Developing Intelligent Space Systems: A Survey & Rubric for Future Missions

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Overview

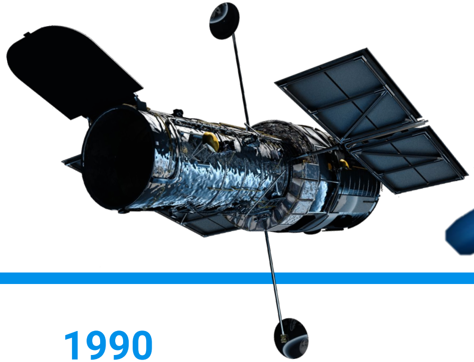
- Motivation
- Timeline of Early Applications of AI in Space
- Types of AI
- How do you evaluate the best AI options?
- Rubric
- Rubric application
- Summary

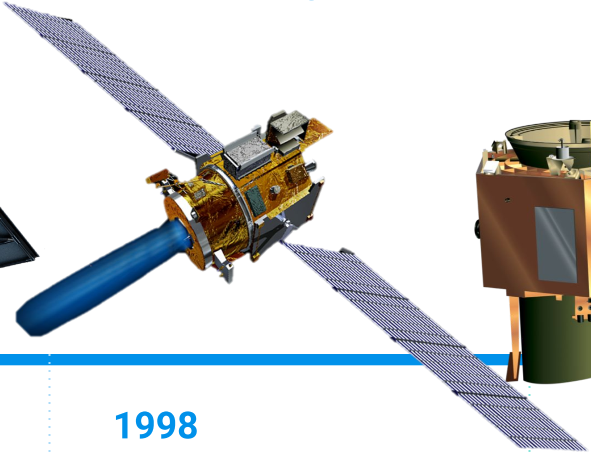
(yes, we're talking about AI)

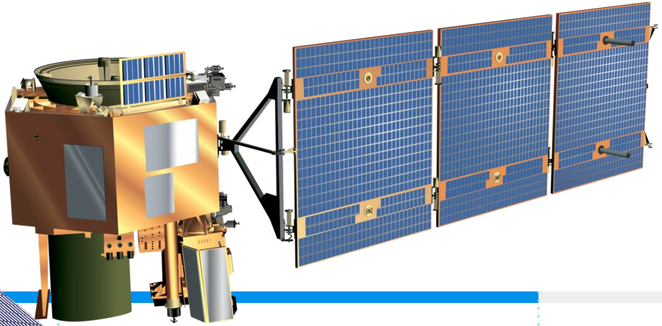
Motivation

- Demystifying AI and its applications in space
- Define AI types
- Survey works of AI in space *(see our paper!)*
- Informed decision making: When to use AI?

Timeline of Early Applications of AI in Space







1990

Spike

Ground-based Hubble Space Telescope **scheduling** with rule-based algorithms and an artificial neural net.

1998

Deep Space 1

Autonomous navigation, self-repair, location and target estimation, and AI-controlled **flight software.**

