

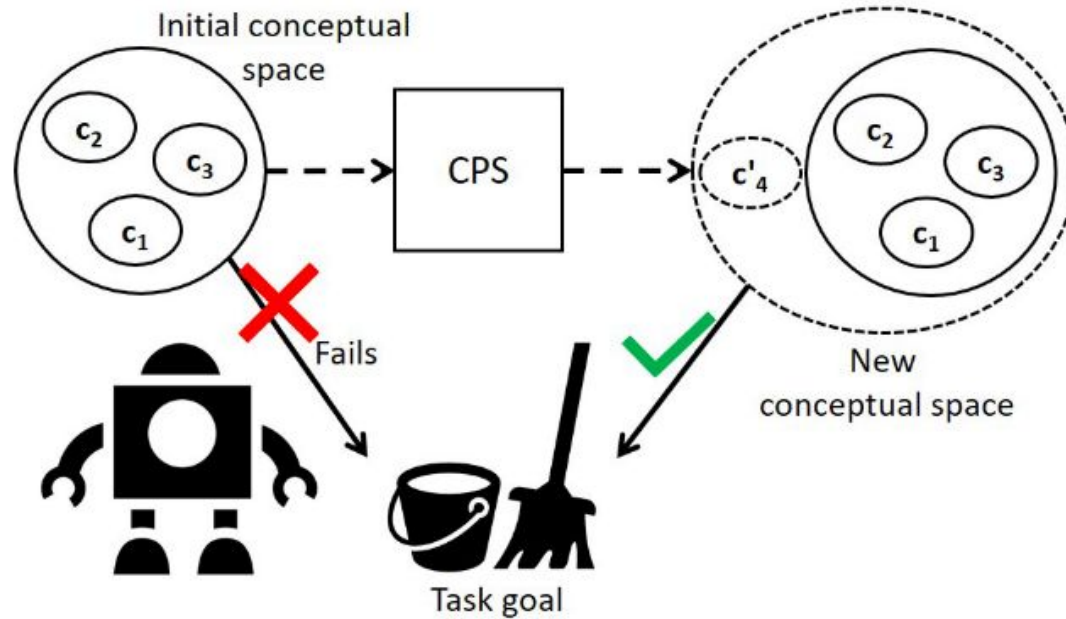


# **Creative Problem Solving (Novelty Resolution) in Intelligent Agents**

**Evana Gizzi Conway**

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Student Engineering Trainee, NASA Goddard Space Flight Center



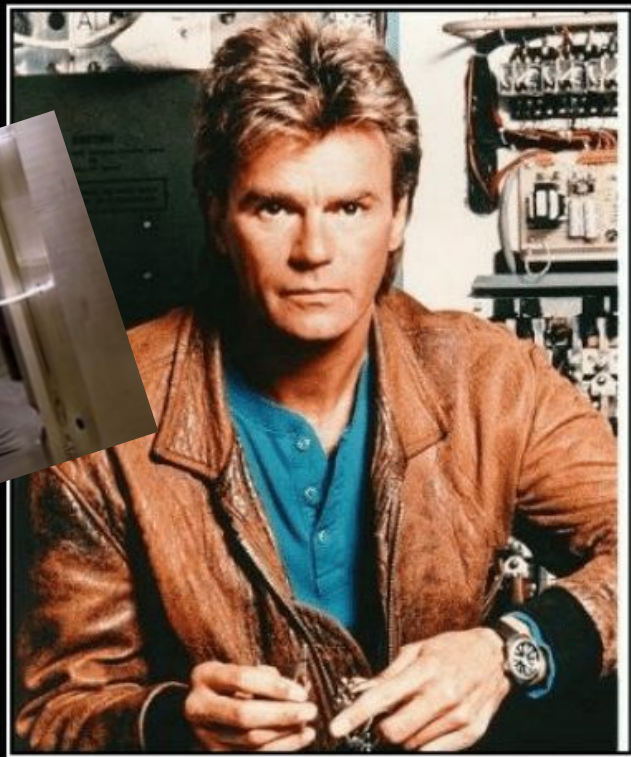
Creative problem solving (CPS) is defined as *the process by which the agent discovers new concepts that were not in the initial conceptual space of the agent, allowing it to accomplish a previously impossible goal. [Gizzi et al. 2020]*

# Puzzle Box Problems





[MacGyverImg1]



MACGYVER

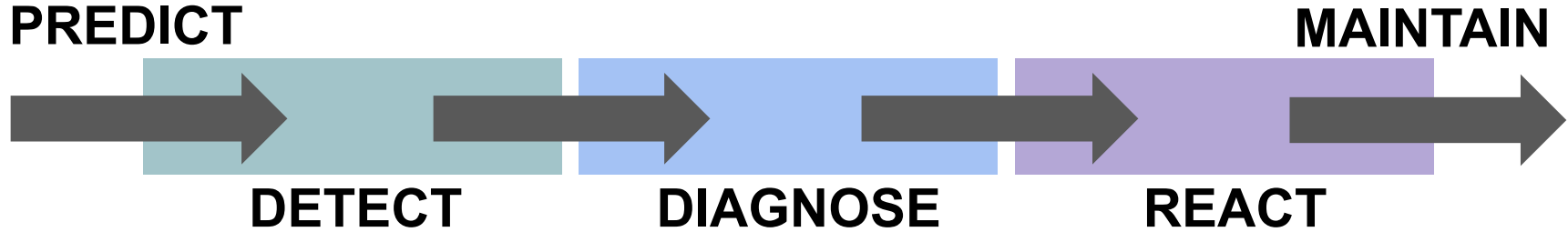
Making the junk drawer fun again since 1985

[MacGyverImg2]



[MacGyverImg3]

# Progression of CPS [Anomaly Handling]



# Research Questions

1. What is CPS?
2. What kinds of problems require CPS, and how can they be detected/distinguished from GPS problems?
3. How can we diagnose the cause of such anomalies which necessitate CPS for problem solving?
4. How can CPS be implemented in intelligent agents, specifically in the context of anomalies?
5. How can an agent get better at CPS over time?

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**(DIAGNOSE)**

**(REACT)**

# Research Questions

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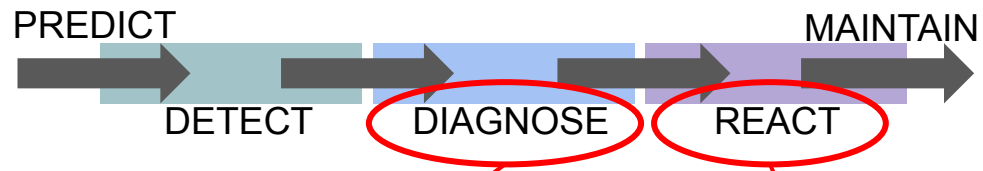
**(DETECT)**

**(DIAGNOSE)**

**(REACT)**

**(MAINTAIN)**

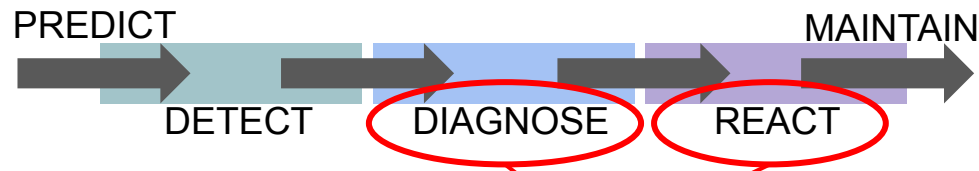




<https://spaceflight.com/spaceflight-inc-signs-multi-launch-agreement-with-hawke-ye-360/>



<https://www.nbcnews.com/mach/science/scientists-say-blind-catlike-robot-could-transform-search-rescue-ncna892116>



## 1. REACT



<https://www.nbcnews.com/mach/science/scientists-say-blind-catlike-robot-could-transform-search-rescue-ncna892116>

## 2. DIAGNOSE



<https://spaceflight.com/spaceflight-inc-signs-multi-launch-agreement-with-hawkeye-360/>

# REACT: Action Discovery in Robotics

Gizzi, E., Castro, M.G., Lin, W., and Sinapov, J. (2021). A Framework for Creative Problem Solving through Action Discovery. In *2021 Robotics: Science and Systems (RSS 2021) Workshop on Declarative and Neuro-Symbolic Representations in Robot Learning and Control (DNR-ROB)*.

# Robotics Example



[ANYmalBot]

# Partial Domain Definition Language (PDDL)

```
    begun (evanas_talk)  
in_process (evanas_talk)  
    complete (evanas_talk)
```

# Partial Domain Definition Language (PDDL)

```
    begun (evanas_talk)  
in_process (evanas_talk)  
complete (evanas_talk)
```

# Partial Domain Definition Language (PDDL)

## **ACTIONS:**

```
call_elevator(:gripper, :elevator,  
:button)  
  preconditions: is_visible(:button)  
  effects: called(:elevator)  
           open(:elevator)
```

# Partial Domain Definition Language (PDDL)

**ACTIONS:**

```
call_elevator(:gripper, :elevator, :button)
  preconditions: is_visible(:button)
  effects: called(:elevator)
           open(:elevator)
```

**arguments**





# Partial Domain Definition Language (PDDL)

## ACTIONS:

```
call_elevator(:gripper, :elevator,  
:button)  
  preconditions: is_visible(:button)  
  effects: called(:elevator)  
         open(:elevator)
```

 **preconditions**

# Partial Domain Definition Language (PDDL)

## ACTIONS:

```
call_elevator(:gripper, :elevator,  
:button)  
  preconditions: is_visible(:button)  
  effects: called(:elevator)  
             open(:elevator)
```

**effects**



# Partial Domain Definition Language (PDDL)

## **ACTIONS:**

```
call_elevator(:gripper, :elevator,  
:button)  
  preconditions: is_visible(:button)  
  effects: called(:elevator)  
           open(:elevator)
```

**ORIGINAL SCENARIO**

# Partial Domain Definition Language (PDDL)

## ACTIONS:

```
call_elevator(:gripper, :elevator,  
:button)  
  preconditions: is_visible(:button)  
  effects: called(:elevator)  
           open(:elevator)
```

```
effects: not(called(:elevator))  
         not(open(:elevator))
```

**ORIGINAL SCENARIO**

**NOVEL SCENARIO**



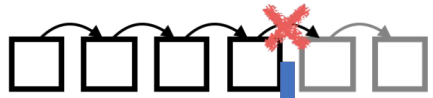
**Original Scenario:** Agent is able to plan for accomplishing a goal state



