A Model of Compliant and Epistemic Human-Aware Task Planner which Anticipates Human Beliefs and Decision

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The Cognitive and Interactive Robot

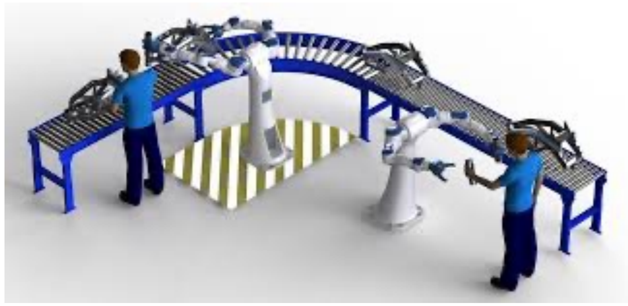
The scientific challenge is to devise and build the **cognitive** and **interactive** abilities to allow **pertinent**, **transparent**, **legible** and **acceptable** behaviours for a that is able to perform **collaborative tasks** with a **human** partner.

→ the service and assistant robot

→ the teammate robot in the factory or the field

Decisional issues during Human-Robot Joint Action

LAAS CNRS



How are we able to collaborate successfully?

What is necessary to be a good partner?

Toward a principled approach to build, deploy and evaluate Human-Robot Joint Action

A. Clodic, E. Pacherie, R. Alami, and R. Chatila, ***Key Elements for Human-Robot Joint Action.*** *in Sociality and Normativity for Robots, R. Hakli and J. Seibt, Eds., Springer International Publishing, 2017, pp. 159-177.*

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Joint Action between Humans

"Joint action can be regarded as any form of social interaction whereby two or more individuals coordinate their actions in space and time to bring about a change in the environment."

Sebanz, N., Bekkering, H., & Knoblich, G. (2006). **Joint action: bodies and minds moving together.** Trends in cognitive sciences.

Coordination tools in joint action

- **Joint Attention**
  - "Perceptual" common ground (Tomasello, 1995, 1999)
  - Mutual manifestness (Pacherie, 2012)

- **Understanding / Facilitating** Intentional Action

- **Shared Representations**
  - Common ground
  - Shared affordances
  - Shared plan elaboration and management
  - Commitment management

- **Duties and obligations linked to joint action**
  - Key notion of Joint Persistent Goal / Intention / Commitment
  - Informing about fact or decision not known by the "partner"
  - Facilitation behaviours and signalling

*A. Clodic, R. Alami, **What Is It to Implement a Human-Robot Joint Action?**, Robotics, AI, and Humanity, Springer International Publishing, pp.229-238, 2021, 978-3-030-54172-9.*

Also, for HRI …. VERY IMPORTANT

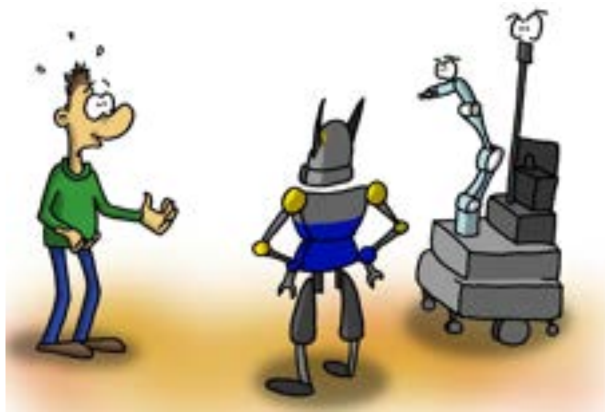
- Human and robot are **not EQUAL**
- Human is not restricted the task at hand
- Human needs to have, at any time, the latitude to change her/his focus or goal, to disengage
- Even, Human might not comply (for unknown reasons) with duties needed for fluent joint action

Also, for HRI …. VERY IMPORTANT

Robot, from its side, should do the maximum, to synthesize:

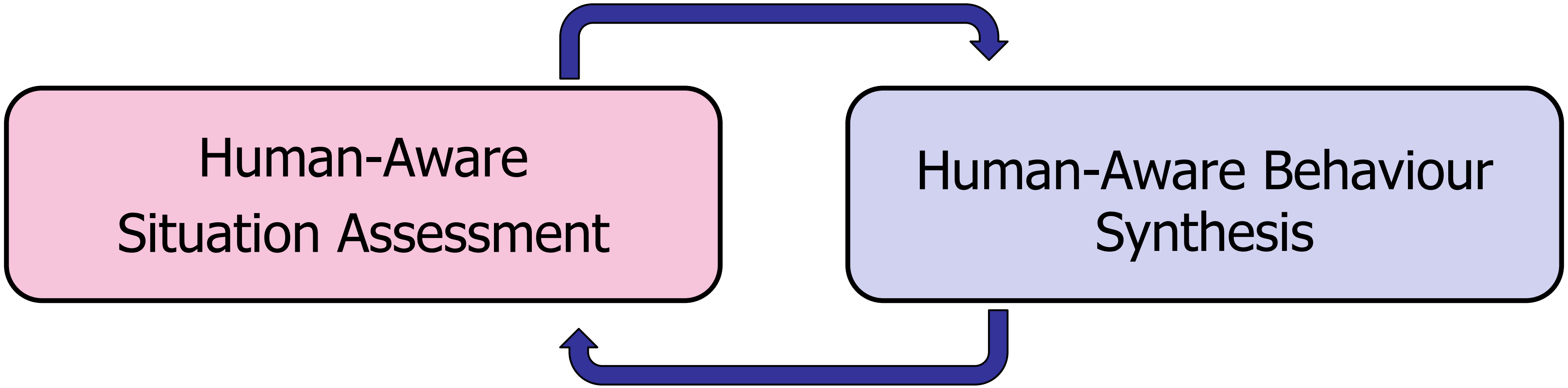
- legible,
- acceptable
- and comfortable

} behaviours



→ (Cost-based) Human-Aware Task and Motion Planning

A constructive approach



Models & et Algorithms:
Human, Robot, Environment, Context, Tasks

A task-oriented architecture for a collaborative robot

Task-Oriented: How to perform a HR task, <u>in the best possible way</u>

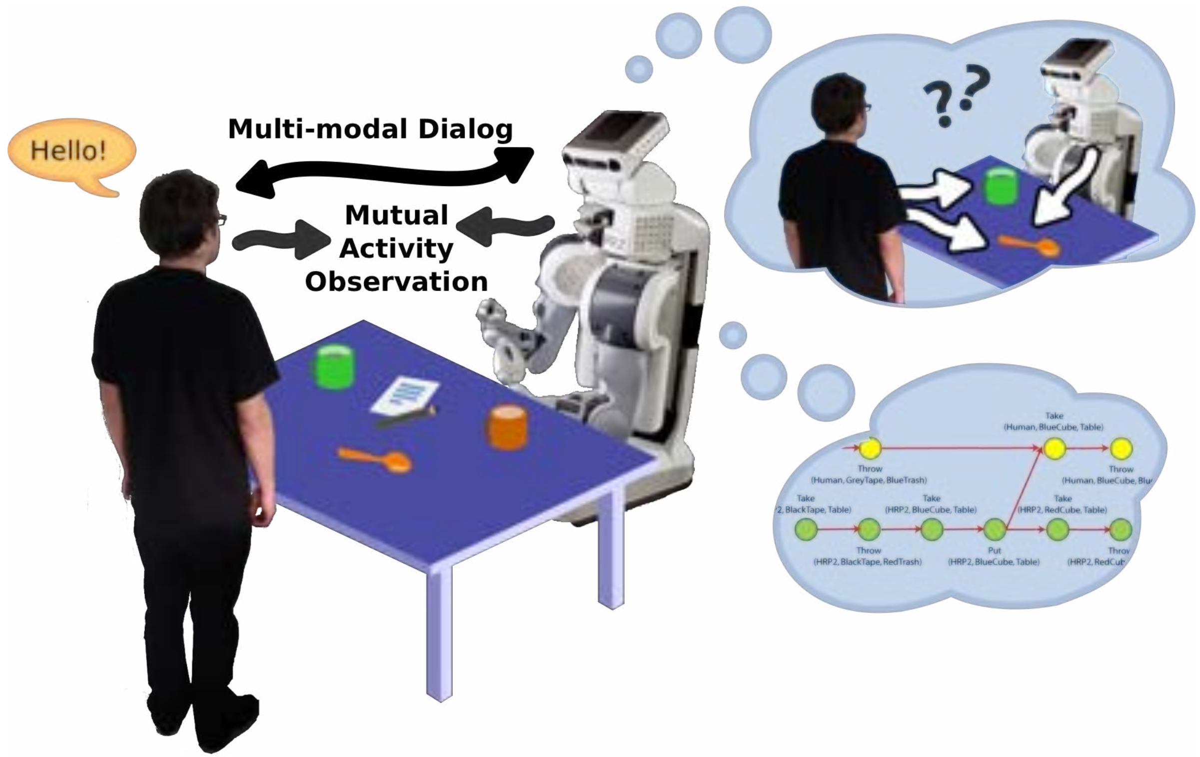
- Efficiency
- Safety
- Acceptability
- Intentionality, Legibility

Plan-Based: Planning and On-Line Deliberation

- Reasoning
- Anticipation
- Pro-active behaviour

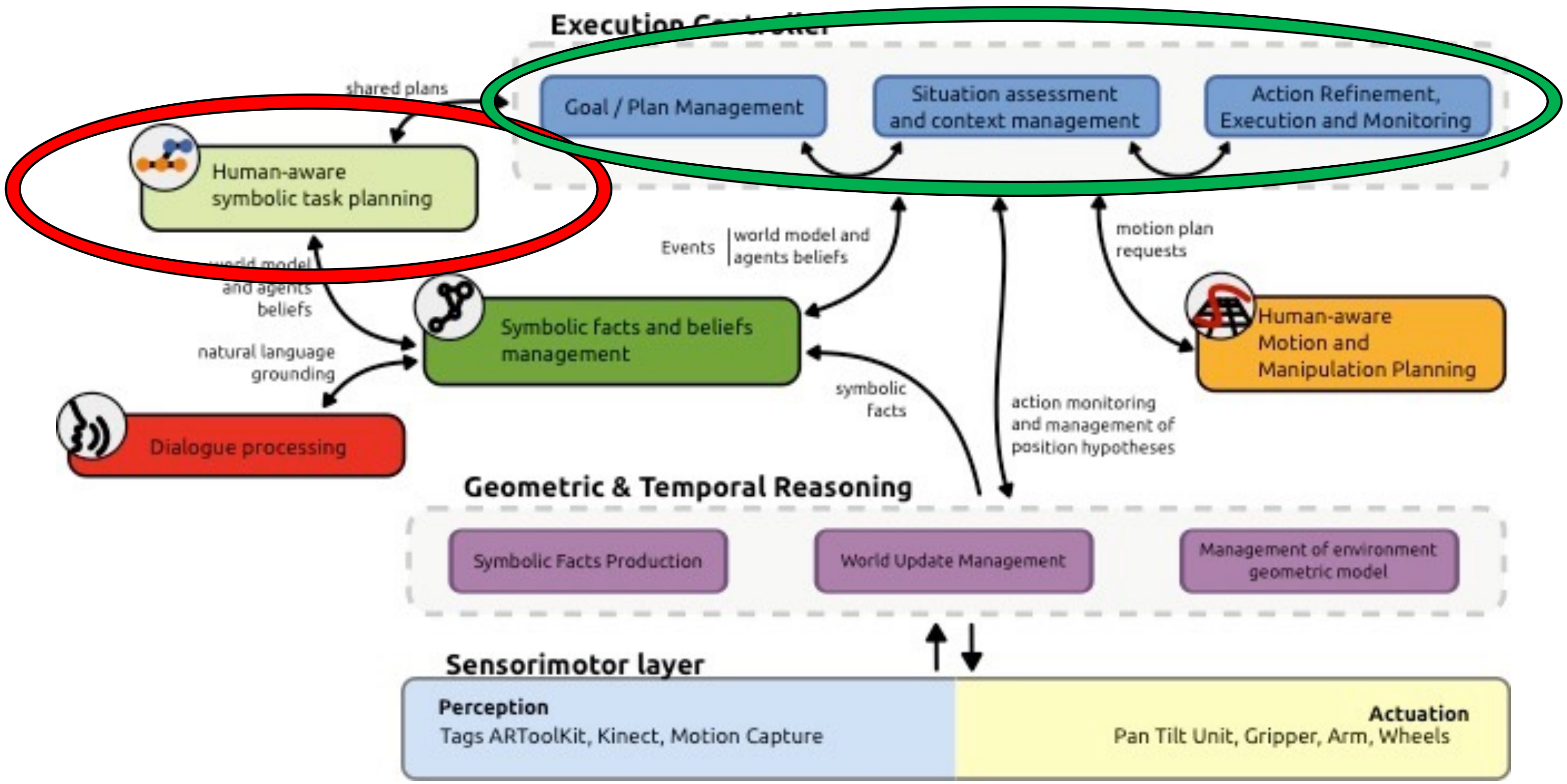
Theory of Mind – Predicting and reasoning about human activity and mental state

H&R Sharing Space, Task and Decision



S. Lemaignan, M. Warnier, E. A. Sisbot, A. Clodic, R. Alami: ***Artificial cognition for social human-robot interaction : An implementation.*** *Artificial Intelligence 247 : 45-69 (2017)*

