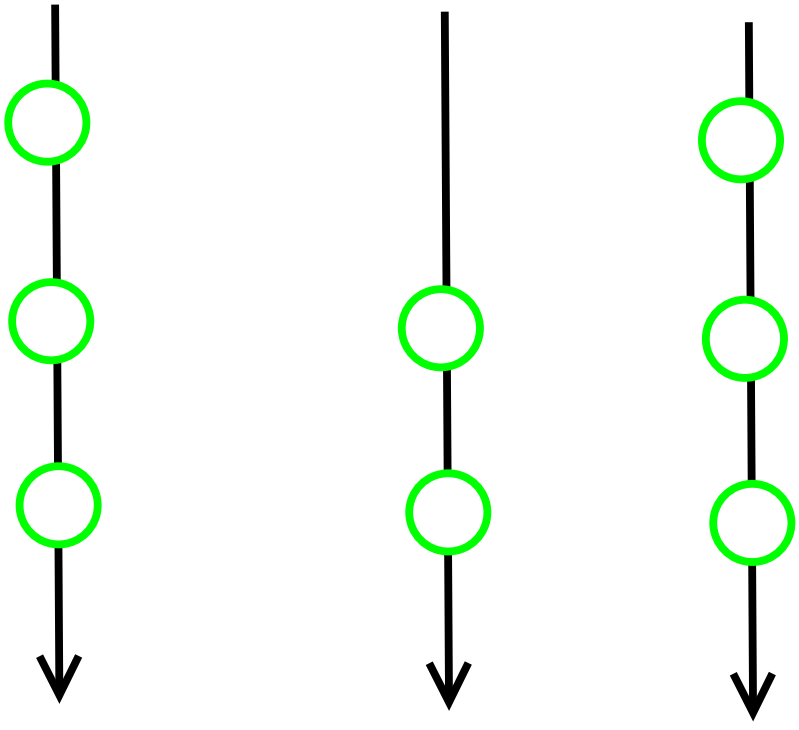

In case there were 2 robots, we would use iCreate × iCreate

Semantics of Agents



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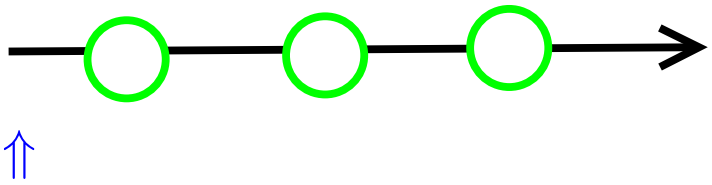

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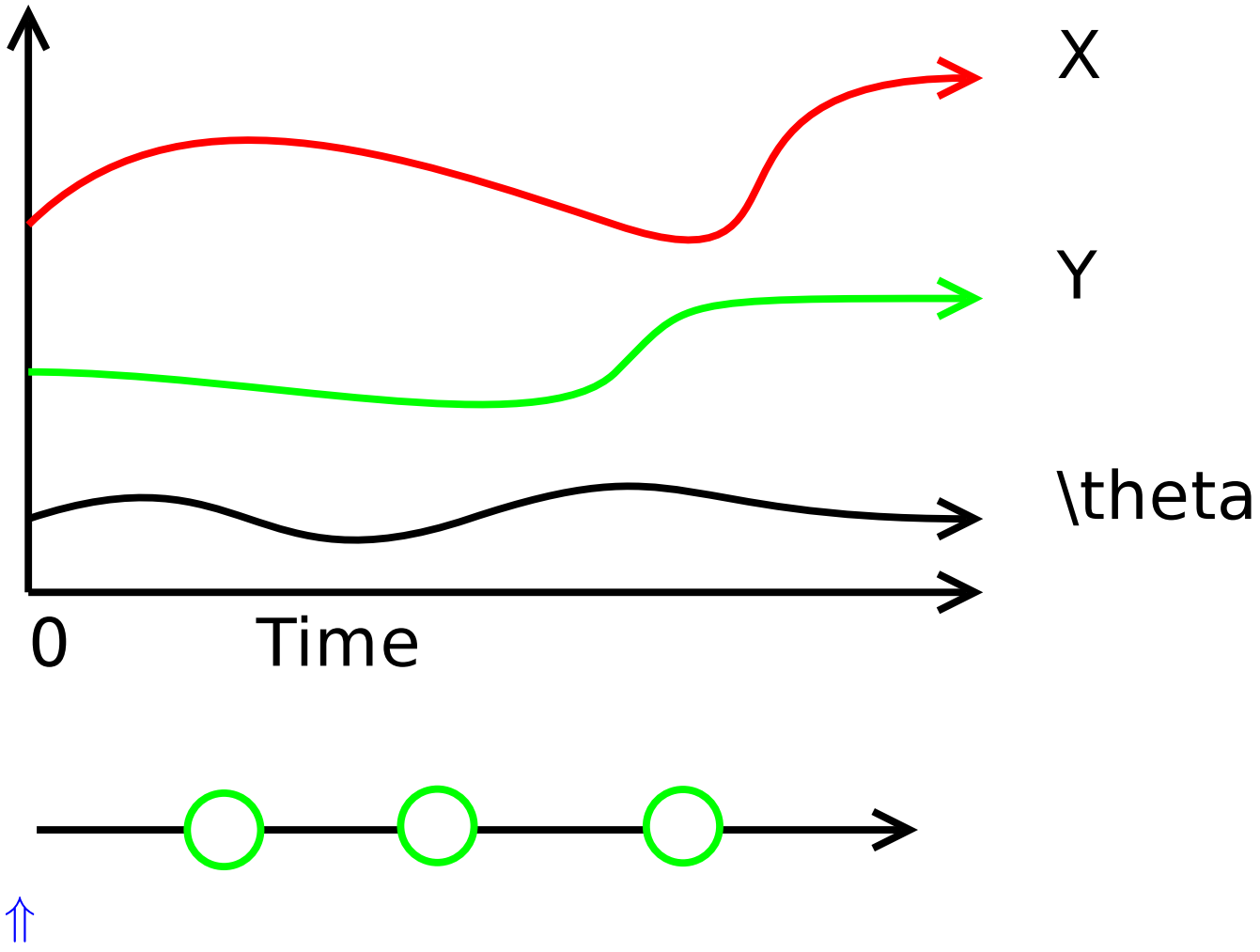

