AI-POMDP Modeling for the Cyber-Defense of Joint Ground Station and Satellite Systems

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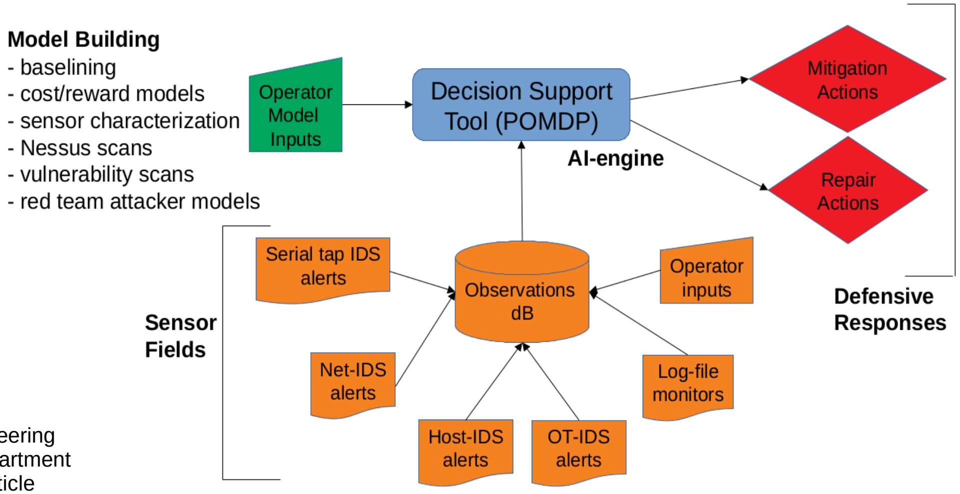
POMDP Inputs, Outputs, Capabilities



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Motivated by Escalating Threats Against ICS

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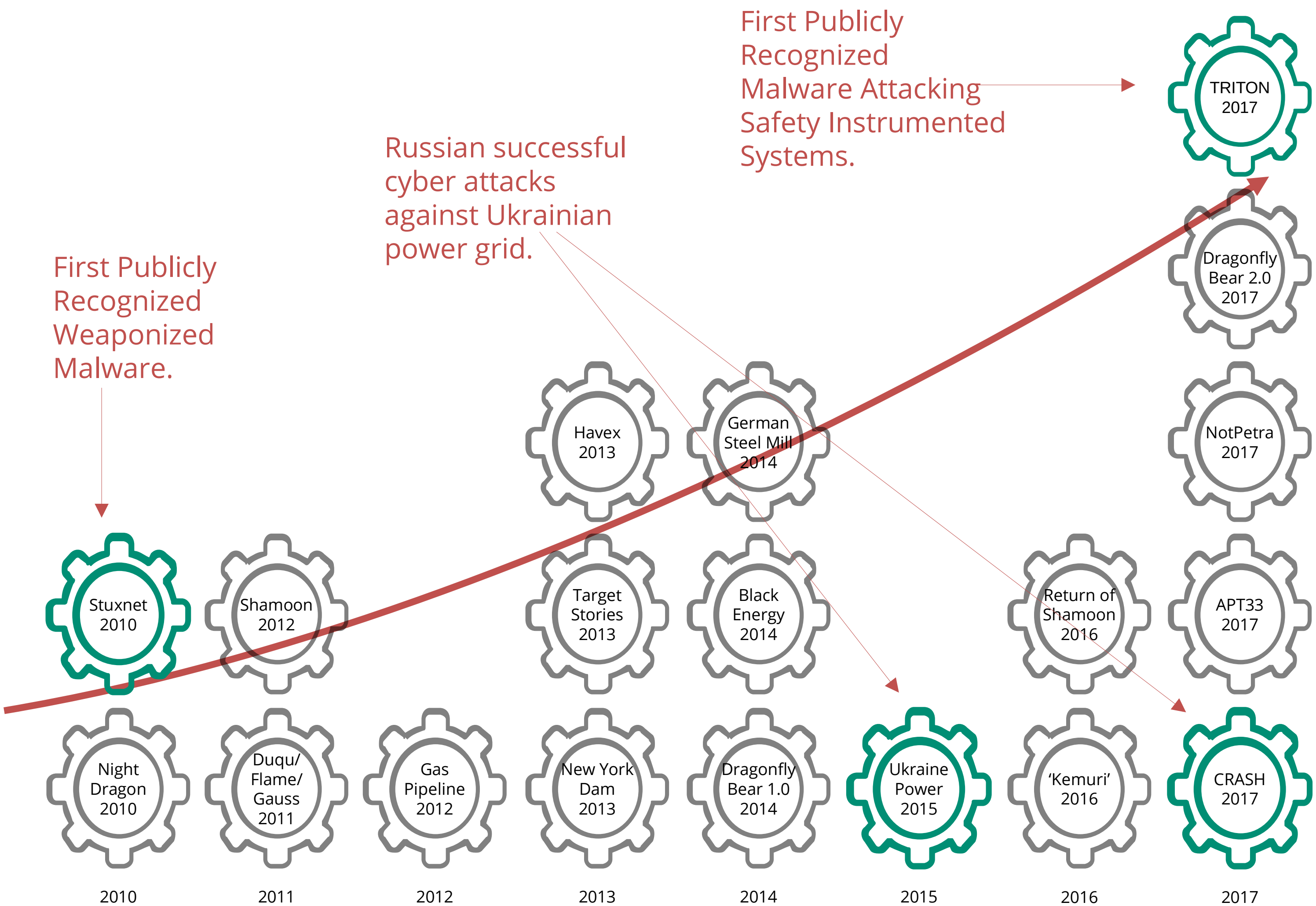

Reference: Hemsley, K.E. and R.E.Fisher, "History of Industrial Control Systems Cyber Incidence", INL Technical Report, DOE/ID-Number-1505628 December (2018).

