

Machine Learning

Artificial Intelligence

What is ML?

Definition

- Arthur Samuel (1959)
 - “field of study that gives computers the ability to learn without being explicitly programmed”
- Herbert Simon (1970)
 - “Learning is any process by which a system improves performance from experience.”
- Tom Mitchell (1998)
 - “a well-posed learning problem is defined as follows: He says that a computer program is set to learn from an experience E with respect to some task T and some performance measure P if its performance on T as measured by P improves with experience E”
- Ethem Alpaydin (2010)
 - Programming computers to optimize a performance criterion using example data or past experience.

Necessity

- Better computational systems
 - Too difficult or too expensive to be constructed manually
 - Systems that automatically adapt
 - Spam filters
 - Systems that discover information in large database → data mining
 - Financial analysis
 - Text/image analyses
- Understanding the biological systems

How to design a ML?

- Improve of task **T**
 - Establish the goal (what has to be learned) – ***objective function*** – and its ***representation***
 - Select a learning algorithm to perform the inference of the goal based on experience
- Respect a performance metric **P**
 - Evaluation of the algorithm's performances
- Based on experience **E**
 - Select an experience database

Examples:

- T: playing checkers
- P: percent of winning games
- E: playing the game
- T: handwritten recognition
- P: percent of correct recognized words
- E: database of images with different words
- T: separate the spams
- P: percent of correct classified emails
- E: databases with annotated emails

Objective Function

What is the function that must be learned?

Ex.: checkers game → a function that:

Selects the next move

Evaluates a move

In order to identify the best next move

Representation of objective function

Different representations:

- Table
- Symbolic rules
- Numeric functions
- Probabilistic functions

There is a trade-off between

- How expressive is meaning of the representation
- Easy of learning

Objective function computation

- Polynomial time
- Non-polynomial time

Ex. for checkers game

A linear combination of `#white_pieces`, `#black_pieces`,
`#white_compromised_pieces`,
`#black_compromised_pieces`

The Learning Algorithm

Selection

- According to the training data
- Induce the hypothesis definition that
 - Match the data
 - Generalize the unseen data
- Main principle
 - Error minimisation (cost function – loss function)

Evaluation

Experimental

- By comparing different methods on different data (cross-validation)
- Collect data based on performances
 - Accuracy, training time, testing time
- Statistical analyse of the differences

Theoretic

- Mathematical analyse of algorithms and theorem proving
 - Computational complexity
 - Ability to match the training data
 - Complexity of the most relevant sample for learning

Comparison between 2 algorithms

Performance measures

- Parameters of a statistic series
- Proportion (percent) computed for a statistical series (ex. Accuracy)

Comparing based on confidence intervals

- For a problem and 2 solving algorithms with performances p_1 and p_2
- Confidence intervals
 $I_1 = [p_1 - \Delta_1, p_1 + \Delta_1]$ and $I_2 = [p_2 - \Delta_2, p_2 + \Delta_2]$
- If $I_1 \cap I_2 = \emptyset \rightarrow$ algorithm 1 works better than algorithm 2 (for the given problem)
- if $I_1 \cap I_2 \neq \emptyset \rightarrow$ impossible to decide

Confidence interval for the mean (average)

- For a statistical series of n data, with computed mean m and dispersion σ , determine the confidence interval of the mean μ
- $P(-z \leq (m-\mu)/(\sigma/\sqrt{n}) \leq z) = 1 - \alpha \rightarrow \mu \in [m - z\sigma/\sqrt{n}, m + z\sigma/\sqrt{n}]$
- $P = 95\% \rightarrow z = 1.96$

Confidence interval for accuracy

- For an accuracy p computed for n data, determine the confidence interval of accuracy
- $p \in [p - z(p(1-p)/n)^{1/2}, p + z(p(1-p)/n)^{1/2}]$
- $P = 95\% \rightarrow z = 1.96$

$P=1-\alpha$	z
99.9%	3.3
99.0%	2.577
98.5%	2.43
97.5%	2.243
95.0%	1.96
90.0%	1.645
85.0%	1.439
75.0%	1.151

Training database

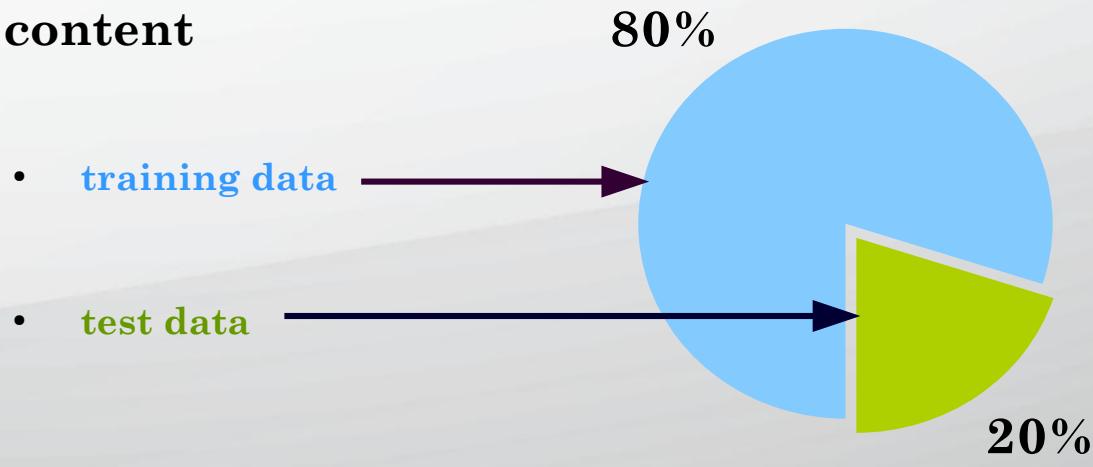
choose the training database based on:

- direct experience
 - pairs (in, out) that are useful for the objective function
 - eg. checkers game → board game annotated by correct or incorrect move
- indirect experience
 - useful feedback (unlike i/o pairs) for the objective function
 - eg. checkers game → sequences of moves and the final score of the game

data sources

- random generated examples
 - positive and negative examples
- positive examples collected by a learner
- real examples

content



characteristics

- independent data
 - otherwise → collective learning
- training and testing data must respect the same distribution law
 - otherwise → *transfer learning/inductive transfer*
 - vehicle recognition → truck recognition
 - text analyses
 - spam filters

Training database

characteristics extracted (attributes) from raw data

- quantitative characteristics → nominal or rational scale
 - continuous values → weight
 - discrete values → # of computers
 - range values → event times
- qualitative characteristics
 - nominal → colour
 - ordinal → sound intensity (low, medium, high)
- structured
 - trees – root is a generalisation of children (vehicle → car, bus, tractor, truck)

data transformation

- standardisation → numerical attributes
 - remove the scale effect (different scale and units)
 - raw values are transformed in z scores
- $Z_{ij} = (x_{ij} - \mu_j)/\sigma_j$, where x_{ij} – value of j^{th} attribute of i^{th} instance, μ_j (σ_j) is the mean (standard deviation) of j^{th} attribute for all instances
- selection of some attributes

ML classification – goal oriented

Intelligent systems for prediction

Aim: predict the output for a new input based on a previously learned model

Eg. predicting sales of a product for a time in the future based on price, calendar month, region, average income

Intelligent systems for regression

Aim: estimation of the (uni or multi variable) function's shape based on a previously learned model

Eg.: estimate the function that models the edge of a surface

Intelligent systems for classification

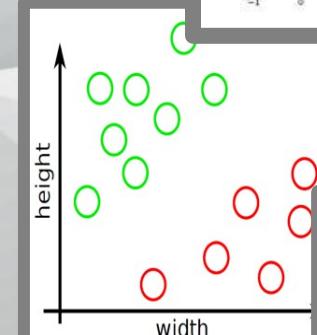
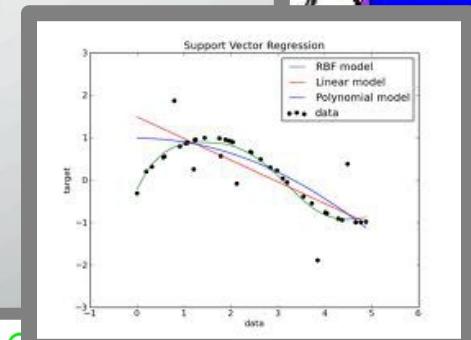
Aim: classify an object into one or more – known or unknown - categories based on their characteristics

