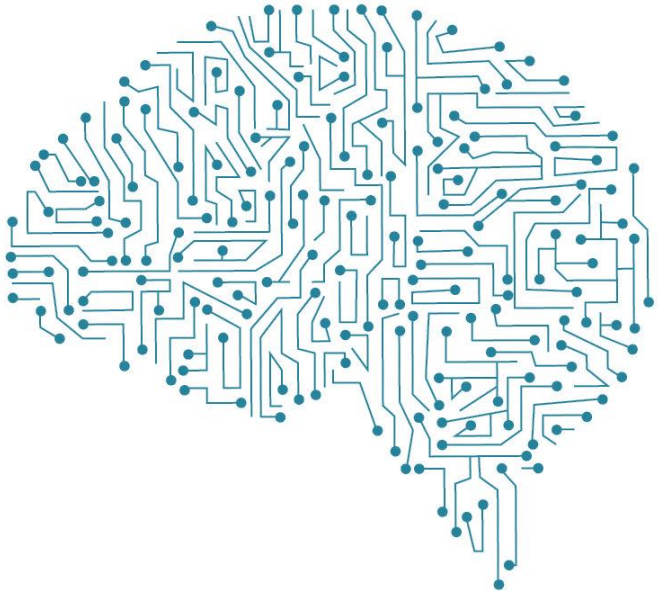
Artificial Intelligence in Space



Towards smarter spacecraft.

Benefits of Autonomy for Space Operations

- **Higher levels of autonomy**
  - Enable new missions due to higher reactivity
  - Optimize use of on-board resources and mission time
  - Reduce operational cost
- **Self-Awareness**
  - Optimize downlink information throughput
  - Increase safety (FDIR) through state estimation and anomaly detection
  - Handle unforeseen situations

Autonomy – ESA View

Autonomy Level	Description	Functions
E-1	1) Mission execution under ground control; 2) Limited onboard capability for safety Issues	1) Real-time control from ground for nominal operations 2) Execution of time-tagged commands for safety issues
E-2	Execution of preplanned, ground-defined, mission operations onboard	Capability to store time-based commands in an onboard scheduler
E-3	Execution of adaptive mission operations onboard	Event-based autonomous operations. Execution of onboard operations control procedures
E-4	Execution of goal-oriented mission operations onboard	Goal-oriented mission re-planning

[ECSS-E-ST-70-11C]

Autonomy – Necessary Conditions

Empowerment

- Sense the world and its own state, make decisions about what to do and carry out these decisions through its own actions