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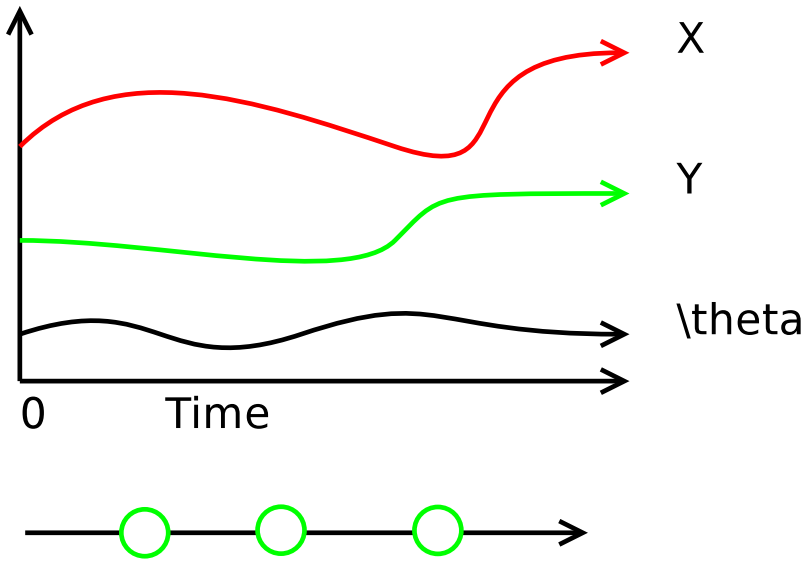
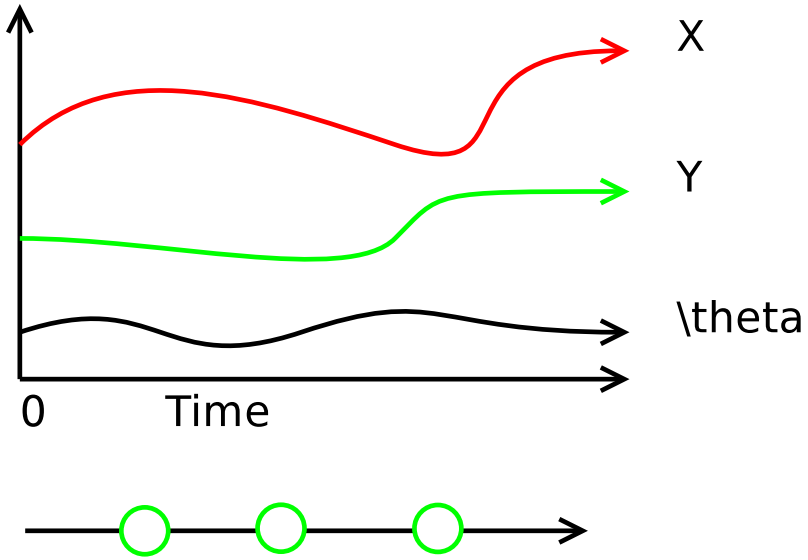


- $PhysModelType \rightarrow (\mathbb{N} \rightarrow \text{option } Event) \rightarrow \texttt{Prop}$

Semantics of Agents



- *PhysModelType* → (ℕ → option *Event*) → `Prop`
- iCreate → (ℕ → option *Event*) → `Prop` ⇑

```
Record iCreate : Type := {
  position : Cart2D (Time →C ℝ);
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  ⋮
```
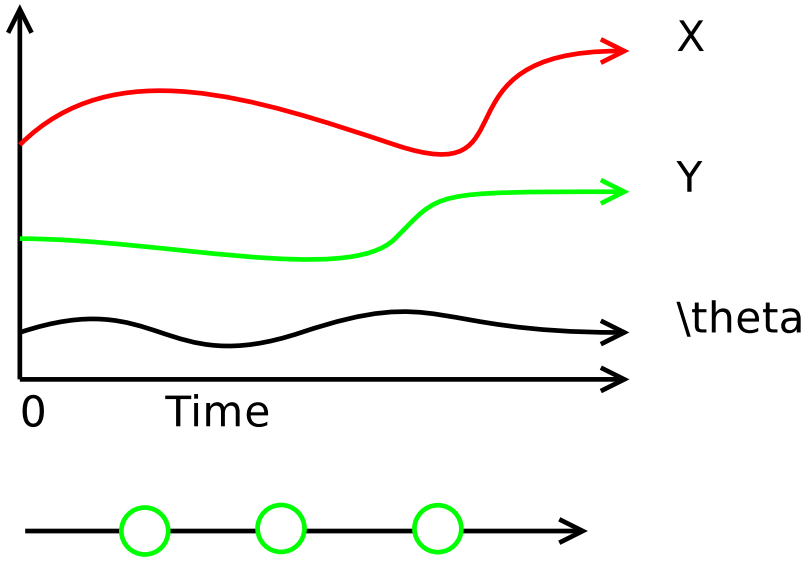

Semantics of Agents



- Can handle non-determinstic devices ⇑
- Uniform treatment of both sensing and actuation devices ⇑

Specification of an iCreate (hardware agent)

```
Definition HwAgent  (ic: iCreate) (evs : nat → option Event): Prop :=
```