2000

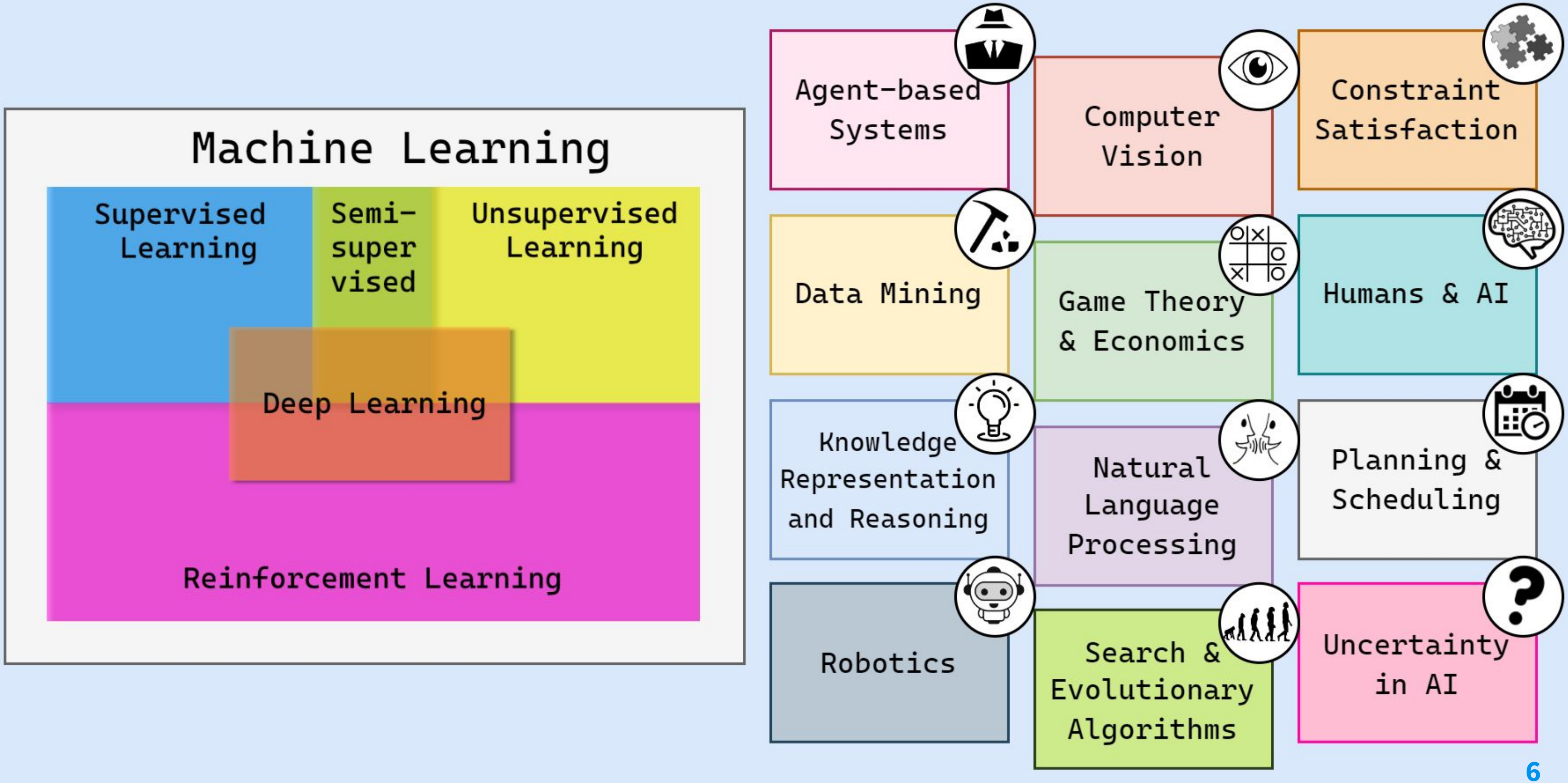
Earth Observing 1

Onboard science analysis and mission planning. **Identified scientific features** in images.