Robot Decisional Architecture: a constructive approach



S. Lemaignan, M. Warnier, E. A. Sisbot, A. Clodic, R. Alami: ***Artificial cognition for social human-robot interaction : An implementation.*** *Artificial Intelligence 247 : 45-69 (2017)*

Elaborating a shared H&R plan

Human-Aware Task Planning

- Human & Robot sharing an activity / Human-Robot Collaboration

- Endow the robot with planning and pro-active abilities

- Take into consideration the human, their abilities and preferences

-> Human-Aware Task Planning

Key assumptions (from Robot perspective)

- Planning for both …. but:
  - Human is a non-controllable agent
  - It is important to determine at each step the beliefs of the human and to decide accordingly
  - It is not always clear to decide beforehand who (H or R) will do what

Recent publications

- Guilhem Buisan , Anthony Favier , Amandine Mayima , Rachid Alami, **HATP/EHDA: A Robot Task Planner Anticipating and Eliciting Human Decisions and Actions**, IEEE International Conference On Robotics and Automation (ICRA 2022)

- Anthony Favier , Shashank Shekhar , Rachid Alami, **Models and Algorithms for Human-Aware Task Planning with Integrated Theory of Mind,** IEEE International Conference on Robot and Human Interactive Communication (RO-MAN 2023)

- Shashank Shekhar , Anthony Favier , Rachid Alami, **An Epistemic Human-Aware Task Planner which Anticipates Human Beliefs and Decisions,** 16th International Conference on Social Robotic (ICSR 2024)

- Anthony Favier , Rachid Alami, **A Model of Concurrent and Compliant Human-Robot Joint Action to Plan and Supervise Collaborative Robot Actions,** Advances in Cognitive Systems (ACS), 2024

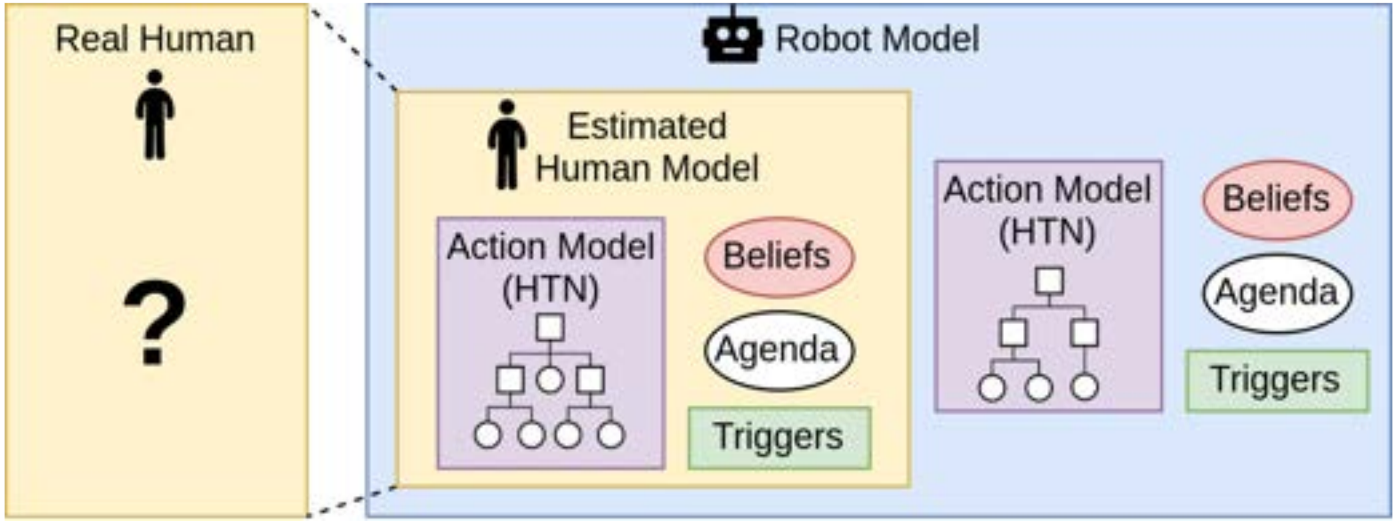
HATP/EHDA

Beliefs: agent's knowledge from their perspective

Agenda: agent's goals

Action Model: agent's capabilities

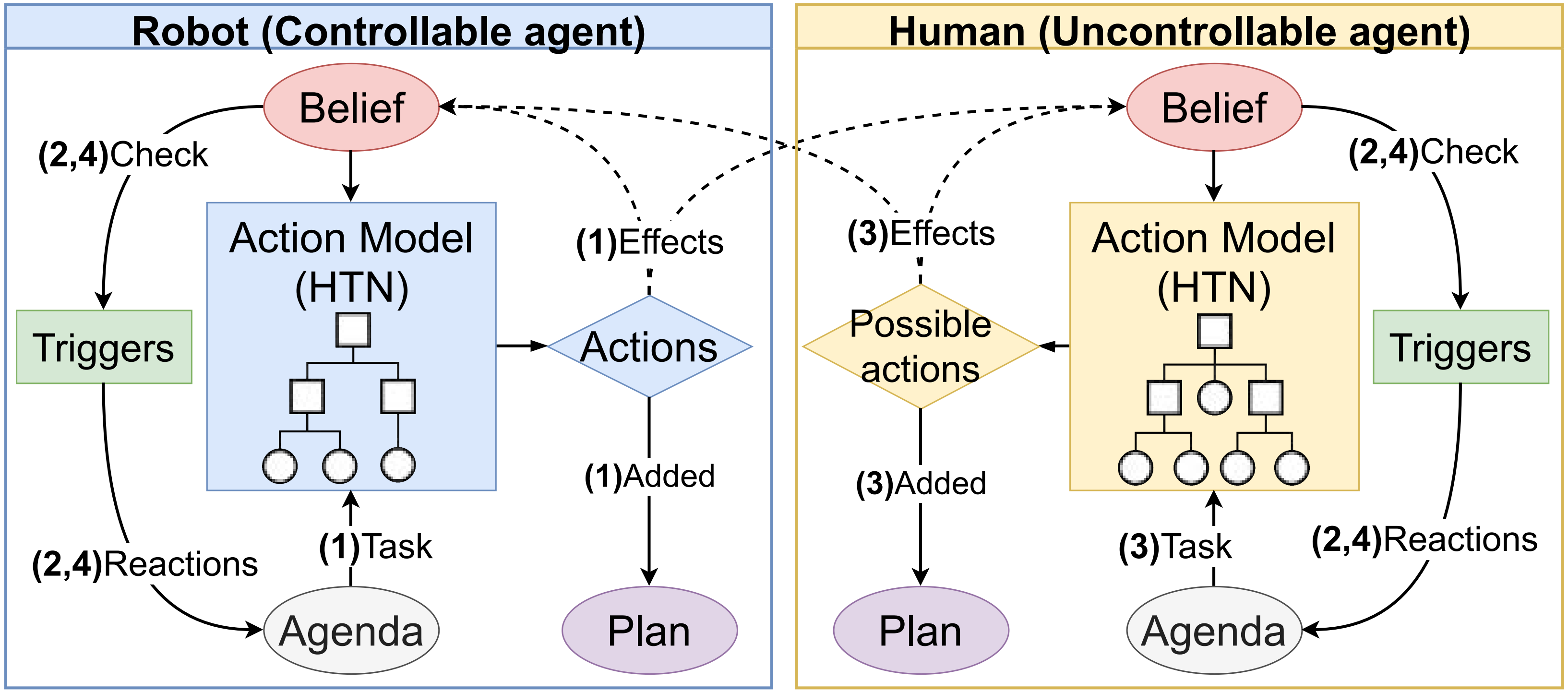
Triggers: agent's possible reaction



Similar structures but fundamentally different models!

G. Buisan, A. Favier1, A. Mayima, R. Alami, ***HATP/EHDA: A Robot Task Planner Anticipating and Eliciting Human Decisions and Actions****, IEEE ICRA 2022*

Planning along two streams



Also anticipating human decision / planning activity based on the estimation of her/his beliefs

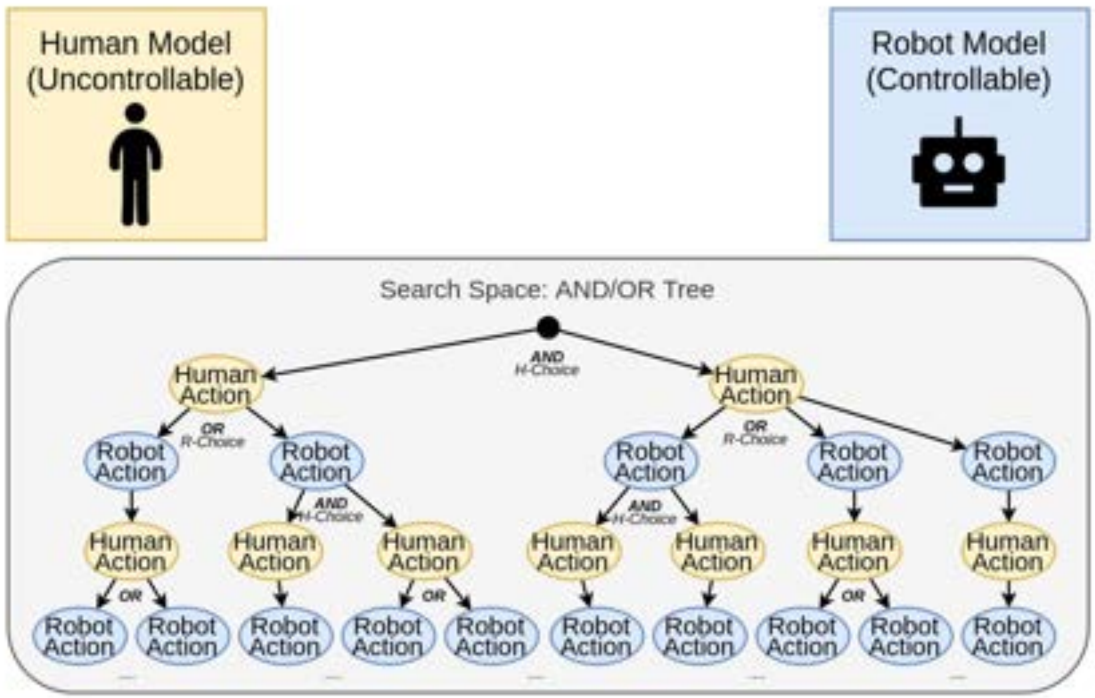
Planning Process: Exploration

Human Actions

- **Estimated** with Human Model
- **Non-deterministic (AND)**

Robot Actions

- **Computed** with Robot Model
- Must find the **Best (OR)**



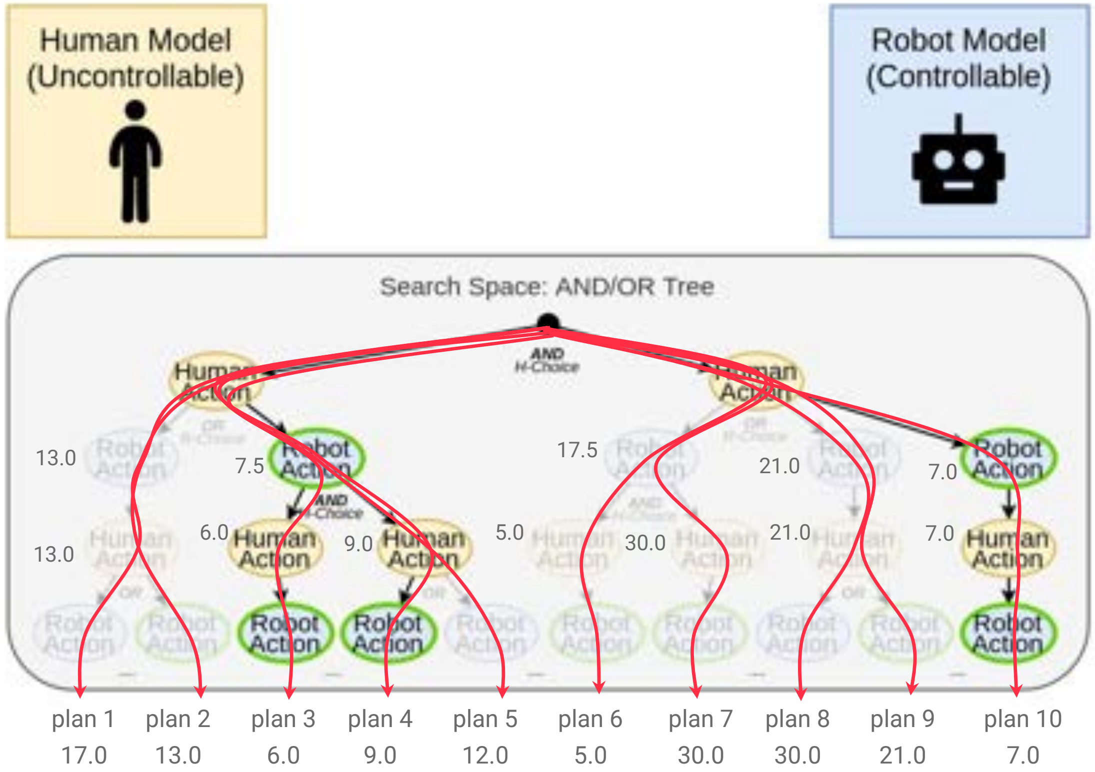
Planning Process: Selection

Evaluate Possible Plan Cost

- **Action** cost
- **Social** cost
- Undesired **state**
- Undesired action **sequence**

Extract Robot Policy

- **Compare** plan costs
- Robot **best** choices: propagate **best** cost
- Human **any** choices: propagate **mean** cost



Reasoning about and anticipating Human beliefs

Theory of Mind for Robots

Theory of Mind (ToM) refers to the ability to attribute mental states to oneself and others, such as beliefs, desires, and intentions.