Controllability

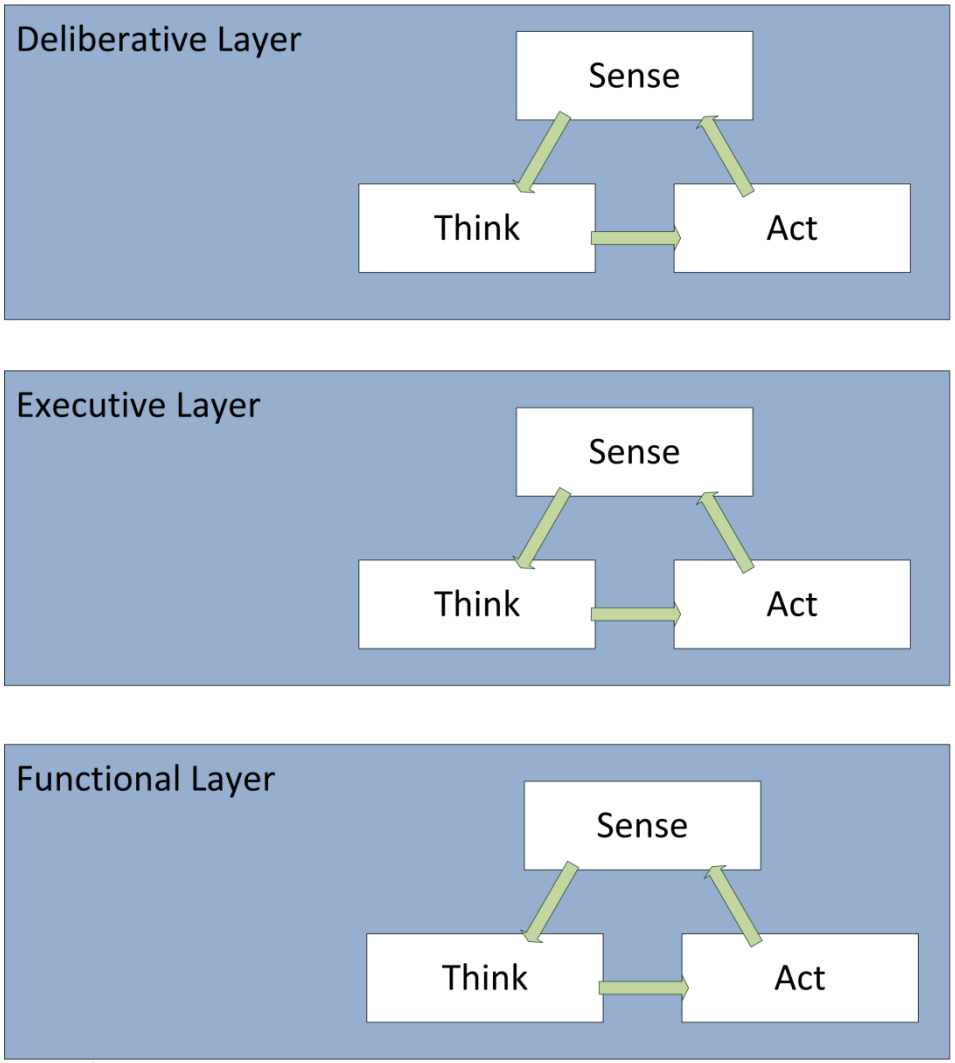
- Human commanding to achieve a set of high-level goals which is transformed in to a sequence of actions to accomplish these

Flexibility

- Flexibly responds to off-nominal situations by adjusting its activity sequence to attain its goals

[Jonsson2007]

On-Board Autonomy



- High-Level Planning
- State Identification
- System Health Management

- Task Orchestration
- Progress Monitoring

- Device Access
- Raw Sensor Data
- Simple Control Loops

[Jonsson2007]

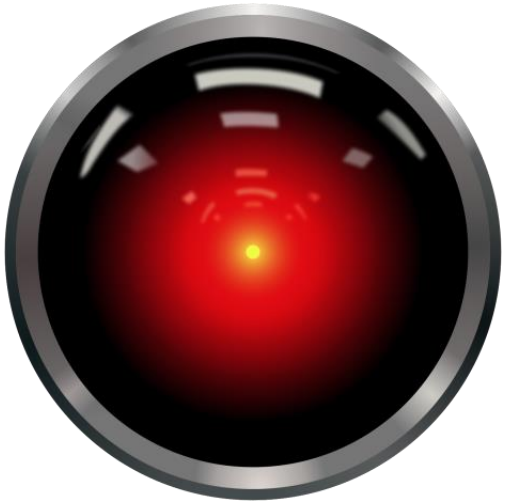
Artificial Intelligence

- Artificial Intelligence (AI) is the ability of a digital system to perform tasks commonly associated with intelligent beings.

- Strong AI
  - Intelligent machines with consciousness, sentience and mind that could perform any intellectual task that a human being can

- Weak / Narrow / Applied AI
  - Machine intelligence that is focused on fulfilling a narrow task

  - Computer programs that given their specific knowledge-base can come to rational decisions with the best or – in case of uncertainty – best expected outcome