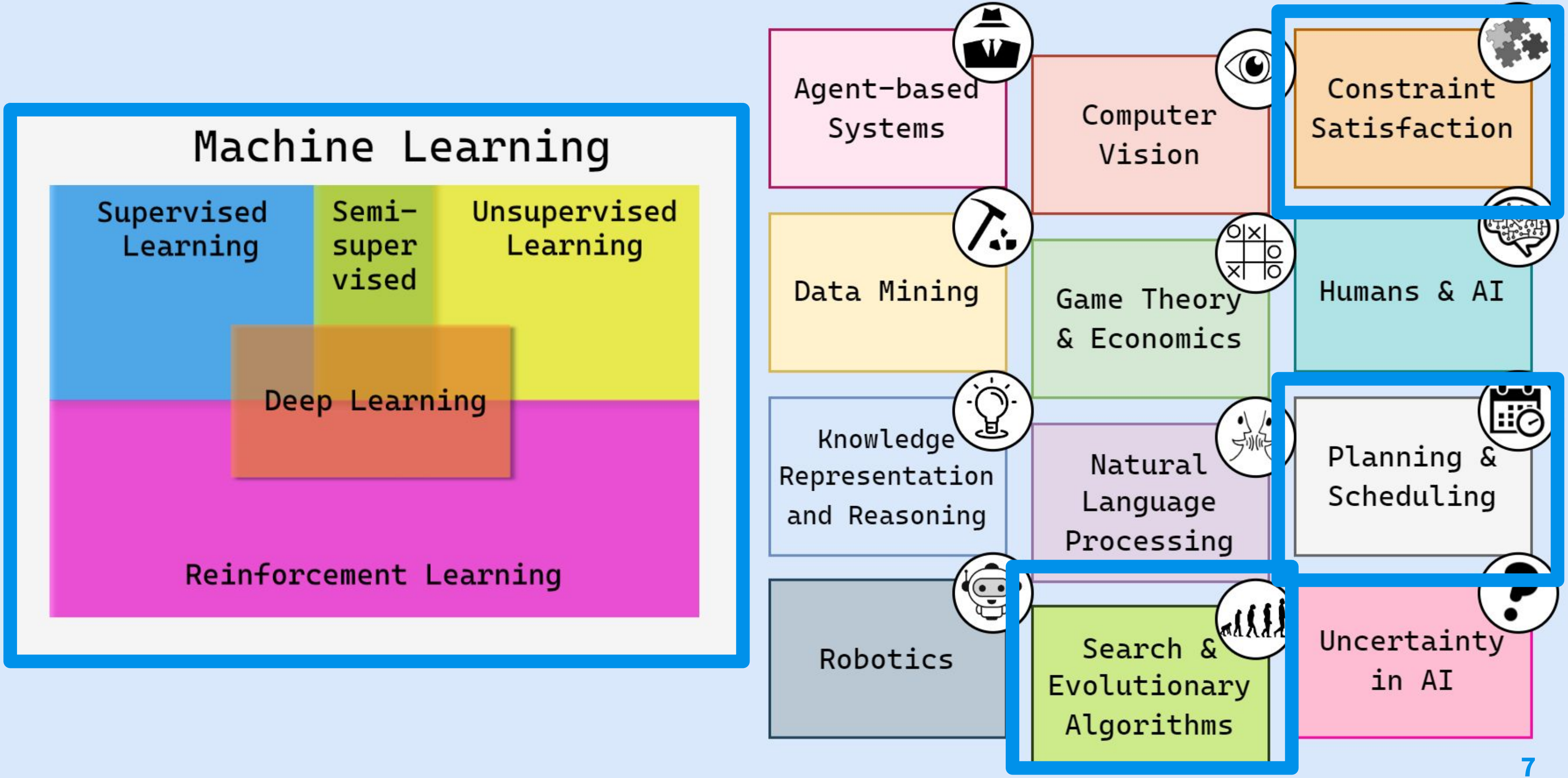
20XX

And beyond…

Artificial Intelligence



Artificial Intelligence



AI

Machine Learning

Type of AI	Constraint Satisfaction	Supervised Learning		Unsupervised Learning			Reinforcement Learning	Evolutionary Algorithms
Method	Find valid assignments to satisfy constraints	Learn relationship between labelled inputs and outputs		Identify patterns, relationships, or structures in unlabelled data to create output			Explore an environment to learn a policy	Optimize by iteratively improving solutions
Task	Assignment	Regression	Classification	Clustering	Dimensionality Reduction	Anomaly Detection	Task Optimization	Parameter Optimization
Algorithms	Constraint propagation, Backtracking (depth-first), local search	Linear classifier (logistical regression, naive bayes), Decision Trees, Random Forest, Genetic Programming	Decision Trees, Random Forest, Support Vector Machines, Gradient Boosting, K-Nearest Neighbor	K-Means, Hierarchical clustering, Gaussian Mixture Models	Principal Component Analysis, t-Distributed Stochastic Neighbor Embedding, Random Forests	Isolation Forest, Local Outlier Factor, Support Vector Machines	Policy Gradient, Actor-Critic, Q-Learning, State-action-reward-state-action, Proximal Policy Optimization, Monte Carlo Tree Search	Genetic algorithm, evolutionary strategy, genetic programming, evolutionary programming, differential evolution
Deep Learning Algorithms	Not commonly used	Artificial neural network, deep neural network	Convolutional Neural Net, Recurrent Neural net, Long Short-Term Memory	Autoencoders, Self-Organizing Maps, Generative Adversarial Networks			Deep Q Learning, Deep Deterministic Policy Gradient	Convolutional neural net
Example Applications	Operations planning, navigation	Scientific prediction	Cloud filtering, feature extraction	Cloud filtering, feature extraction	Spacecraft health management	Spacecraft health management	Long-term navigation, tracking	Satellite configuration optimization