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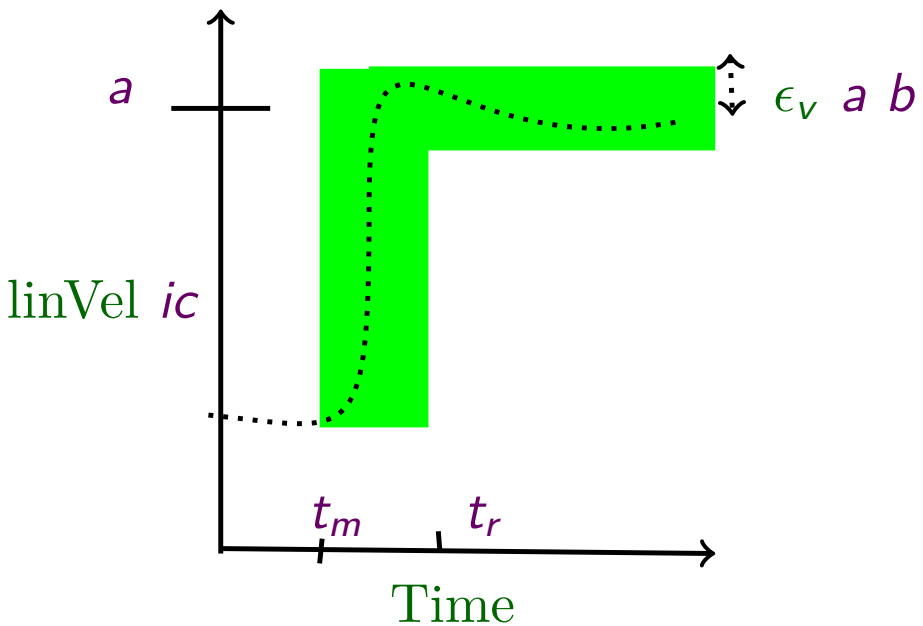
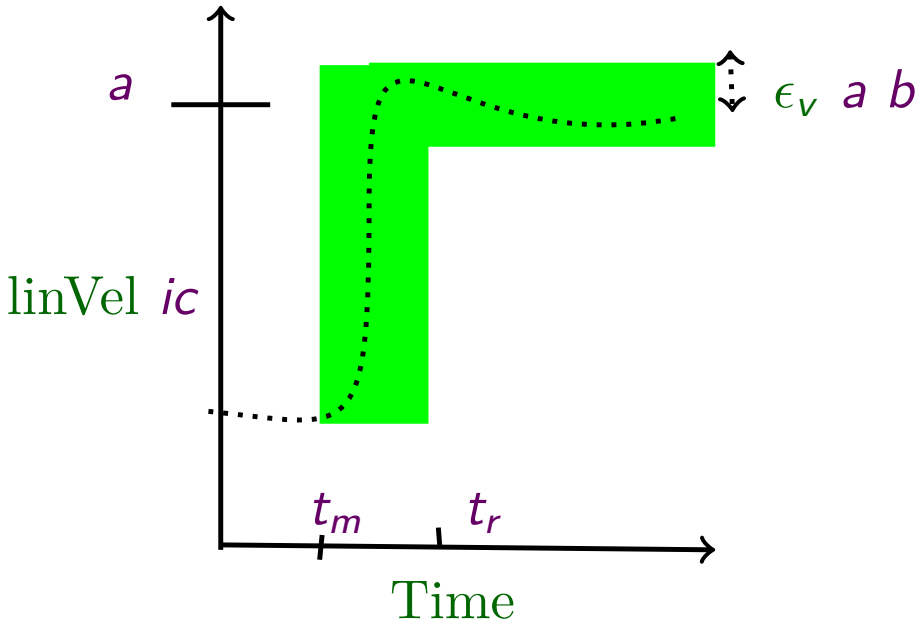
Definition HwAgent  (ic: iCreate) (evs : nat → option Event): Prop :=
onlyRecvEvts evs ∧ ∀ t: QTime,
  let (lastCmd, t_m ) := latestVelPayloadAndTime evs t in
  let a : Q := rad (lastCmd) in
  let b : Q := θ (lastCmd) in ∃ t_r : QTime, (t_m ≤ t_r ≤ t_m + reacTime)
    ∧ (∀ t' : QTime, (t_m ≤ t' ≤ t_r)
        → ( Min ({linVel ic} t_m) (a - ε_v a b)
            ≤ {linVel ic} t' ≤ Max ({linVel ic} t_m) (a+ ε_v a b)))
    ∧ (∀ t' : QTime, (t_r ≤ t' ≤ t) → |{linVel ic} t' - a | ≤ ε_v a b )
```



Specification of an iCreate (hardware agent)

⇑

`Definition` HwAgent (*ic*: iCreate) (*evs* : nat → option *Event*): `Prop` :=



{| v := *a*; w := *b* |} ⇑

