Motion Planning and Continuous Control in a Unified Cognitive Architecture

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Cognitive Architectures

A *cognitive architecture* is a unified theory of the mind that:

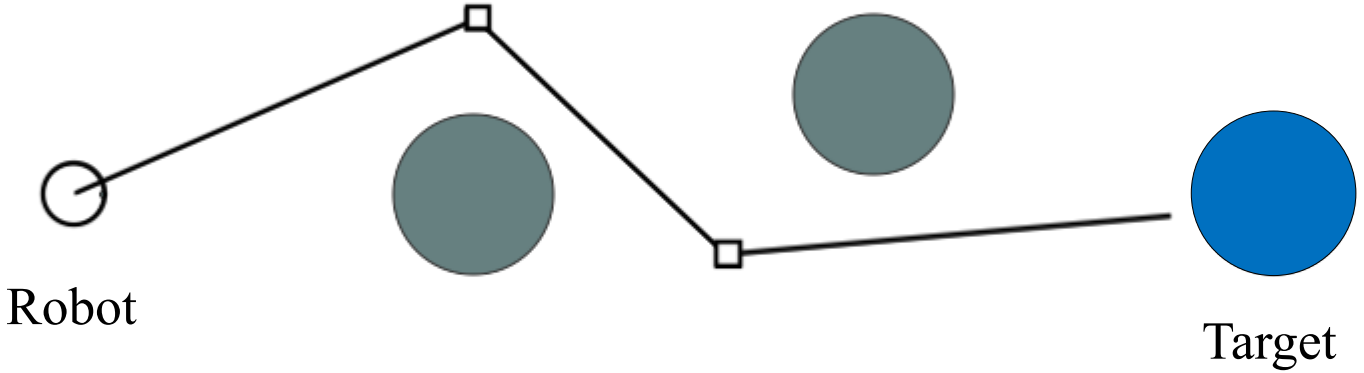
- Specifies what remains *constant* across different domains
- Incorporates many assumptions from *cognitive psychology*
- Offers a *programming language* for building intelligent systems

The PUG architecture (Langley et al., 2016) assumes that:

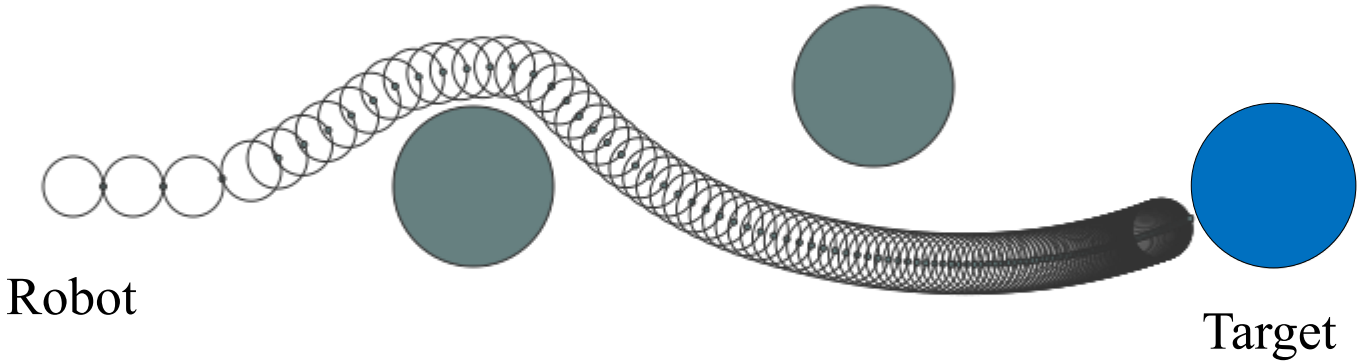
- *Symbolic relations are grounded in quantitative descriptions*
- *Relations have associated utilities that reflect tradeoffs*
- *Discrete skills have associated control equations*
- *Mental simulation creates trajectories to guide planning*

This talk reports a recent extension – PUG/C – that unifies symbolic and numeric processing more deeply.