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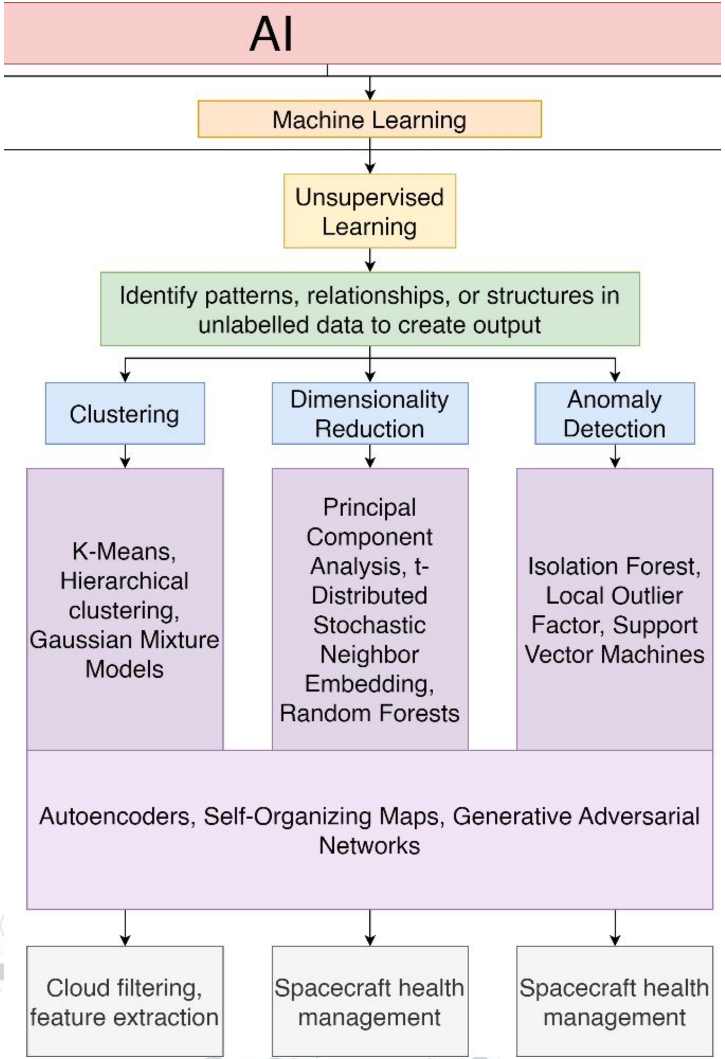
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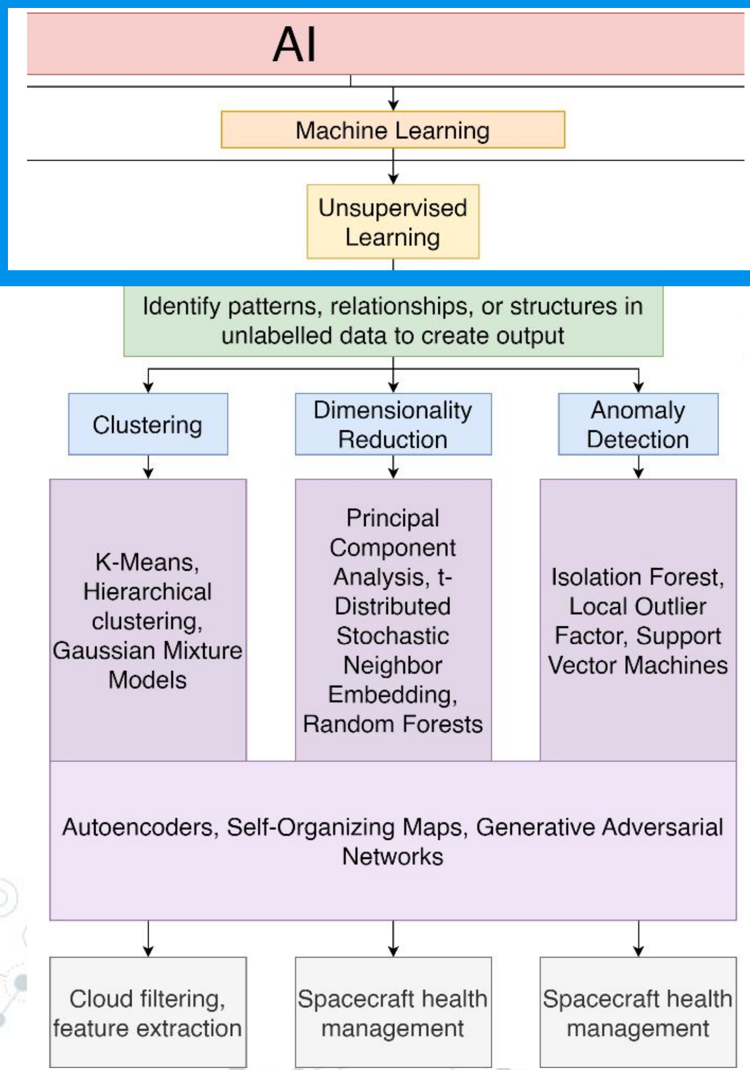