Eg.: diagnostic systems for cancer: malign or benign or normal

Intelligent systems for planning

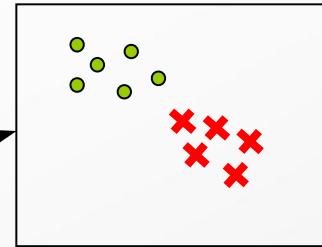
Aim: generate a sequence of optimal actions for performing a task

Eg.: planning the moves of a robot from a position to a source of energy



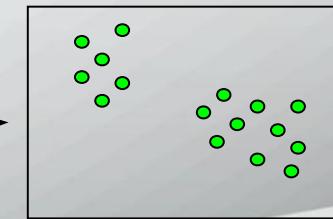
ML classification – based on learning experience

- Intelligent systems with supervised learning



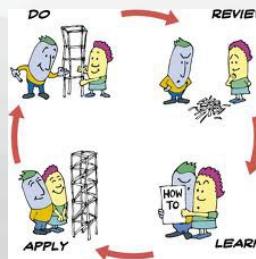
data is labeled

- Intelligent systems with unsupervised learning

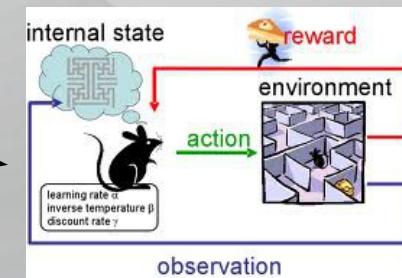


data is not labeled

- Intelligent systems with active learning



- Intelligent systems with reinforcement learning



Supervised learning

Aim

to provide a correct output for a new input

Definition

for a given data set (examples, instances, cases)

- training data – pairs ($attribute_data_i, output_i$), where
 - $i = 1, N$ (N = number of training data pairs)
 - $attribute_data_i = (atr_{i1}, atr_{i2}, \dots, atr_{im})$, m – number of attributes (characteristics, properties) for one data
 - $output_i$
 - a category from a predefined given set with k elements (number of classes) → classification problem
 - a real number → regression problem
- teste data – a set ($attribute_data_i$), $i = 1, n$ (n = number of test pairs).

determine

- a function (unknown) that maps the input attributes to the output on the training data set
- the output (class/value) associated with the test data (new) using the detected function

Other names

classification (regression), inductive learning

Process → 2 steps

- **Training**

learning the classification model – using an algorithm

- **Testing**

test the model with new data (not seen in the training step)

Feature

DB is labeled (for learning and sometimes also for testing)

Suitable problem types

- regression, classification

Supervised learning learning quality

We consider a performance measure for the algorithm that is evaluated during both steps, training and testing, separately.

ex. accuracy (Acc = number of samples correctly classified / total number of samples)

Evaluation Methods

for a large dataset	for a small dataset	for a very small dataset
disjunctive sets for training and testing	cross validation with h equal sub sets of the dataset	leave one out cross validation

Difficulties: **over-fitting** – good performance on training data but very poor on testing data

Performance measures:

- statistical, efficiency, robustness, scalability, interpretability, compactness, ...

Statistical metrics

Classification Accuracy

- the ratio of number of correct predictions to the total number of input samples

$$Acc = \frac{TP + TN}{N}$$

– works well only if there are equal number of samples belonging to each class.

Confusion Matrix

describes the complete performance of the model.

		Reality	
		positiv class	negativ class
computed results	positiv class	True positiv (TP)	False positiv (FP)
	negativ class	False negative (FN)	True negative (TN)

Precision

- the number of correct positive results divided by the number of positive results predicted by the classifier.

$$Prec = \frac{TP}{TP + FP}$$

Recall

- the number of correct positive results divided by the number of all relevant samples

$$Recall = \frac{TP}{TP + FN}$$

F1 Score

- is the Harmonic Mean between precision and recall.
- the range for F1 Score is [0, 1]

$$F1 = 2 * \frac{1}{\frac{1}{Prec} + \frac{1}{Recall}}$$

- how precise your classifier is (how many instances it classifies correctly),
- how robust it is (it does not miss a significant number of instances).

Mean Squared Error

- is the average of the squares of the differences between the original values and the predicted values.

$$MeanSquaredError = \frac{1}{N} \sum_{i=1}^N (y_i - \hat{y}_i)^2$$

- it is easier to compute the gradient

Unsupervised learning

Aim

to detect a model or a internal util structure of the data

Definition

for a given data set (examples, instances, cases)

- training data – a set $\{attribute_data_i \mid i=1, N\}$ where
 - N = number of training data pairs
 - $attribute_data_i = (atr_{i1}, atr_{i2}, \dots, atr_{im})$, m – number of attributes (characteristics, properties) for one data
- teste data – a set $(attribute_data_j), i=1, n$ (n = number of test pairs).

determine

- an unknown function that groups the training data in several classes
 - the number of classes k can be predefined or unknown
 - the data from one class are similar
- the output is the class the new input data (new) using the detected function

Examples of distances

consider two points p and q from R^m

- Euclidean $d(p, q) = \sqrt{\sum_{j=1}^m (p_j - q_j)^2}$
- Manhattan $d(p, q) = \sum_{j=1}^m |p_j - q_j|$
- Mahalanobis – measures the distance between a point p and a distribution Q
- Internal product $d(p, q) = \sum_{j=1}^m p_j q_j$
- Cosine $d(p, q) = \sum_{j=1}^m p_j q_j / (\sqrt{\sum_{j=1}^m p_j^2} \sqrt{\sum_{j=1}^m q_j^2})$
- Hamming – number of differences between p and q
- Levenshtein – the minimum number of transformations necessary to change p in q

Distance vs. Similarity

Distance → min

Similarity → max

Unsupervised learning

Other names

- clustering

Process → 2 steps

- Training
 - learning (determine), using an algorithm, the existing clusters
- Testing
 - test the model with new data (not seen in the training step)

Feature

- DB is not labeled (for learning and sometimes also for testing)

Learning quality

Suitable problem types

- Identifying some classes (clusters)
 - Genome analysis
 - Image processing
 - Social network analysis
 - Market segmentation
 - Astronomic data analysis
 - Computer clustering
- Dimensional reduction
- Identifying data properties (causes, explanations, etc.)
- Modeling data density

Internal criteria – high similarity within a cluster and reduced one between clusters

- distance inside the cluster
 - distance between the clusters
 - Davies-Bouldin index
 - Dunn Index
- External criteria – using benchmarks made from already grouped data sets
- Comparison with known data – almost impossible in practice
 - Precision
 - Recall
 - F1-measure

Active learning

The algorithm can receive supplementary information during the learning step in order to improve it's performance.

Example: what is the subset of the training data that will facilitate the learning process.

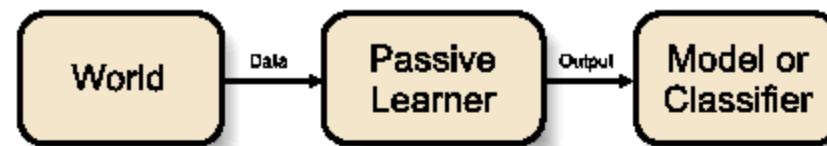


Figure 1.1: General schema for a passive learner.



Figure 1.2: General schema for an active learner.