PUG's Navigation Behavior



Desired Navigation Behavior



PUG's Knowledge Structures

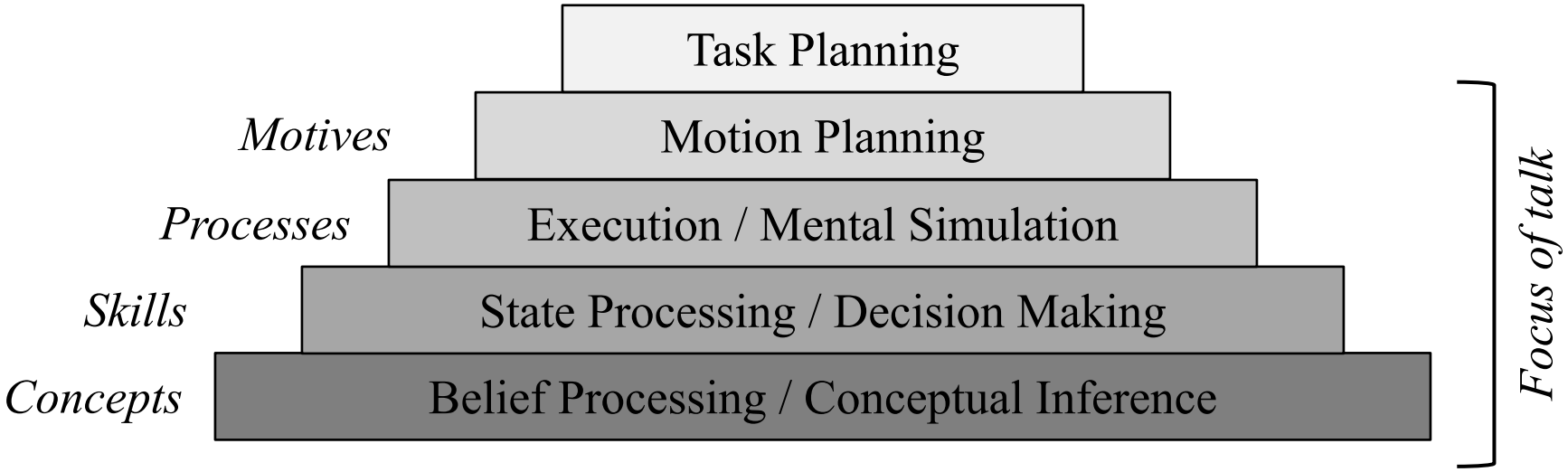
PUG/C incorporates four distinct types of generic, long-term knowledge structures:

- ***Concepts*** – Define relational categories, attributes, and *veracity*
- ***Skills*** – Specify *control values* based on match to *target concepts*
- ***Processes*** – Predict *changes* in attributes given current values
- ***Motives*** – Indicate *utility* of relations conditioned on situation

The architecture uses these elements for conceptual inference, reactive control, heuristic evaluation, and plan generation.

PUG's Layered Processes

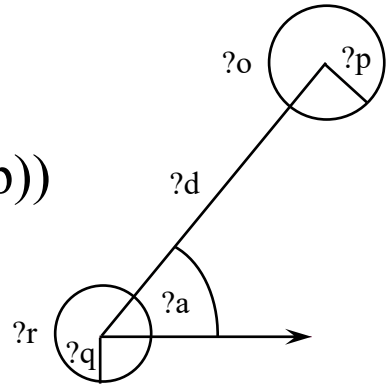
Like other cognitive architectures, PUG/C operates in *cycles* that use knowledge to produce new short-term structures.



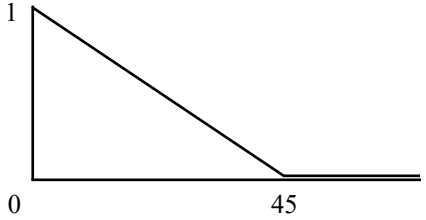
These levels are organized in a ***cascaded*** manner, with each one using results produced by those below it.