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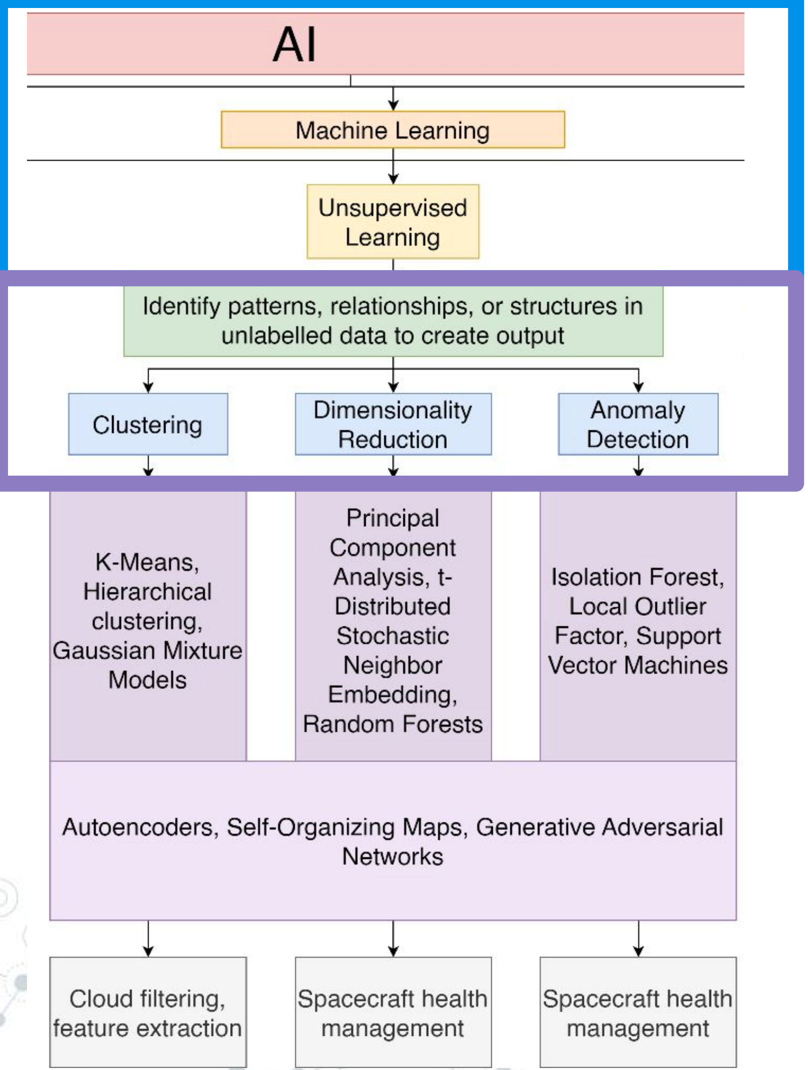
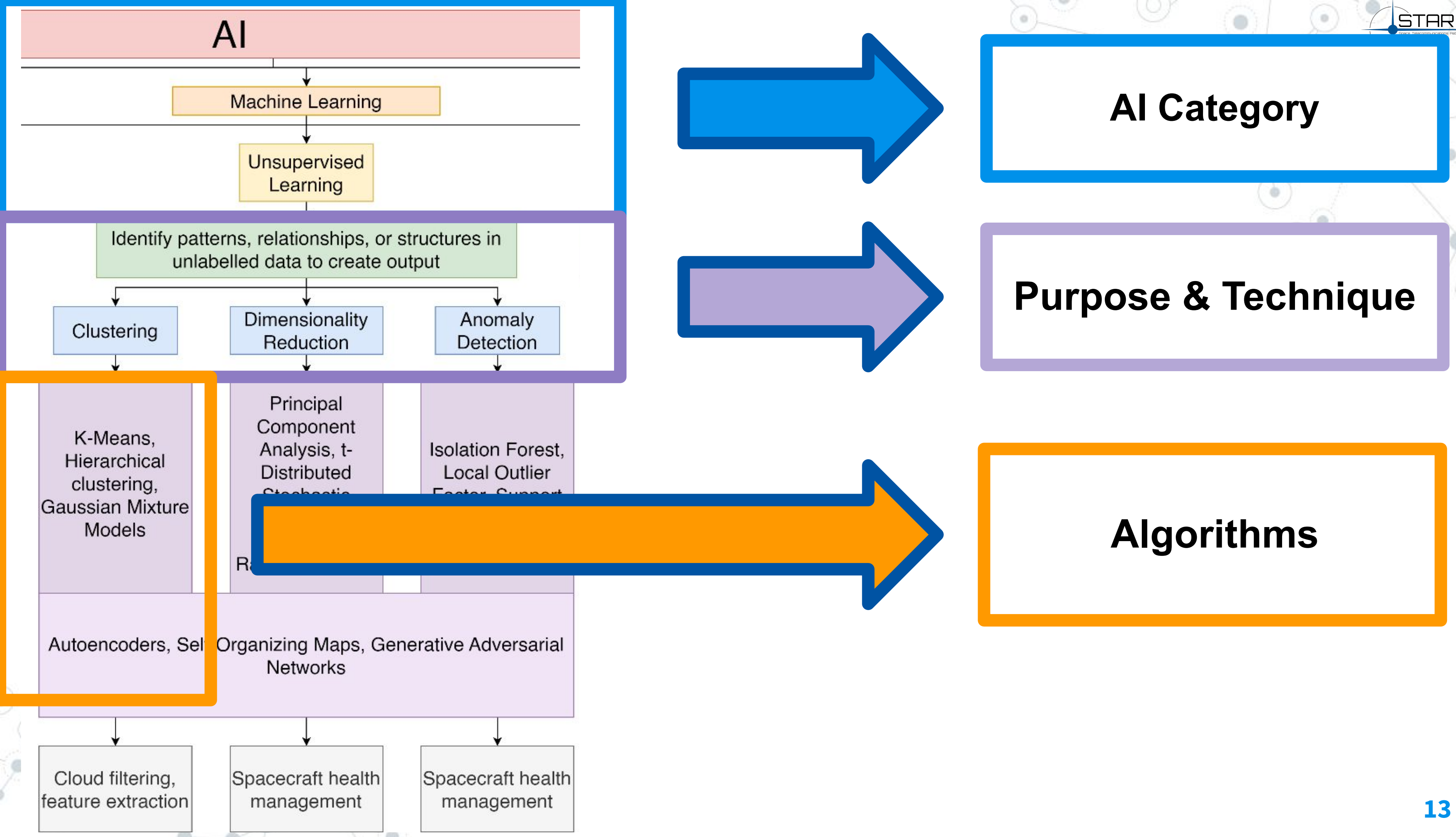
AI Category