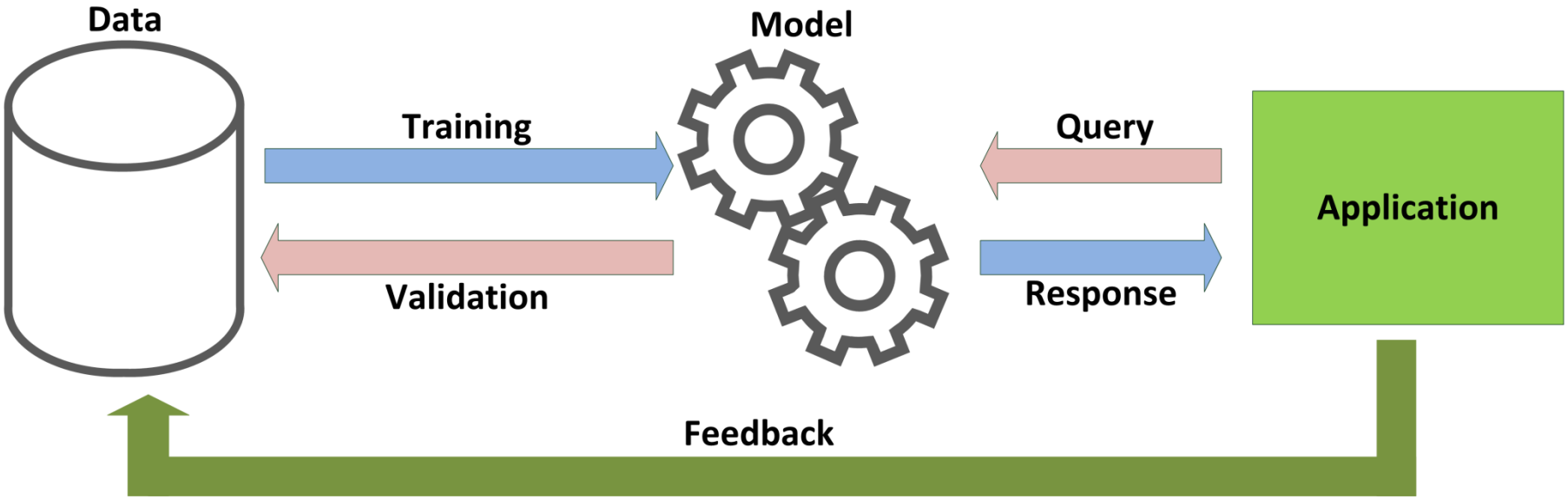
Artificial Intelligence – Problem Domains

- **Knowledge Representation**
  - Representing knowledge about the world (a model thereof) such that a computer can efficiently read and process it
- **Perception**
  - Deduce aspects of the world given sensor input (NLP, Computer Vision, …)
- **Reasoning**
  - Generate conclusions from available knowledge using logic (and probability)
- **Planning**
  - Finding and realizing strategies for reaching a certain goal or maximizing the utility
- **Learning**
  - Improving an algorithm’s performance through experience

Machine Learning

A computer program is said to learn from experience E with respect to some class of tasks T and performance measure P if its performance at tasks in T, as measured by P, improves with experience E.

Tom M. Mitchell



Machine Learning (continued)

	Supervised	Unsupervised
Approach	Knowledge-based	Data-based
Training	Labeled data	Preprocessed data
System Insight	Semantic analysis	Pattern-based analysis
Modeling	High manual effort	Limited search space
Extrapolation	Weak	Strong
Verification	Manageable	Very difficult