The **Sally & Anne** test is a well-known when to evaluate the "Theory of Mind" capabilities of young children.

Theory of Mind is a **crucial social skill**!
Children develop it between the age of 3 and 5.
Robots **should be endowed** with such capabilities.

Modeling and Integrating ToM in Planning

ToM at Execution (Devin 2016)

- **Maintains** Human's beliefs and plan progression
- **Reacts** to relevant missed information

ToM at Planning

- Allow to **explore** and **anticipate**
- **Fewer** works in this direction

ToM at Planning: How?

Scripted in domain
Conditional effects
Not generalizable…

Our solution

- **Perspective shift reasoning** is done **inside** the planner
- Modeling focused on action effects, not on influence on agent's beliefs

Modeling and Integrating ToM in Planning

Inference Process

Learn from observing an **action execution**.

(being the actor or co-present with them)

Observation Process

Learn from observing the **state**.

(any OBS state variable co-located with agent)

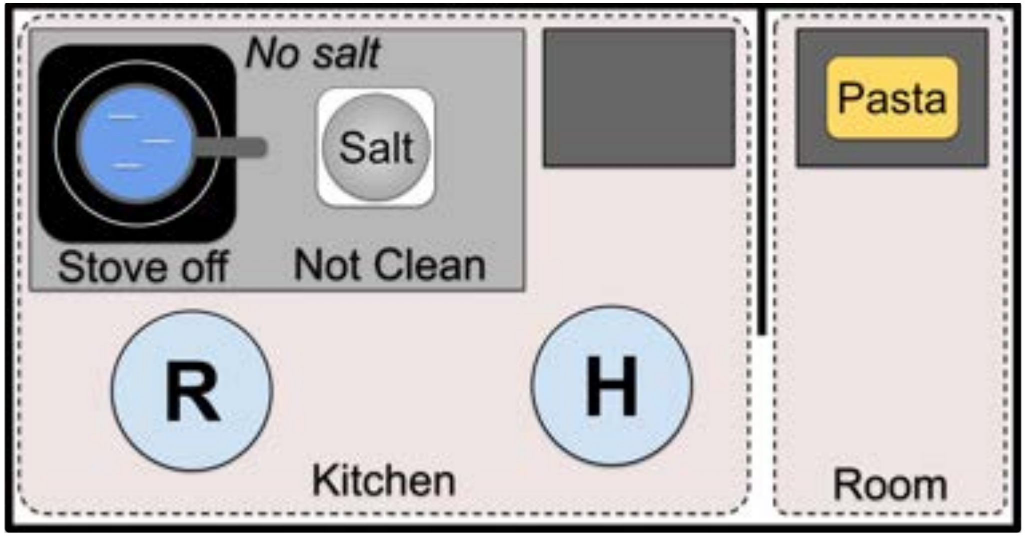
Relevant belief divergence:
A belief divergence is called **relevant** if it **influences** the next action(s) the human is likely to perform, either in terms of number, name, parameters, or effects.

➡ We tackle such divergence either with:

Minimal verbal communication

Delaying a non-observed robot action

Modeling and Integrating ToM in Planning



Pasta Cooking Shared Task

Shared goal:

$$saltIn = true$$
$$stoveOn = true$$
$$at(\texttt{pasta}) = \texttt{pot}$$

Robot goal:

$$counterClean = true$$

State variables:

$$X = \{saltIn, stoveOn, counterClean, at(\texttt{R}), at(\texttt{H}), at(\texttt{pasta})\}$$

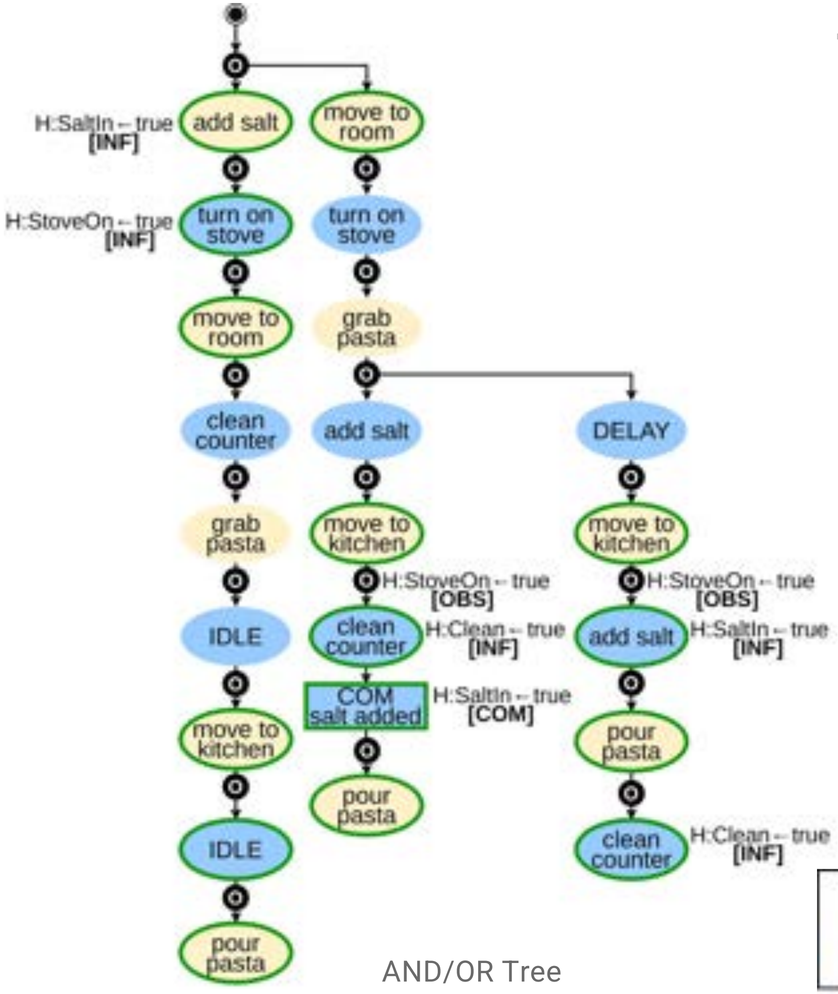
Modeling and Integrating ToM in Planning: **Planning Human perception at each step**

	HATP/EHDA		New!	
State variable	**Value in Robot Belief**	**Value in Human Belief**	**Observability Type**	**Location**
saltIn	*true*	*false*	INF	*kitchen*
stoveOn	*true*	*false*	OBS	*kitchen*
counterClean	*false*	*false*	INF	*kitchen*
at(R)	*kitchen*	*kitchen*	OBS	*kitchen*
at(H)	*kitchen*	*kitchen*	OBS	*kitchen*
at(pasta)	*room*	*room*	OBS	*room*

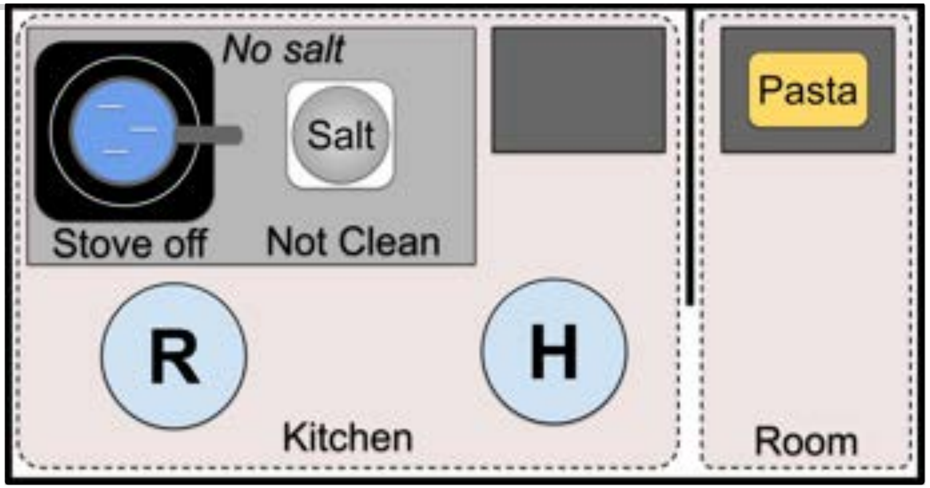
OBS = observable
INF = inferable

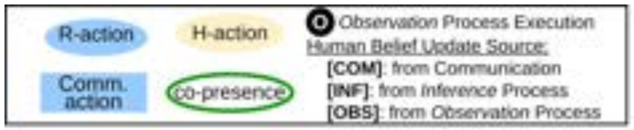
- Human beliefs may differ: Belief Divergence / **False Belief**
- Allows to define and use a notion of **co-presence / co-location** for agents and facts.
- Symbolically model **visibility** from each agents' perspective.