Reinforcement learning

Aim

Learning, over a period of time, a course of action (behavior) that maximizes long-term rewards (earnings)

Characteristic

Interaction with the environment (actions → rewards)
Decision sequence

Problems' type

Ex. Training a Dog (Good and Bad Dog)

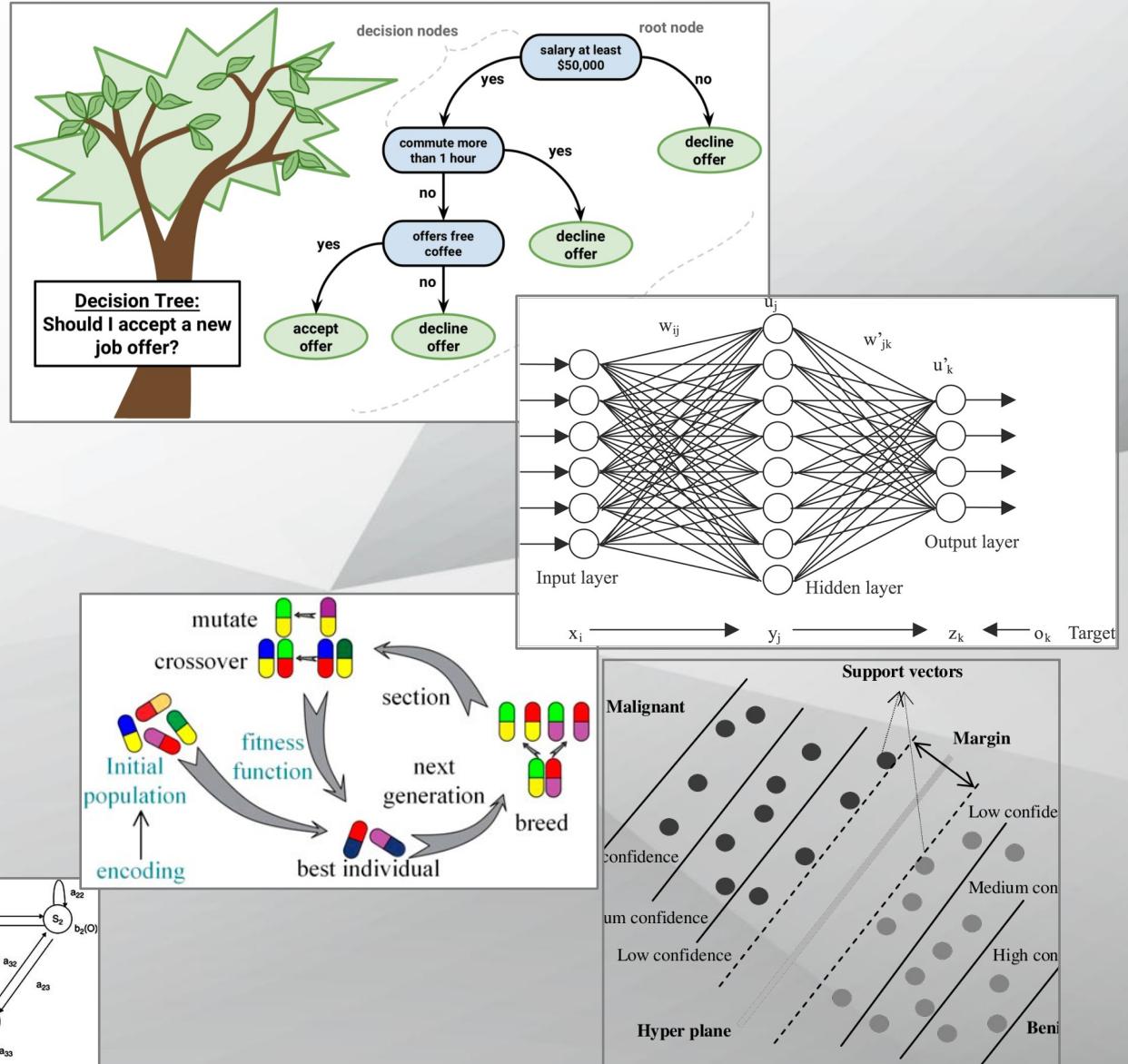
Supervised learning

Decision → consequence (malignant or benign cancer)

Intelligent Systems

Based on algorithm

- Decision trees
- Artificial Neural Networks
- Evolutionary algorithms
- Support Vector Machines
- Hidden Markov Models



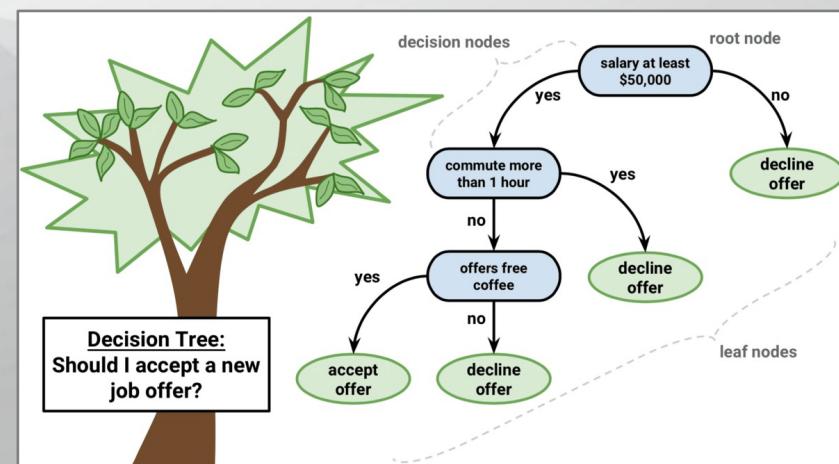
Decision Trees (DT)

Aim

- divide a collection of articles in smaller sets by successively applying some decision rules → asking more questions
 - each question is addressed based on the answer of the previous question
 - elements are characterized by non-metric information

Definition

- Decision tree – a special graph (bi-color and oriented tree)
 - Contains three node types:
 - Decision nodes → possibilities of decider (a test on an attribute of item that must be classified)
 - Hazard nodes → random events outside the control of decider (exam results, therapy consequences)
 - Result nodes → final states that have a utility or a label
 - Decision and hazard nodes alternate on the tree levels
 - Result nodes → leaf (terminal nodes)
 - (oriented) edges of the tree consequences of decisions (can be probabilistic)
 - Each internal node corresponds to an attribute
 - Each branch under a node (attribute) corresponds to the value of that attribute
 - Each leaf corresponds to a class



Problems solved with DT

Properties

- problem's instances are represented by a fixed number of attributes, each attribute having a finite number of values;
- objective function takes discrete values;
- DT represents a dis-junction of more conjunctions, each conjunction being “attribute a_i has value v_j ”;
- training data could contain errors;
- training data could be incomplete;
 - Some data have not all attributes.