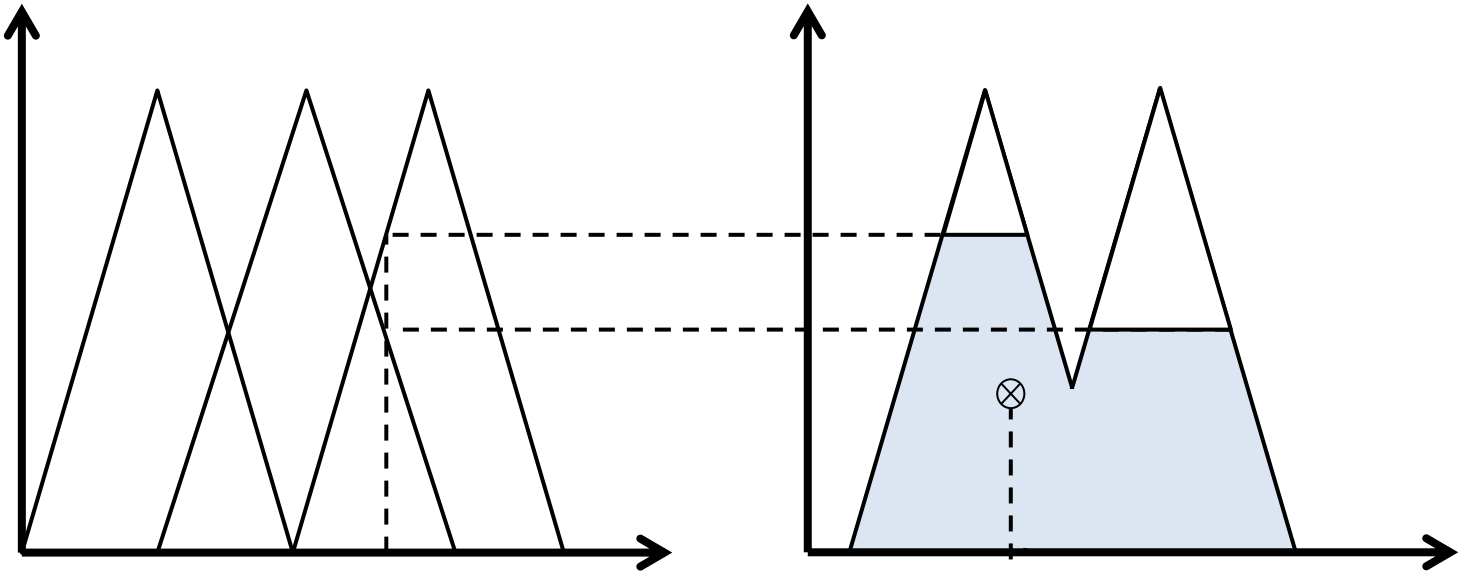
Ideally, a combined system using a shallow unsupervised analysis and deep supervised diagnostics would be advisable!

Machine Learning (continued)

- **Classification**
  - Prediction of a discrete number (i.e. classes) given a number of characteristical features
  - Examples:
    - Image recognition
- **Regression**
  - Prediction of a continuos number given an input vector
  - Examples
    - Telemetry forecasting
- **Clustering**
  - Grouping datasets such that datasets from the same group share certain similarities
  - Examples:
    - Image segmentation
- **Dimensionality Reduction**
  - Feature selection and projection
  - Examples:
    - Efficient encoding, feature extraction

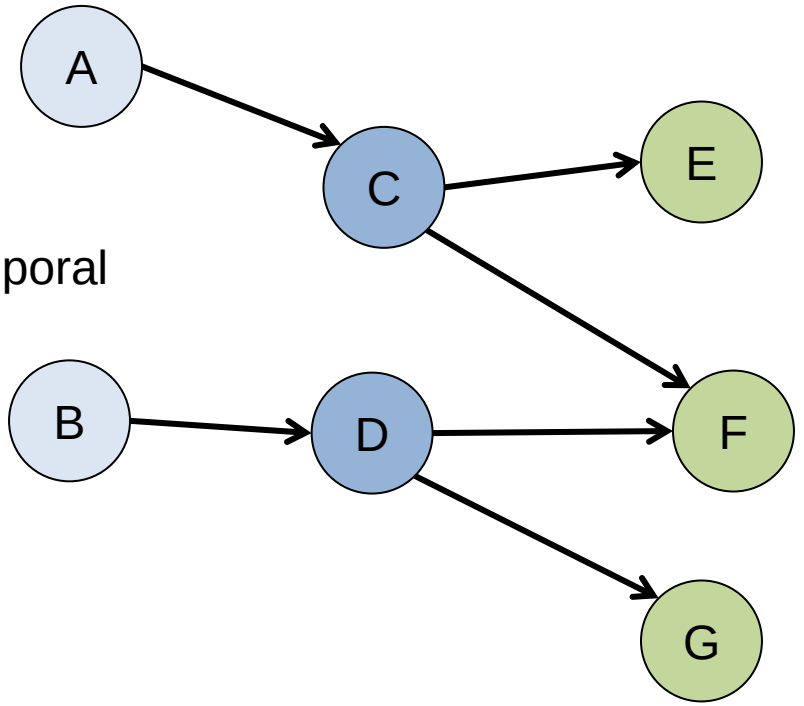
Fuzzy Logic

- Fuzzyfication: Affiliation to fuzzy sets instead of sharp value
- Fuzzy relations: AND, OR, NOT
- Fuzzy inference on a IF-THEN rule base
- Defuzzification: Center of gravity of the resulting surface