Example scenario

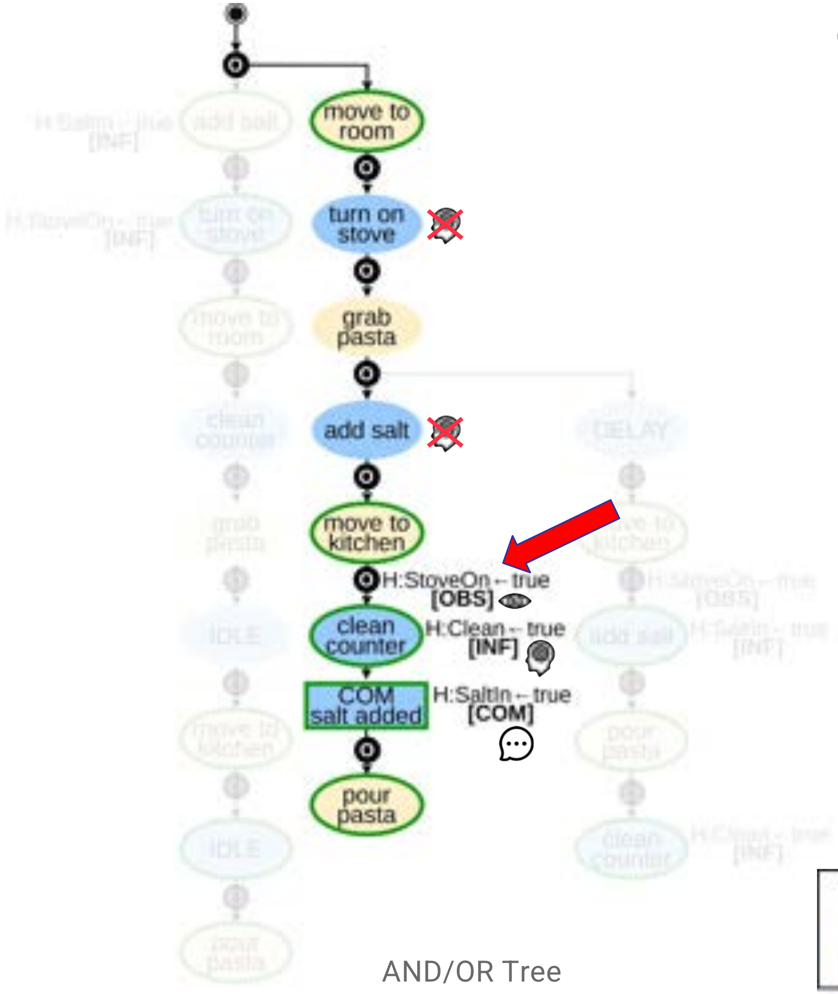


AND/OR Tree

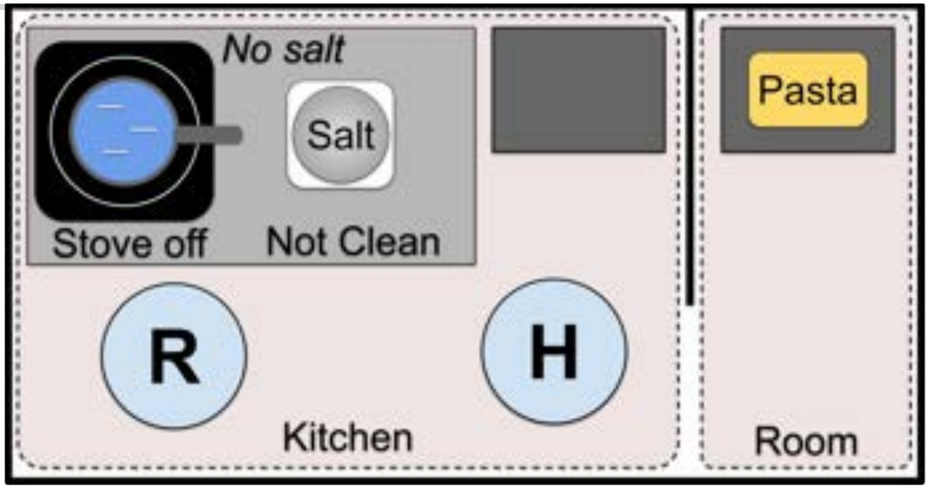




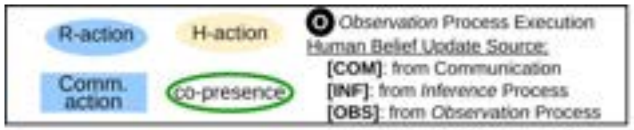
Example scenario



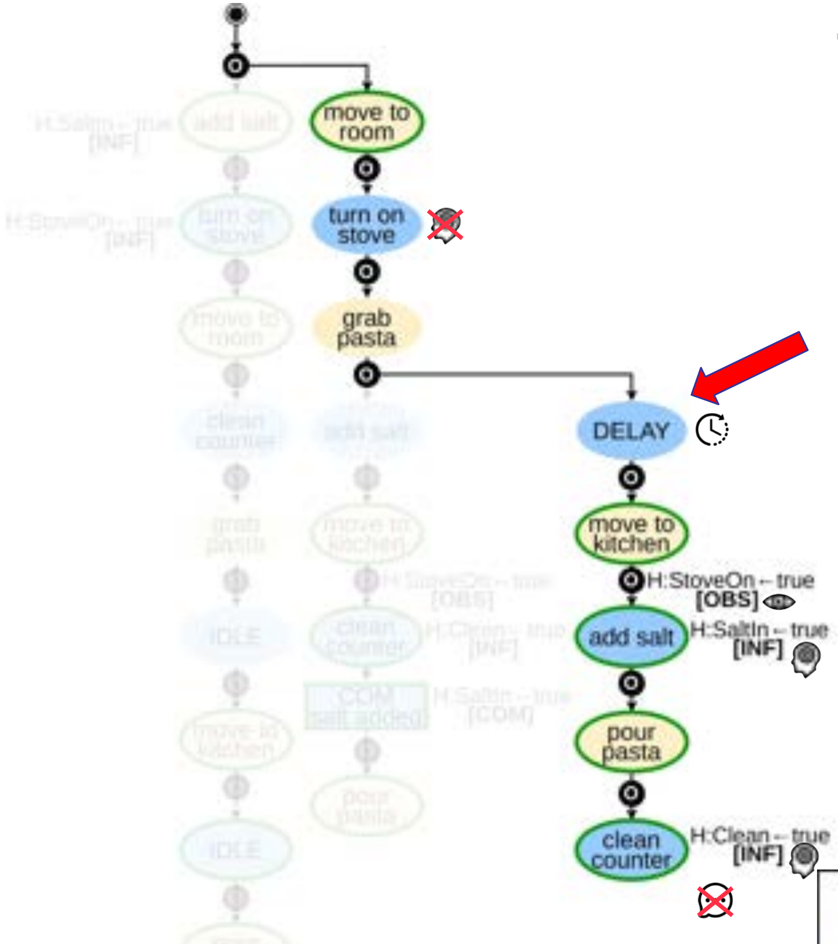
AND/OR Tree



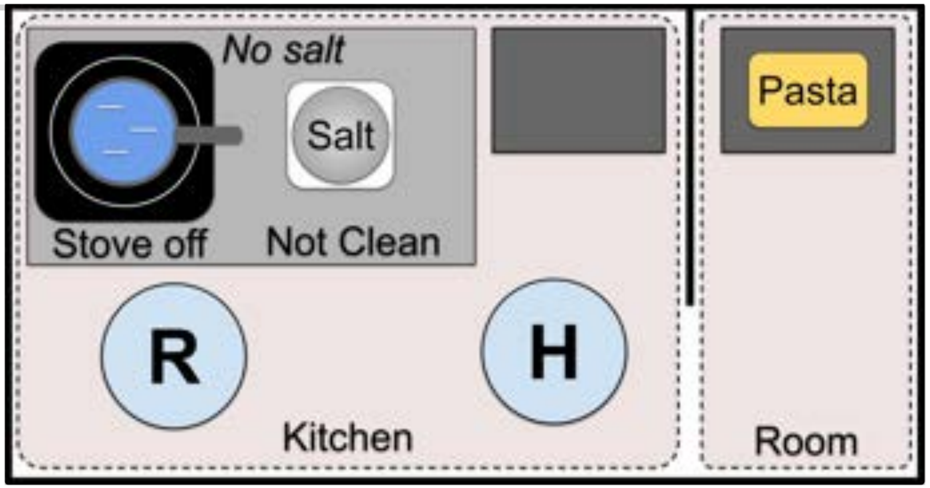
- Human **misses 2 actions**, creating **2 false beliefs**.
- Observation process: H:stoveOn←True.
  But the robot **must communicate** about the **salt**.



Example scenario

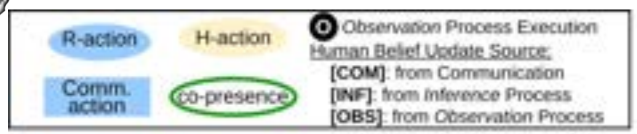


AND/OR Tree

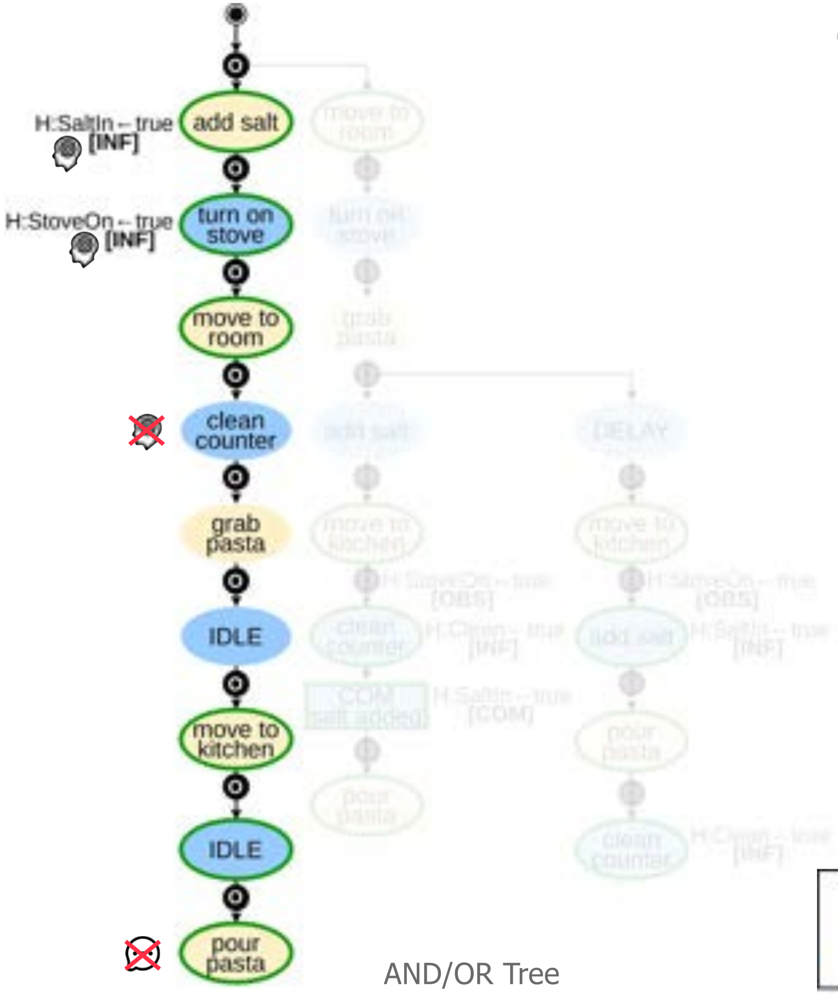


Action AddSalt is **delayed**. Human **misses 1 action**.

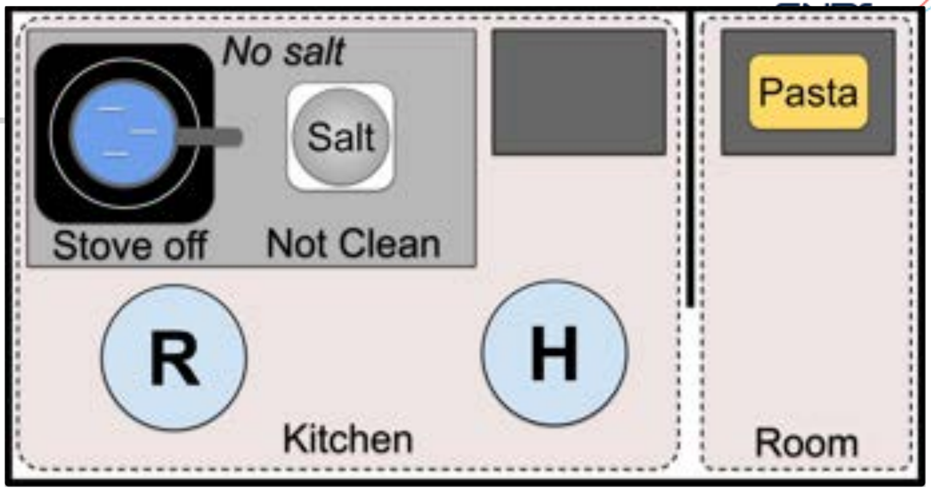
Observation process: H:stoveOn←True.
Hence, **no communication** is required.



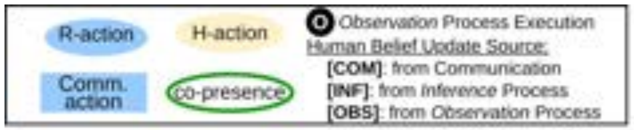
Example scenario



AND/OR Tree

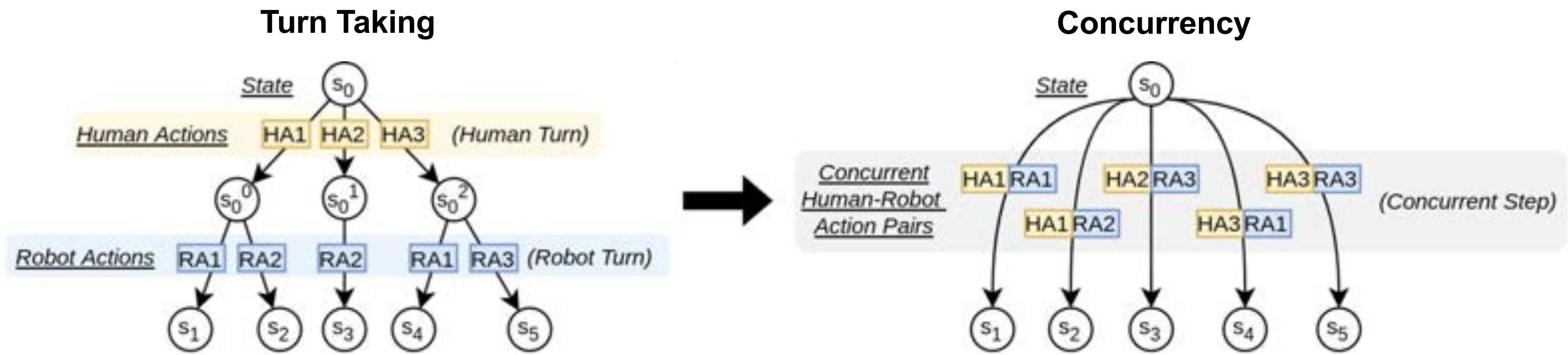


- Human starts by "adding salt" and observe the robot "turning on the stove". Thus, there is **no false beliefs**.
- Human misses "clean counter", creating **1 false belief**.
- However, this false belief is **not relevant**. Thus, **no communication** is needed.



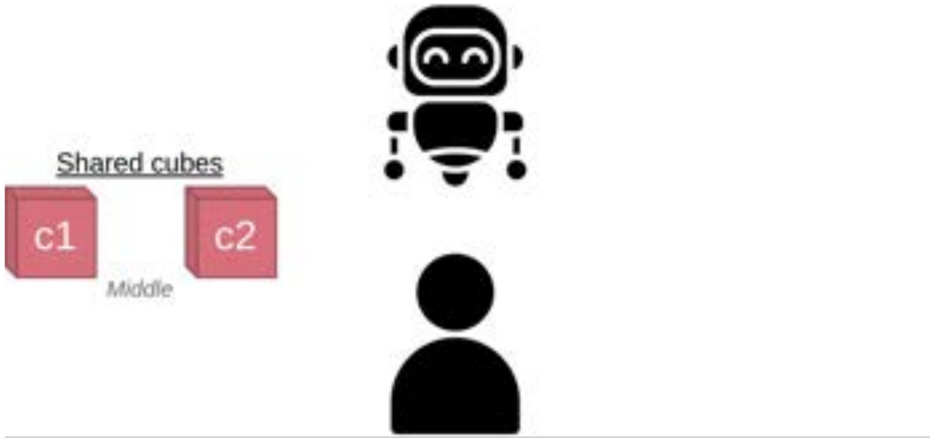
The challenge of concurrency

Challenge of concurrency



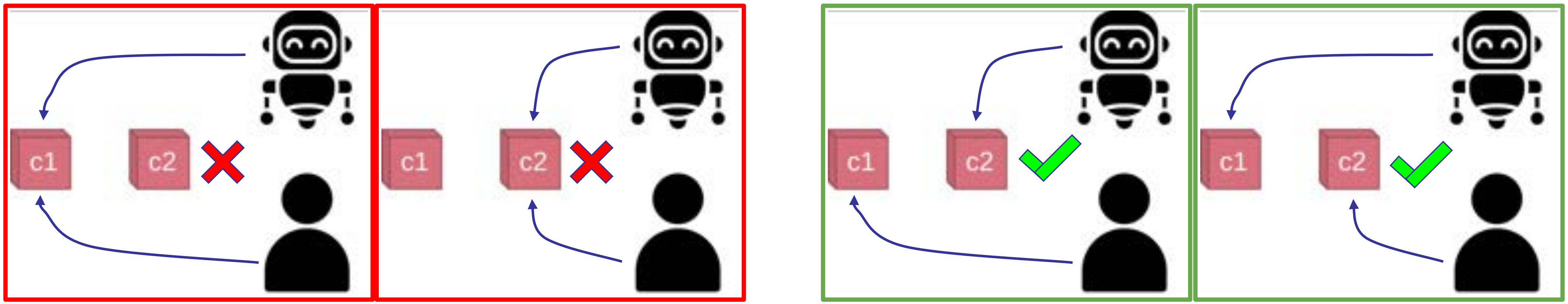
Concurrency raises a number of **challenges** for task planning.