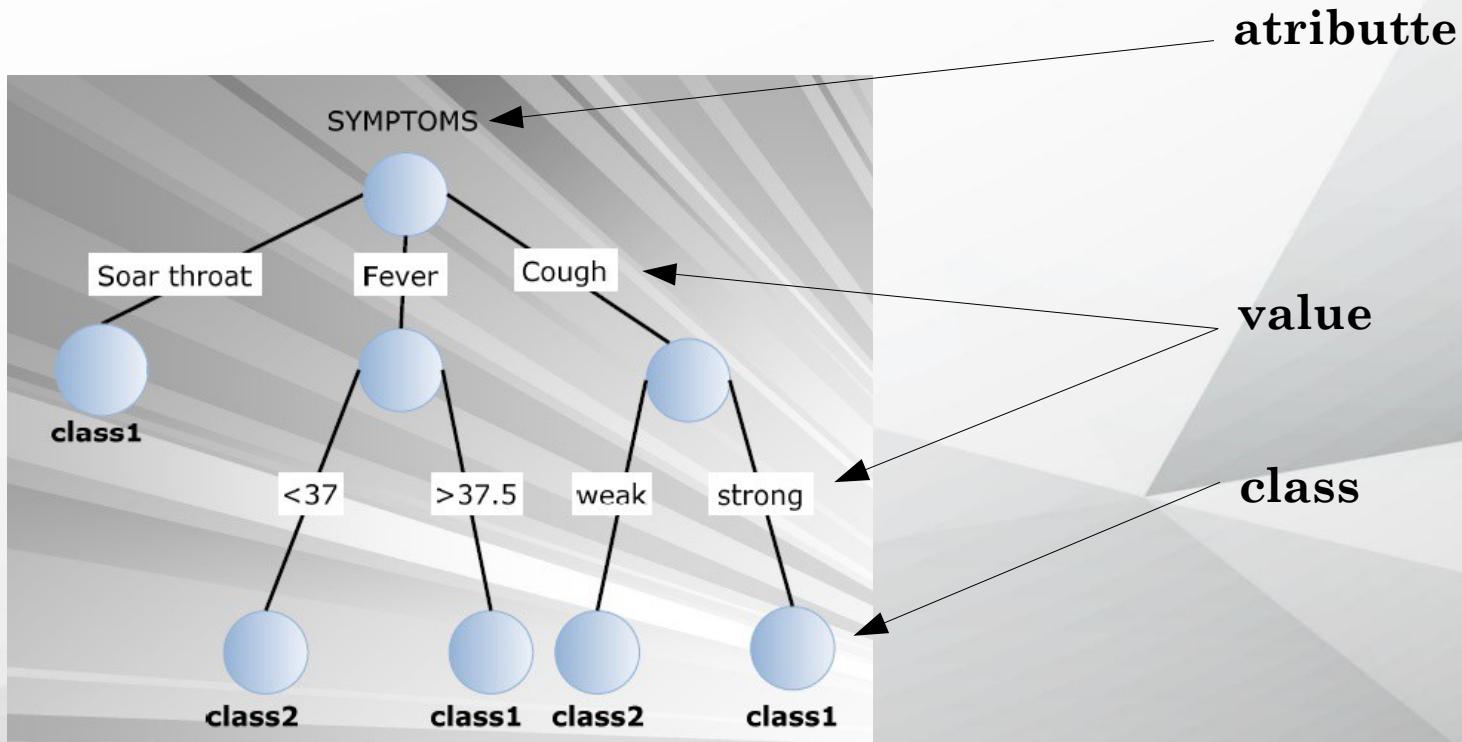
Classification problem

- Binary classifications
 - Instances are $[(attribute_{ij}, value_{ij}), class_i], i=1,2,\dots,n, j=1,2,\dots,m$, and $class_i$ taking 2 values;
- Multi-class (k-class)
 - Instances are $[(attribute_{ij}, value_{ij}), class_i], i=1,2,\dots,n, j=1,2,\dots,m$, and $class_i$ taking k values;

Regression problems

- instead to label each node by the label of a class, each node has associated a real value or a function that depends on the inputs of that node;
- input space is split in decision regions by parallel cuttings to Ox and Oy ;
- discrete outputs are transformed in continuous functions;
- quality of problem solving:
 - Prediction error (square or absolute)

Examples of DT



Example of train data for DT

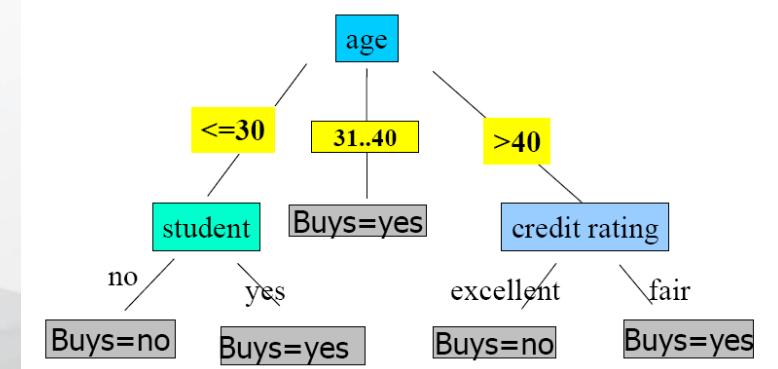
Credits

Approved or not

ID	Age	Has_Job	Own_House	Credit_Rating	Class
1	young	false	false	fair	No
2	young	false	false	good	No
3	young	true	false	good	Yes
4	young	true	true	fair	Yes
5	young	false	false	fair	No
6	middle	false	false	fair	No
7	middle	false	false	good	No
8	middle	true	true	good	Yes
9	middle	false	true	excellent	Yes
10	middle	false	true	excellent	Yes
11	old	false	true	excellent	Yes
12	old	false	true	good	Yes
13	old	true	false	good	Yes
14	old	true	false	excellent	Yes
15	old	false	false	fair	No

Examples of DT

rec	Age	Income	Student	Credit_rating	Buys_computer(CLASS)
r1	<=30	High	No	Fair	No
r2	<=30	High	No	Excellent	No
r3	31...40	High	No	Fair	Yes
r4	>40	Medium	No	Fair	Yes
r5	>40	Low	Yes	Fair	Yes
r6	>40	Low	Yes	Excellent	No
r7	31...40	Low	Yes	Excellent	Yes
r8	<=30	Medium	No	Fair	No
r9	<=30	Low	Yes	Fair	Yes
r10	>40	Medium	Yes	Fair	Yes
r11	<=30	Medium	Yes	Excellent	Yes
r12	31...40	Medium	No	Excellent	Yes
r13	31...40	High	Yes	Fair	Yes
r14	>40	Medium	No	Excellent	No



Process – DT

Tree construction (induction)

Based on training data

Works bottom-up or top-down (splitting)

Using the tree as a problem solver

All decisions performed along a path
from the root to a leaf form a rule

Rules from DT are used for labeling
new data

Pruning

Identify and move/eliminate branches
that reflect noise or exceptions

Tree construction

Split the training data into subsets based on the characteristics of data

a node – question related to a property

branches of a node – possible answers to the question of the node

initially, all examples are located in the root

- an attribute gives the root label and its values give the branches

on next levels, examples are partitioned based on their attributes → order of attributes

- for each node, an attribute is (recursively) chosen – its values → branches

splitting – greedy decision making

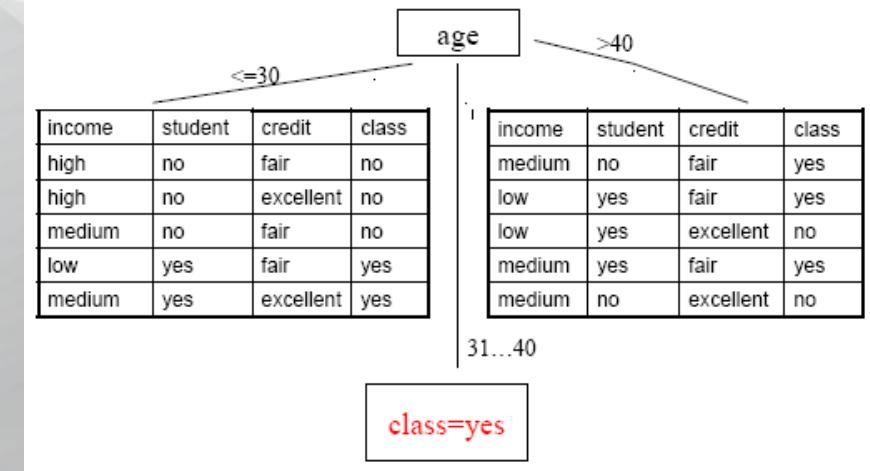
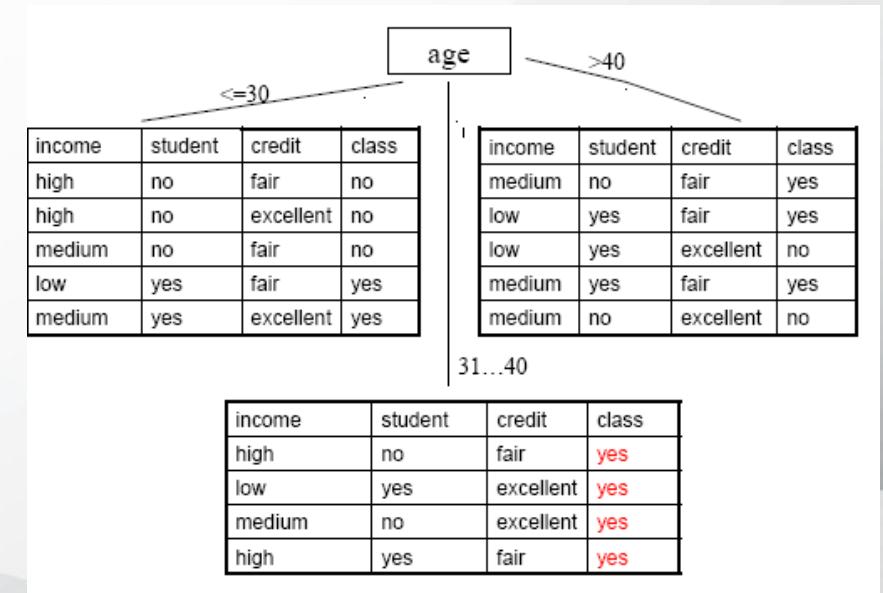
Iterative process