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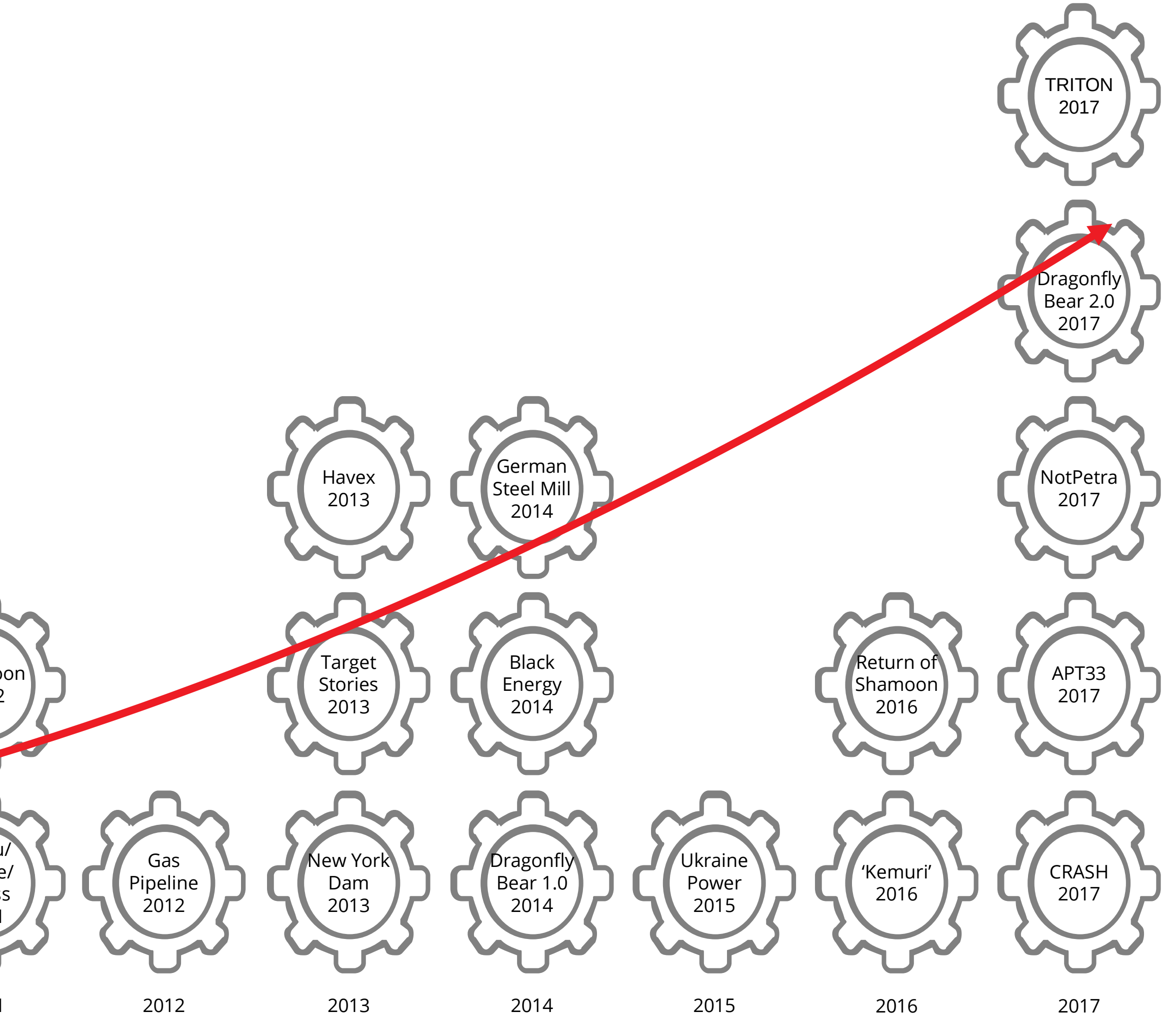

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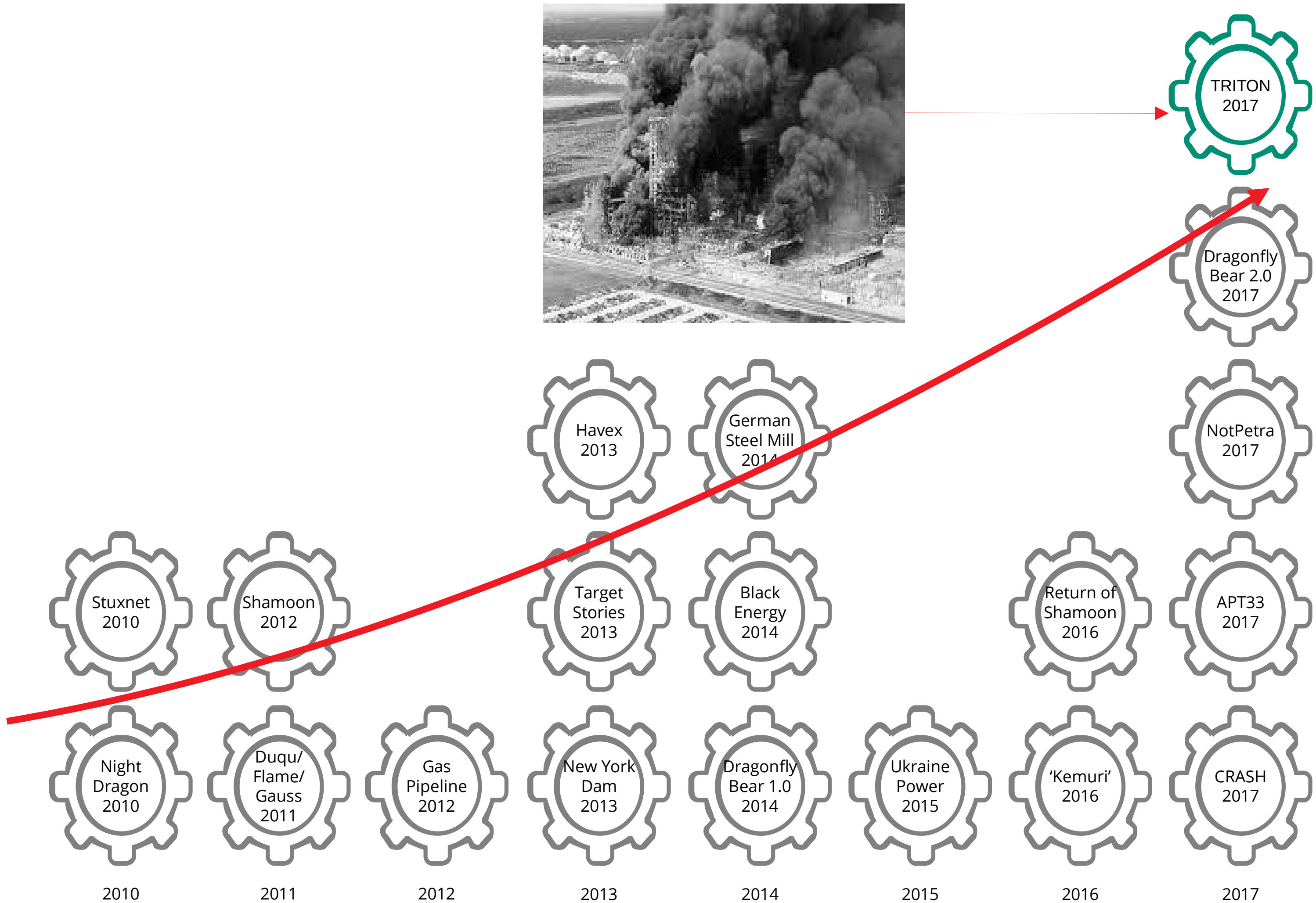