Planning Concurrent and Compliant Actions and Decisions

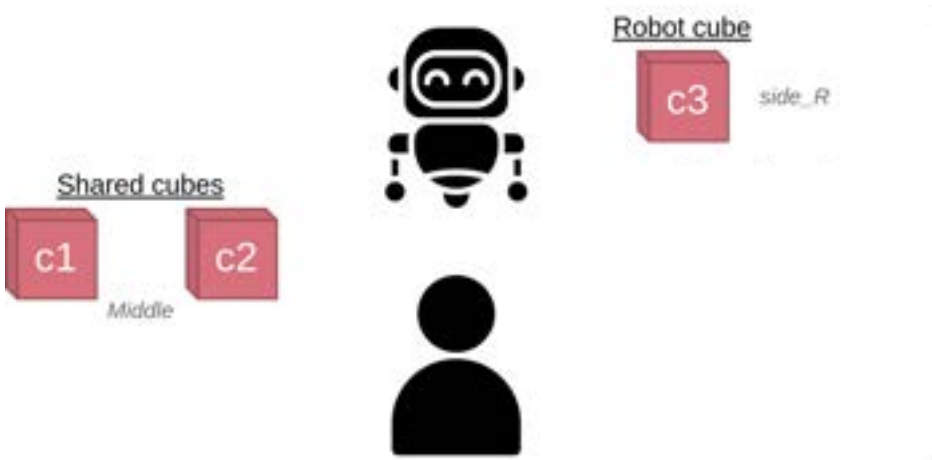


Agents must **coordinate** in two ways:

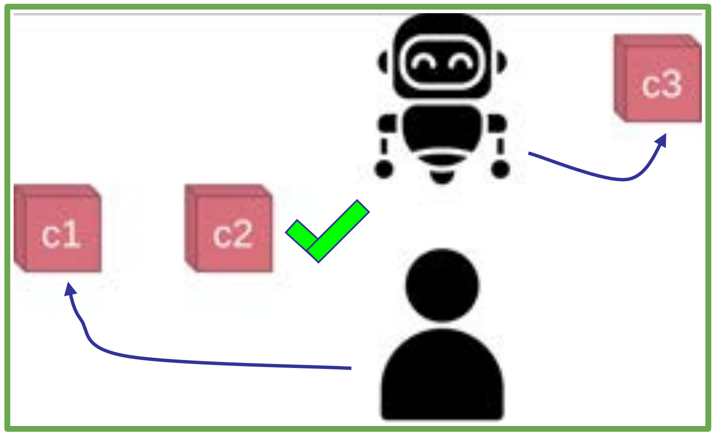
- **Avoid** direct **conflicts**, e.g., picking the same object
- One must be **compliant** to the other

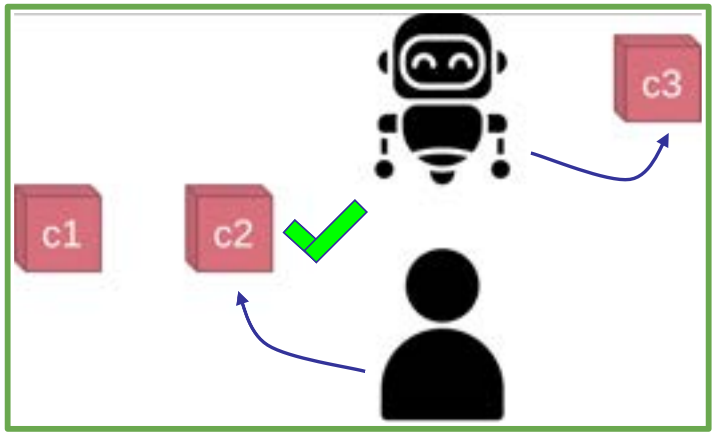


Planning Concurrent and Compliant Actions and Decisions

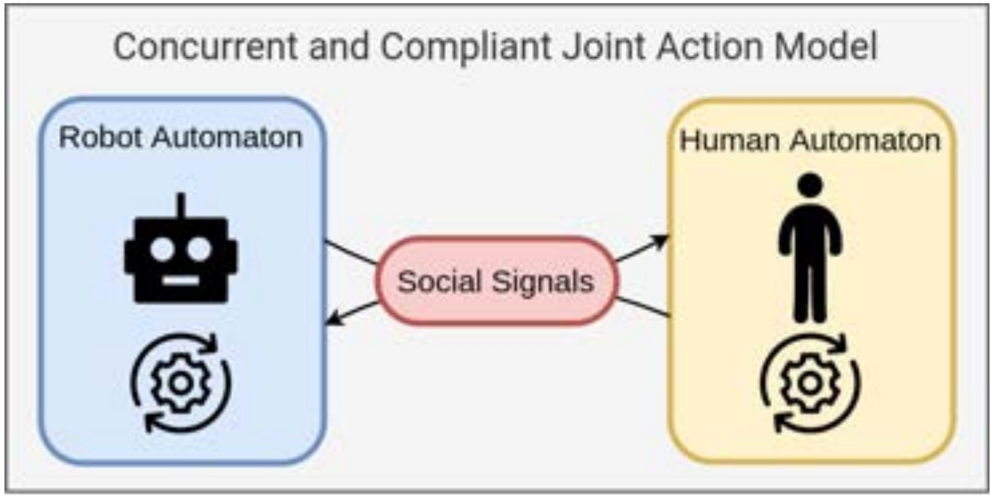


Sometimes wise to **ensure no conflicts**,
even if less task efficient





Planning Concurrent and Compliant Actions and Decisions



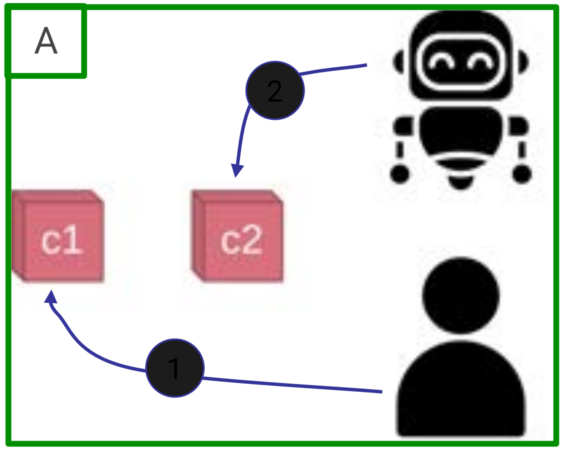
Robot automaton

- ➔ **Execution** of the policy
- ➔ **Compliance** to human **online** decisions

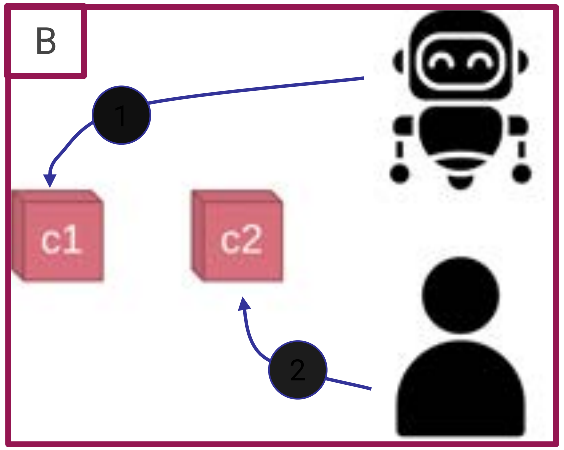
Human automaton

- ➔ **Synchronization** with the robot
- ➔ **Doesn't dictate** decisions!

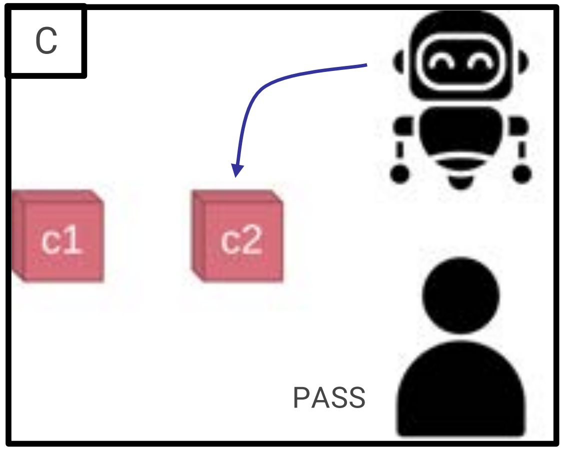
Planning Concurrent and Compliant Actions and Decisions



Human act first
Robot complies

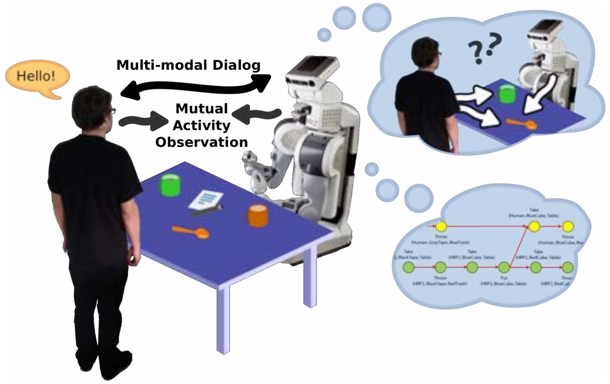


Human let Robot act first
Human complies



Human decides to PASS
Robot act alone

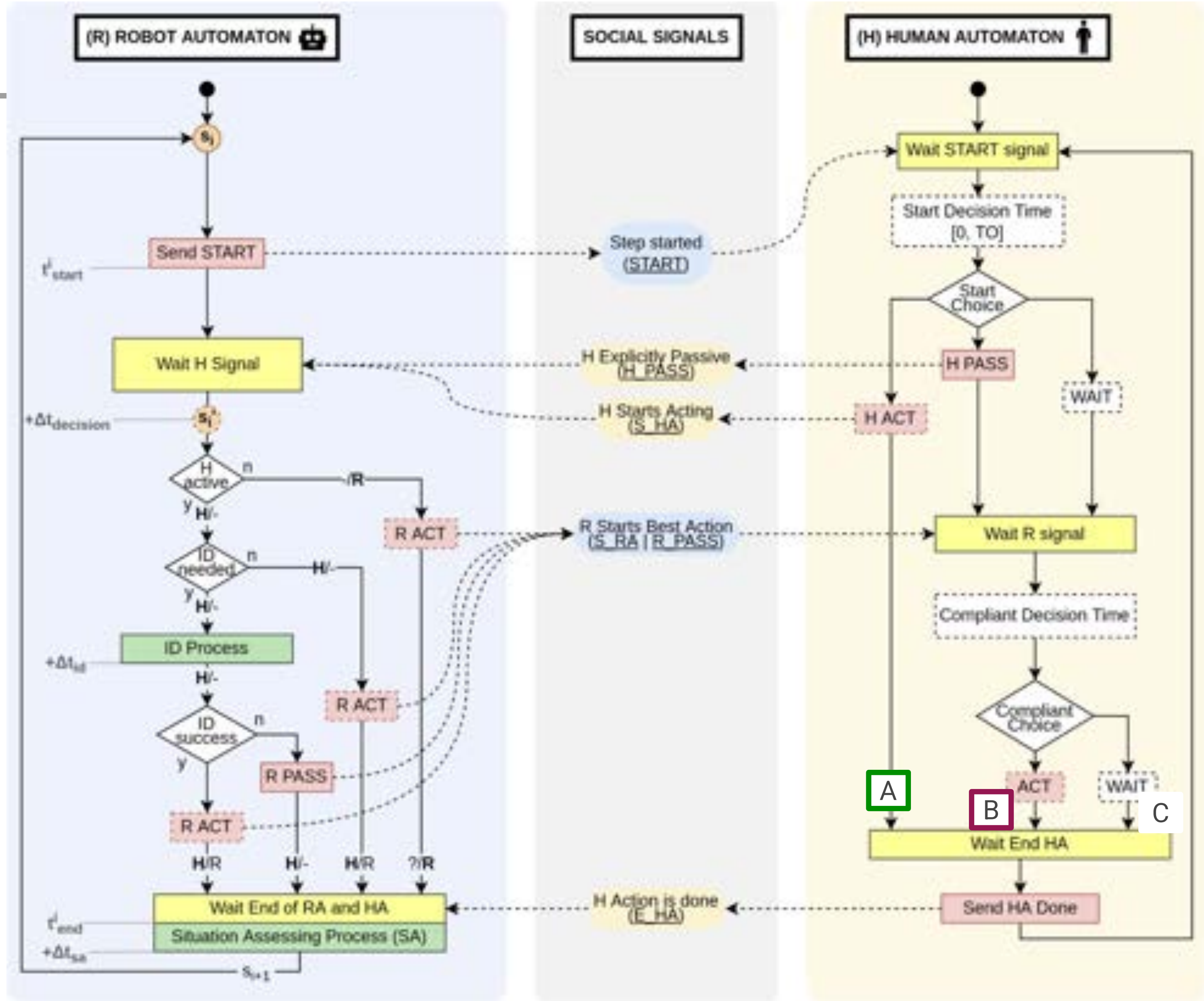
Interaction Model



Use of social signals
& Mutual Perception

Anticipate coordinations
Facilitate fluency

(Usually for execution controller)