stop conditions:

- all examples from a node belong to the same class → node is a leaf and is labeled by $class_i$
- there are no left examples → node becomes a leaf and is labeled by the majority class of training data
- there are no attributes

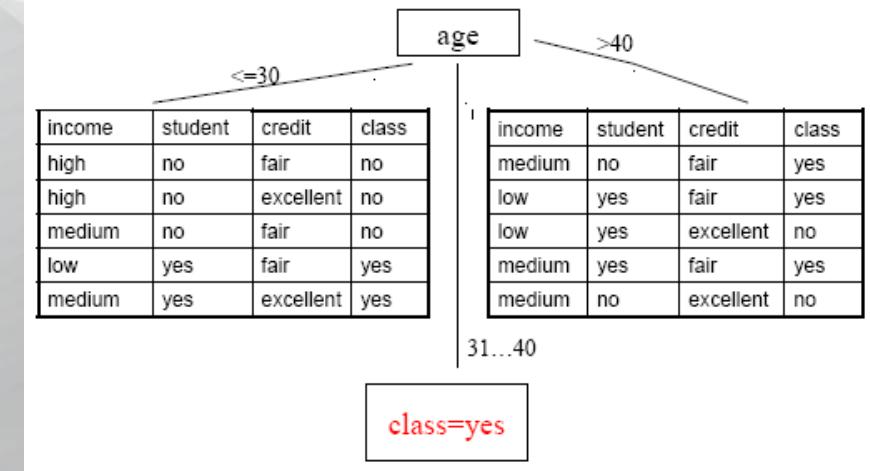
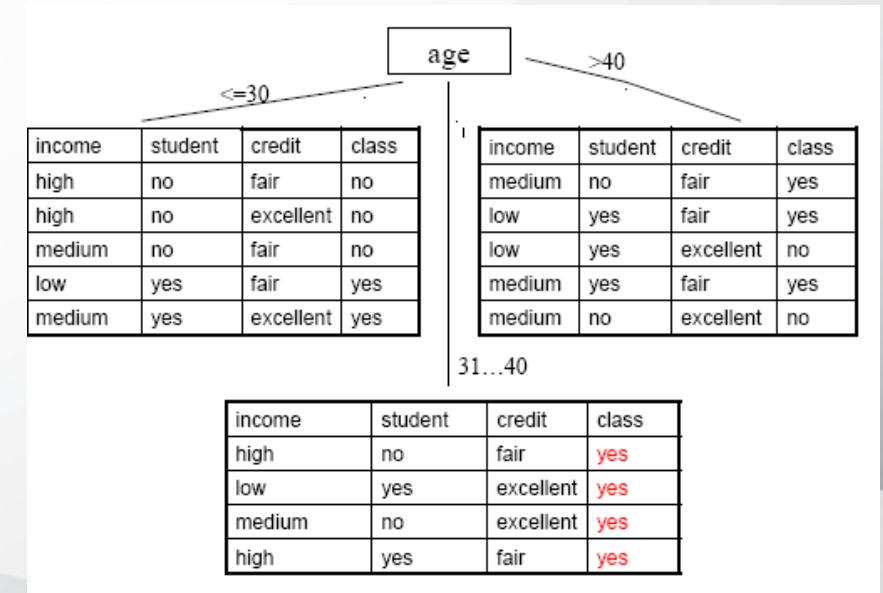
Example – tree construction

rec	Age	Income	Student	Credit_rating	Buys_computer(CLASS)
r1	<=30	High	No	Fair	No
r2	<=30	High	No	Excellent	No
r3	31...40	High	No	Fair	Yes
r4	>40	Medium	No	Fair	Yes
r5	>40	Low	Yes	Fair	Yes
r6	>40	Low	Yes	Excellent	No
r7	31...40	Low	Yes	Excellent	Yes
r8	<=30	Medium	No	Fair	No
r9	<=30	Low	Yes	Fair	Yes
r10	>40	Medium	Yes	Fair	Yes
r11	<=30	Medium	Yes	Excellent	Yes
r12	31...40	Medium	No	Excellent	Yes
r13	31...40	High	Yes	Fair	Yes
r14	>40	Medium	No	Excellent	No



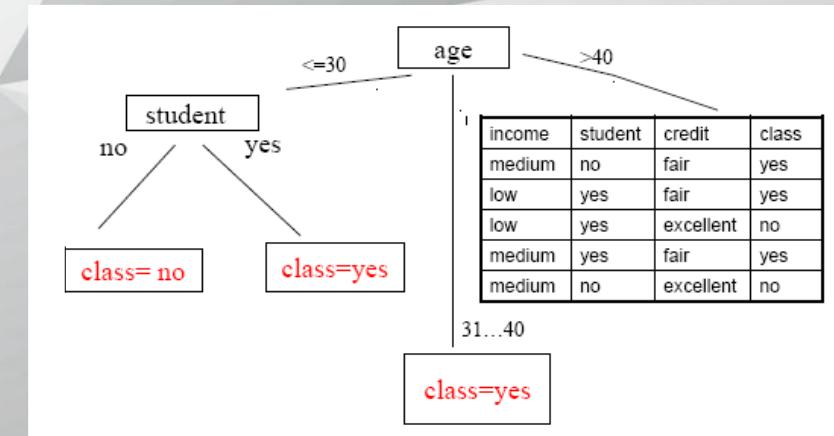
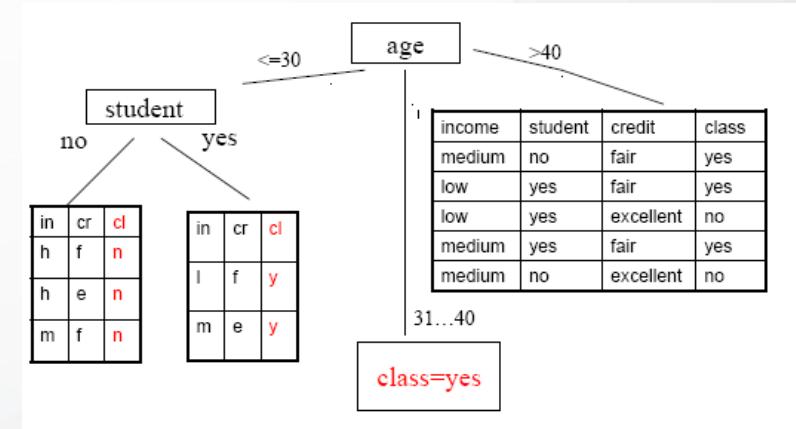
Example – tree construction

rec	Age	Income	Student	Credit_rating	Buys_computer(CLASS)
r1	<=30	High	No	Fair	No
r2	<=30	High	No	Excellent	No
r3	31...40	High	No	Fair	Yes
r4	>40	Medium	No	Fair	Yes
r5	>40	Low	Yes	Fair	Yes
r6	>40	Low	Yes	Excellent	No
r7	31...40	Low	Yes	Excellent	Yes
r8	<=30	Medium	No	Fair	No
r9	<=30	Low	Yes	Fair	Yes
r10	>40	Medium	Yes	Fair	Yes
r11	<=30	Medium	Yes	Excellent	Yes
r12	31...40	Medium	No	Excellent	Yes
r13	31...40	High	Yes	Fair	Yes
r14	>40	Medium	No	Excellent	No