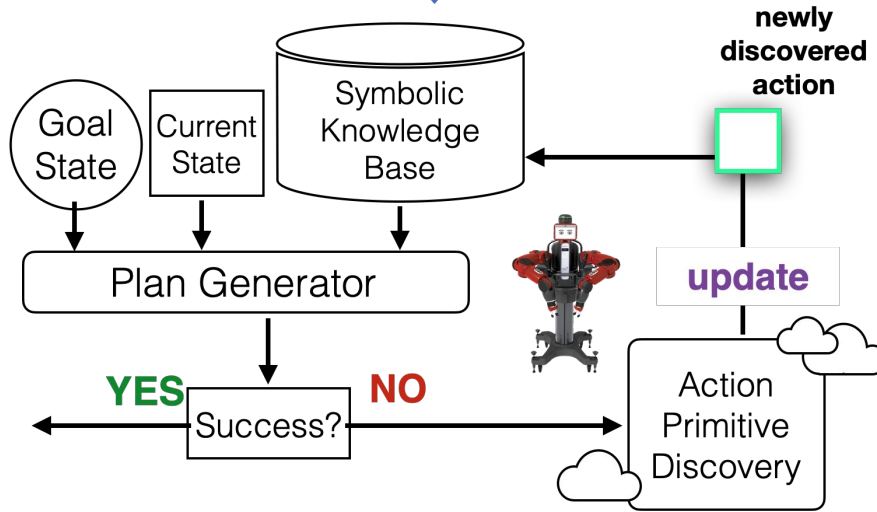
**Novel Scenario:** Something about the environment has changed such that the agents plan is not able to be executed successfully



**Original Scenario:** Agent is able to plan for accomplishing a goal state

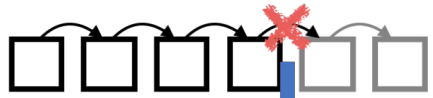


**Novel Scenario:** Something about the environment has changed such that the agents plan is not able to be executed successfully

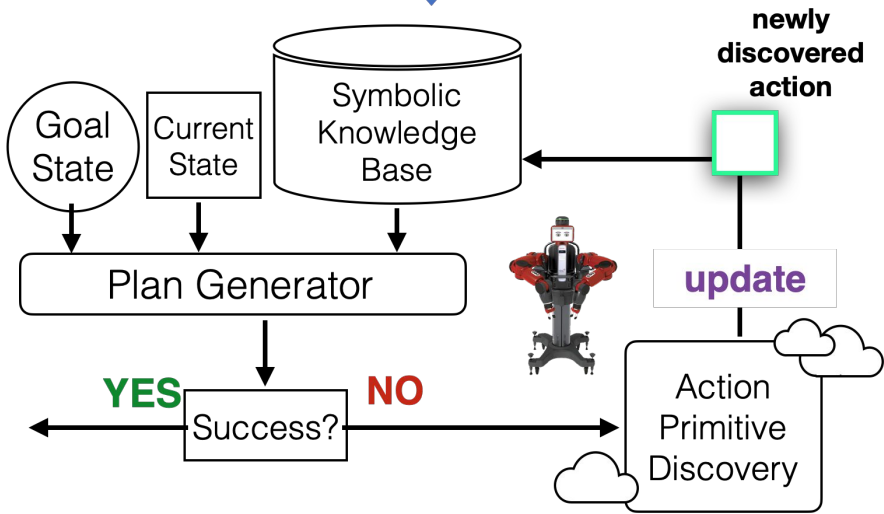




**Original Scenario:** Agent is able to plan for accomplishing a goal state

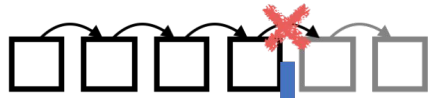


**Novel Scenario:** Something about the environment has changed such that the agents plan is not able to be executed successfully

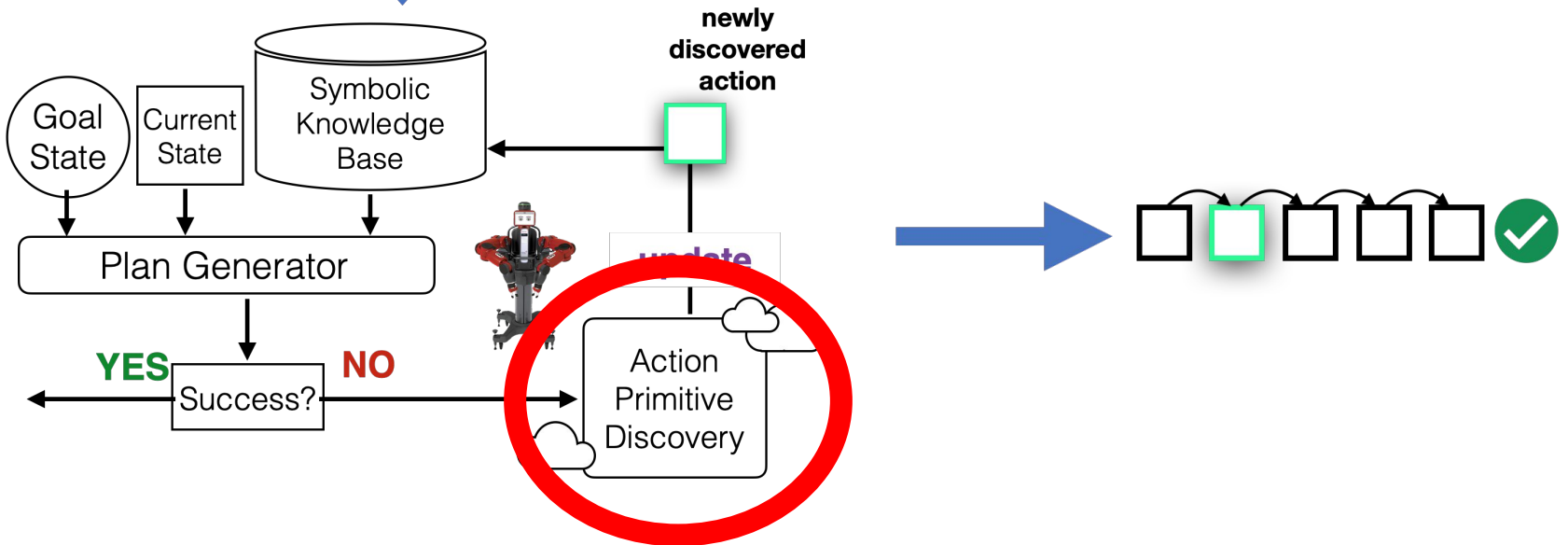




**Original Scenario:** Agent is able to plan for accomplishing a goal state



**Novel Scenario:** Something about the environment has changed such that the agents plan is not able to be executed successfully



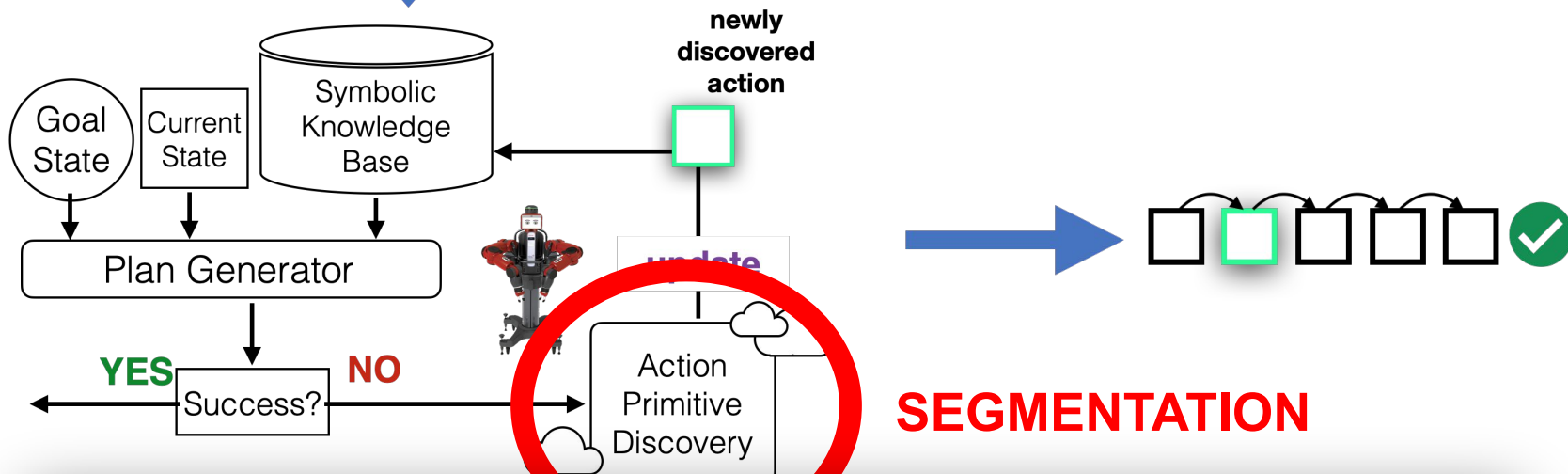




**Original Scenario:** Agent is able to plan for accomplishing a goal state

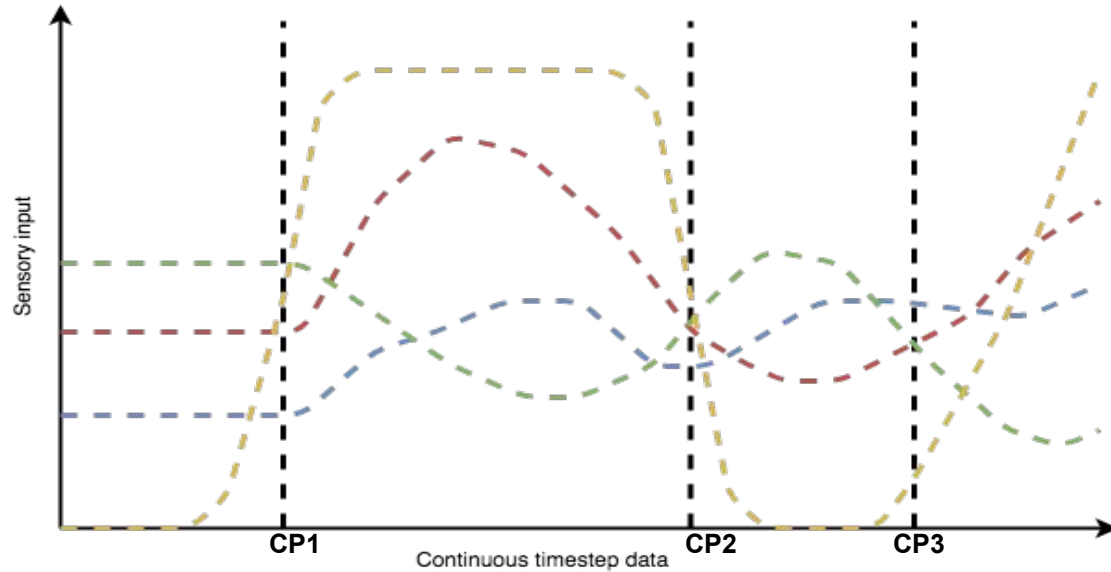


**Novel Scenario:** Something about the environment has changed such that the agents plan is not able to be executed successfully



Gizzi, E., Castro, M.G., and Sinapov, J. (2019). Creative Problem Solving by Robots using Action Primitive Discovery. In *2019 Joint IEEE 9th International Conference on Development and Learning and Epigenetic Robotics (ICDL-EpiRob)* (pp. 228-233). IEEE.