AI Category

Purpose & Technique



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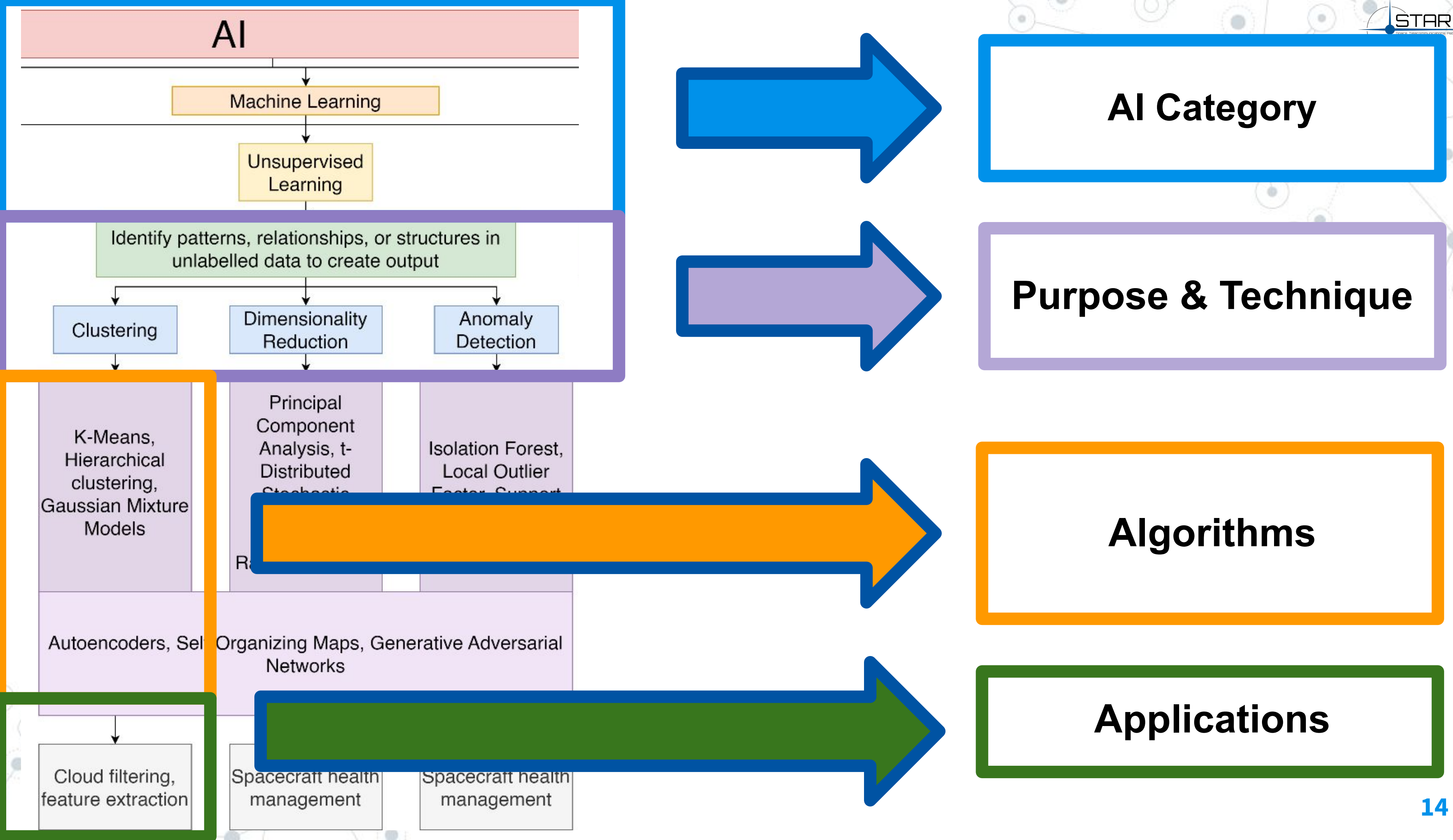
AI Category
Purpose & Technique
Algorithms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AI Category
Purpose & Technique
Algorithms
Applications

How do you evaluate the best AI options?