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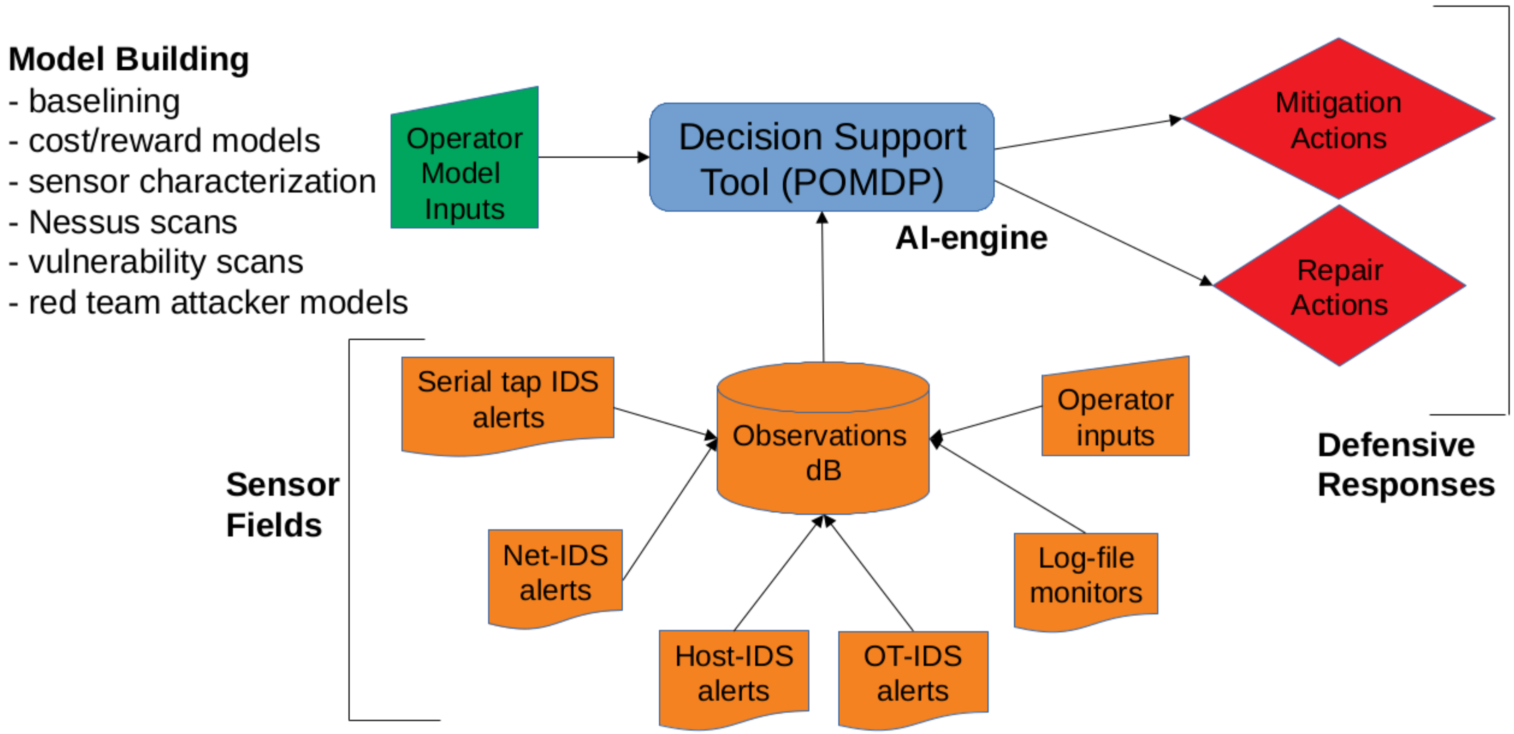
Bottom Line Up Front

- We have developed a Decision Support prototype based upon an POMDP Artificial Intelligence (AI) agent (see diagram below).
- This currently acts as a Security Orchestration and Automated Response (SOAR) system for Industrial Control Systems.
- Initial testing in protection against cyber-attacks on an emulated ICS have been favorable.
- Working on the development of multiple Operator Interfaces for deployment.

★ Exploring applications of this technology to defense of joint Ground Station/Satellite systems.



Technical Details

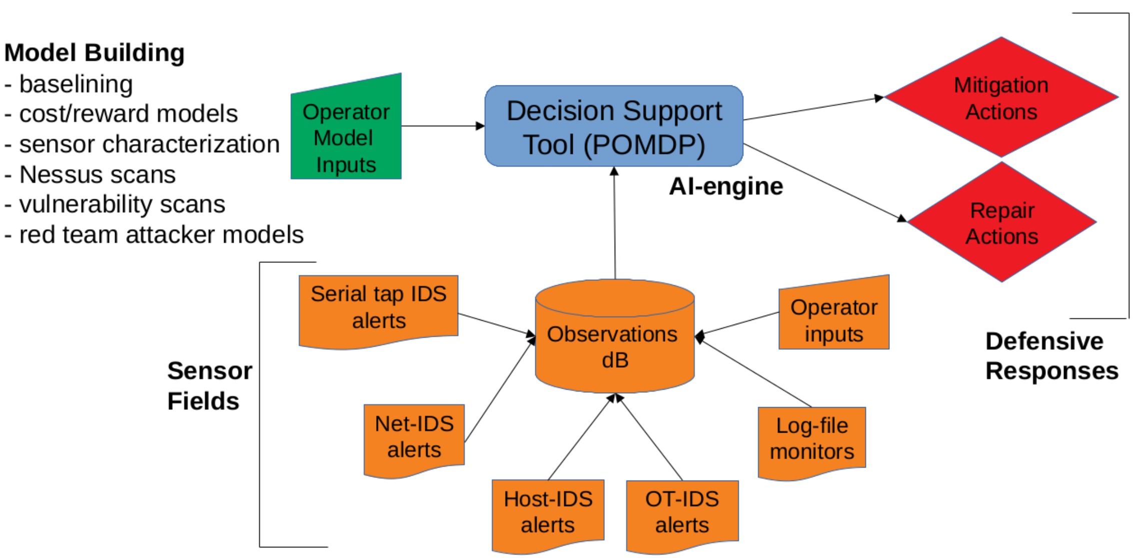
Unclassified Unlimited Release

Requirements and Design

Design, Develop and Test a Decision Support System (DSS) to support novice cyber defenders of the nation's critical GS/Satellite systems.

The DSS must be:

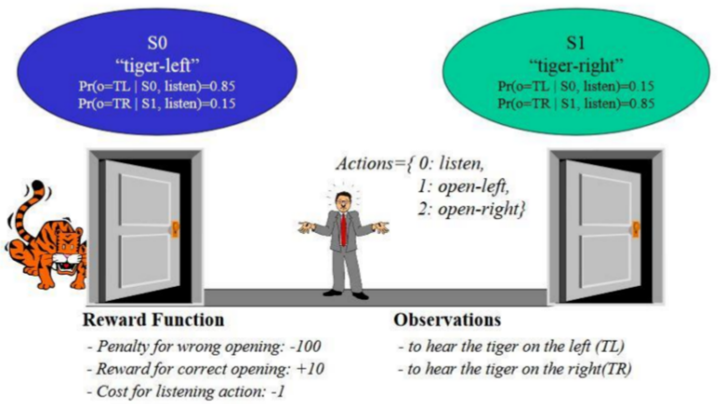
- Effective in the defense of GS/Satellite environments,
- Does not require vast, labeled datasets to train,
- Does not require running thousands to millions of trials to learn,
- Contain an AI Expert System Shell to simplify configuration and deployment,
- Intuitive and easily described,
- Scalable and
- Well tested and validated.