Software Agents

$$S \to \text{Message} \to \quad (S \times \mathsf{list}\ \text{Message}). \qquad \Uparrow$$

Software Agents

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$$\text{SwSemantics} : \quad (S \to \text{Message} \to (S \times \text{list Message})) \to$$
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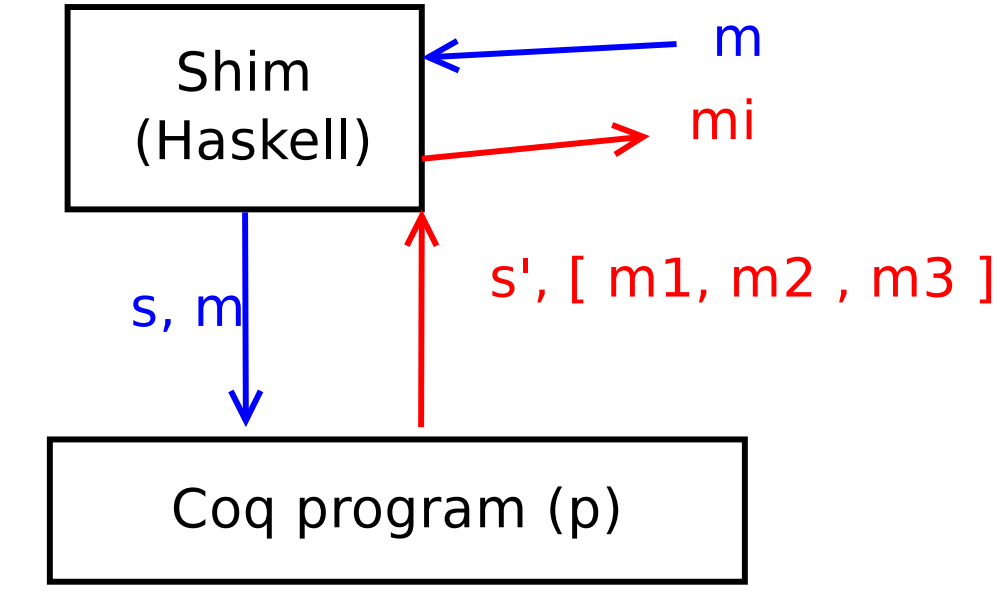

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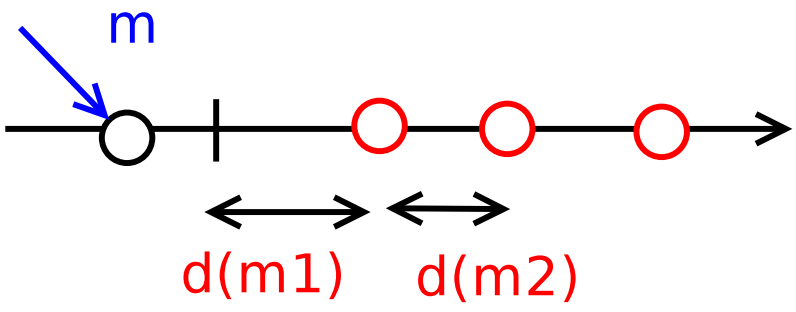

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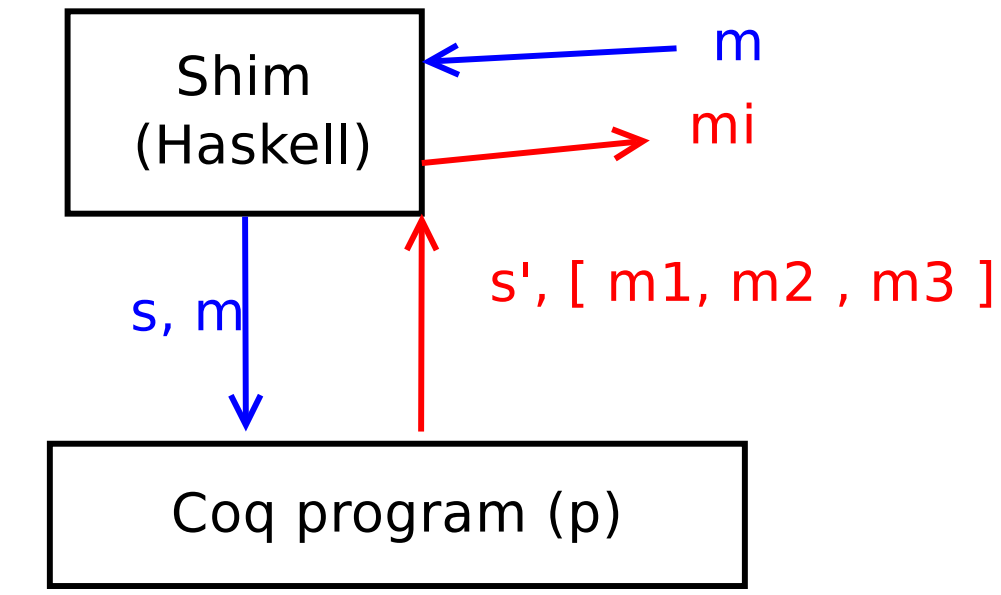

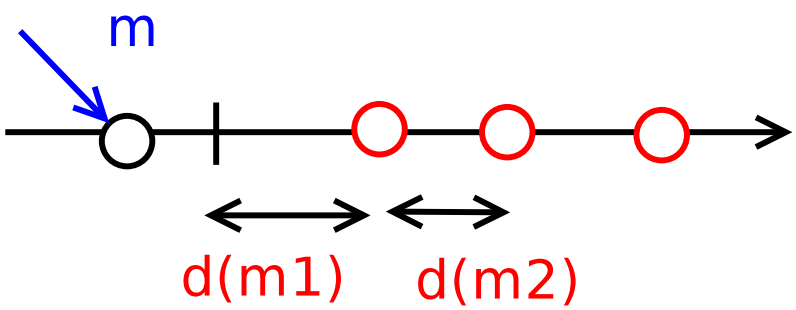

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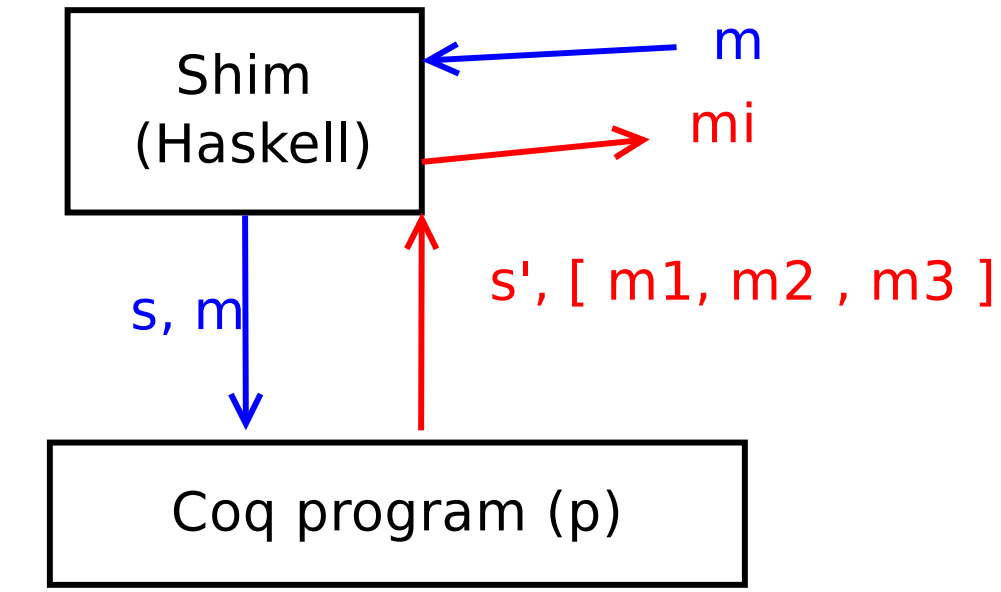

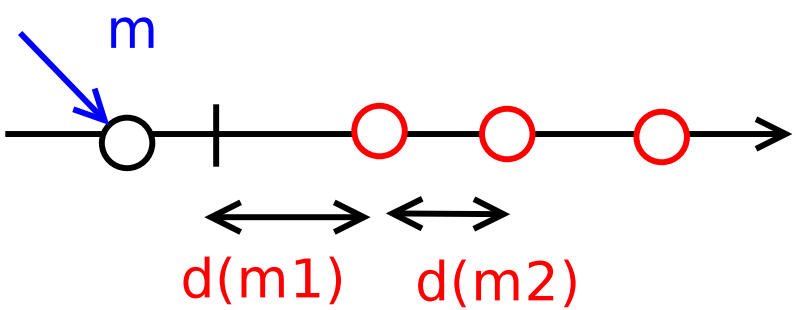

The Program in our running example