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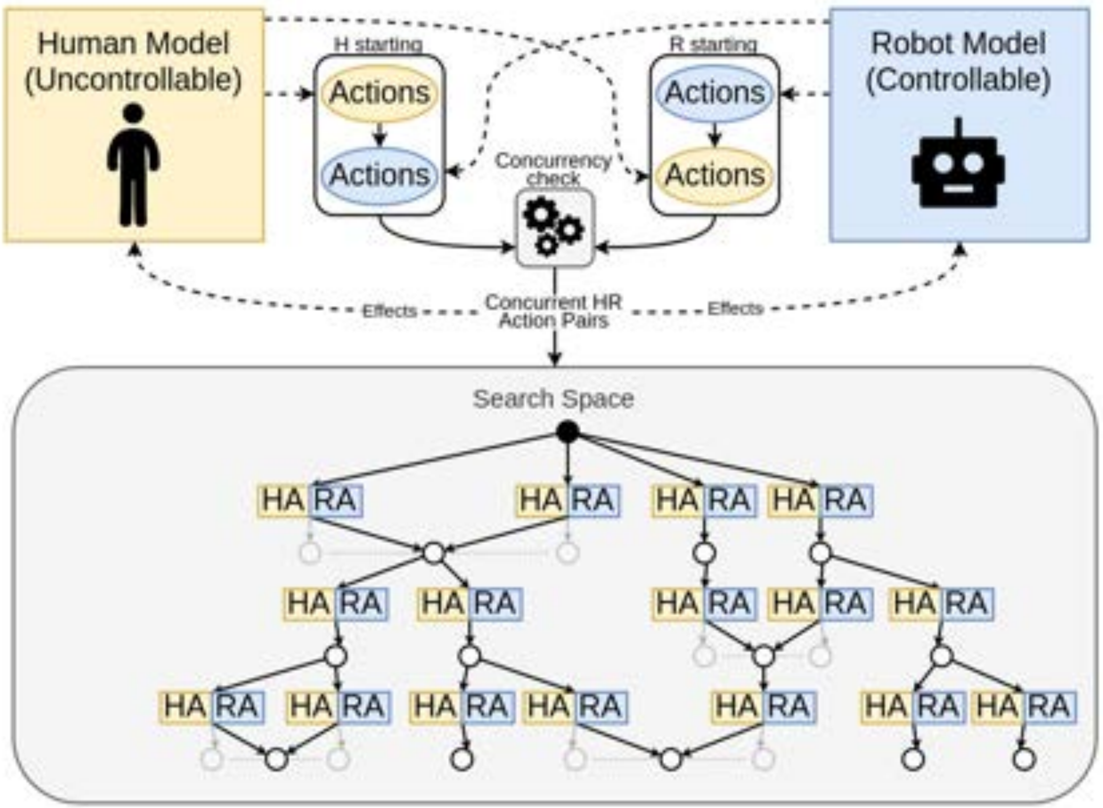
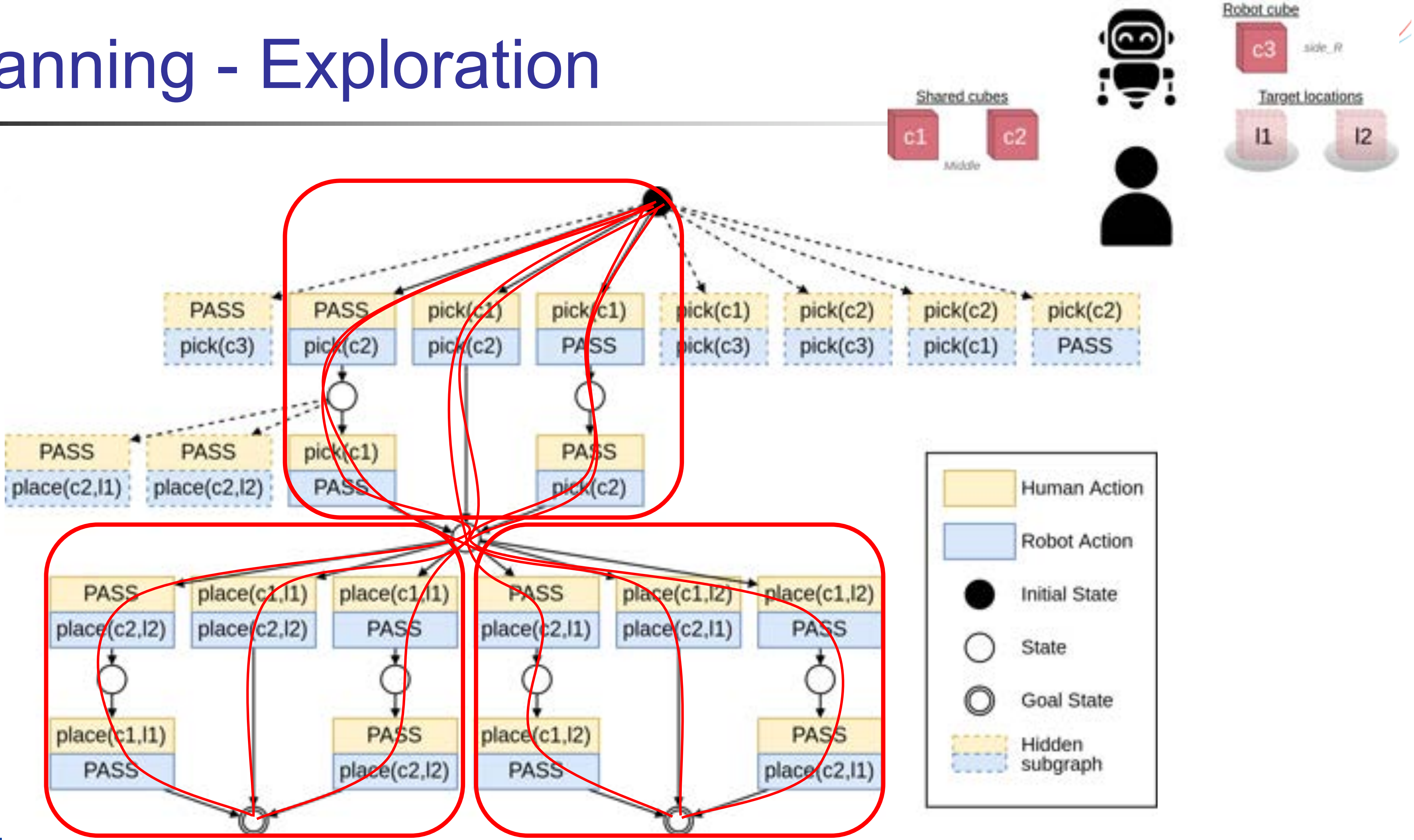
Planning - Exploration

Exploration Phase

- **Two steps horizon**
  - ➔ Concurrent HR action pairs
- **Complemented with passive actions**
  - ➔ Suggested by Joint Action model
- **Merge similar states**
  - ➔ Directed Acyclic Graph (DAG)

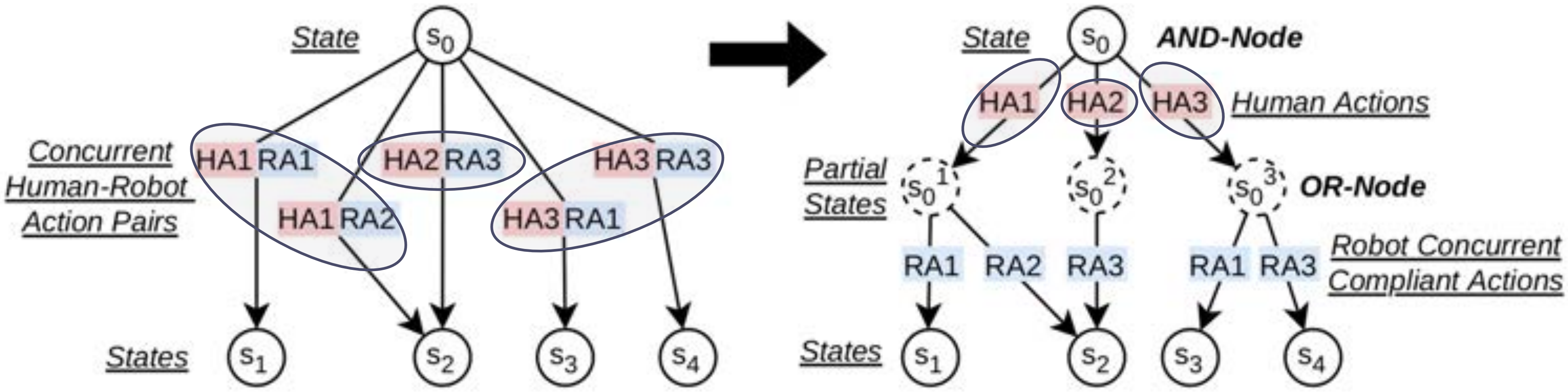


Planning - Exploration



Policy Generation

Generating the robot policy consists in identifying the best robot action to execute concurrently with every estimated human action



Policy Generation

Each branch of the AND/OR tree is a feasible plan.

To generate the robot policy, every plan is evaluated by computing the following set of metrics:

Generic

- **Time of End of Human Duty:** Time step after which the human can remain passive
- **Human Effort**: Sum of the costs of all human actions.
- **Time of Task Completion:** The time step at which the task is fully achieved.
- **Global Effort**: The sum of the costs of all actions.

Task dependent:

- **Number of steps passive:** while holding a cube

Policy Generation

Examples of human preferences: min or max of each metric in a specified priority

HUMAN-MIN-WORK:

(Minimal Human Effort > Earliest End of Human Duty > Best Overall Cost > Earliest End of Task)

EARLIEST-END-OF-HUMAN DUTY:

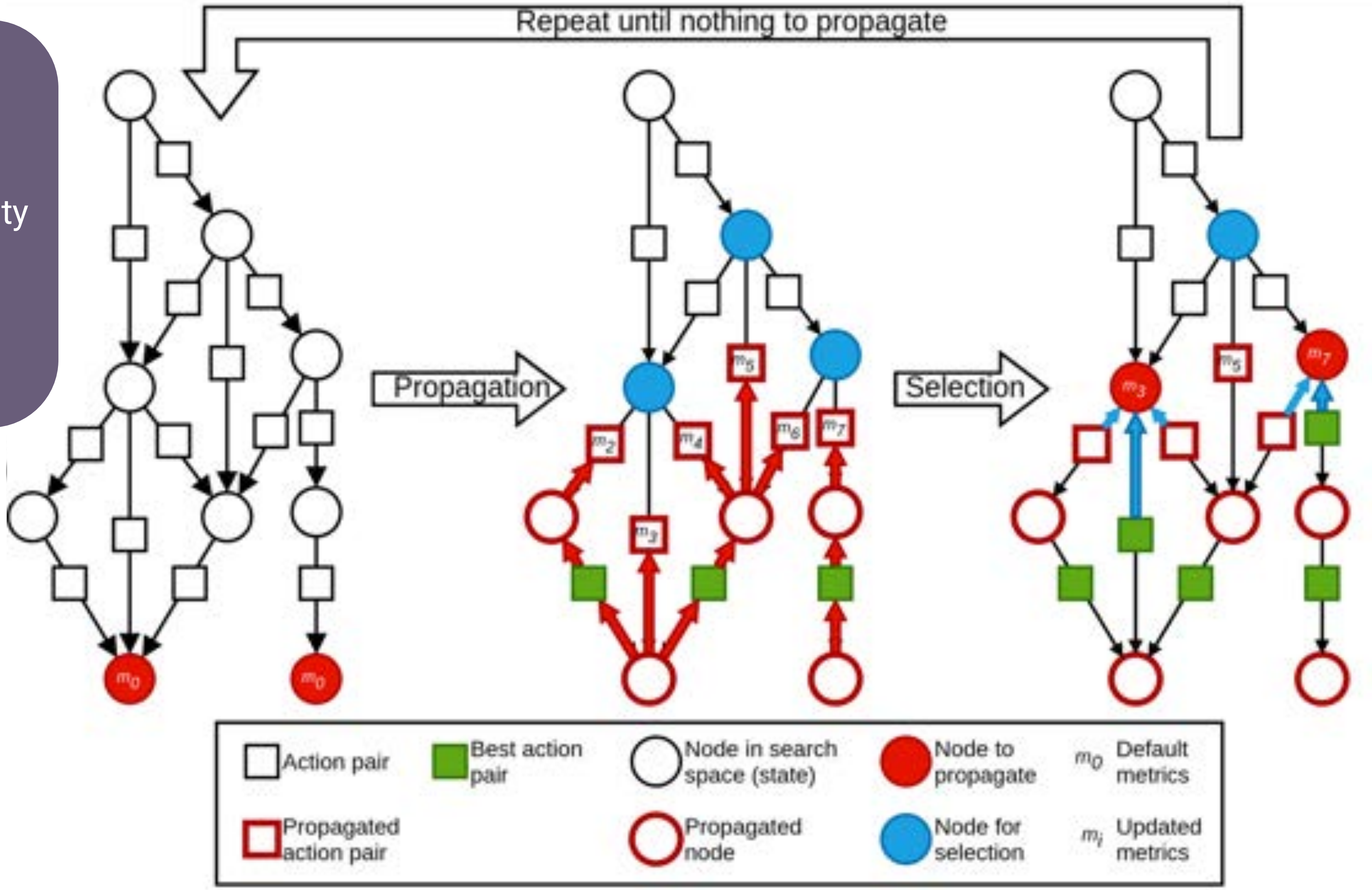
(Earliest End of Human Duty > Minimal Human Effort > Best Overall Cost > Earliest End of Task)