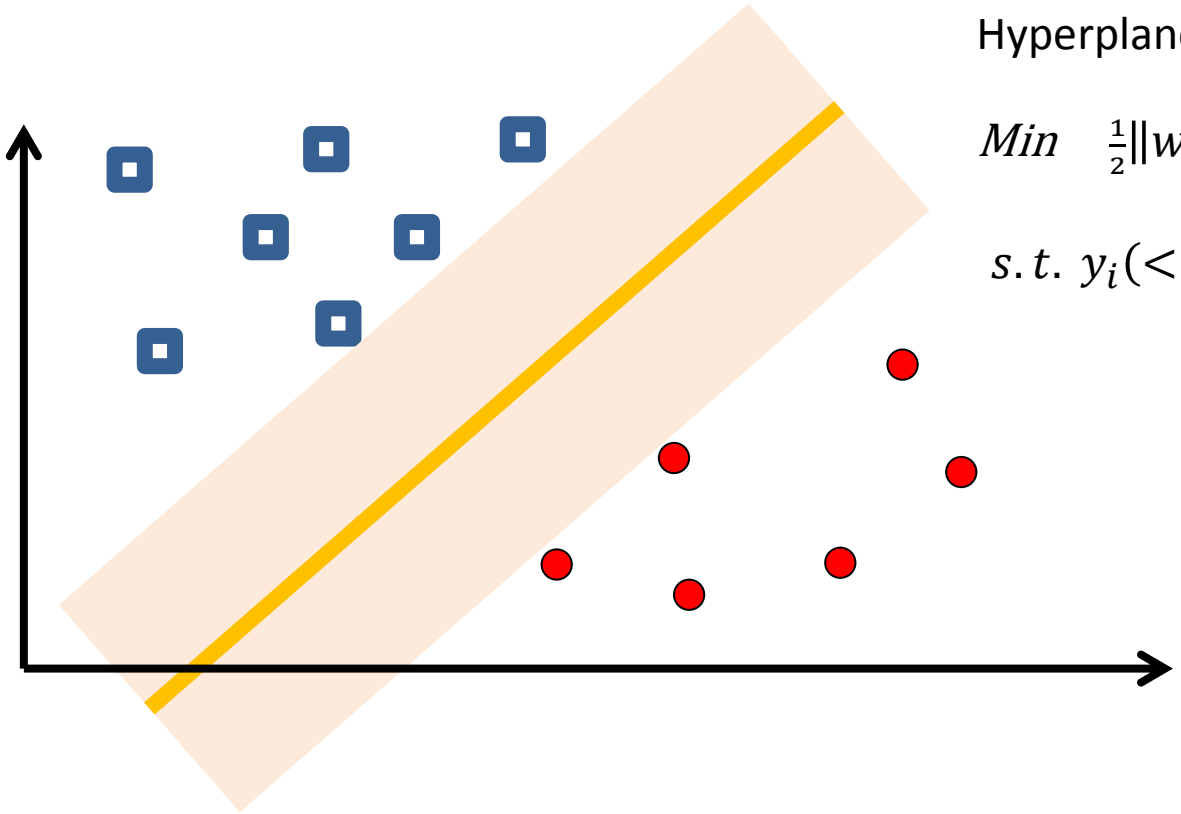
Bayesian Networks

- Graphical represenation of dependencies between statistical variables in a cause-effect fashion
- Answers queries such as $\Pr(A = True \mid E = True, F = False)$
- Parameter Learning
- Structure Learning
- Dynamic Bayesian Networks to model temporal dependencies



Support Vector Machines (SVM)

- Given a set of labeled training data $(\overrightarrow{x_i}, y_i), y_i \in \{-1,1\}$, an SVM calculates a hyperplane seperating the data with the widest margin possible
- Transformation to higher dimensions is possible using kernels