```
                                                                    ⇑
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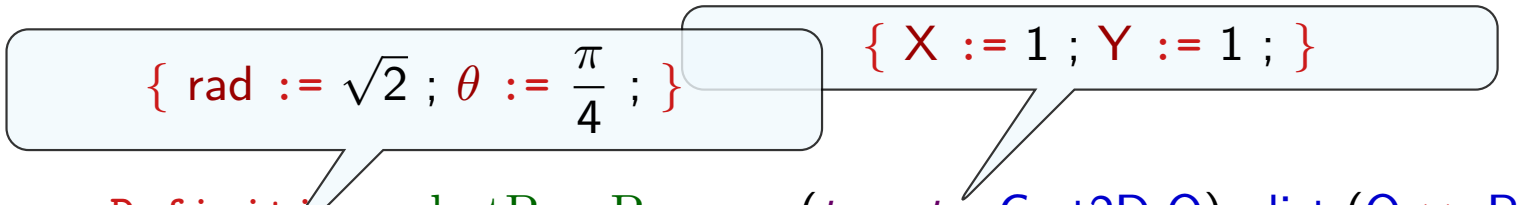


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$\frac{\pi}{4}$

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```

The Program in our running example

$\sqrt{2}$

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```

tapprox *r 1000* ϵ is a rational of the form $\frac{\cdots}{1000}$

$|$ tapprox *r res* ϵ - r $| \leq \frac{1+2*\epsilon}{2*res}$

Robbert Krebbers and Bas Spitters. "Type classes for efficient exact real arithmetic in Coq". In: *LMCS* 9.1 (Feb. 14, 2013)

Constructive Reals

$\mathrm{CR} \cong \mathbb{Q}^+ \to \mathbb{Q}$

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Errett Bishop. *Foundations of constructive analysis*. McGraw-Hill, 1967. 394 pp.

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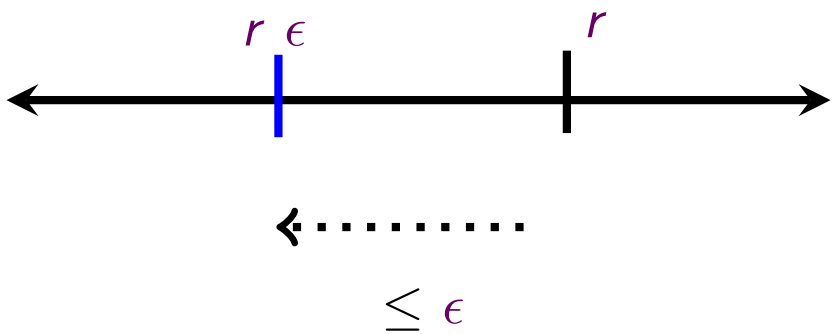
$r : \mathrm{CR}$
$\epsilon : \mathbb{Q}^+$

$r\ \epsilon : \mathbb{Q}$



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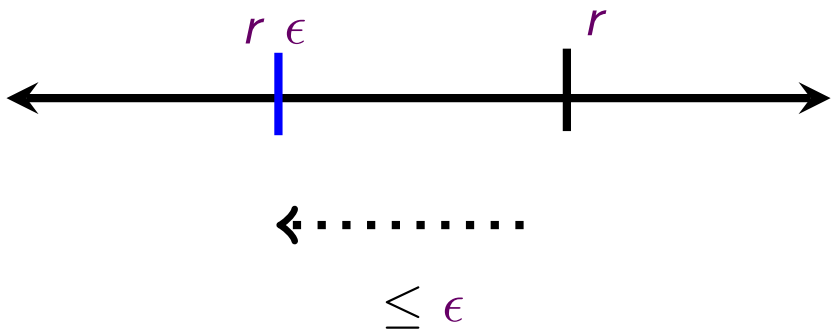