Rubric Categories

- Improvement Over Current State-of-the-Art
- Consistency of Output
- Availability of Training Data
- Risk Benefit
- Explainability
- Robustness Over Space Environment
- Robustness Over Resource Constraints
- Necessity for Human Intervention
- Computational Cost
- Operation and Integration Complexity
- Maintainability
- Provability
- Legality and Morality

Rubric Categories

Improvement Over Current State-of-the-Art

Consistency of Output

Availability of Training Data

Risk B

Necessity for Human Intervention

Computational Cost

Operation and Integration Complexity

- Training data for the agent is high-quality, accessible, abundant, well balanced, and diverse.
- If not readily available, data can be easily generated.
- The data are free from biases that could distort the results.
- **Ex:** To predict satellite health, if telemetry data for certain fault conditions is scarce, simulated fault data can be used. To avoid bias, the data can include various satellite types, operating conditions, and fault scenarios.

Rubric Categories

- The system performs as intended under abnormal or unknown inputs.
- In space scenarios, this includes radiation effects, equipment malfunctions, and unexpected hazards.
- The system retains its functionality, even if it enters a "safe" mode.
- **Ex:** During unexpected space weather events, the algorithm is capable of recognizing unusual inputs, and can switch to a radiation-aware "safe" mode.

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Robustness Over Space Environment

Robustness Over Resource Constraints

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Provability

Legality and Morality

Rubric Categories

Improvement Over Current State-of-the-Art

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Robustness Over Resource Constraints

Necessity for Human Intervention

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Legality and Morality

- The system operates as intended under typical space conditions.
- This includes dealing with limited power, communication blackouts, microgravity, and radiation.
- **Ex:** At EOL, there is still power to run these algorithms. The algorithms have graceful degradation options while still having meaningful output.

Rubric Categories

- The system can be rigorously proven to avoid unsafe conditions.
- This assurance can be due to barrier functions or other security features.
- **<u>Ex:</u>** Autonomous satellite navigation can be rigorously assured so that the decision-making algorithm will never lead the satellite into an unsafe state, such as a collision course with other planetary bodies or spacecraft.

Improvement Over Current State-of-the-Art

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Robustness Over Space Environment

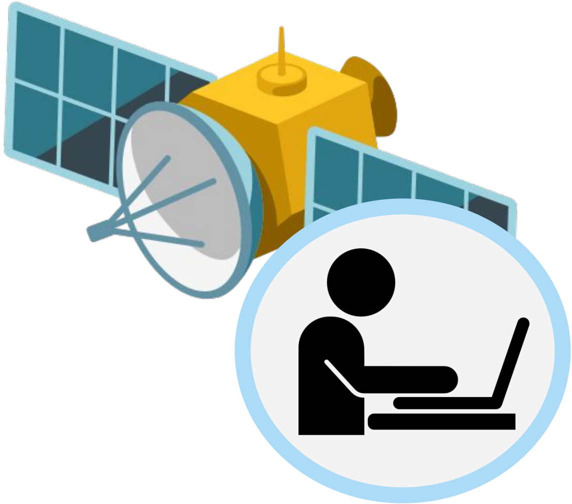
Robustness Over Resource Constraints

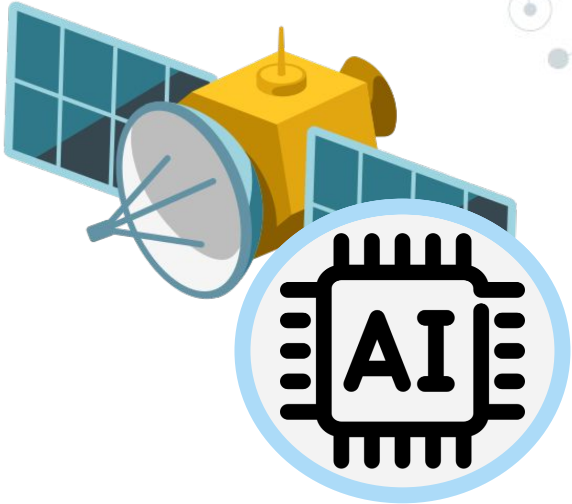
Necessity for Human Intervention

Provability

Legality and Morality

Rubric Application: FIRESAT

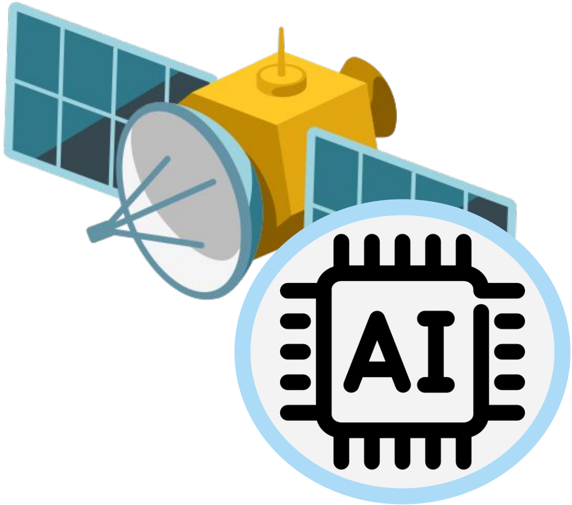




- Human reviews images from the ground manually
- Identifies emergency situations and commands the satellite on future passes to image them

- AI can identify storms forming, wildfires, or other natural disasters and track them
- Trained on a dataset of natural disasters in different locations, states of formation, and orientations.