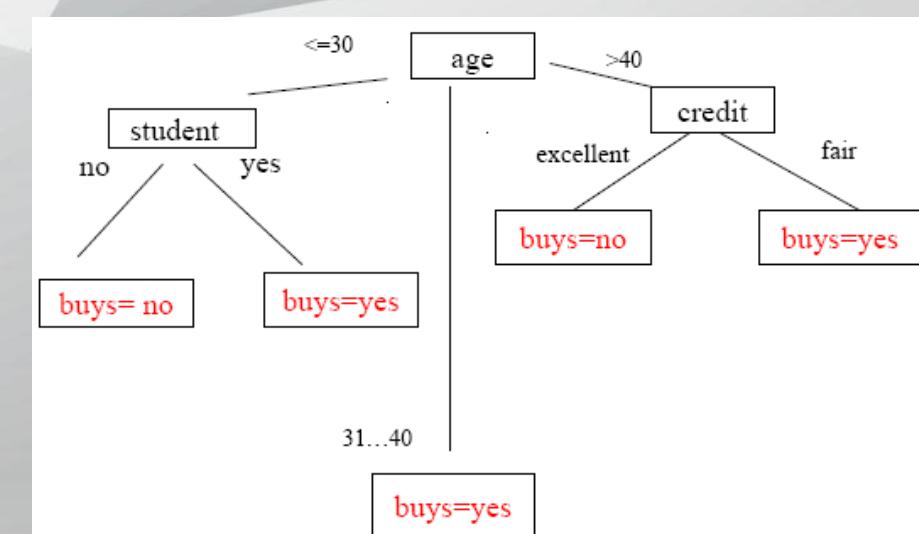
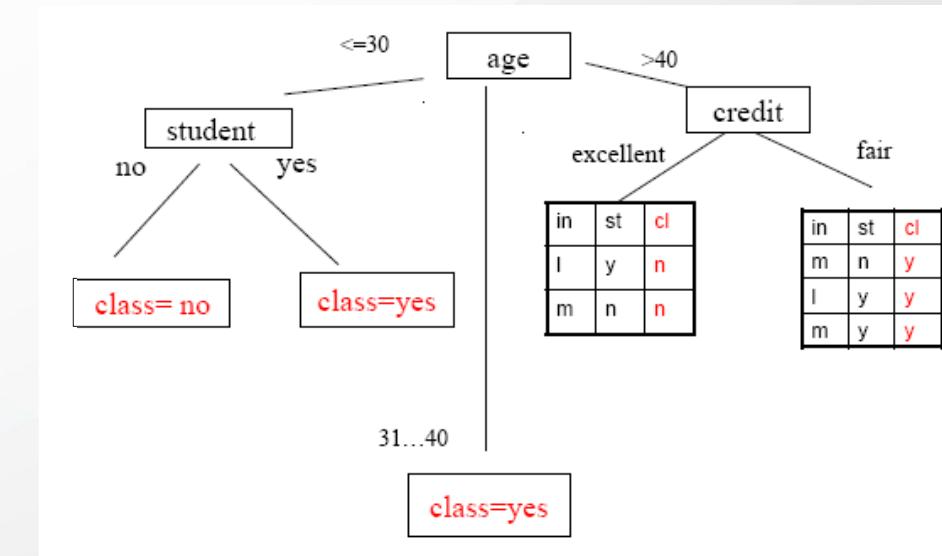
Example – tree construction

rec	Age	Income	Student	Credit_rating	Buys_computer(CLASS)
r1	<=30	High	No	Fair	No
r2	<=30	High	No	Excellent	No
r3	31...40	High	No	Fair	Yes
r4	>40	Medium	No	Fair	Yes
r5	>40	Low	Yes	Fair	Yes
r6	>40	Low	Yes	Excellent	No
r7	31...40	Low	Yes	Excellent	Yes
r8	<=30	Medium	No	Fair	No
r9	<=30	Low	Yes	Fair	Yes
r10	>40	Medium	Yes	Fair	Yes
r11	<=30	Medium	Yes	Excellent	Yes
r12	31...40	Medium	No	Excellent	Yes
r13	31...40	High	Yes	Fair	Yes
r14	>40	Medium	No	Excellent	No



Example – tree construction

rec	Age	Income	Student	Credit_rating	Buys_computer(CLASS)
r1	<=30	High	No	Fair	No
r2	<=30	High	No	Excellent	No
r3	31...40	High	No	Fair	Yes
r4	>40	Medium	No	Fair	Yes
r5	>40	Low	Yes	Fair	Yes
r6	>40	Low	Yes	Excellent	No
r7	31...40	Low	Yes	Excellent	Yes
r8	<=30	Medium	No	Fair	No
r9	<=30	Low	Yes	Fair	Yes
r10	>40	Medium	Yes	Fair	Yes
r11	<=30	Medium	Yes	Excellent	Yes
r12	31...40	Medium	No	Excellent	Yes
r13	31...40	High	Yes	Fair	Yes
r14	>40	Medium	No	Excellent	No



ID3/C4.5 algorithm

```
generate(D, A){    //D – a partitioning of training data, A – list of attributes
    create a new node N
    if examples from D belong to a single class C then
        node N becomes a leaf and is labeled by C
        return node N
    else
        if A=∅ then
            node N becomes a leaf and is labeled by majority class of D
            return node N
        else
            separation_attribute = AttributeSelection(D, A)
            label node N by separation_attribute
            for all possible values vj of separation_attribute
                let Dj – set of examples from D that have separation_attribute=vj
                if Dj =∅ then
                    add a leaf (to node N) labeled by majority class of D
                else
                    add a node (to node N) return by generate(Dj, A–separation_attribute)
            return node N
}
```

Greedy, recursive, top-down, divide-and-conquer

AttributeSelection(D,A)

selects the attribute that corresponds to a node (root or internal node)

- Random
- Attribute with the fewest/most values
- Based on a pre-established order:
- Information gain
 - Gain rate
 - Distance between partitions created by the attribute

Information gain

An impurity measure

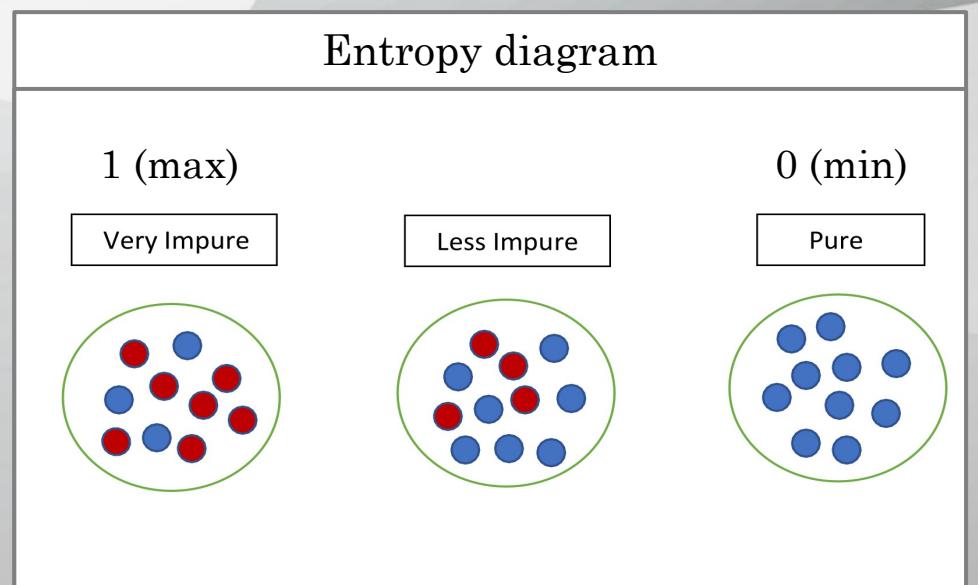
- 0 (minim) – if all examples belong to the same class
- 1 (maxim) – if examples are uniform distributed over classes