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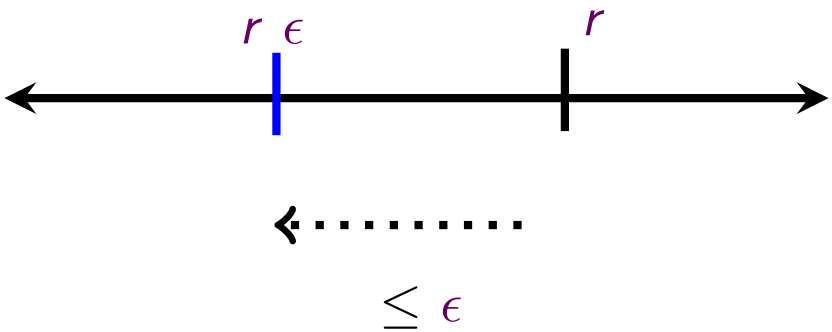

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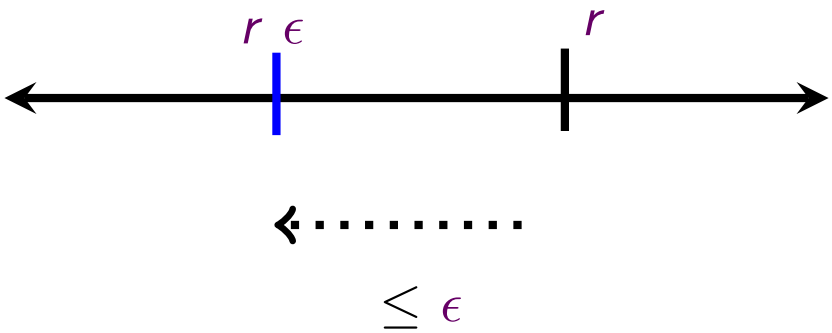

$+ : \lambda\ (r_1 : \mathrm{CR})\ (r_2 : \mathrm{CR}).\ \ \lambda\ (\epsilon : \mathbb{Q}^+)\ .\ \ \ (r_1\ \frac{\epsilon}{2} + r_1\ \frac{\epsilon}{2})$

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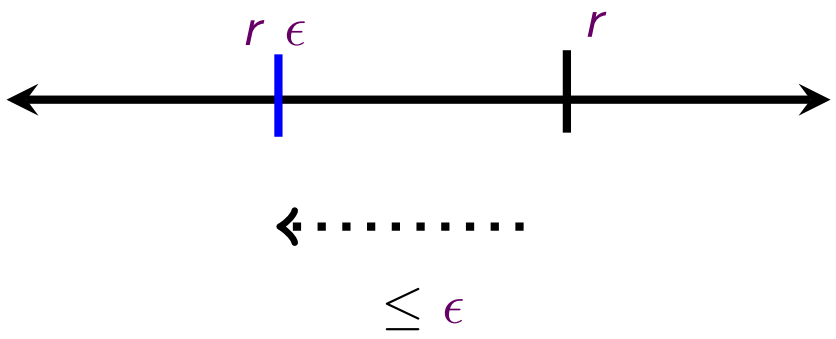

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$$\forall\ (\theta : \mathrm{CR}).\ (\cos\ \theta)^2 + (\sin\ \theta)^2 = 1$$

Discrete computations over CR

$$\texttt{if}\ (r < \pi)\ \text{then}\ \ldots\ \text{else}\ \ldots$$

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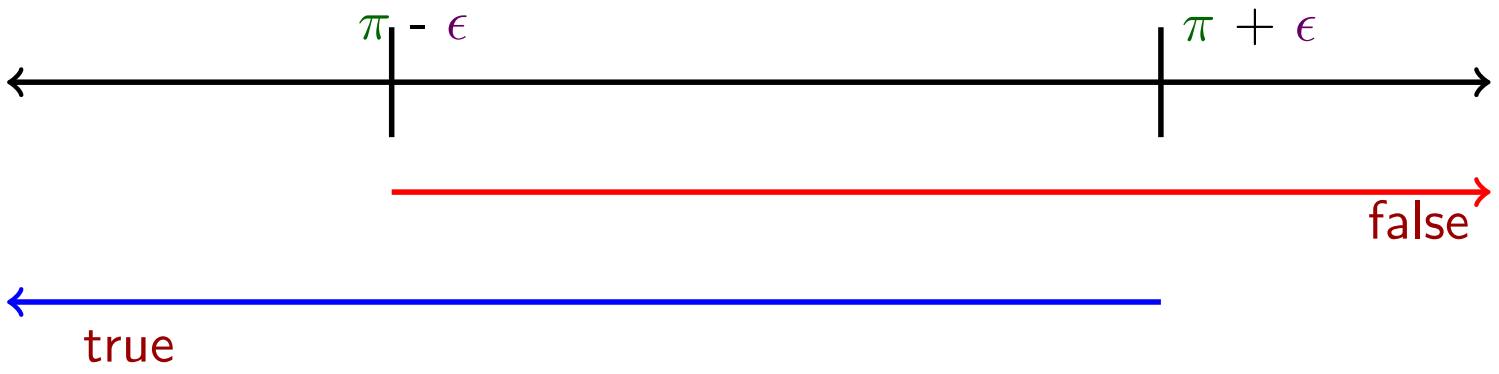