PUG Concepts

```
((robot-at ^id (?r ?o) ^distance ?d)
   :elements    ((robot ^id ?r ^radius ?q)
                 (object ^id ?o ^distance ?d ^radius ?p))
   :veracity    ((linear ?d (+ ?p ?q) 10.0)) )
```




```
((robot-facing ^id (?r ?o) ^angle ?a)
  :elements    ((robot ^id ?r)
                (object ^id ?o ^angle ?a))
  :veracity    ((linear ?a 0.0 45.0)) )
```



Here the function *(linear obs max min)* returns *1* if the observed value *obs* ≤ *max*, *0* if *obs* ≥ *min*, and *obs/(max − min)* when *max* < *obs* < *min*.

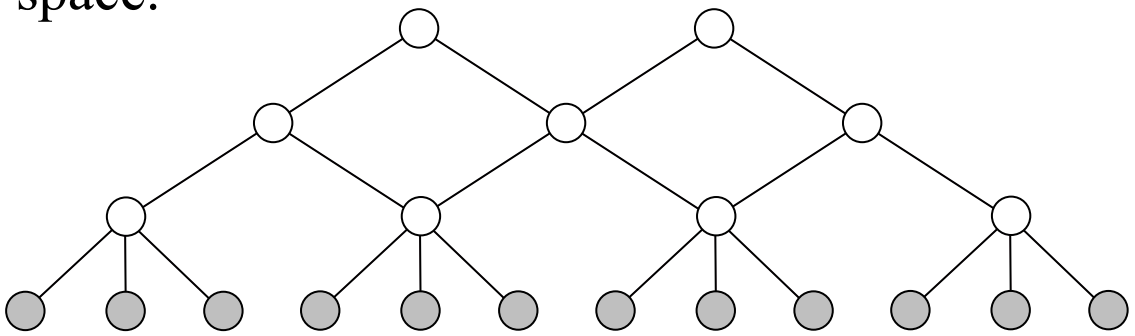
Beliefs are ground instances of concepts that relate specific entities.

Conceptual Inference in PUG

At the lowest level, *conceptual inference* derives beliefs that are consistent with perceptions / predictions:

- Matches conceptual rules to infer beliefs like (*robot-at R1 O1*)
  - Computes ***values*** of numeric attributes associated with beliefs
  - Calculates ***veracity*** (degree of match) for each inferred belief
- Applies this recursively to generate the full deductive closure

Together, the resulting beliefs describe the current ***state*** as a point in N-dimensional space.

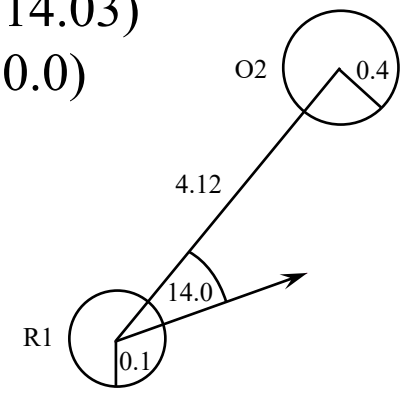


PUG Beliefs

Perceptions:	**Veracity**	**Utility**
(robot ^id R1 ^radius 0.15 ^move-rate 0.0 ^turn-rate 0.0)	1.00	0.0
(object ^id O1 ^distance 2.0 ^angle 0.0 ^radius 0.4)	1.00	0.0
(object ^id O2 ^distance 4.123 ^angle 14.03 ^radius 0.4)	1.00	0.0
(object ^id O3 ^distance 6.0 ^angle 0.0 ^radius 0.4)	1.00	0.0

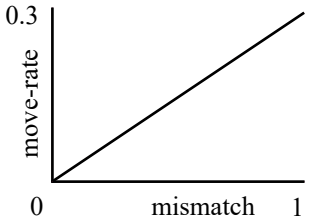
Inferred Beliefs:

(robot-at ^id (R1 O1) ^distance 2.0)	0.85	0.0
(robot-at ^id (R1 O2) ^distance 4.12)	0.62	0.0
(robot-facing ^id (R1 O1) ^angle 0.0)	1.00	0.0
(robot-facing ^id (R1 O2) ^angle 14.03)	0.69	0.0
(robot-facing ^id (R1 O3) ^angle 0.0)	1.00	0.0
(approaching ^id (R1 O1))	0.91	−20.0

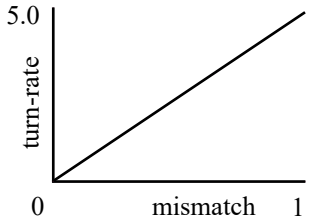


PUG Skills

```
((move-to ?r ?o)
  :elements    ((robot ^id ?r ^turn-rate ?t)
                (object ^id ?o ^angle ?a))
  :tests       ((> ?a -90) (< ?a 90))
  :control     ((robot ^id ?r ^move-rate (* 0.3 $MISMATCH)))
  :target      ((robot-at ^id (?r ?o))) )
```




```
((turn-to ?r ?o)
  :elements    ((robot ^id ?r)
                (object ^id ?o ^angle ?a ^distance ?d))
  :control     ((robot ^id ?r ^turn-rate (* 5.0 (sign ?a) $MISMATCH)))
  :target      ((robot-facing ^id (?r ?o))) )
```



Here the symbol *$MISMATCH* stands for one minus the *veracity* of the matched target concept.

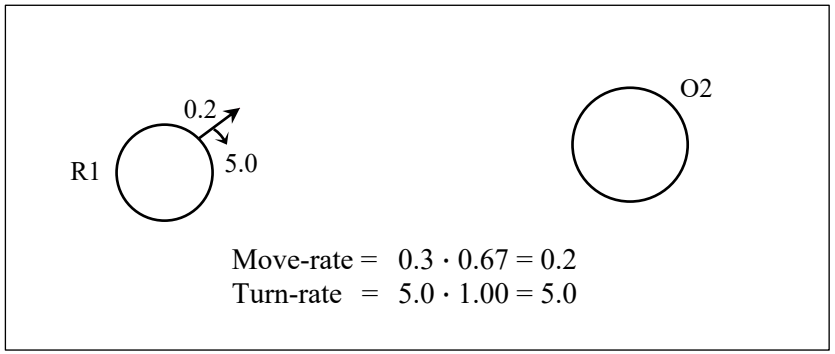
Intentions are ground instances of skills that involve specific entities.

State Processing / Decision Making

When PUG carries an out an active intention associated with skill S, whether mentally or externally, it:

- Checks that S's conditions match the current beliefs
- Finds degree of *mismatch* M to S's target belief
- Ensures the mismatch does not fall below threshold
- Else inserts M into S's equations to find control values

If *multiple* intentions apply, then PUG takes the *vector sum* of control values (as with potential fields).



PUG Processes

```
((move-relative ?r ?o)
  :elements    ((robot ^id ?r ^move-rate ?m)
                (object ^id ?o ^distance ?d ^angle ?a))
  :changes     ((object ^id ?o ^distance (*dd ?d ?a ?m)
                                ^angle    (*da ?d ?a ?m))) )

((turn-relative ?r ?o)
  :elements    ((robot ^id ?r ^turn-rate ?t)
                (object ^id ?o ^angle ?a))
  :changes     ((object ^id ?o ^angle (- ?t))) )
```

Here the functions **dd* and **da* calculate change in the robot's *distance* and *angle* relative to an object as it moves forward.