# Bayesian Change Point Detection

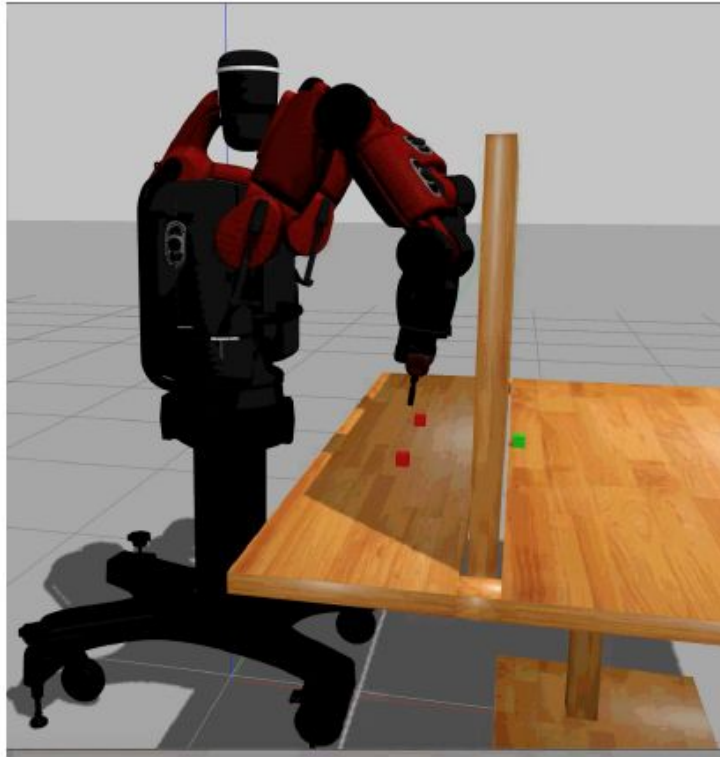


- = number of pixels of object\_1 visible to agent
- = object\_1's distance from left gripper
- = object\_1's distance from right gripper
- = object\_1's distance from robot center point

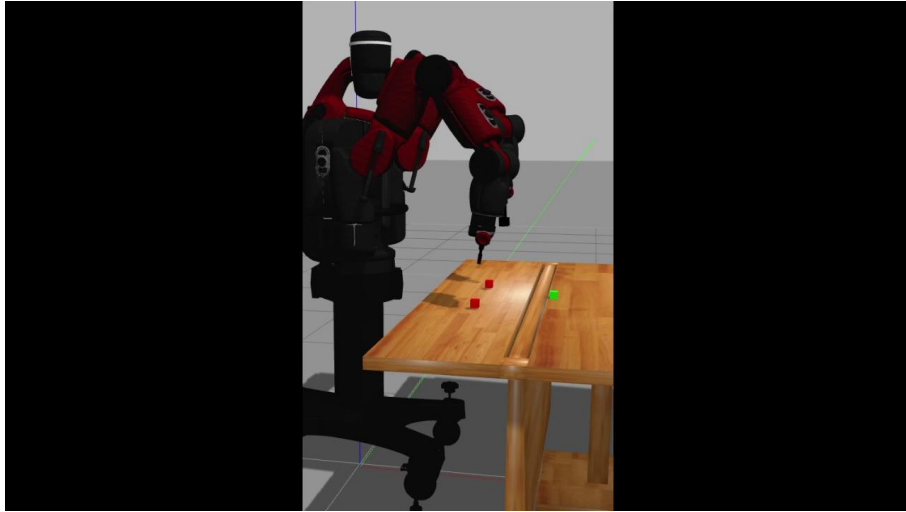


[ANYmalBot] edited

# Illustrative Example



# Illustrative Example



**ORIGINAL SCENARIO**



**NOVEL SCENARIO**

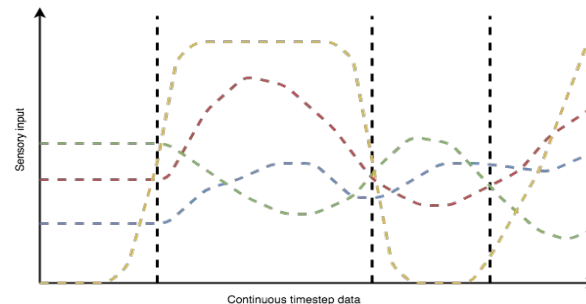
# Action-Object Combination List

(candidate actions to vary)

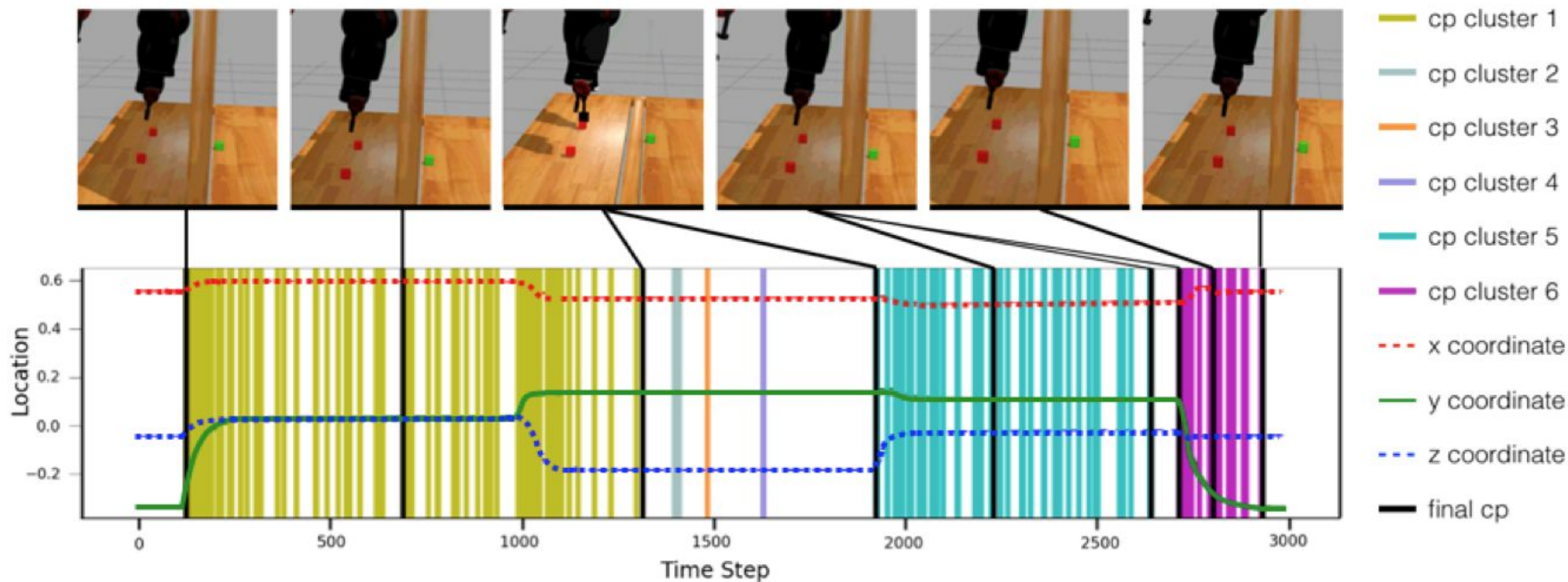
```
press_button(r_gripper, l_button)
press_button(r_gripper, r_button)
obtain_object(r_gripper, wall)
obtain_object(r_gripper, table)
obtain_object(r_gripper, block)
press_button(l_gripper, l_button)
press_button(l_gripper, r_button)
obtain_object(l_gripper, wall)
obtain_object(l_gripper, table)
obtain_object(l_gripper, block)
```

# Action-Object Combination List (candidate actions to vary)

```
press_button(r_gripper, l_button)
press_button(r_gripper, r_button)
obtain_object(r_gripper, wall)
obtain_object(r_gripper, table)
obtain_object(r_gripper, block)
● press_button(l_gripper, l_button)
press_button(l_gripper, r_button)
obtain_object(l_gripper, wall)
obtain_object(l_gripper, table)
obtain_object(l_gripper, block)
```

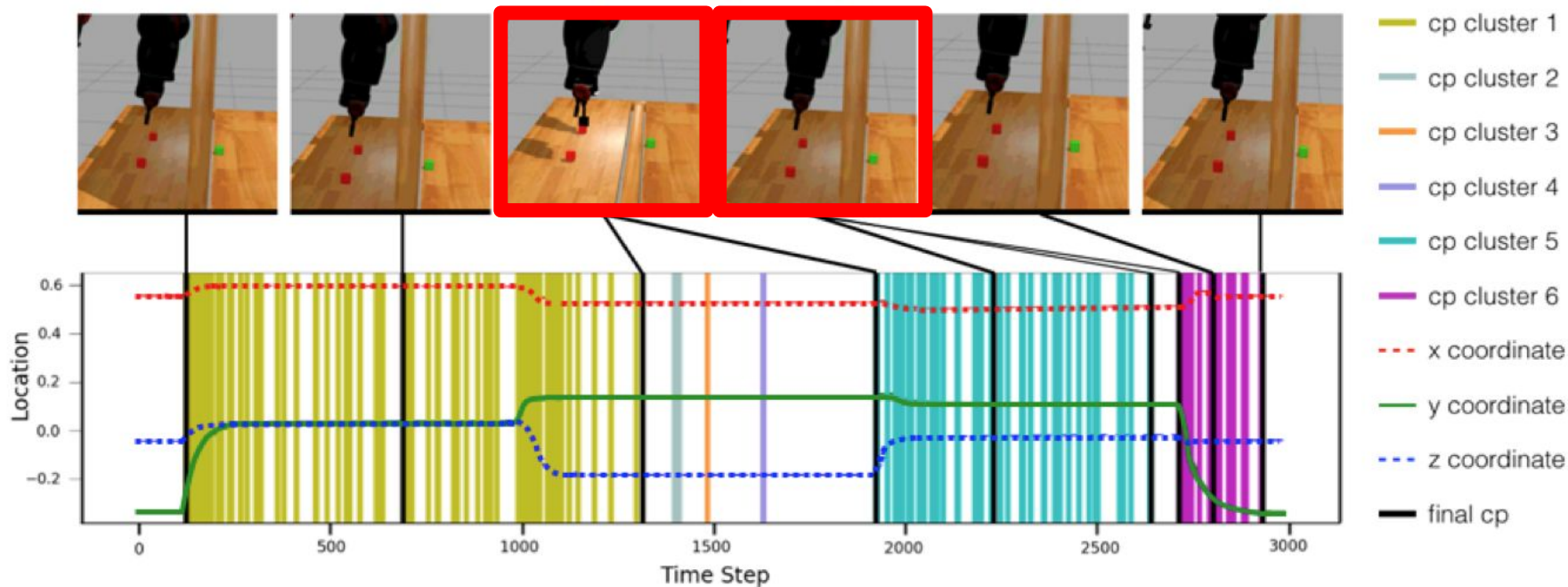


# Results





# Results



$a_f =$

```
obtain_object(:gripper, :loc0, :object, :loc1)
  preconditions: at(:gripper, :loc0)
                 at(:object, :loc1)
  effects: at(:object, :loc0)
           obtained(:object)
```