- → Specified by the human /robot has to comply
- → Or only estimated by the robot

Policy Generation

Metrics to characterize plans

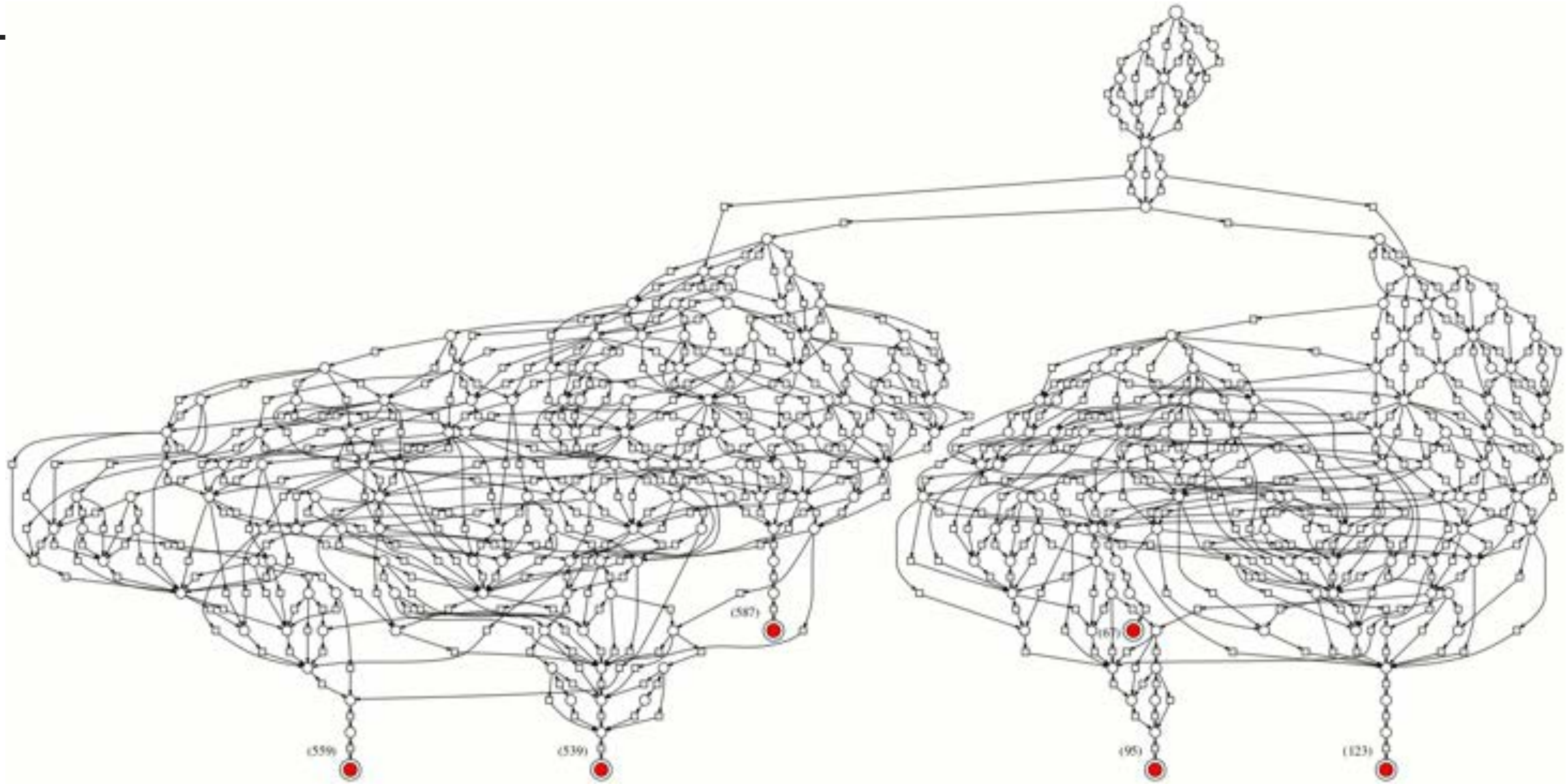
- **Objective metrics:**
  - Time of Task Completion
  - Time of End of Human Duty
  - Human Effort
  - Global Effort
- **Specific metrics:**
  - Passive While Holding



Planner **is given** an **estimation** of human's **preferences**
➔ **Compare** metrics

Best robot action are identified
➔ Added to **policy**

Policy Generation

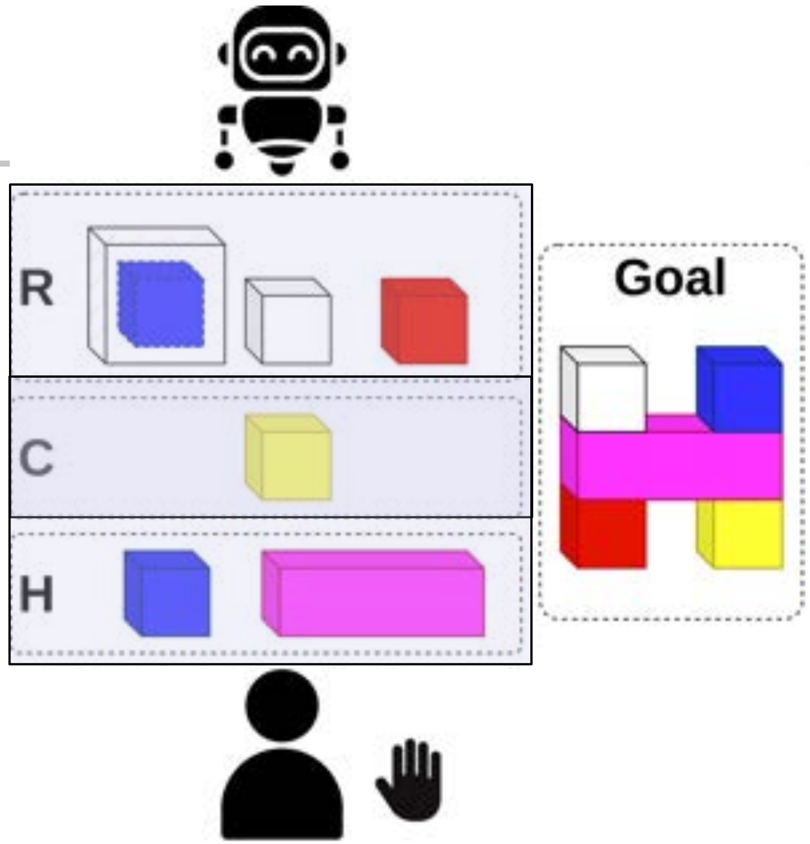


1) Empirical Evaluation

HR Simulations

- **BlocksWorld** domain
- HR Collaboration to stack **colored cubes**
- Match **goal pattern**

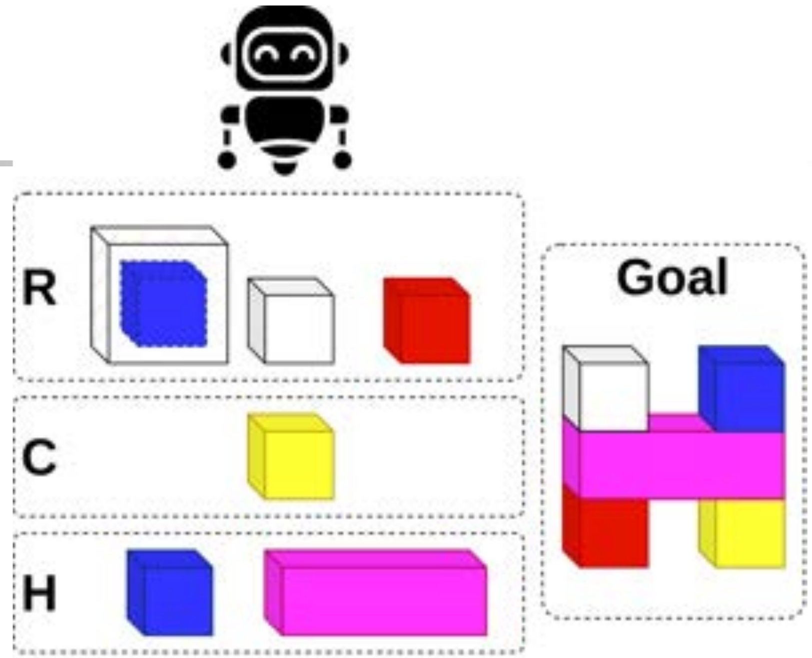
- Colored cubes disposed on a table
- Can reach **near cubes** (R & H) and **center** (C)
- Robot must **open** the **box** to reach blue cube



Empirical Evaluation

Simulating human and robot behaviors

- “**Exact**” human preferences
  → Human policy
- **Estimated** human preferences
  → Robot policy



Earlyest Task Completion:

1. Time of Task Completion
2. Global Effort
3. Human Effort
4. Time of End of Human Duty
5. *Passive While Holding

- Human is committed to help
- Parallelize actions

Minimum Human Effort:

1. Human Effort
2. Time of End of Human Duty
3. Global Effort
4. Time of Task Completion
5. *Passive While Holding

- Human does the least
  → pink bar

Earlyest End of Human Duty:

1. Time of End of Human Duty
2. Time of Task Completion
3. Human Effort
4. Global Effort
5. *Passive While Holding

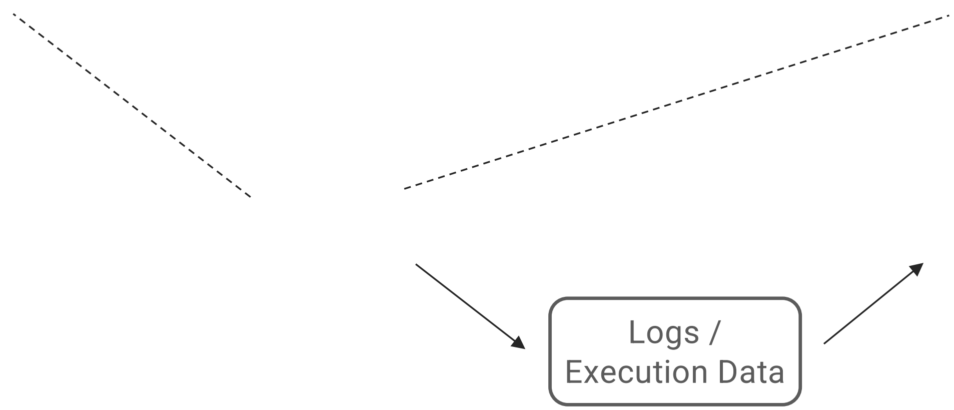
- Human commits to be free early
  → yellow + pink bar

2) User study -Interactive Simulator

Execute policy on simulated robot

Human can interact in real-time

Explicit social signals and mutual perception are emulated



2) User Study with 25 participants

Two execution regimes

- our joint action model **Human-First (HF)**
- a baseline where the robot always takes the initiative, forcing the human to comply, referred to as **Robot-First (RF)**.

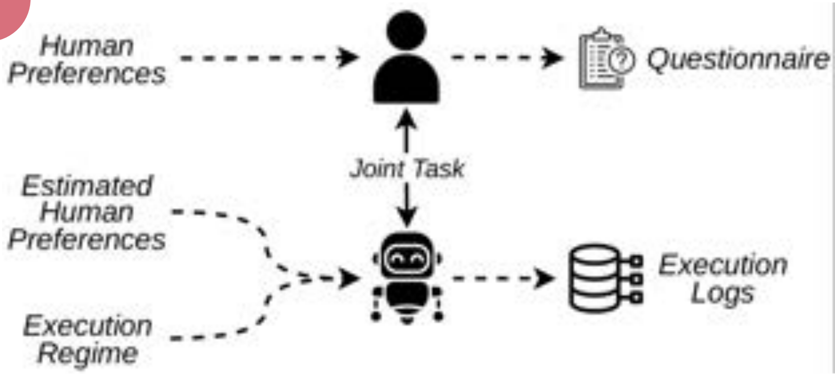
Human Preferences

(1) Early Task Completion
(2) Early End of Human Duty

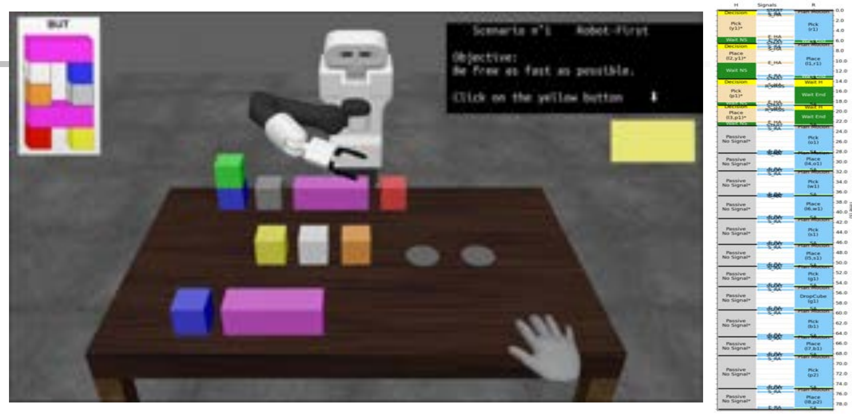
Pairs of Pref. & Estimated Pref.