Rubric Application: FIRESAT



SCORE	DESCRIPTION
0	System is incapable of fulfilling that criteria
1	Fills it poorly
2	Fills it on par with state-of-the-art
3	Improves upon state-of-the-art

FIRESAT Score

Improvement Over Current State-of-the-Art	3	Necessity for Human Intervention	3
Consistency of Output	3	Computational Cost	1
Availability of Training Data	3	Operation and Integration Complexity	2
Risk Benefit	2	Maintainability	2
Explainability	3	Provability	3
Robustness Over Space Environment	2	Legality & Morality	3
Robustness Over Resource Constraints	3	**SCORE:** 31/39 = 80%	

Summary

- AI techniques and applications in space overview
- Using the right AI model for specific tasks
- Outlined a rubric for effective AI use in spacecraft research
- Usage of rubric for AI usage determination

THANK YOU!

Backup - Rubric Categories

Improvement Over Current State-of-the-Art

- When given the same inputs, the solution returned by the system is an improvement on the results from the non-AI counterparts.
- This improvement includes accuracy, quality, and completeness.
- **Ex:** AI enabled cloud detection algorithms may outperform traditional methods in accurately and rapidly identifying clouds, allowing for improved mission performance.

Robustness Over Space Environment

Robustness Over Resource Constraints

Necessity for Human Intervention

Provability

Legality and Morality

Backup - Rubric Categories

Improvement Over Current State-of-the-Art

Consistency of Output

Robustness Over Resource Constraints

Necessity for Human Intervention

Computational Cost

Legality and Morality

- When given the same inputs, the system gives a consistent, correct output.
- It does not produce a solution that is drastic or unexpected. Its outputs follow the required rules and requirements at all times.
- **Ex:** Control system for instrument pointing consistently takes the most efficient route to the target.

Backup - Rubric Categories

- System failure or off-nominal output does not jeopardize the mission.
- Such anomalies do not cause mechanical or electronic damage to the spacecraft or its environment.
- **<u>Ex:</u>** If an image identification algorithm fails to operate, it does not end the rest of the mission.

Risk Benefit

Explainability

Robustness Over Space Environment

Robustness Over Resource Constraints

Operation and Integration Complexity

Maintainability

Provability

Legality and Morality

Backup - Rubric Categories

Improv
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- The system provides understandable explanations of how it reaches conclusions.
- The explanations focus on individual physical aspects, not technical details.
- These explanations are easily comprehensible, comprehensive, and logical.
- **<u>Ex:</u>** A risk prediction algorithm provides the factors that lead to its conclusion.

Explainability

Robustness Over Space Environment

Robustness Over Resource Constraints

Maintainability

Provability

Legality and Morality

Backup - Rubric Categories

Improvement Over Current State-of-the-Art

Consistency of Output

Availal Trainin

stness Space nment

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Necessity for Human Intervention

Computational

Legality and Morality

- The system can act as intended under expected space conditions, where human interaction is limited.
- The system can act independently from human intervention.
- The system does not need to be constantly commanded to reset.
- **Ex:** A navigation algorithm that, when reaching unknown locations, does not need to be manually updated.

Backup - Rubric Categories

Improvement Over Current State-of-the-A rt

Consistency of Output

Availability of Training Data

Risk E

Robustness ver ource traints

Necessity for Human Intervention

Computational Cost

Operation and

- The system does not incur significant power, time, or data requirement when compared to a non-AI counterpart.
- It is able to complete its tasks in the time required to perform the mission.
- **Ex:** A pointing algorithm that performs similarly to a traditional counterpart.

Backup - Rubric Categories

Improvement Over Current State-of-the-Art

Consistency of Output

Availability of Training Data

Risk Benefit

Necessity for Human Intervention

Computational Cost

Operation and Integration Complexity

- The system is comprehensible and easily understood by its users.
- It can be integrated with spacecraft hardware without the need for costly, custom hardware.
- **Ex:** An AI enabled board that is compatible with existing space systems.

Backup - Rubric Categories

- The system allows for easy updates and maintenance.
- Feature improvements and alterations don't require a complete system overhaul.
- The system can be effortlessly restarted.
- **Ex:** An AI board that can have code uploaded to it remotely to make improvements.

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Risk Benefit

Explainability

Robustness Over Space Environment

Robustness Over Resource Constraints

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Maintainability

Provability

Legality and Morality

Backup - Rubric Categories

Improvement Over Current State-of-the-Art

Consistency of Output

Robustness Over Space Environment

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Necessity for Human Intervention

Computat
Cost

- The system does not break any laws, including those about AI implementation and outer space treaties.
- The system has been assessed regarding its ethical implications.
- **<u>Ex:</u>** An automated imaging system does not break any laws about targets that are permitted to be taken.

Legality and Morality