Constructivity helps even in logical reasoning

$$\sqrt{((cos\ \tfrac{1}{2}))} < exp(cos(sin(arctan\ \pi)))$$

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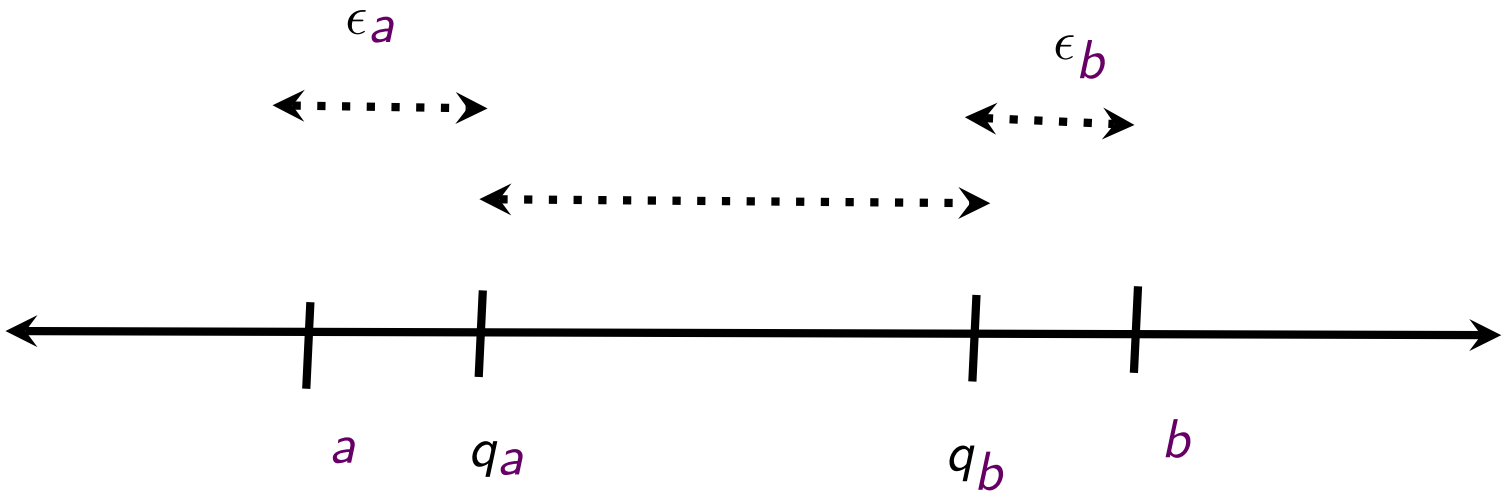
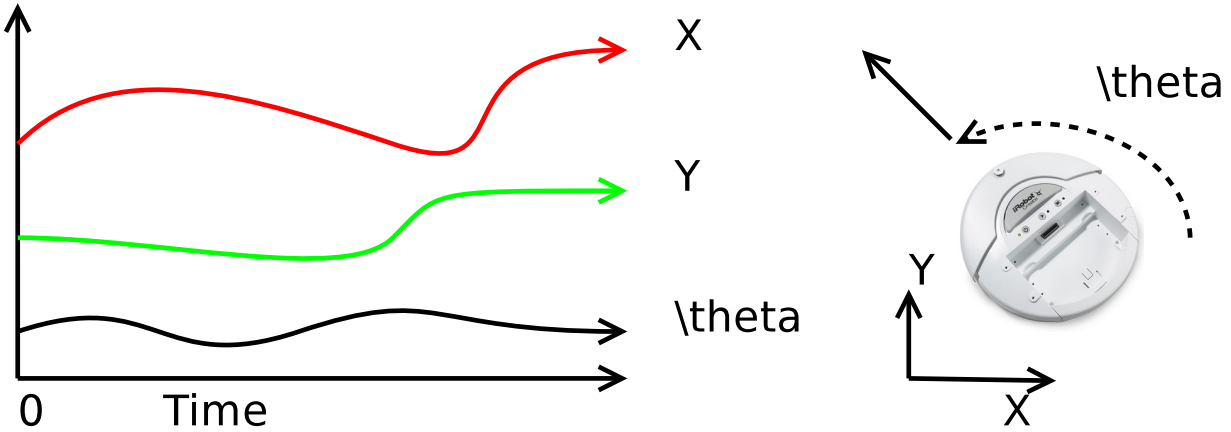


Recap: How to Specify a CPS in ROSCoq

- Define the physical model as a Coq type



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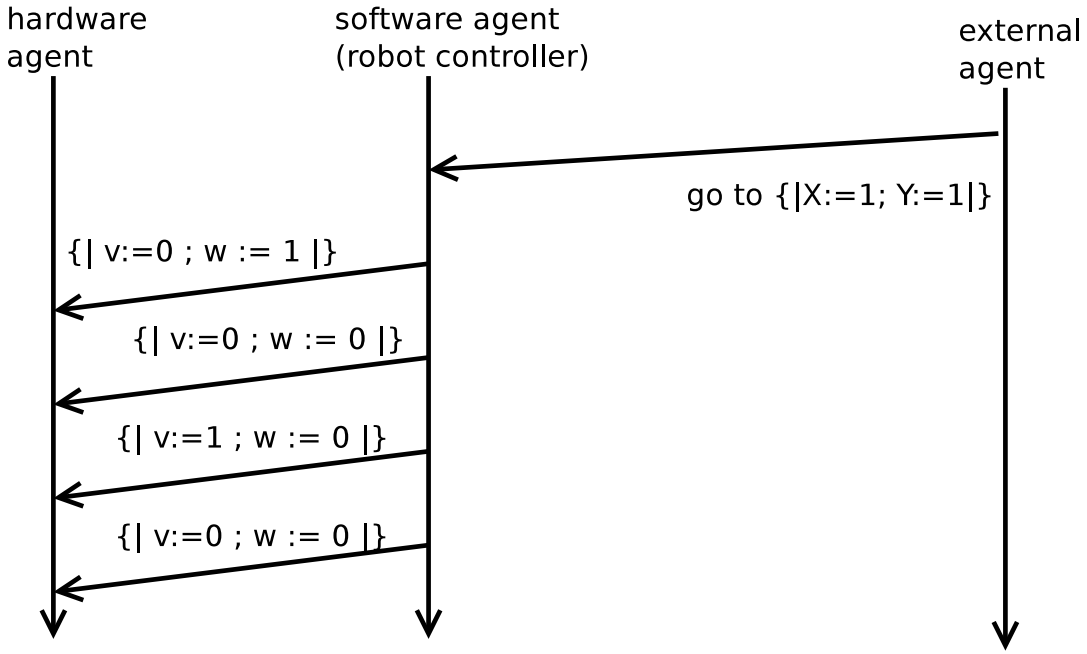