Reactive Execution / Mental Simulation

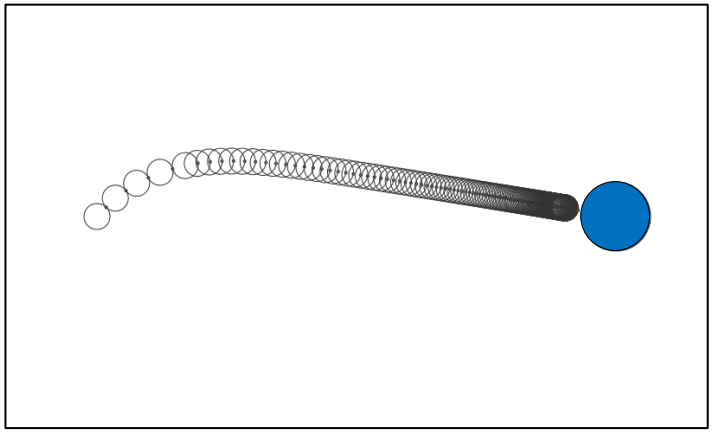
PUG/C applies skills and invokes state processing repeatedly to generate ***motion trajectories***.

- When the architecture carries out actions in the environment, this corresponds to ***reactive control***.
  - This operation does ***not*** require processes, as it has no need to predict future states.
- When the system imagines carrying out actions in its mind, it corresponds to ***mental simulation***.
  - This operation ***does*** rely on processes (applied in parallel) to predict the succeeding state.

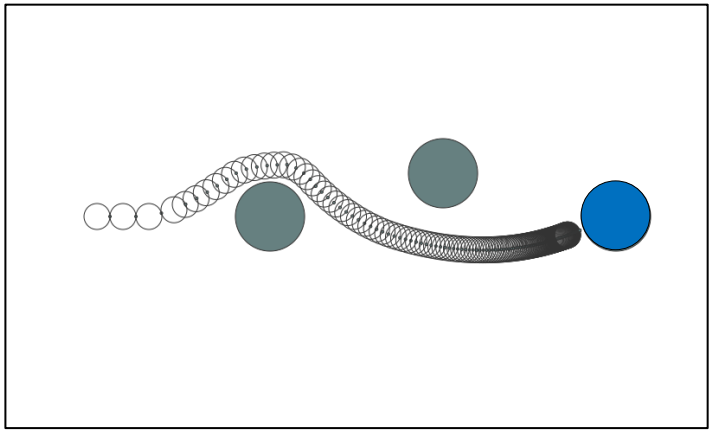
Each trajectory follows deterministically from an intention set (i.e., skill instances) that constitute a ***motion plan***.

Reactive Execution / Mental Simulation

PUG/C applies skills and invokes state processing repeatedly to generate ***motion trajectories***.



(move-to R1 O1)
(turn-to R1 O1)



(move-to R1 O3)
(turn-to R1 O3)
(avoid-on-left R1 O1)
(avoid-on-right R1 O2)

Concurrent Intentions

Each trajectory follows deterministically from an intention set (i.e., skill instances) that constitute a ***motion plan***.

PUG Motives

```
((robot-at ^id (?r ?o))
  :conditions  ((robot ^id ?r ^radius ?rr)
                (object ^id ?o ^type target ^distance ?d ^radius ?or))
  :utility     (cond ((< ?d (+ ?rr ?or 0.25))  10.0)
                     (t  0.0))
  :type        achievement )

((approaching ^id (?r ?o))
  :conditions  ((robot ^id ?r ^radius ?rr)
                (object ^id ?o ^type obstacle ^distance ?d ^radius ?or))
  :utility     (cond ((< ?d (+ ?rr ?or))  −20.0)
                     (t  0.0))
  :type        maintenance )
```

An *achievement* motive assigns utility to a belief only on its first match, where a *maintenance* motive does so repeatedly.

Heuristic Search for Motion Plans

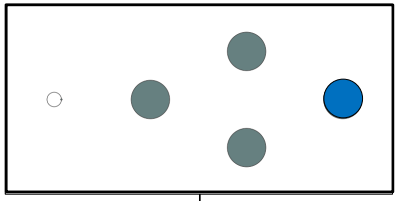
PUG/C combines motives with mental simulation to carry out greedy search through a space of motion plans.