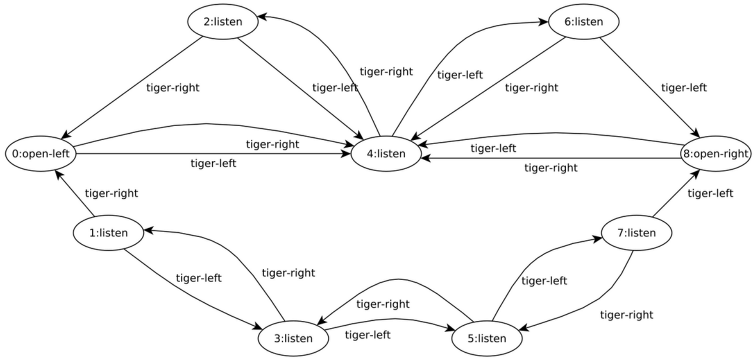
We chose POMDP AI !

What is a POMDP - the Tiger Problem

A POMDP Example: The Tiger Problem



The Tiger Problem Policy Graph (solved)



The POMDP Configuration: The Tiger Problem

This example is from the Examples section of 'pomdp.org'

discount: 0.75
values: reward
states: tiger-left tiger-right
actions: listen open-left open-right
observations: tiger-left tiger-right

T:listen
identity

T:open-left
uniform

T:open-right
uniform

O:listen
0.85 0.15
0.15 0.85

O:open-left
uniform

O:open-right
uniform

R:listen : * : * : * -1
R:open-left : tiger-left : * : * -100
R:open-left : tiger-right : * : * 10
R:open-right : tiger-left : * : * 10
R:open-right : tiger-right : * : * -100

Why an AI based upon POMDP

+ Russell, S. and P. Norvig, “Artificial Intelligence”, define four levels of artificial intelligence agents. These are:

a) Simple Reflex Agents, ← least sophisticated

b) Model Based Reflex Agents,

c) Goal Based Agents and

d) Utility Based Agents. ← most sophisticated

+ State of the Art in cyber-defense deployments is Simple Reflex Agents, i.e., think ‘Table Lookup’, ‘Playbooks’, etc.

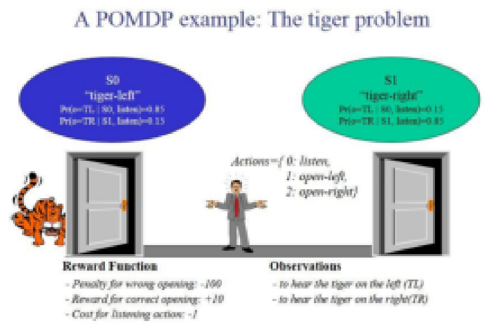
+ If we ran Simple Reflex Agent for the Tiger Problem, its long term reward would be

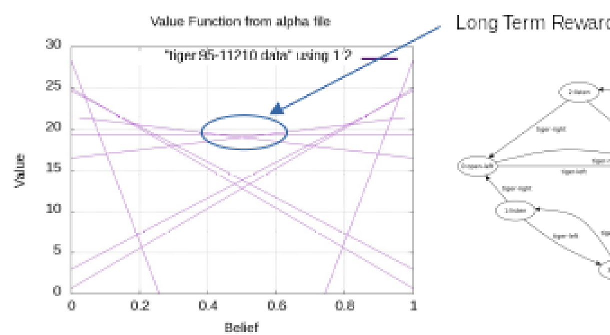
0.85x10 – 0.15x100 = - 6.5

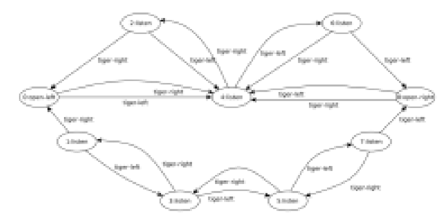
+ If we ran a Utility Based Agent, e.g., a POMDP, for the Tiger Problem, its long term reward would be (see diagram to the right)

+19.5 !

What do you want in your wallet ?