Based on data entropy

- Expected number of bits required by coding the class of an element from data
- Binary classification (2 classes): $E(S) = -p_+ \log_2 p_+ - p_- \log_2 p_-$, where
 - p_+ - proportion of positive examples in dataset S
 - p_- - proportion of negative examples in dataset S
- Multi-class classification: $E(S) = \sum_{i=1, 2, \dots, k} -p_i \log_2 p_i$
 - data entropy related to target attribute (output attribute), where
 - p_i – proportion of examples from class i in dataset S

Information gain of an attribute

- How the elimination of attribute a reduces the dataset's entropy
- $Gain(S, a) = E(S) - \sum_{v \in \text{values}(a)} |S_v| / |S| E(S_v)$
- $\sum_{v \in \text{values}(a)} |S_v| / |S| E(S_v)$ – expected information



Example – Information gain

	a1	a2	a3	Class
d1	big	red	circle	class 1
d2	small	red	square	class 2
d3	small	red	circle	class 1
d4	big	blue	circle	class 2

$$S = \{d_1, d_2, d_3, d_4\} \Rightarrow p_+ = \frac{2}{4}, p_- = \frac{2}{4} \Rightarrow E(S) = -p_+ \log_2 p_+ - p_- \log_2 p_- = 1$$

$$S_{v=\text{big}} = \{d_1, d_4\} \Rightarrow p_+ = \frac{1}{2}, p_- = \frac{1}{2} \Rightarrow E(S_{v=\text{big}}) = 1$$

$$S_{v=\text{small}} = \{d_2, d_3\} \Rightarrow p_+ = \frac{1}{2}, p_- = \frac{1}{2} \Rightarrow E(S_{v=\text{small}}) = 1$$

$$S_{v=\text{red}} = \{d_1, d_2, d_3\} \Rightarrow p_+ = \frac{2}{3}, p_{\text{minus}} = \frac{1}{3} \Rightarrow E(S_{v=\text{red}}) = 0.923$$

$$S_{v=\text{blue}} = \{d_4\} \Rightarrow p_+ = 0, p_- = 1 \Rightarrow E(S_{v=\text{blue}}) = 0$$

$$S_{v=\text{circle}} = \{d_1, d_3, d_4\} \Rightarrow p_+ = \frac{2}{3}, p_{\text{minus}} = \frac{1}{3} \Rightarrow E(S_{v=\text{circle}}) = 0.923$$

$$S_{v=\text{square}} = \{d_4\} \Rightarrow p_+ = 0, p_- = 1 \Rightarrow E(S_{v=\text{square}}) = 0$$

Formula for information gain

$$\text{Gain}(S, a) = E(S) - \sum_{v \in \text{values}(a)} \frac{|S_v|}{|S|} E(S_v)$$

$$\rightarrow \text{Gain}(S, a_1) = 1 - \left(\frac{|S_{v=\text{big}}|}{|S|} E(S_{v=\text{big}}) + \frac{|S_{v=\text{small}}|}{|S|} E(S_{v=\text{small}}) \right) = 1 - \left(\frac{2}{4} 1 + \frac{2}{4} 1 \right) = 0$$

$$\rightarrow \text{Gain}(S, a_2) = 1 - \left(\frac{|S_{v=\text{red}}|}{|S|} E(S_{v=\text{red}}) + \frac{|S_{v=\text{blue}}|}{|S|} E(S_{v=\text{blue}}) \right) = 1 - \left(\frac{3}{4} 0.923 + \frac{1}{4} 0 \right) = 0.307 \quad \star$$

$$\rightarrow \text{Gain}(S, a_3) = 1 - \left(\frac{|S_{v=\text{circle}}|}{|S|} E(S_{v=\text{circle}}) + \frac{|S_{v=\text{square}}|}{|S|} E(S_{v=\text{square}}) \right) = 1 - \left(\frac{3}{4} 0.923 + \frac{1}{4} 0 \right) = 0.307 \quad \star$$

Gain rate

Penalises an attribute by integrating a new term that depends on spreading degree and on uniformity degree of separation – *Split information*

Split information

- entropy related to possible values of attribute a
- describes the potential worth of splitting a branch from a node

$$\text{SplitInformation}(S, a) = - \sum_{v=\text{value}(a)} \frac{|S_v|}{|S|} \log_2 \frac{|S_v|}{|S|}$$

where S_v is the proportion of examples from dataset S that have attribute a with value v

Information gain ratio is the ratio between the *information gain* and the *split information* value:

$$IGT(S, a) = \frac{\text{gain}(S, a)}{\text{SplitInformation}(S, a)}$$

aims to reduce a bias towards multi-valued attributes!

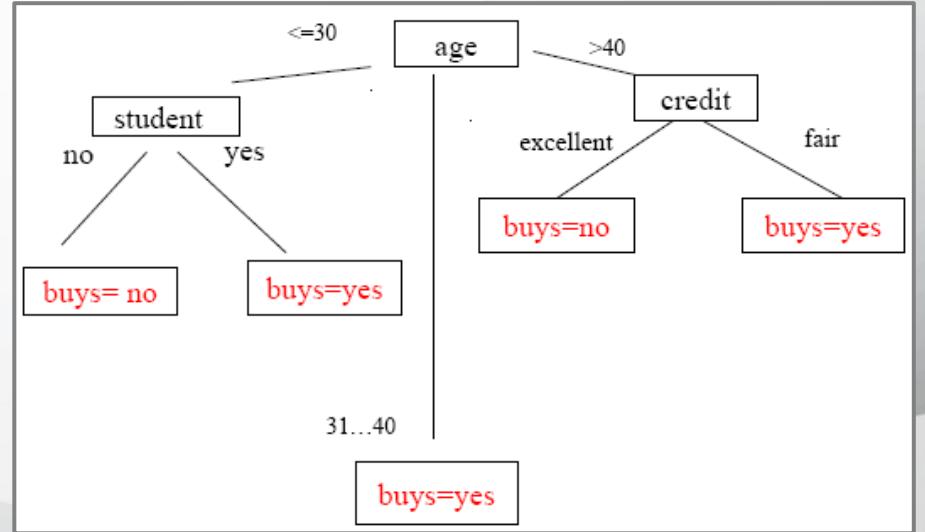
Using a tree as a solver

Extract the rules from the constructed tree

- IF $age = “<=30”$ AND $student = “no”$ THEN $buys_computer = “no”$
- IF $age = “<=30”$ AND $student = “yes”$ THEN $buys_computer = “yes”$
- IF $age = “31\dots 40”$ THEN $buys_computer = “yes”$
- IF $age = “>40”$ AND $credit_rating = “excellent”$ THEN $buys_computer = “no”$
- IF $age = “>40”$ AND $credit_rating = “fair”$ THEN $buys_computer = “yes”$

Use the rules for classifying the test data (new data)

- for x (a data without class) – rules can be written as predicates
- IF $age(x, <=30)$ AND $student(x, no)$ THEN $buys_computer(x, no)$
- IF $age(x, <=30)$ AND $student(x, yes)$ THEN $buys_computer(x, yes)$



Difficulties

- *Underfitting* – DT constructed on training data is too simple → large classification error during training and testing
- *Overfitting* – DT constructed on training data match the training data, but it cannot generalize new data

Solutions

- Pruning – remove some branches (not useful, redundant) → smaller tree
- Cross-validation

Pruning a tree

pre-pruning

Increasing the tree is stopped during construction by stopping the division of nodes that become leaf labeled by majority class of examples from that node

post-pruning

After the DT is constructed, eliminate the branches of some nodes that become leaf → classification error reduces (on testing data)

Motivation – simplifying the tree

- After the DT is constructed, classification rules are extracted in order to represent the knowledge as *if-then* rules (easy to understand)
- A rule is created by traversing the DT from root to a leaf
- Each pair (*attribute, value*) \leftrightarrow (*node, edge*) – is a conjunction in the premise of the rule (*if part*), except the last node of the path that is a leaf and represents the consequence (*output, then part*) of the rule

Conclusion

Advantages

- Easy to understand and interpret
- Can use nominal or categorized data
- Decision logic can be easily followed (rules are visible)
- Works better with large data

Disadvantages

- Instability due to some changes in the training data
- Complexity due to the representation
- Difficult to use
- The DT construction is expensive
- The DT construction requires a lot of information

Tool example:

WEKA J48



THANK YOU !