- Starting from an empty plan, it retrieves intentions that would ***achieve its target beliefs***.
- Mental simulation produces a trajectory and uses motives to assign ***utilities*** to each belief and state.
- If some of these beliefs have ***negative utility***, PUG retrieves intentions that would help ***avoid*** them.
- When multiple repairs are possible, it selects the candidate plan / trajectory with the ***highest utility***.

This search continues until it finds an acceptable motion plan.

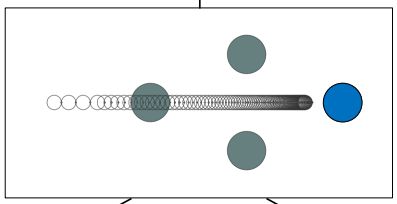
Heuristic Search for Motion Plans

Empty Plan

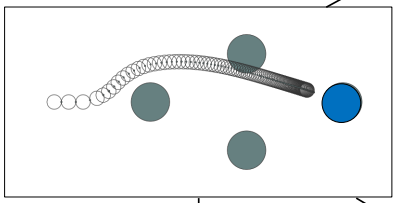


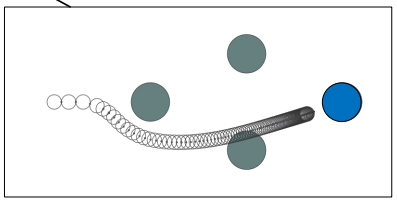
Here the agent wants to reach a target object.

But the initial trajectory collides with an obstacle.

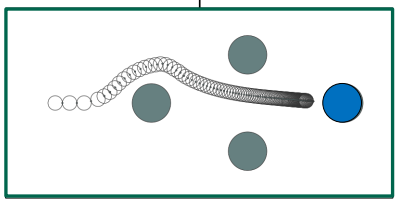


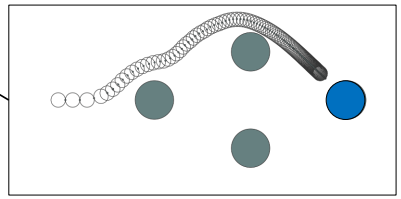
Search adds new intentions that improve utility.





Final Plan





Related and Future Research

PUG/C incorporates insights from a number of paradigms:

- Cognitive architectures (Soar, ICARUS, teleoreactive systems)
- Error-driven feedback control and potential fields
- Qualitative reasoning and quantitative simulation

But it combines ideas from these efforts in a unified framework.

Future research will add support for ***places*** (virtual objects) and large-scale ***maps*** (topological networks).

We will also integrate PUG/C with PUG/X, an earlier extension that combined ***task planning***, ***execution***, and ***monitoring***.

Summary Remarks

PUG/C is a cognitive architecture for embodied, human-like agents that incorporates:

- Concepts, motives, skills, and processes that have both ***symbolic*** and ***numeric*** elements
- ***Cascaded processing*** with layers for inference, state processing, mental simulation, motion planning, and task planning
- Skills' target concepts match to different degrees, which serve as error signals that enable continuous control
- Mental simulation and motivational processing support ***greedy search*** through a space of continuous motion plans

We demonstrated PUG/C's behavior on scenarios that parallel skill application, obstacle avoidance, and motion planning.

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PUG's Layered Processes

Like other cognitive architectures, PUG/C operates in *cycles* that use knowledge to produce new short-term structures.

The framework differs in that it relies on five processing levels:

- ***Belief processing*** – Inference from perceptions / predictions
- ***State processing*** – Applies skills, processes, motives
- ***Execution / Mental simulation*** – Generates trajectories
- ***Motion planning*** – Heuristic search for an intention set
- ***Task planning*** – Search for a sequence of motion plans

These levels are organized in a ***cascaded*** manner, with each one using results produced by those below it.