$a_s =$

```
action_attempt_1_trial4_seg12(:gripper, :button, :object)
  preconditions:
  effects: is_visible(:object)
           pressed(:button)
```

$a_f =$

```
obtain_object(:gripper, :loc0, :object, :loc1)
  preconditions: at(:gripper, :loc0)
                 at(:object, :loc1)
  effects: at(:object, :loc0)
           obtained(:object)
```

$a_s =$

```
action_attempt_1_trial4_seg12(:gripper, :button, :object)
  preconditions:
  effects: is_visible(:object)
           pressed(:button)
```

$a_f =$

```
obtain_object(:gripper, :loc0, :object, :loc1)
  preconditions: at(:gripper, :loc0)
                 at(:object, :loc1)
                 is_visible(:object)
                 pressed(:button)
  effects: at(:object, :loc0)
           obtained(:object)
```

$a_s =$

```
action_attempt_1_trial4_seg12(:gripper, :button, :object)
  preconditions:
  effects: is_visible(:object)
           pressed(:button)
```

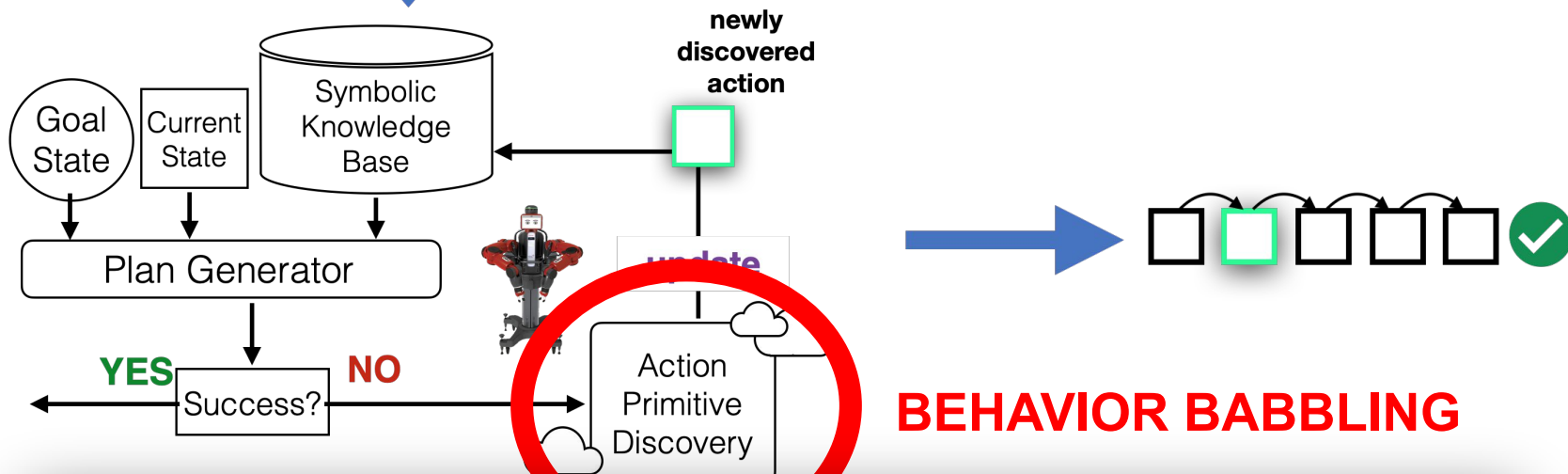




**Original Scenario:** Agent is able to plan for accomplishing a goal state

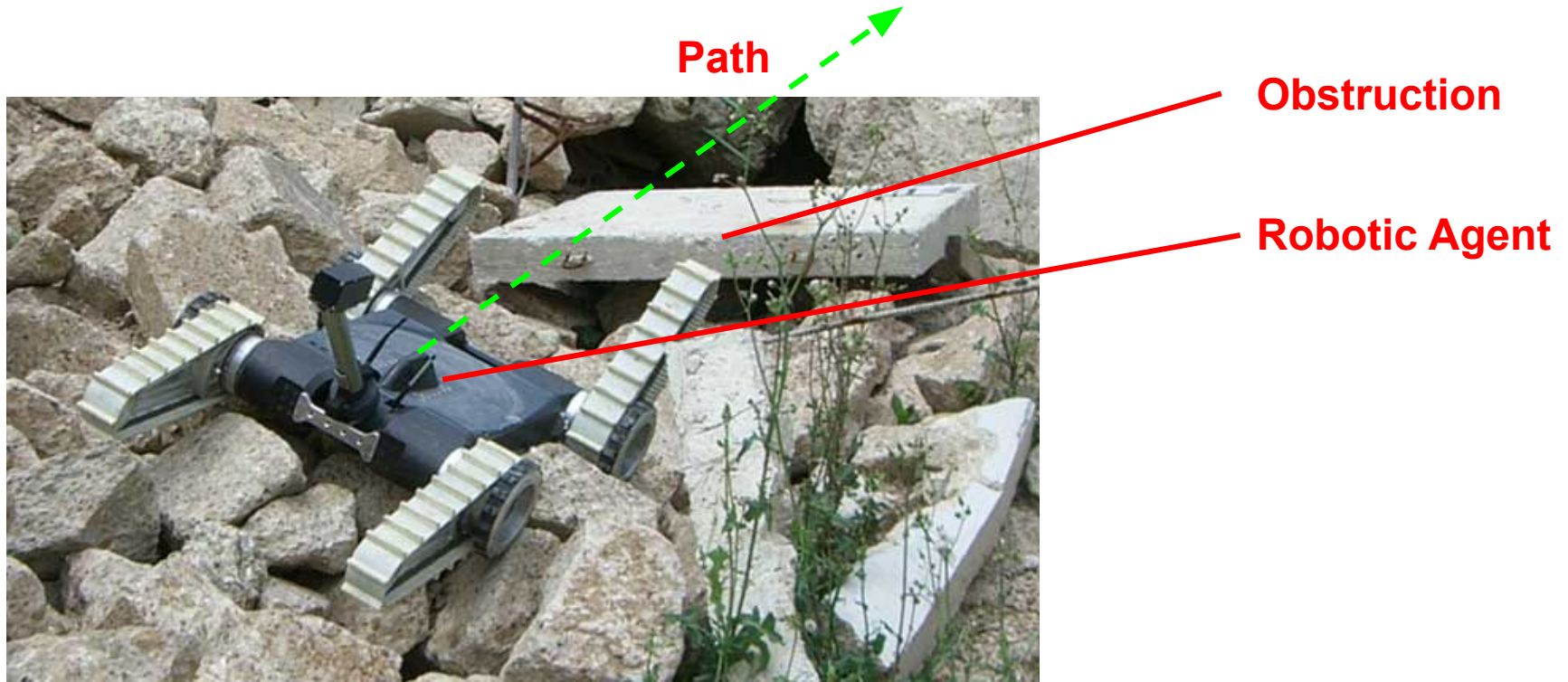


**Novel Scenario:** Something about the environment has changed such that the agents plan is not able to be executed successfully



Gizzi, E., Hassan, A., Lin, W., Rhea, K., and Sinapov, J. (2021). Toward Creative Problem Solving Agents: Action Discovery through Behavior Babbling. In *2021 IEEE International Conference on Development and Learning (ICDL)* (pp. 1-7). IEEE.





<https://gcn.com/articles/2021/07/01/robots-surfside-rescue.aspx>





## **ORIGINAL SCENARIO**

mass : 5.0 kg

push (arm, object)

<https://gcn.com/articles/2021/07/01/robots-surfside-rescue.aspx>



### **ORIGINAL SCENARIO**

mass : 5.0 kg

`push (arm, object)`

### **NOVEL SCENARIO**

mass : 20.0 kg

`push (arm, object)`

<https://gcn.com/articles/2021/07/01/robots-surfside-rescue.aspx>



<https://gcn.com/articles/2021/07/01/robots-surfside-rescue.aspx>

### **ORIGINAL SCENARIO**

mass : 5.0 kg

`push(arm, object)`

- **rate:** 2.0 m/s
- **MM:** 1.0 meter
- **orientation:** 180°

### **NOVEL SCENARIO**

mass : 20.0 kg

`push(arm, object)`





<https://gcn.com/articles/2021/07/01/robots-surfside-rescue.aspx>

### ORIGINAL SCENARIO

mass : 5.0 kg

push (arm, object)