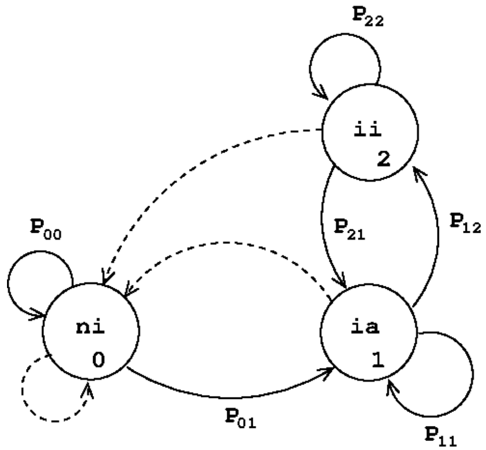




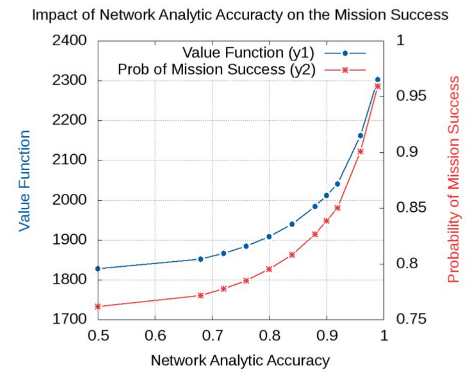


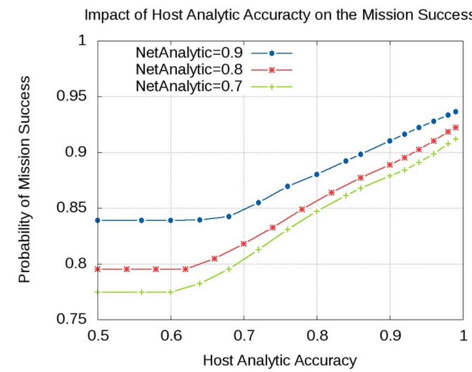
A POMDP Cyber Example

A POMDP Example: Day in the Life of a Host

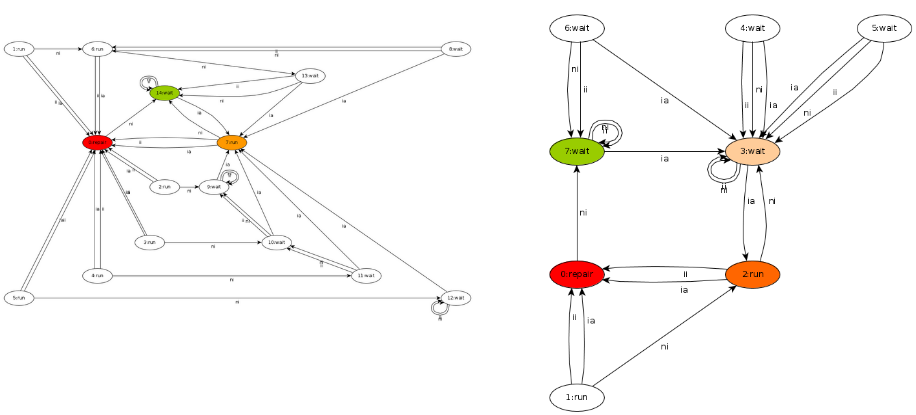


The Host POMDP Studies

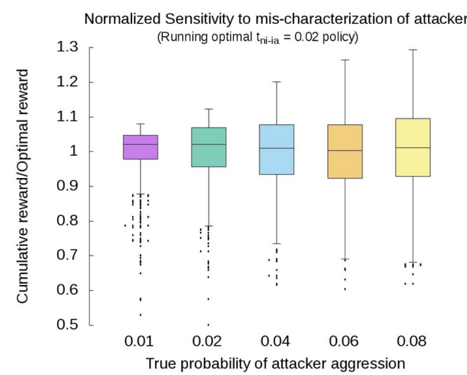




The Host Problem Policy Graph (solved)

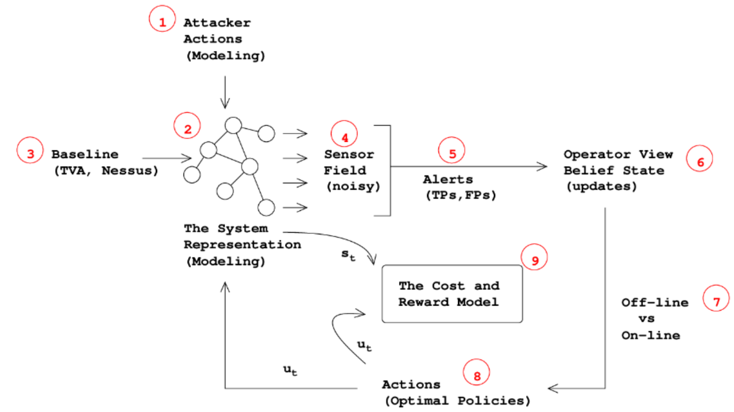


Sensitivity Studies or errors in POMDP modeling

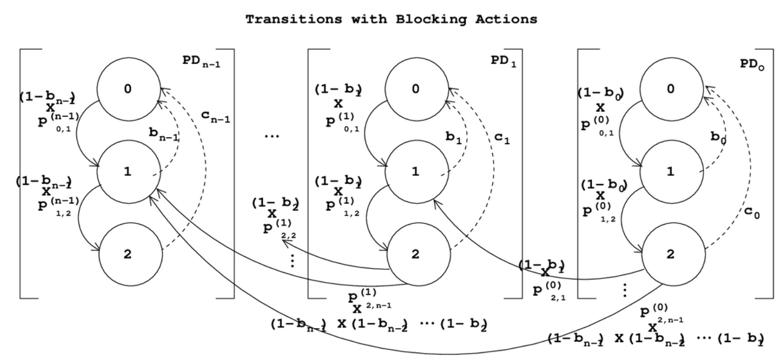


Algorithmic Approach and its Advantages

- We have chosen to implement our DSS based upon a Partially Observable Markov Decision Process (POMDP) models.
- The models comprising the brains of the DSS will be based upon Domain Expertise and will 'hit the ground running'.
- The POMDP models comprising the DSS will not require vast data sets for Deep Machine Learning.
  - Large data sets from SCADA/ICS and malicious attacks are extremely hard to obtain.
- The POMDP models comprising the DSS will not require learning optimal policies through extensive trial and error.
  - In these environments trials cannot be performed on actual systems.
  - On emulation models trials are extremely time consuming.



POMDP Components



An ICS POMDP Logic Model

Unclassified Unlimited Release

Test and Evaluation Methods

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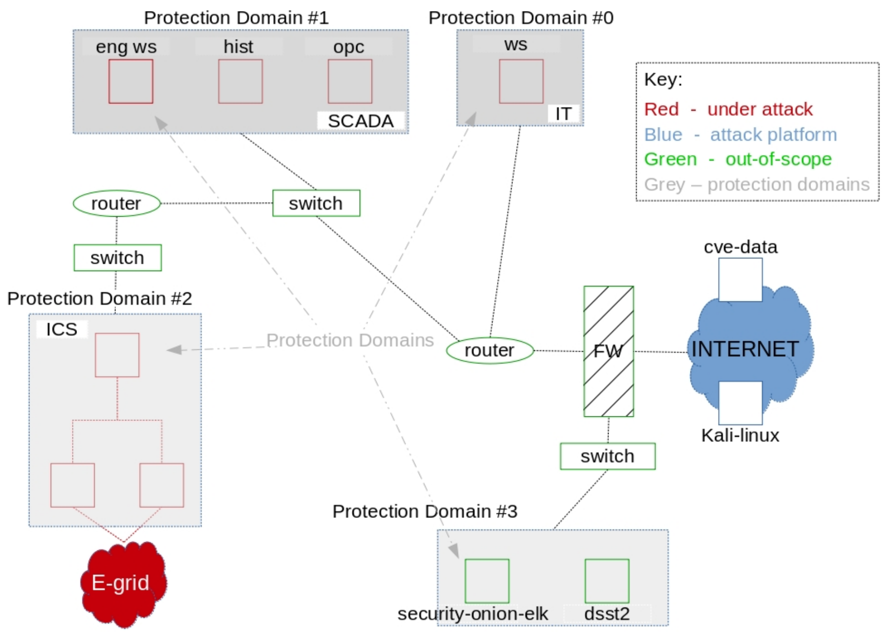
No data! Just Experimentation, Test and Evaluation ...

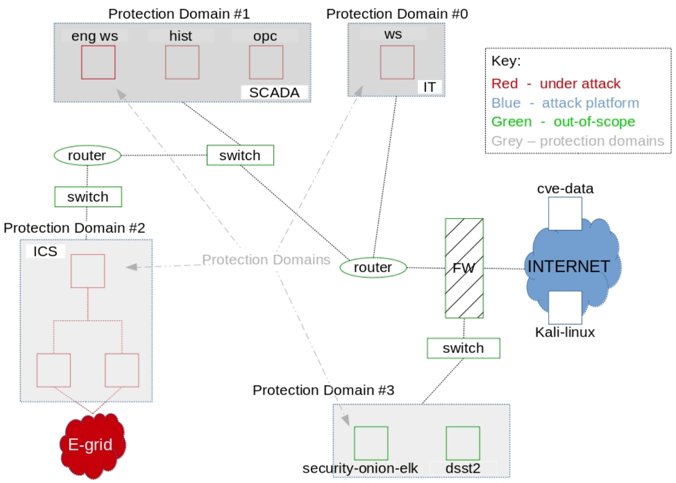
- We will use domain expertise to develop our POMDP models and then extensively test them out on high fidelity emulation models of SCADA/ICS systems.
- We are using SCEPTRE to emulate SCADA/ICS environments and CobaltStrike for cyber attack scripting and we plan on running live Red Team attacks against our systems in the future. Derived from the previous programs.
- Red Teaming capabilities taken from previous programs and expanded.