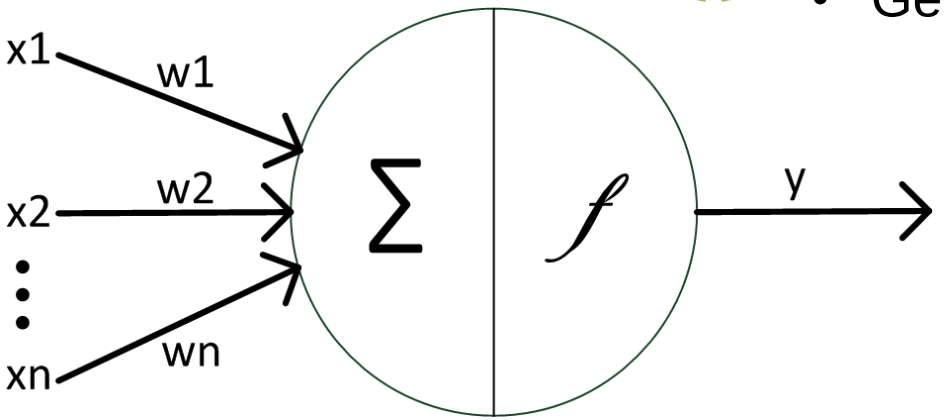
Hyperplane: $< w, x > + b = 0$

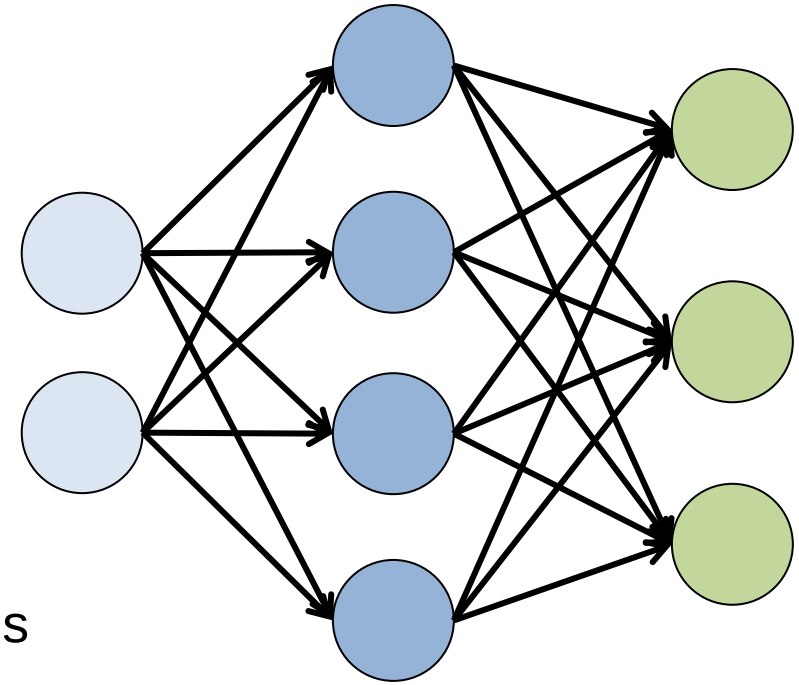
$Min \quad \frac{1}{2}\|w\|_2^2$

$s.t.\ y_i(< w, x_i > + b) \geq 1$

Artificial Neural Networks

- No inherent system knowledge
- Strong in pattern and feature recognition
- Generalization