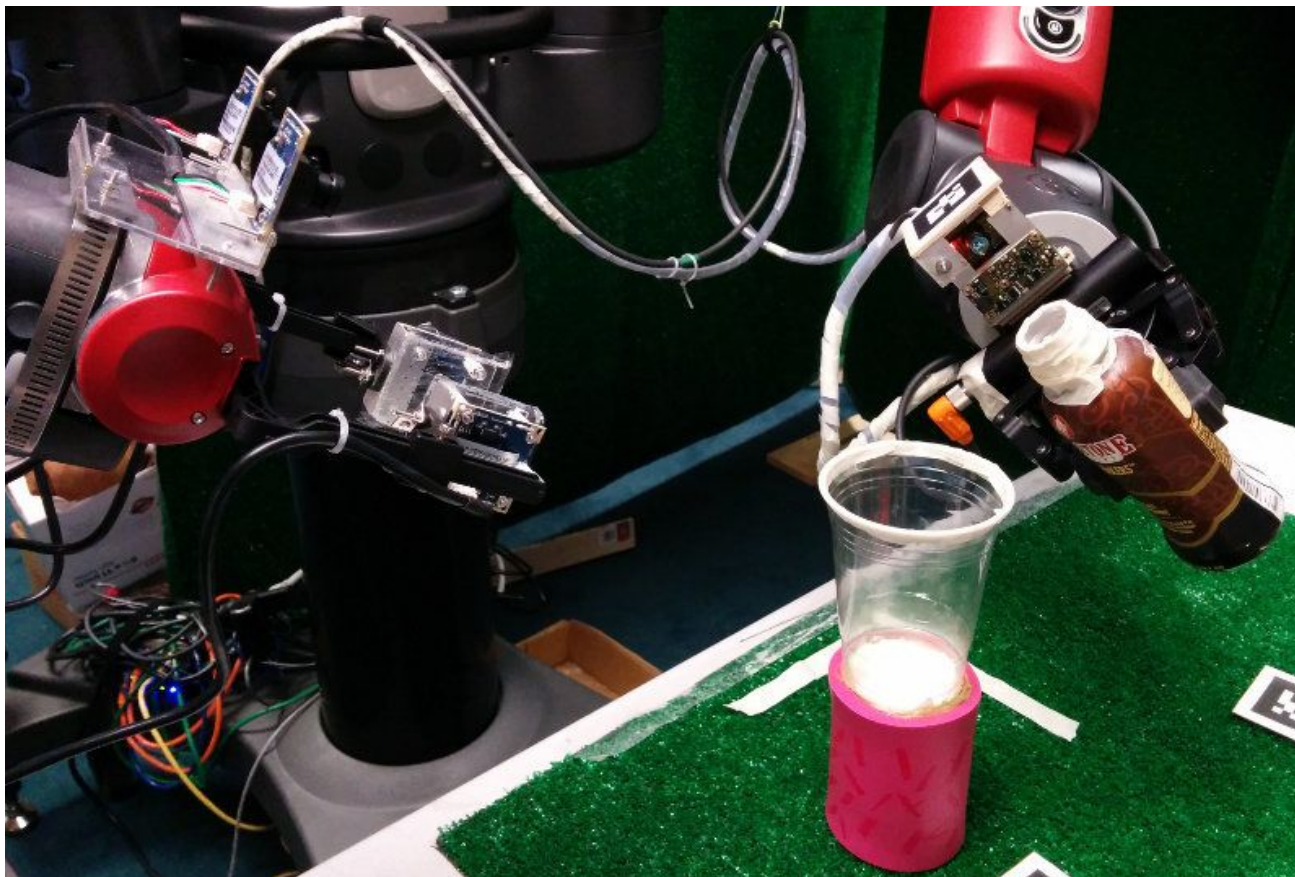
- rate: 2.0 m/s
- MM: 1.0 meter
- orientation: 180°

### NOVEL SCENARIO

mass : 20.0 kg

push -> strike

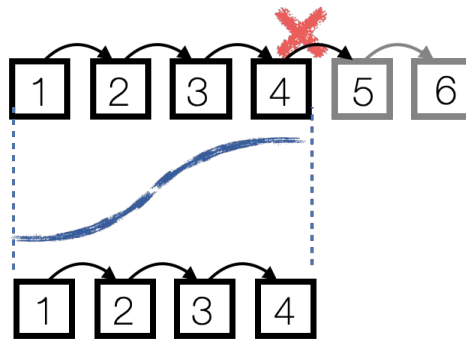
- rate: 10.0 m/s
- MM: 1.0 meter
- orientation: 180°



[https://www.researchgate.net/publication/308994545\\_Stereo\\_Vision\\_of\\_Liquid\\_and\\_Particle\\_Flow\\_for\\_Robot\\_Pouring/figures?lo=1&utm\\_source=google&utm\\_medium=organic](https://www.researchgate.net/publication/308994545_Stereo_Vision_of_Liquid_and_Particle_Flow_for_Robot_Pouring/figures?lo=1&utm_source=google&utm_medium=organic)

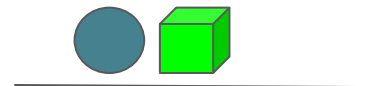
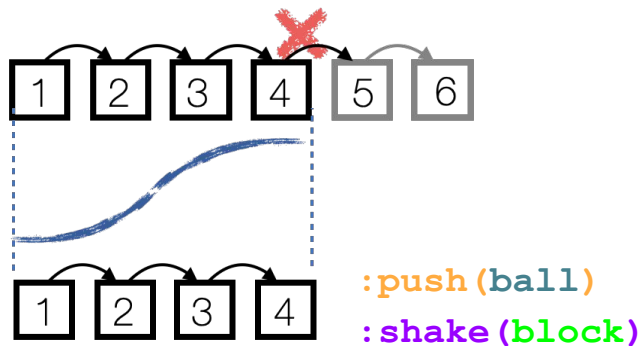
## Passive Incubation:

Generate variation candidates



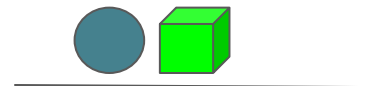
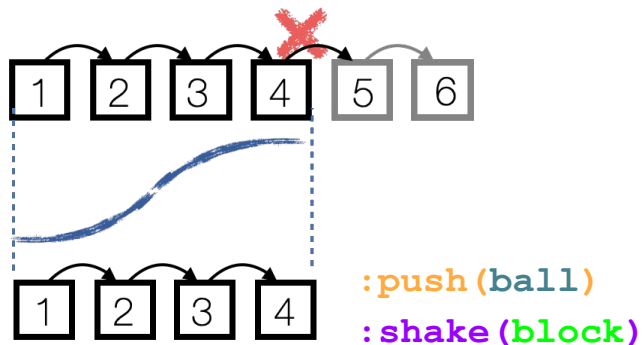
## Passive Incubation:

Generate variation candidates

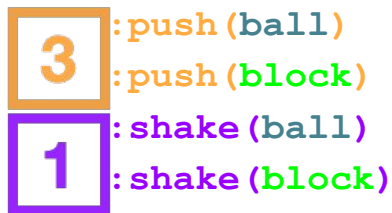


## Passive Incubation:

Generate variation candidates



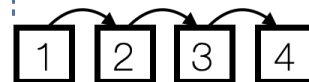
## Focused Mode



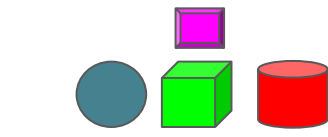


## Passive Incubation:

Generate variation candidates



:push(ball)  
:shake(block)



### Focused Mode

**3** :push(ball)  
:push(block)  
**1** :shake(ball)  
:shake(block)

...

### De-Focused Mode

**3** :push(ball)  
:push(block)  
:push(cup)  
:push(button)  
**1** :shake(ball)  
:shake(block)  
:shake(cup)  
:shake(button)

...

:drop(ball)  
:drop(block)  
:drop(cup)  
:drop(button)

## Passive Incubation:

Generate variation candidates

## Focused Mode

3	:push(ball)
	:push(block)
1	:shake(ball)
	:shake(block)

## Passive Incubation:

Generate variation candidates

### Focused Mode

**3** :push(ball)  
:push(block)

**1** :shake(ball)  
:shake(block)

:push(ball), rate  
:push(ball), movementMagnitude  
:push(ball), orientation

## Passive Incubation:

Generate variation candidates

### Focused Mode

**3** :push(ball)  
:push(block)

**1** :shake(ball)  
:shake(block)

:push(ball), rate  
:push(ball), movementMagnitude  
:push(ball), orientation  
:push(block), rate  
:push(block), movementMagnitude  
:push(block), orientation

## Passive Incubation:

Generate variation candidates

### Focused Mode

3

:push(ball)  
:push(block)

1

:shake(ball)  
:shake(block)

:push(ball), rate

:push(ball), movementMagnitude

:push(ball), orientation

:push(block), rate

:push(block), movementMagnitude

:push(block), orientation

:shake(ball), rate

:shake(ball), movementMagnitude

:shake(ball), orientation

## Passive Incubation:

Generate variation candidates

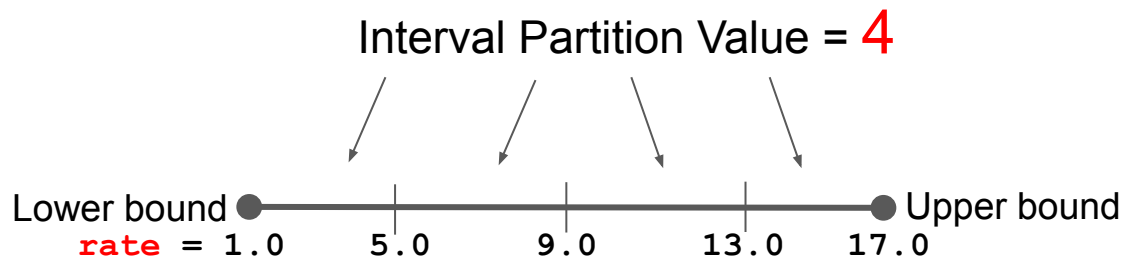
### Focused Mode

**3** :push(ball)  
:push(block)  
**1** :shake(ball)  
:shake(block)

:push(ball), rate  
:push(ball), movementMagnitude  
:push(ball), orientation  
:push(block), rate  
:push(block), movementMagnitude  
:push(block), orientation  
:shake(ball), rate  
:shake(ball), movementMagnitude  
:shake(ball), orientation  
:shake(block), rate  
:shake(block), movementMagnitude  
:shake(block), orientation

## Active Incubation:

Evaluate variation candidates



Candidate to execute

:push(ball), rate



:push(ball), rate=1.0

:push(ball), rate=5.0

:push(ball), rate=9.0

:push(ball), rate=13.0

:push(ball), rate=17.0

## **Active Incubation:**

Evaluate variation candidates

**Inheritance Condition:** Actions which accomplish the same results as the original action are added.  
**(Focused Mode)**

**Novelty Condition:** Actions which accomplish results which are novel to the original candidate action are added.  
**(De-Focused Mode)**