SCEPTRE Emulation Modeling of Industrial Control Systems.

Simulating an attacker

- **Role**
  - Conduct simulated attacks on systems within the network.
- **Intent**
  - Simulate actions an attacker might take to gain access to target systems and compromise certain components.
  - Test how existing NIDS and HIDS systems respond and how the POMDP model responds.
  - Help conceptualize how a real-world attack might affect the system.
- **Process**
  - Simulate IT/OT environment using SCEPTRE.
  - Create an attacker system sitting outside Network (Kali-linux, Cobalt Strike).
  - Use Cobalt Strike to plant/communicate with beacons on compromised machines.
  - Establish foothold in network by using known vulnerabilities to compromise an IT system.
  - Use this foothold to launch attacks on other systems in the OT network.



Results – Representative, Simple Attacks

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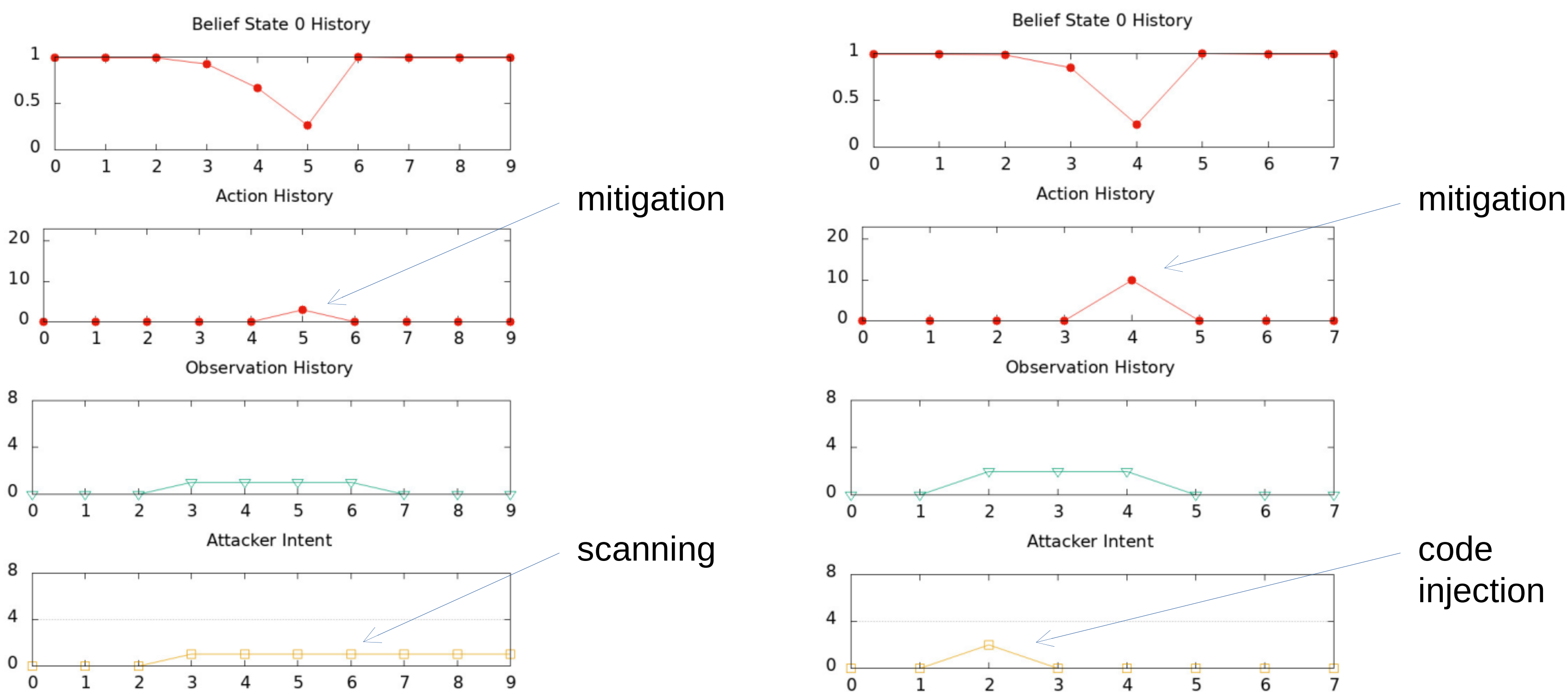
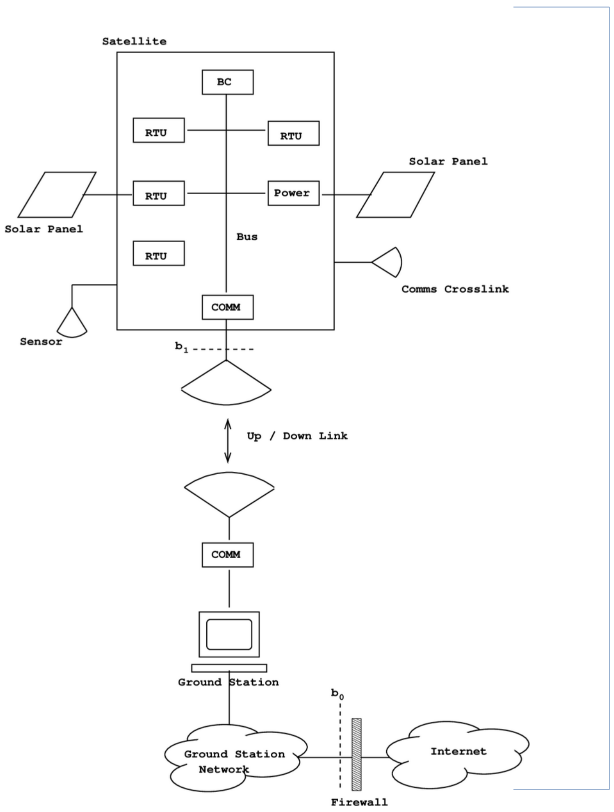
- Our system reacts to the attacks thrown at it with a reasonable and explainable response.
- We are testing with more attack types and are constrained only in the quality of the sensors.
- The response is reasonable even when the attacker is deviating from our attack modeling.