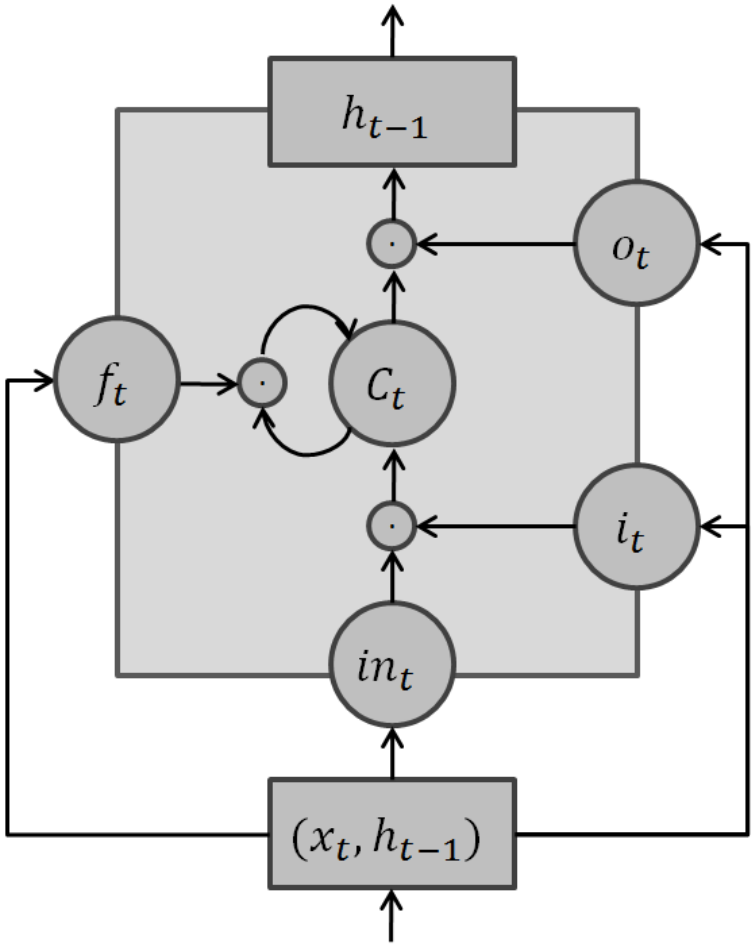




- Large amounts of training data
- Overfitting
- Verification is extremely hard
- Highly dependent on initial values