# **Experiment 1**

Simple Scenario

# **Experiment 2**

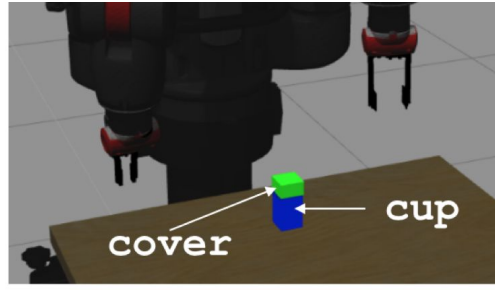
Focused Case

# **Experiment 3**

De-Focused Case

## Experiment 1

Simple Scenario



**GOAL** Uncover the cup

**NOVEL SCENARIO** Cover is too heavy

**NOVEL ACTION** :push -> :strike

(increased rate parameter)

## Experiment 2

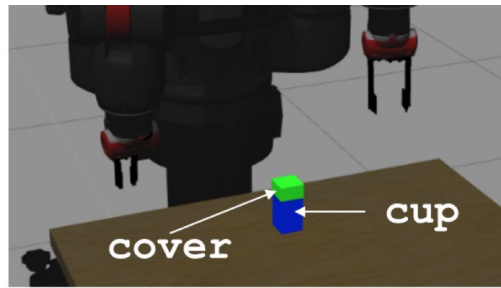
Focused Case

## Experiment 3

De-Focused Case

## Experiment 1

Simple Scenario



**GOAL** Uncover the cup

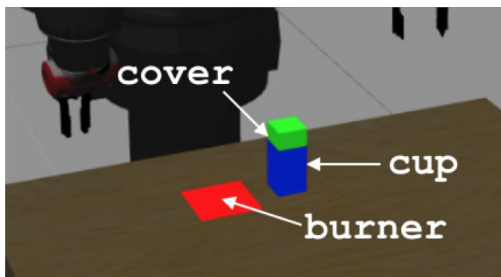
**NOVEL SCENARIO** Cover is too heavy

**NOVEL ACTION** :push -> :strike

(increased rate parameter)

## Experiment 2

Focused Case



**GOAL** Cook food

**NOVEL SCENARIO** Cover gets knocked off table (light weight)

**NOVEL ACTION** :push -> :nudge

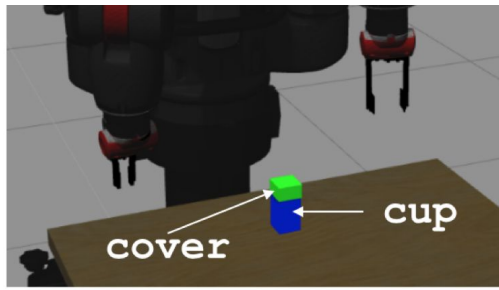
(decreased rate or movementMagnitude parameter)

## Experiment 3

De-Focused Case

## Experiment 1

Simple Scenario



**GOAL** Uncover the cup

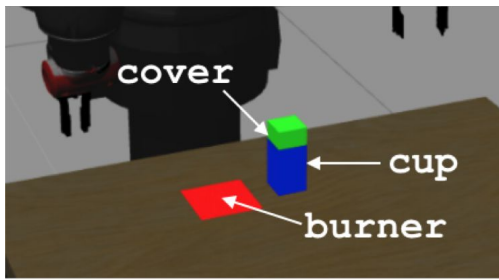
**NOVEL SCENARIO** Cover is too heavy

**NOVEL ACTION** :push -> :strike

(increased rate parameter)

## Experiment 2

Focused Case



**GOAL** Cook food

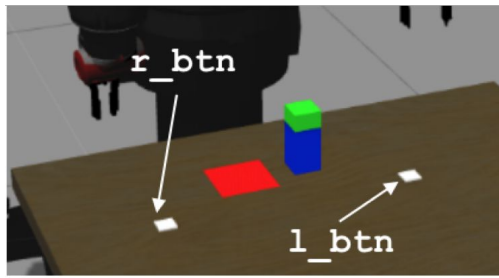
**NOVEL SCENARIO** Cover gets knocked off table (light weight)

**NOVEL ACTION** :push -> :nudge

(decreased rate or movementMagnitude parameter)

## Experiment 3

De-Focused Case



**GOAL** Cook food

**NOVEL SCENARIO** Burner must first be turned on

**NOVEL ACTION** :push -> :press

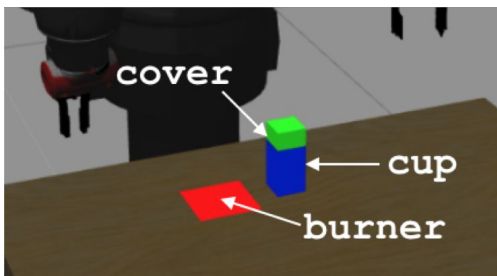
(variation of orientation parameter)

**NOVEL ACTION** :shake -> :press

(variation of orientation parameter)

## Experiment 2

Focused Case



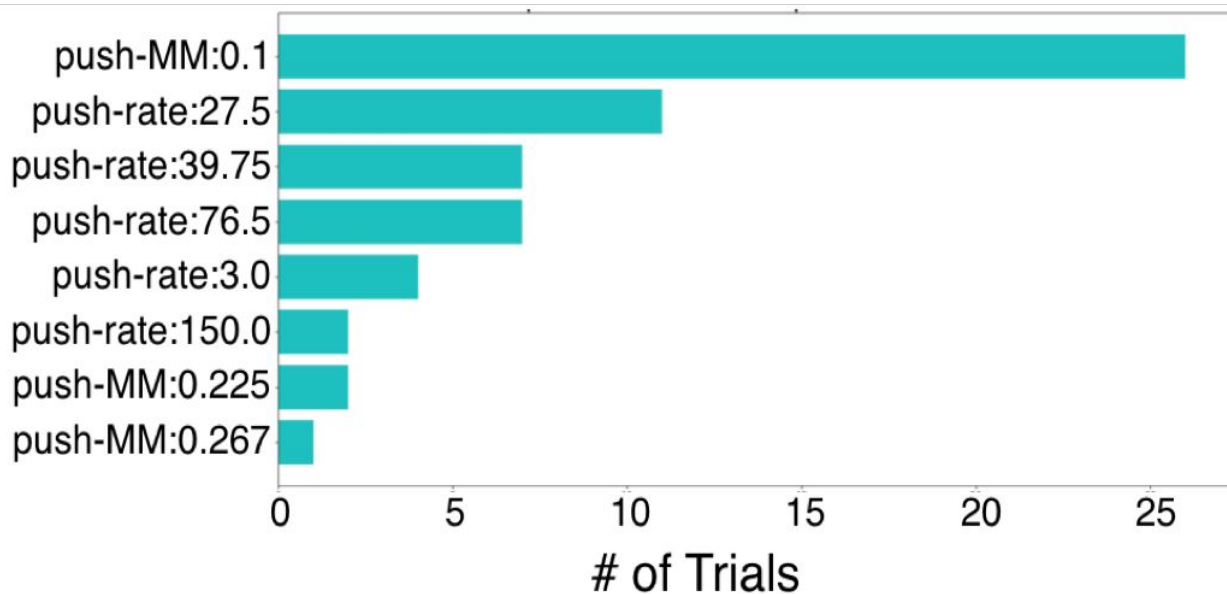
**GOAL** Cook food

**NOVEL SCENARIO** Cover gets knocked off table (light weight)

**NOVEL ACTION** :push -> :nudge

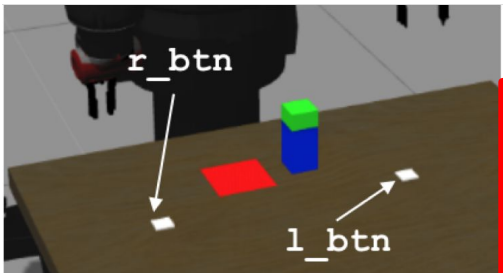
(decreased rate or movementMagnitude parameter)

**Experiment 2:  
# of Trials per  
Success Action**



## Experiment 3

Defocused Case



**GOAL** Cook food

**NOVEL SCENARIO** Burner must first be turned on

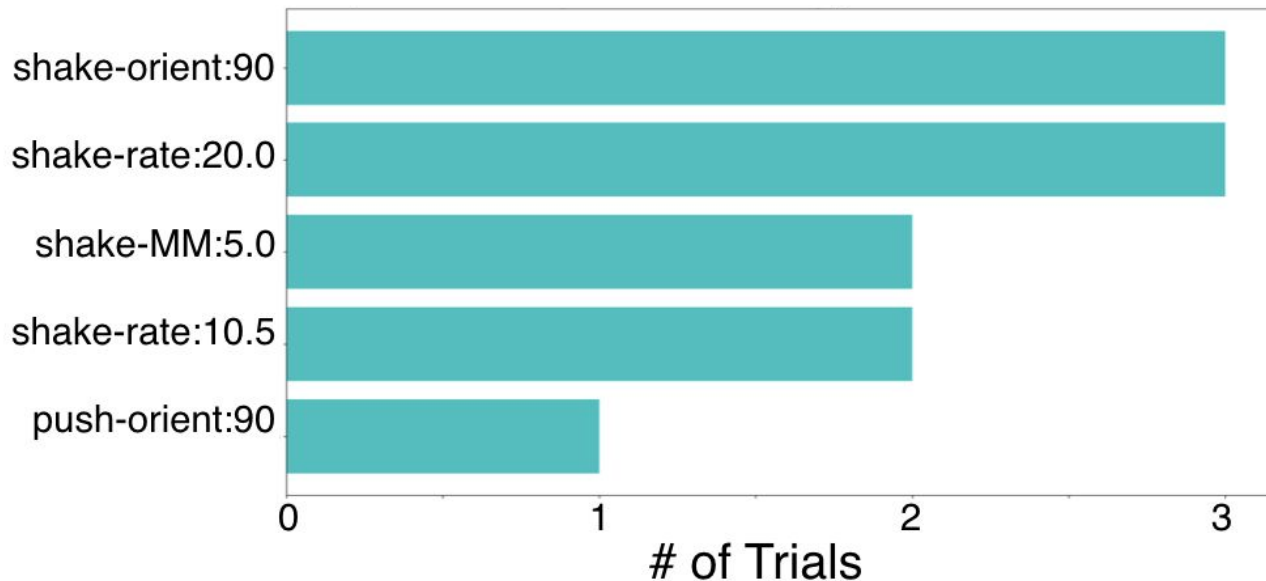
**NOVEL ACTION** :push -> :press

(variation of orientation parameter)

**NOVEL ACTION** :shake -> :press

(variation of orientation parameter)