- **Pair A**: pref. (1) **correctly** estimated
- **Pair B**: pref. (1) **wrongly** estimated
- **Pair C**: pref. (2) **wrongly** estimated

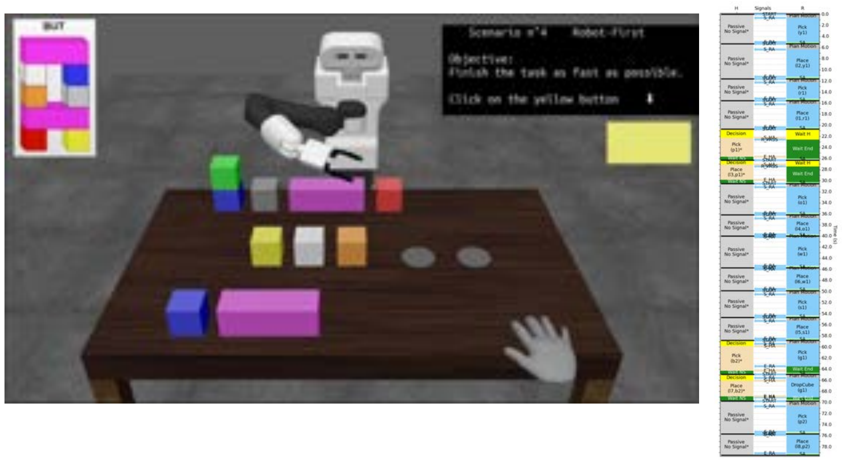
Combining the pairs and execution regimes:
➔ **6 scenarios**



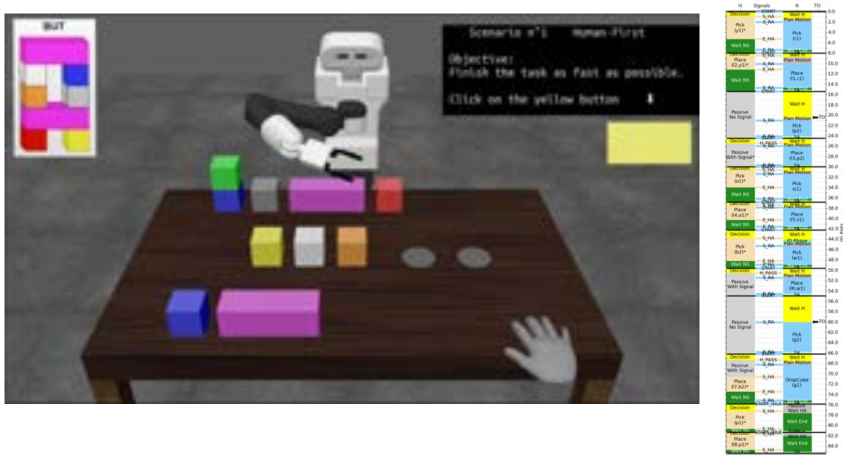
HF – Early end of task



RF - Early end of duty for H



RF - Wrong estimation of human willingness to contribute to the task



HF - H Pass .. But finally no

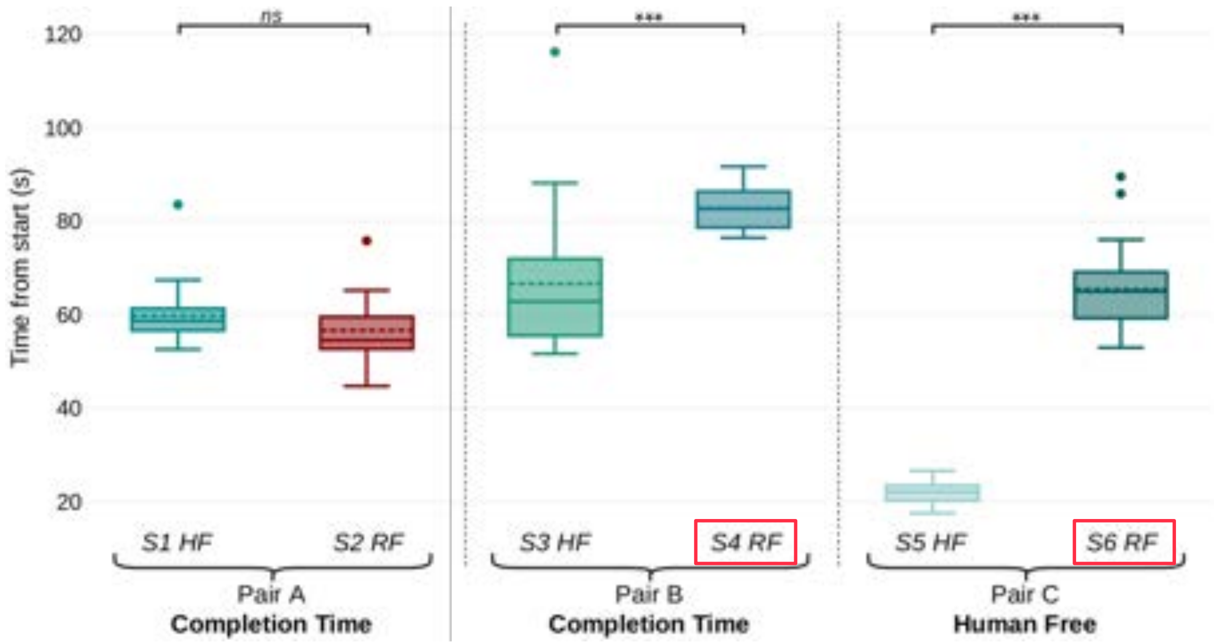
Objective results

S4 & S6 are scenarios with RF and wrong estimations!

Pair A (Finish early + correct)
- Non significant difference between HF and RF
- RF is even better

Pair B (Finish early + wrong)
- RF significantly longer than HF
- HF performs almost similarly

Pair C (be free early + wrong)
- RF obliged to stay significantly longer than HF



RF is **strongly affected** by **erroneous** estimated preferences.
HF is **robust** thanks to the **compliance** to human **online decisions**.

→ Confirms preliminary results

Subjective results

S4 and S6 (RF + wrong) received **lower** answers:
➔ In line with the objective results

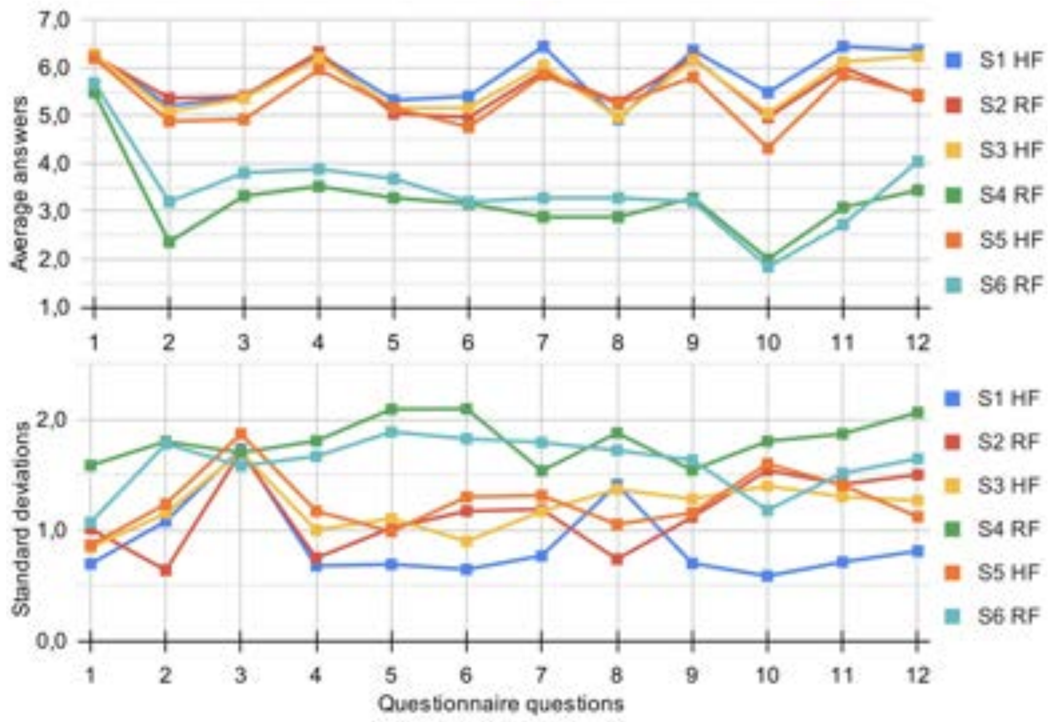
Statistical Analysis of the Variance (ANOVA) with repeated measures showed that using **RF** with **erroneous** estimation:

- **Interaction** is significantly **less *Positive***
- **Collaboration** is significantly **less *Adaptive*** and ***Efficient***
- **Robot Actions** are significantly **less *Appropriate*** and ***Accommodating***

Our compliant joint action model is effective to solve the task and robust to human preferences.

Robot perception		Interaction		Collaboration		Acting	
1	Responsive	4	Positive	7	Adaptive	10	Appropriate
2	Competent	5	Simple	8	Useful	11	Accommodating
3	Intelligent	6	Clear	9	Efficient	12	Predictable

Table 1. Questionnaire 12 numbered items, grouped in four categories.



Conclusion

HATP/EHDA

- We claim it is a **relevant approach** for HRC task planning problems
- Mandatory to **preserve** human's online **latitude** of decisions
- **Must anticipate** human probable behaviors

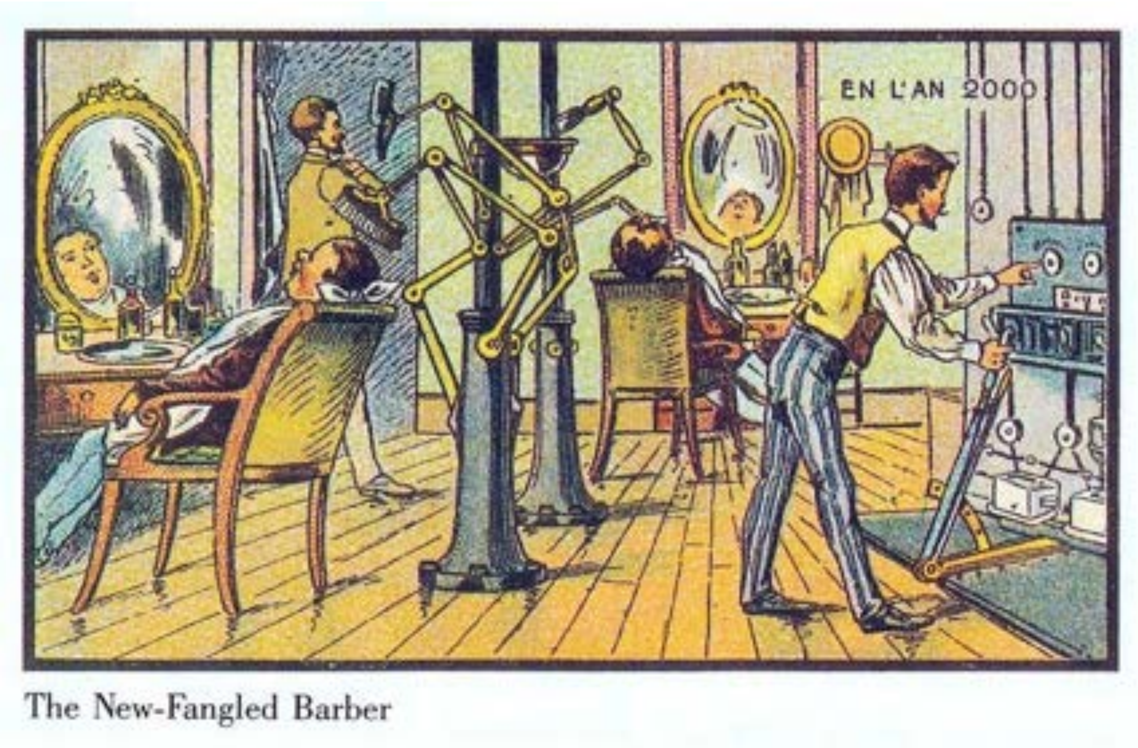
Concurrency

- Concurrent and compliant joint action **model** capturing **human's** inherent **uncontrollability**.
- Model comes from joint action literature and describes how to **coordinate** with **social signal**.
- Produce concurrent robot policy **compliant** with **online human decisions** and **preferences**.
- We showed how proper anticipation permits to be compliant and how it is **robust** to erroneous estimations of human preferences.

Future Work?

- Balance between HF and RF
  - Dynamically switch between regimes
- Same action duration hypothesis
  - Consider explicit time?
  - Several actions in one step?
- No physical joint action
  - Lifting a table together?

Merci … Questions ?



Futuristic pictures by Jean-Marc Côté issued in France in1900 (cited by I. Asimov)

« Science et Vie » magazine
June 1960

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