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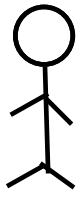

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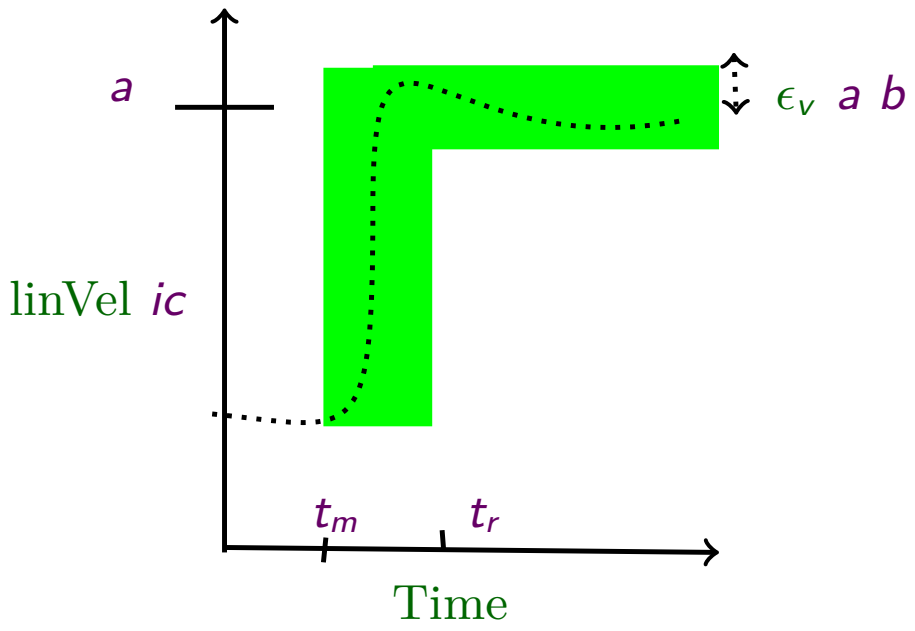

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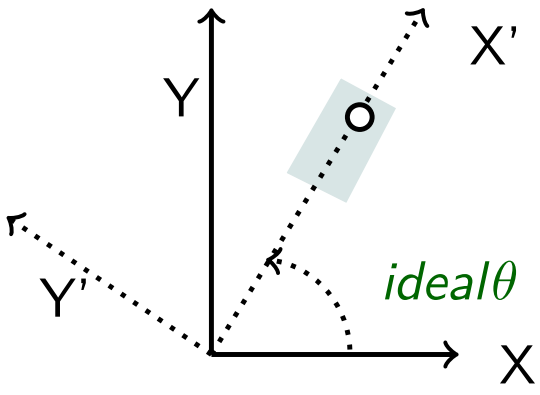
Proved Property



⇑

```
Definition ErrY': ℝ := (ϵv 0 w) * ( reacTime + Ev01TimeGapUB)
+ (Sin (θErrTrans + θErrTurn)) * ( | target | + speed*timeErr
                                    + Ev23TimeGapUB * (ϵv speed 0) )
.
```

Experiments

target		actual		video link
X	Y	X	Y	
-1	1	-1.06	0.94	vid1
-1	-1	-1.02	-0.99	vid2
1	1	1.05	0.94	vid3

Ongoing/Future Work

- General Shim in Haskell[6][7]
  - Importing ROS message types in Coq

[6] https://github.com/acowley/roshask

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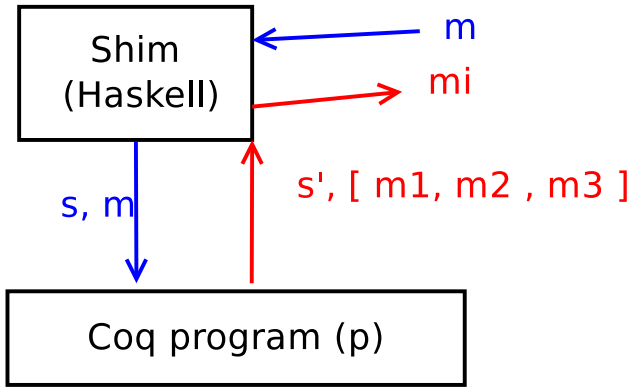

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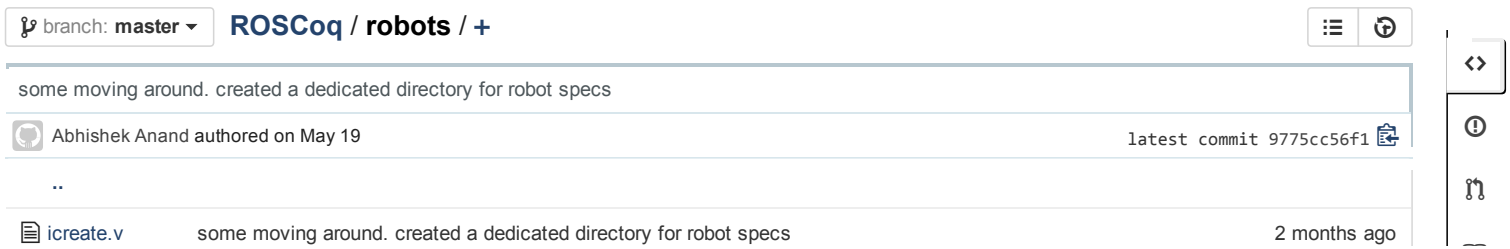

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[8] Thierry Coquand and Erik Palmgren. "Metric Boolean algebras and constructive measure theory". In: *Archive for Mathematical Logic* 41.7 (Oct. 1, 2002), pp. 687–704.

Questions

http://www.cs.cornell.edu/~aa755/ROSCoq/
http://github.com/aa755/ROSCoq