**Experiment 3:  
# of Trials per  
Success Action**



# Summary on **REACT**

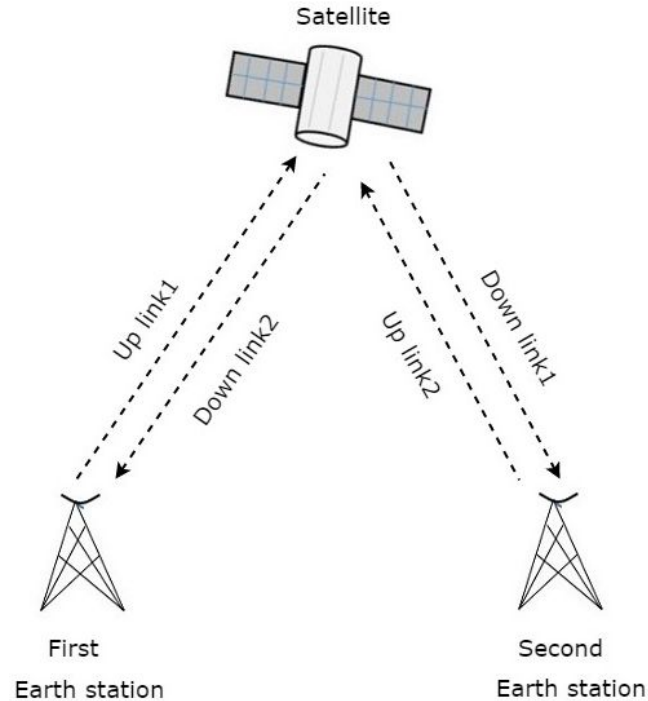
- Action discovery is a viable path toward novelty resolution
  - Not always necessary
- Important to examine the relationship between levels of knowledge abstraction
  - Hybrid approaches
- Limitations
  - These methods rely on many interaction trials/counterfactual reasoning (not always possible without a simulator)
  - Not capable of learning entirely new controllers from scratch
- Future Work
  - Life long creative problem solving (LLCPS)

# **DIAGNOSE:** Fault Diagnosis in Spacecraft

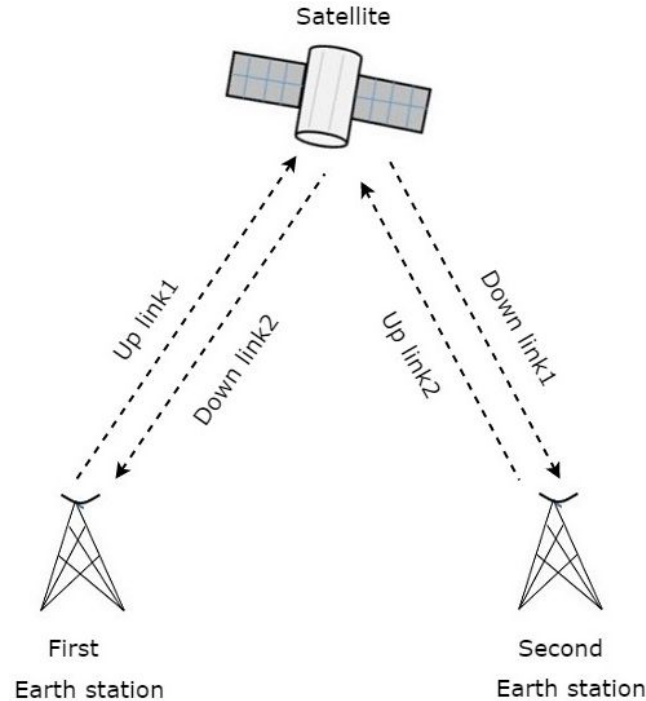




# Background and Motivation



# Background and Motivation



Issues:

- Time delay
- Bandwidth
- Proximity

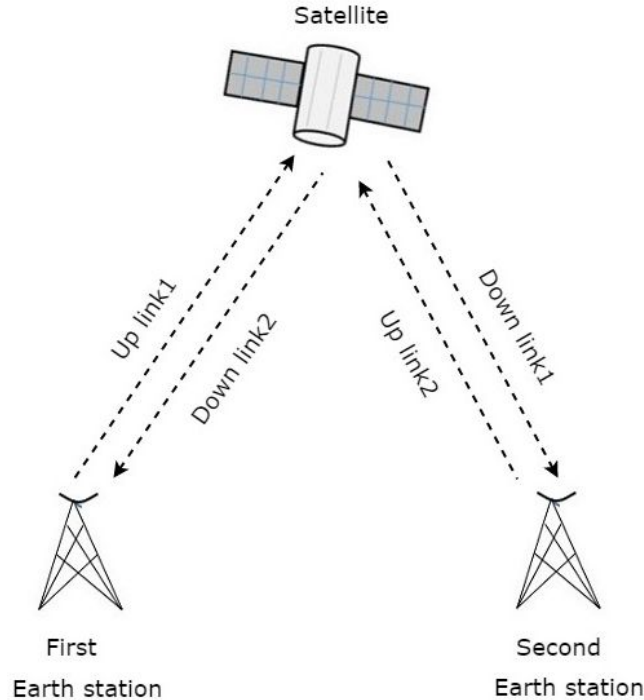
**Data Loss**

# Background and Motivation

Status



Safe mode



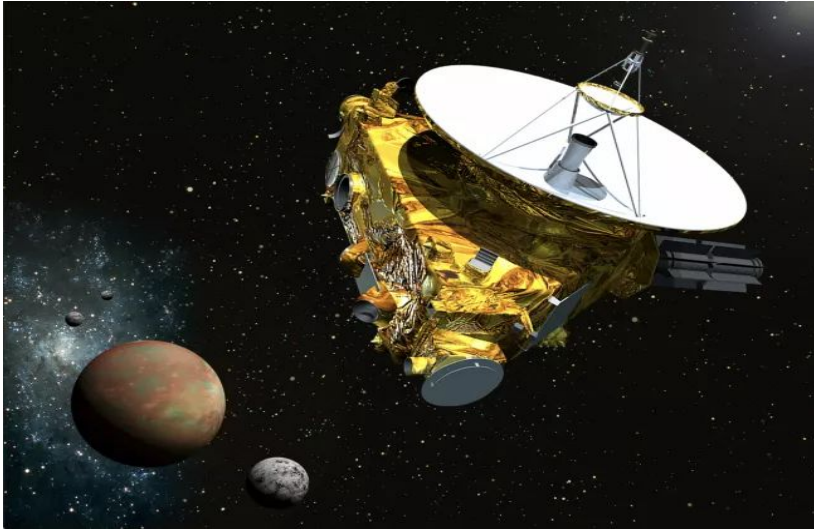
Issues:

- Time delay
- Bandwidth
- Proximity

**Data Loss**

# Safe Mode Examples

“The investigation into the anomaly that caused New Horizons to enter “safe mode” on July 4 has concluded that no hardware or software fault occurred on the spacecraft.”



“NASA’s New Horizons Plans July 7 Return to Normal Science Operations.” NASA Blogs. July 5, 2015.

Cofield, Calla, “NASA’s New Horizons Spacecraft Wakes Up for Pluto Encounter in 2015.” Space.com. December 7, 2014.



Grecius, Tony, “Mars 2020 Perseverance Healthy and on Its Way.” NASA Blogs. July 30, 2020.

“We set the limits for the temperature differential conservatively tight for triggering a safe mode. The philosophy is that it is far better to trigger a safe mode event when not required, than miss one that is.”

## Goal of Project RAISR:

Intelligently diagnose cause of fault, given the symptom.

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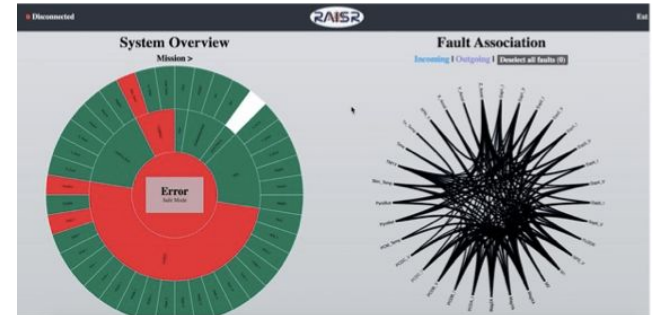
Evana Gizzi [GSFC-587]  
Dr. James Marshall [GSFC-587]  
Nicholas Pellegrino [GSFC-587-OSSI]  
Jeff St. Jean [GSFC-587-OSSI]  
Christopher Chapman [GSFC-587-OSSI]  
Hayley Owens [GSFC-587-OSSI]  
Gabriel Rasskin [GSFC-587-OSSI]  
Christopher Trombley [GSFC-587]  
Carrie Kuzio [WFF-589]  
Ahmed Ghalib [WFF-811]

# Artificial Intelligence (AI) Constructs Examined

- Classification and Predictive
  - Long Short-term Memory (LSTM) Neural Networks
  - Autoencoders, Variational Autoencoders, Shapley Values
  - Convolutional Neural Networks (CNN)
  - Kalman Filters
  - Telemetry vector Clustering
- Graph-based
  - Association Rule Mining
    - Function classification (curve smoothing, function fitting, feature extraction)
  - Causality
  - Walkdown Algorithm
- Reinforcement Learning
  - Partially Observable Markov Decision Processes (POMDP)
  - Proximal Policy Optimization (PPO), forest of POMDPs

## Algorithms and Tools Developed

- Importance Sampling
- 2 Diagnostic Algorithms
- Diagnosis GUI
- python/cFS adapter (Marshall)





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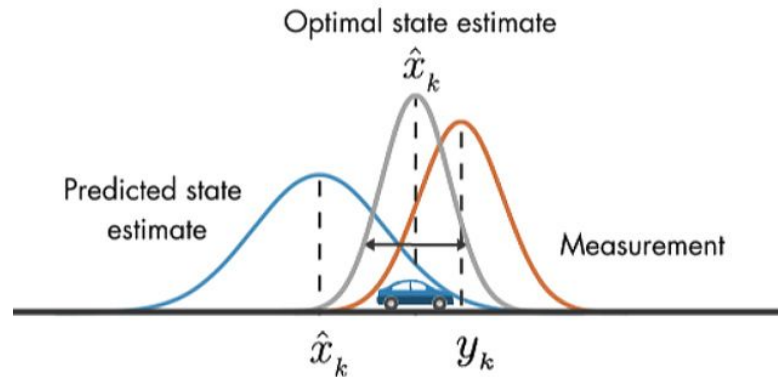
## Algorithms and Tools Developed

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- Diagnosis GUI
- **python/cFS adapter (Marshall)**

# Preliminaries: Kalman Filters

- Dynamic linear estimation models able to provide a prediction from previously measured data
- Account for noise in sensor readings

**How “broken” is a  
mnemonic, relative to itself?**



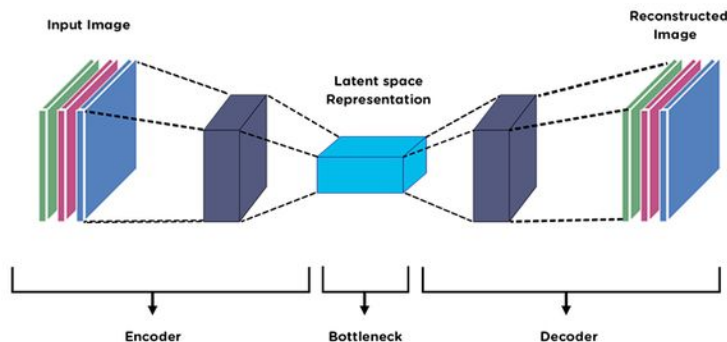
<https://www.mathworks.com/videos/understanding-kalman-filters-part-3-optimal-state-estimator--1490710645421.html>

# Preliminaries: Autoencoders

- Unsupervised neural network representation learners
- Can encode information into a latent space representational form, and decode latent space back into original high dimensional form
- Use Shapley Values and reconstruction error

How “broken” is a  
mnemonic, relative to the  
telemetry landscape?