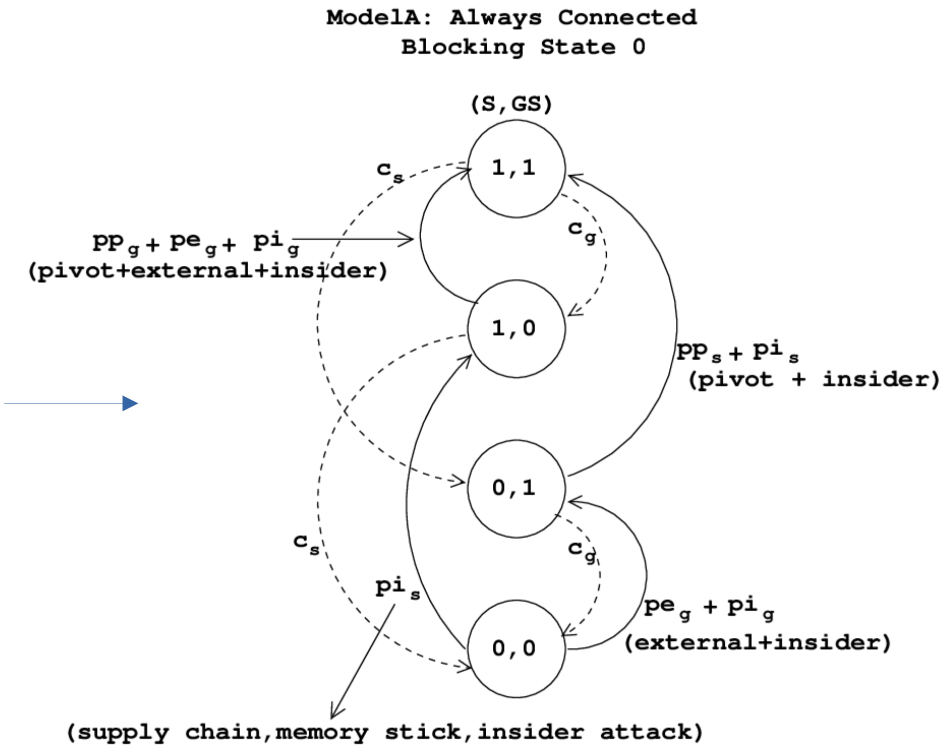


Simplified POMDP model of GS/Satellites

- POMDP cyber modeling of permanently connected GS/Satellite system.
- Solid arrows represent attack vectors. Dashed arrows represent 'Actions'.
- Firewall actions represented through topology changes to POMDP model.



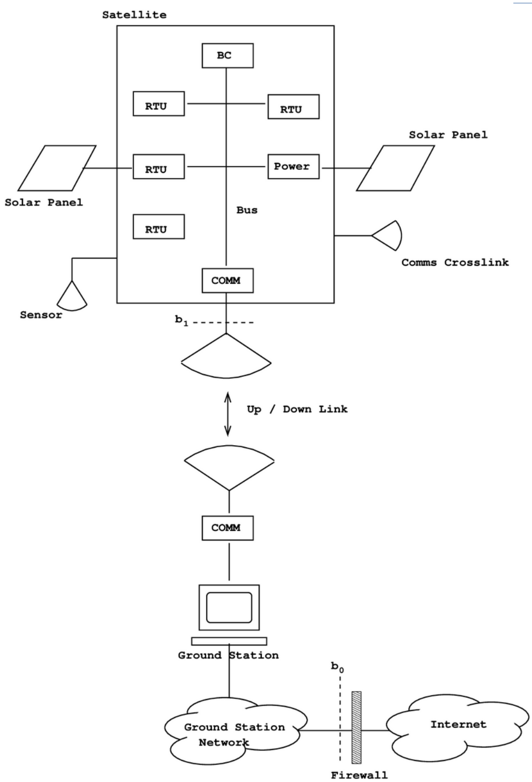
Abstract GS/Satellite system diagram



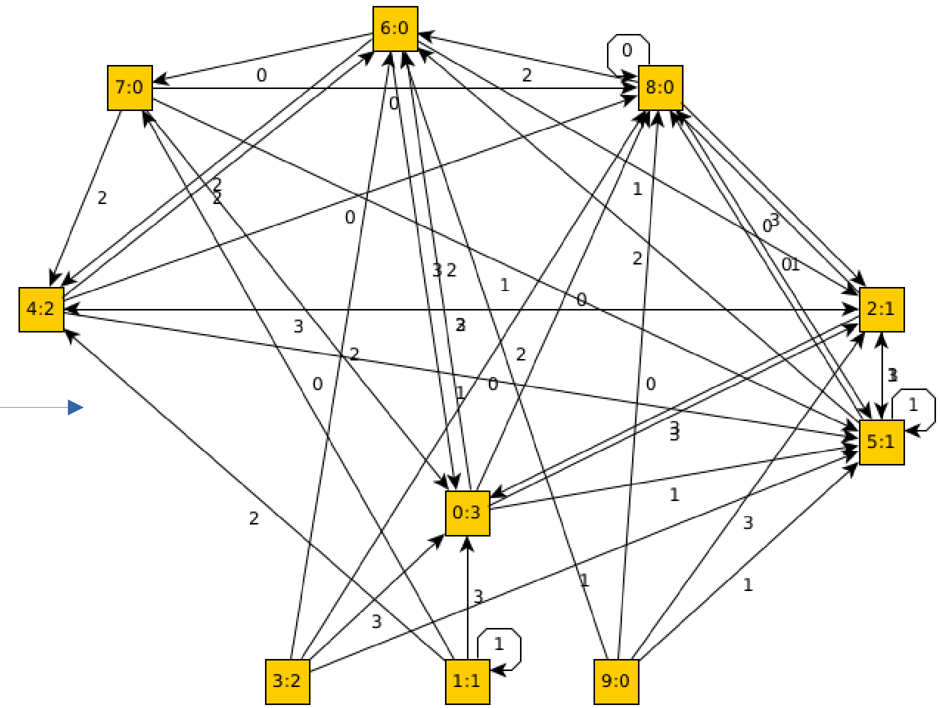
Associated POMDP of GS/Satellite

Policy Graph of Simplified GS/Satellite Model

- A policy graph for permanently connected ground stations and satellite system.



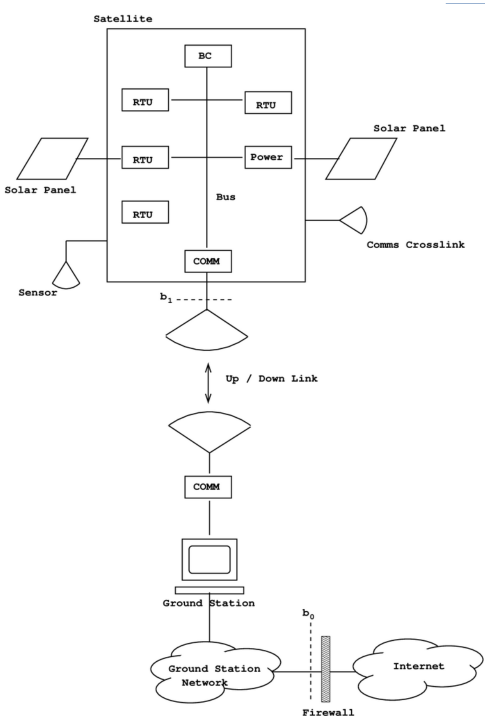
An abstracted Ground Station and Satellite system diagram



- Nodes represent different Belief States.
- Node labels contain arbitrary label followed by optimal action.
- Arrows labeled by Observations indicate transitions to next Belief State.