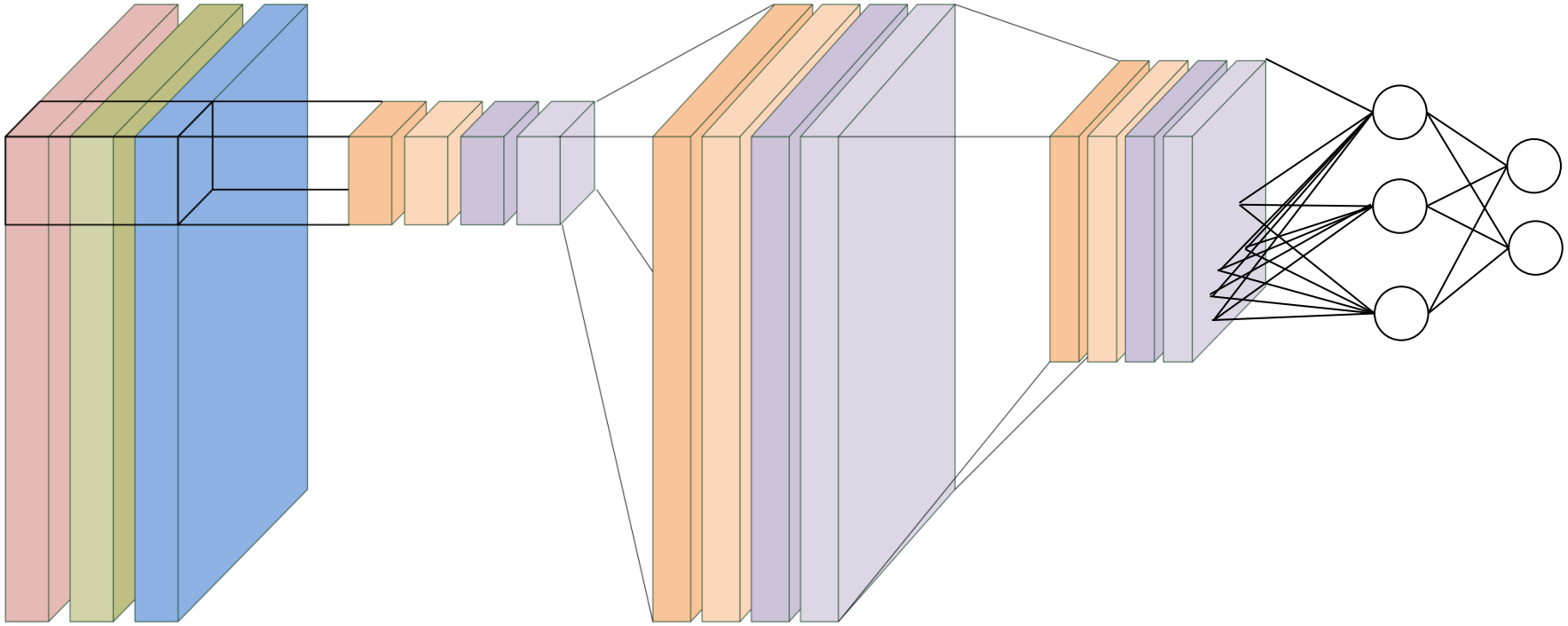
Artificial Neural Networks - LSTM

- Long Short-Term Memories
- Temporal dependencies through state-keeping
- No vanishing or explosion of gradients during backpropagation
- Applications in speec recognition and time series analysis



Artificial Neural Networks - CNN

- Convolutional Neural Networks
- Applications in Image Recognition



RGB Image

Convolution – Filters

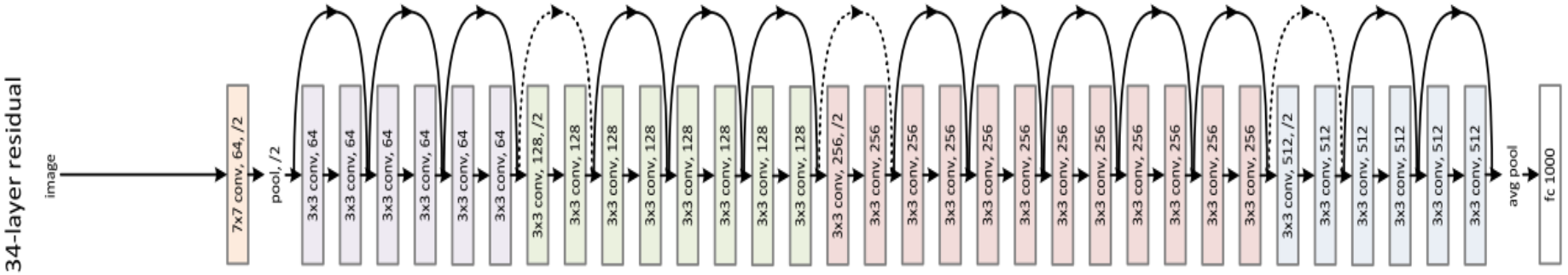
Excitation Matrices

Pooling

FC-Layer(s)

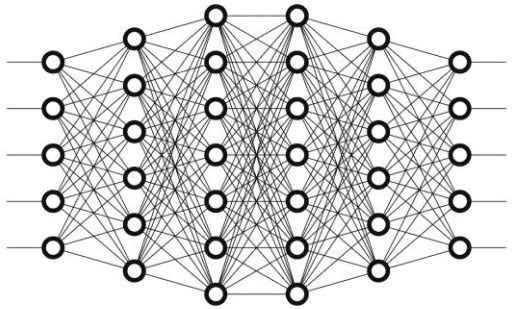
Image Recognition - State of the Art (continued)

- ResNet (ImageNet competition winner in 2015) superseded human performance in image classification



- 3.6 Billion FLOPS
  - Infeasible for almost all on-board satellite systems
  - Hardware-acceleration desirable, even for small models

Research Focus at DLR's Institute of Space Systems



- Self-Aware Spacecraft
  - State Estimation
  - Anomaly Detection and Telemetry Selection
  - On-Board Machine Learning

- On-Board Autonomy
  - Fault Detection Isolation and Recovery
  - Goal-based Planning and Scheduling
  - Optimized Payload Operations

- Payload Processing
  - On-board analysis of multidimensional data

[Google TPU]

- Hardware Acceleration for Tensor Processing and Neural Networks
  - Heterogeneous systems
  - IP cores

Thank You!