(contextual)

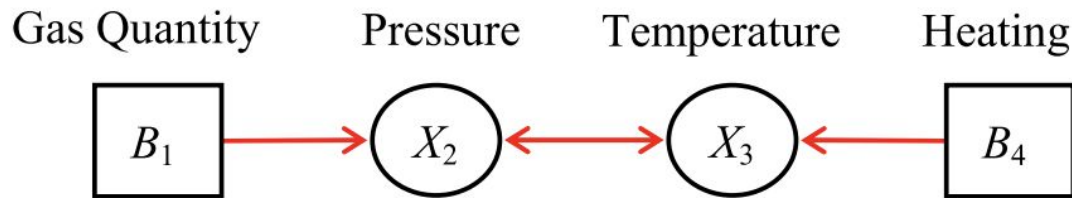


<https://medium.com/@birla.deepak26/autoencoders-76bb49ae6a8f>

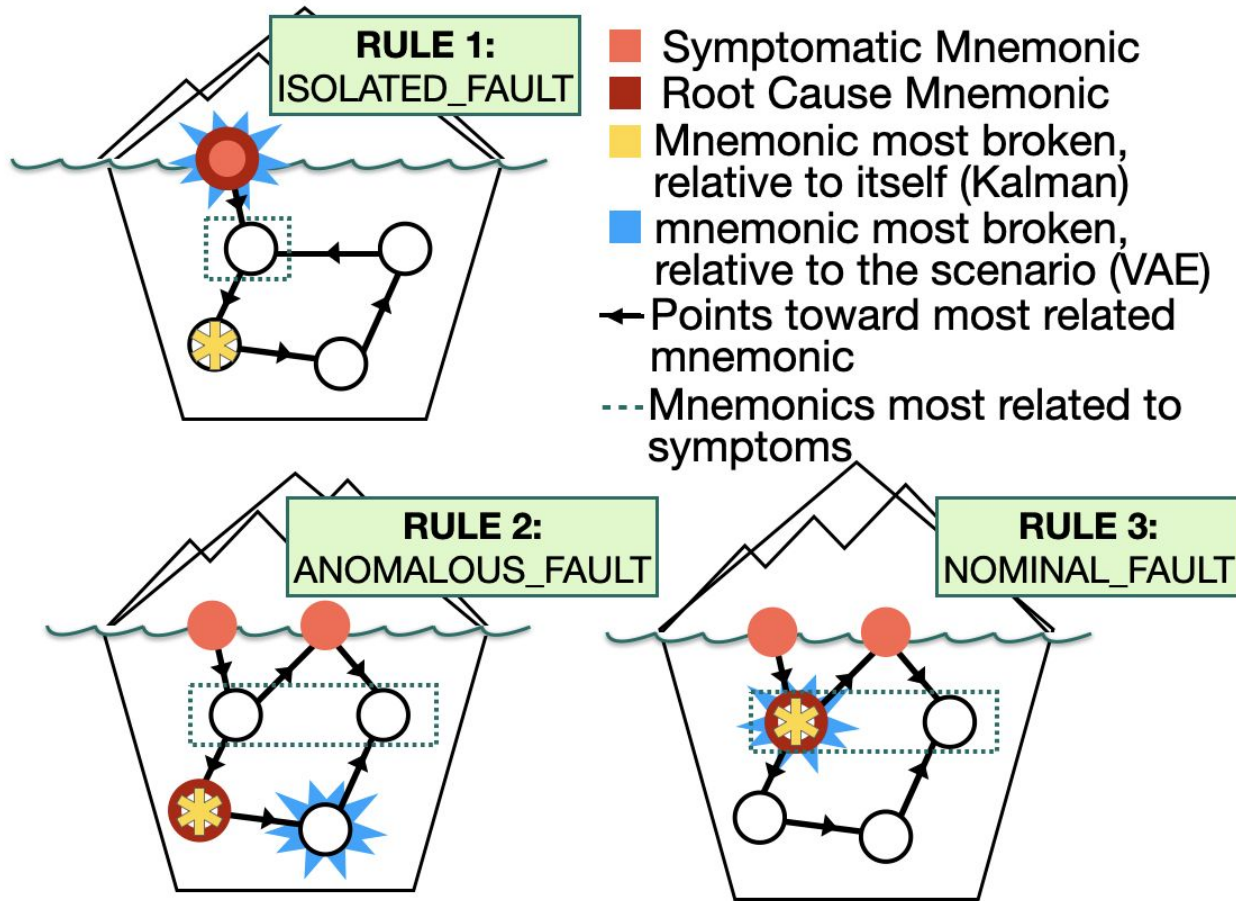
# Preliminaries: Causality

- Measures the level of directional “instantaneous relatedness” among mnemonics
- Utilizes conditional probabilities and derivatives (do-calculus) to capture event changes
- Similar to traditional correlation calculation, with more restrictions to induce causal relationships

**Which mnemonics are related to which other mnemonics, in an “instantaneous” sense?**



Zhang, Q., Dong, C., Cui, Y., & Yang, Z. (2013). Dynamic uncertain causality graph for knowledge representation and probabilistic reasoning: statistics base, matrix, and application. IEEE Transactions on Neural Networks and Learning Systems, 25(4), 645-663.



**Figure 1:** Classes of faults diagnosed by RAISR using spacecraft telemetry

# Outcomes

- Software Platform
  - Performance Tested on 4 datasets of varying complexity levels
  - Baseline Tested against state of art AI approaches (0.7 vs 0.55 in worst case performance of RAISR)
- Hardware-in-the-loop
  - Benchmark Tests on Raspberry Pi ARM architecture (COVID contingency plan)
  - Ablation Study on constituent parts
- Paper in review process

# Distributed Spacecraft Mission (DSM)



<https://spaceflight.com/spaceflight-inc-signs-multi-launch-agreement-with-hawkeye-360/>

# Distributed Spacecraft Mission (DSM)

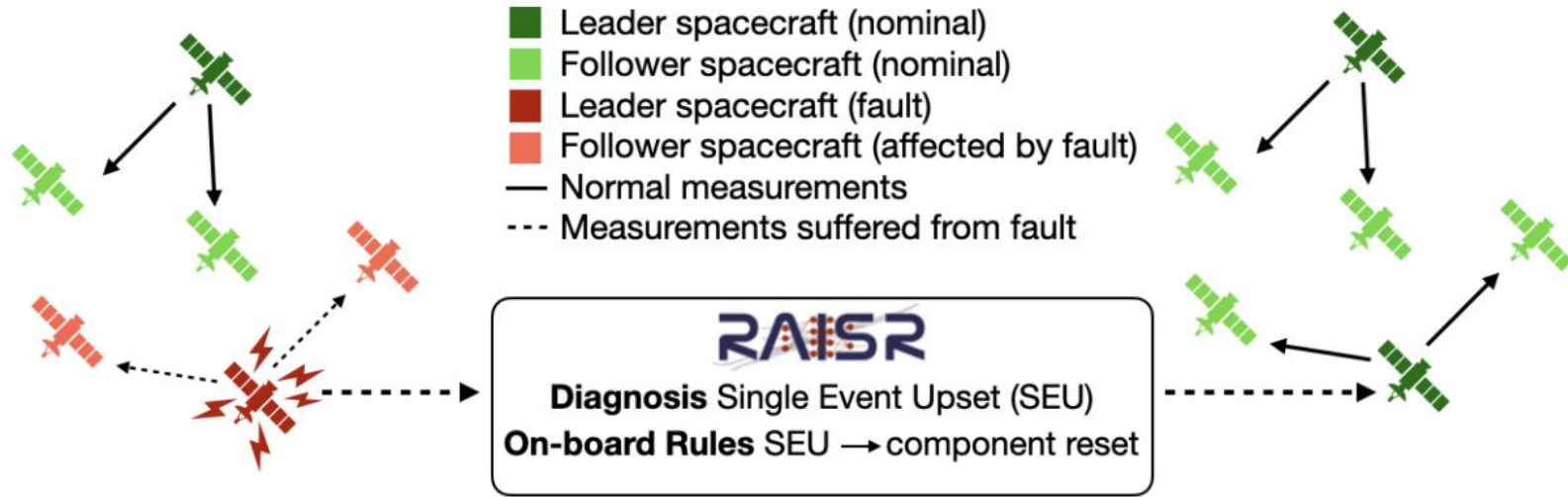


<https://www.space.com/europea-plumes-stealth-particles-mystery.html>

- Intelligent Science Payload
- Onboard Processing
- **Fault Detection and Mitigation**
- autoNGC
- Communication Systems
- DSM Emulation Environment
- System Engineering & MBSE



# RAISR applied to DSM



**Figure 2:** Shows RAISR resolving a fault in a traditional single leader-follower multi-agent system (MAS) navigation structure

# Summary & Future Work



- Fault diagnosis is a necessary step toward
  - Resilient space flight (true autonomy)
  - Enabling next gen space flight, like constellation missions
- Future Work (DSM)
  - Algorithmic Thrust/TRL Boosting thrust
  - Broadening RAISR to “system resilience”

# References - Images

[MacGyverImg1] <https://sharetv.com/shows/macgyver/episodes/284074>

[MacGyverImg2] <https://me.me/i/macgyver-making-the-junk-drawer-fun-again-since-1985-icanhascheezburger-com-a5626df3836149ed923388c614003da3>

[MacGyverImg3] <http://www.fanpop.com/clubs/macgyver/images/41776422/title/1985-macgyver-photo>

[ANYmalBot] <https://youtu.be/gM1z60aeunU>

Thank you!  
**Questions?**