Modeling intermittent connectivity

- One approach to model distributed, interacting multiple agents under intermittent connectivity situations, one for the GS and one for the Satellite.
- Seems overly complicated; tracking unnecessary components.
- Still requires a split/rejoin procedure.



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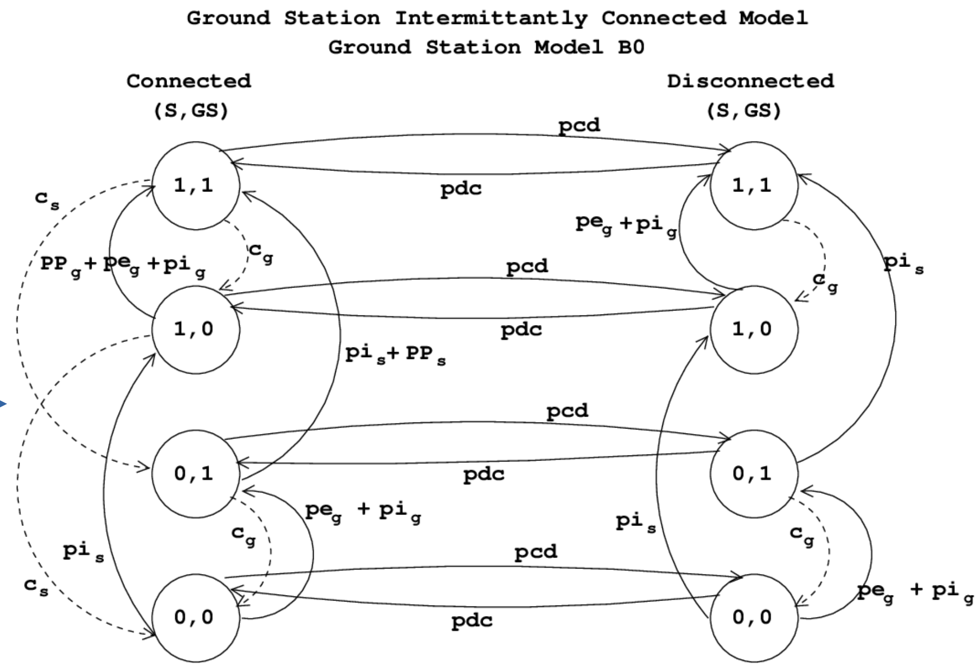
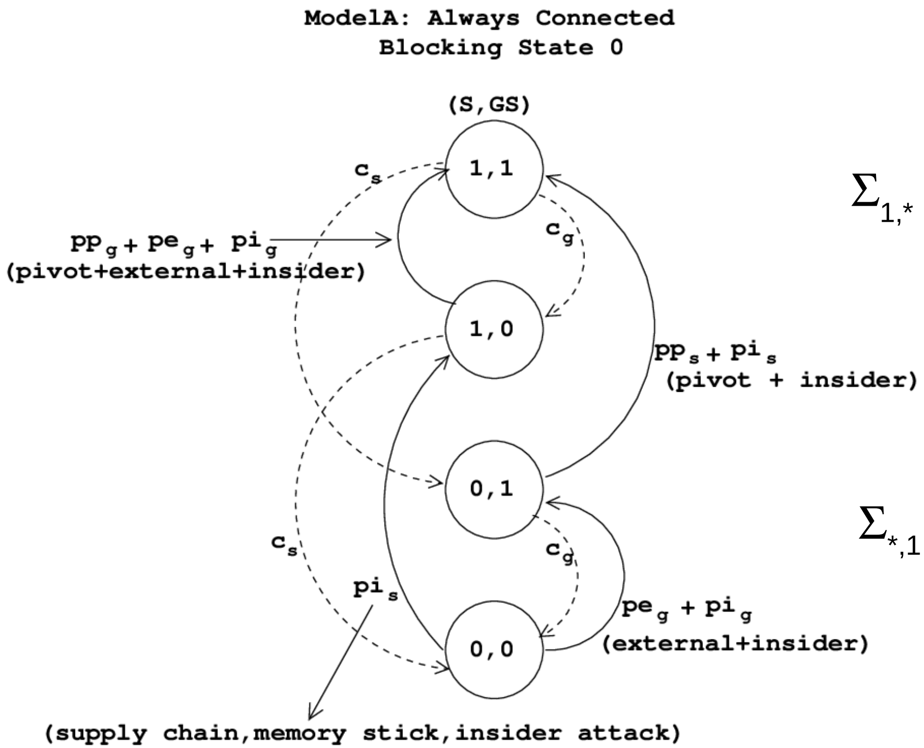


Ground Station directed agent model

Reduction modeling intermittent connectivity

- So, ...another approach is to maintain reduced models when disconnected.
- Then reconstruct full model upon re-connection.



An abstracted Ground Station and Satellite system diagram

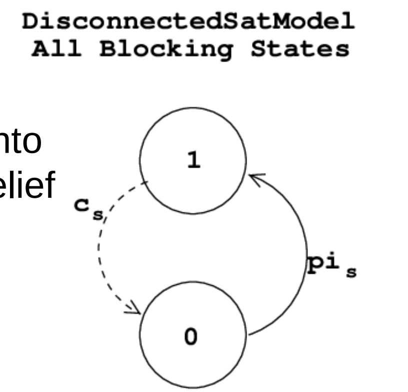
$\Sigma_{1,*}$

$\Sigma_{*,1}$

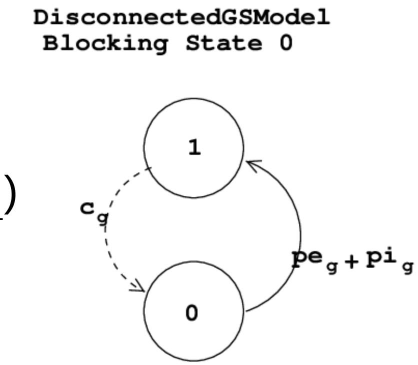
Disconnect

Reduce belief state into separate b_s and b_g belief states.

$b_s = (b_{s,0}\ ,\ b_{s,1})$



$b_g = (b_{g,0}\ ,\ b_{g,1})$



Rejoin

Merge Belief State probabilities of b_s and b_g into a connected model Belief State for connected model on right.

Potential Future Work

- Develop and experiment with higher fidelity models of the Ground Stations and Satellite systems.
- Perform simulation studies of the performance of the high fidelity GS/Satellite models under attack.
- Explore potential emulation platforms for more realistic studies, attack scenarios, etc. in order to better assess the capabilities of POMDP models defending GS/Satellite systems against cyber attacks.

Questions ?

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