Artificial Neural Networks

Artificial Intelligence

Intelligent Systems - ANNs

Aim example

binary classification for any input data
(discrete or continuous)

- data can be separated by:
 - ◆ a line $\rightarrow ax + by + c = 0$ (if $m = 2$)
 - ◆ a plan $\rightarrow ax + by + cz + d = 0$ (if $m = 3$)
 - ◆ a hyperplan $\rightarrow \sum a_i x_i + b = 0$ (if $m > 3$)
- How do we identify the optimal values of a, b, c, d, a_i ?
 - ◆ Artificial Neural Networks (ANNs)
 - ◆ Support Vector Machines (SVMs)

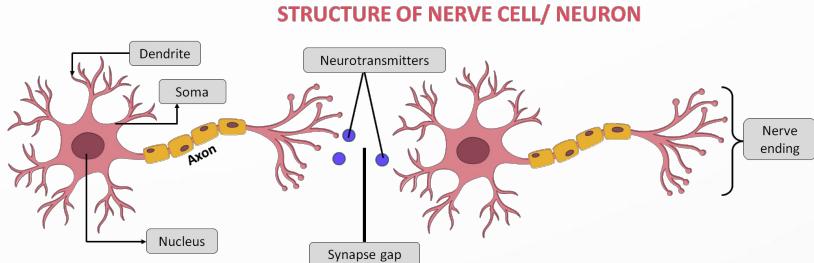
Why ANN?

some tasks can be easily done by humans, but they are difficult to be encoded as algorithms

- Shape recognition
 - Old friends
 - Handwritten
 - Voice
- Rational processes
 - Car driving
 - Piano playing
 - Basketball playing
 - Swimming

such tasks are too difficult to be formalized and done by a rational process

The learning process (brain)



Human brain

- ~10.000.000.000 of neurons connected through synapses

A neuron

- has a body (soma), an axon, and more dendrites
- can be in a given state
 - Active state – if the input information is over a given stimulation threshold
 - Passive state – otherwise

Synapse

- link between the axon of a neuron and the dendrites of other neurons
- take part to information exchange between neurons
- 5.000 connections/neuron (average)
- during a life, new connections can appear

Brain → Neural network

- complex system, non-linear and parallel that processes information
- information is stored and processed by the entire network, not only by a part of network

Models for information processing:

- learning
- storing
- memorizing

Learning

- a basic characteristic
- useful connections become permanent (others are eliminated)

Memory

Short time memory

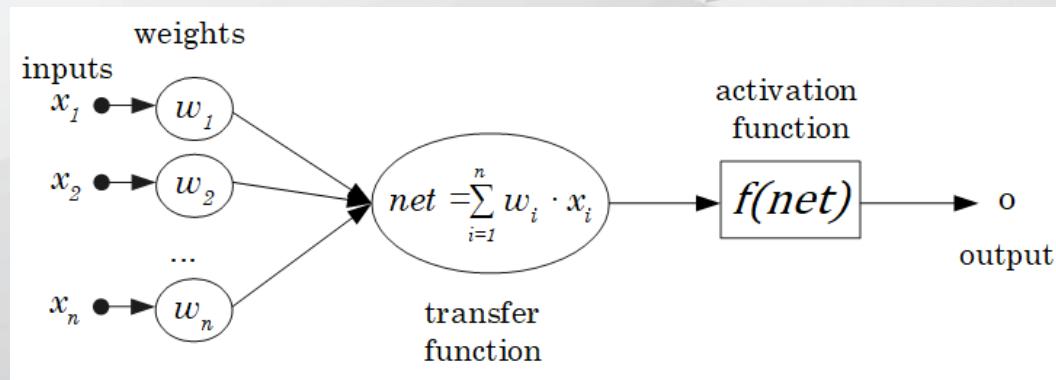
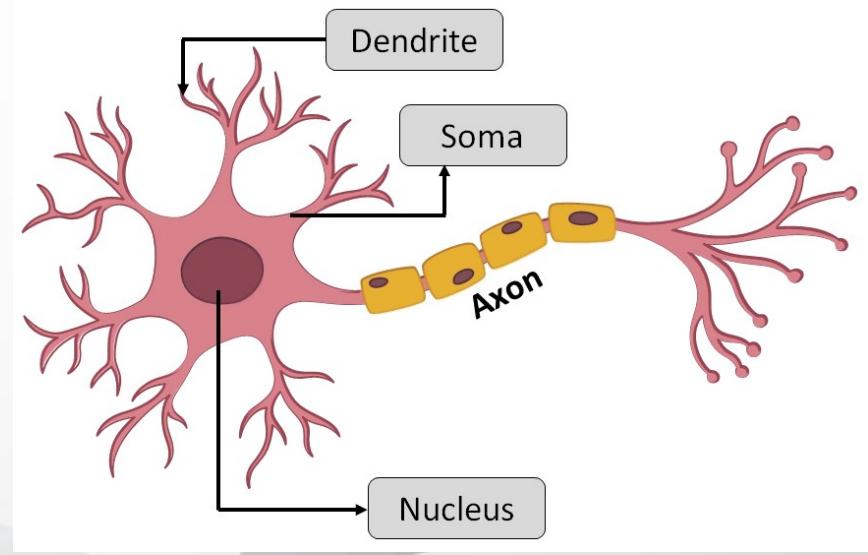
- immediately → 30 sec.
- working memory

Long term memory

- capacity
- increasing along life
- limited → learning a poetry strophe by strophe
- influenced by emotional states

Biology versus artificial

BNN	ANN
Soma	Node
Dendrite	Input
Axon	Output
Activation	Processing
Synapse	Weighted connection

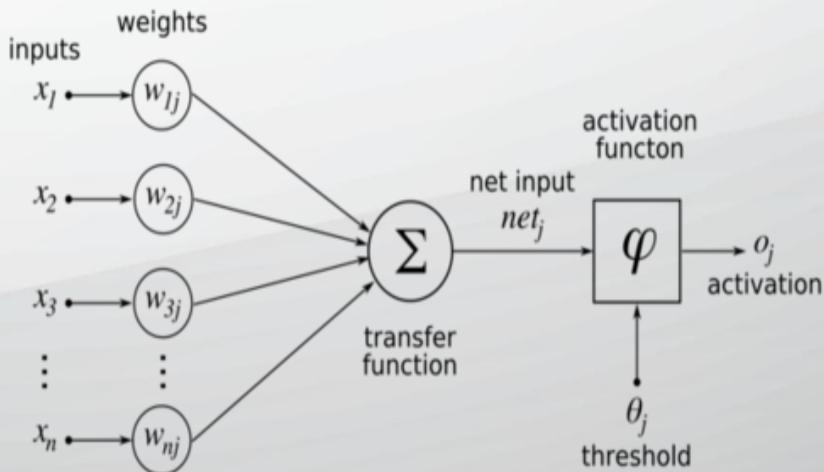


The perceptron

Learning Objectives

By the end of this section you should be able to answer there questions:

1. what is a perceptron?
2. what activation function has a perceptron?
3. what problems can (and can't) be solved by a perceptron?
4. how is trained a perceptron?



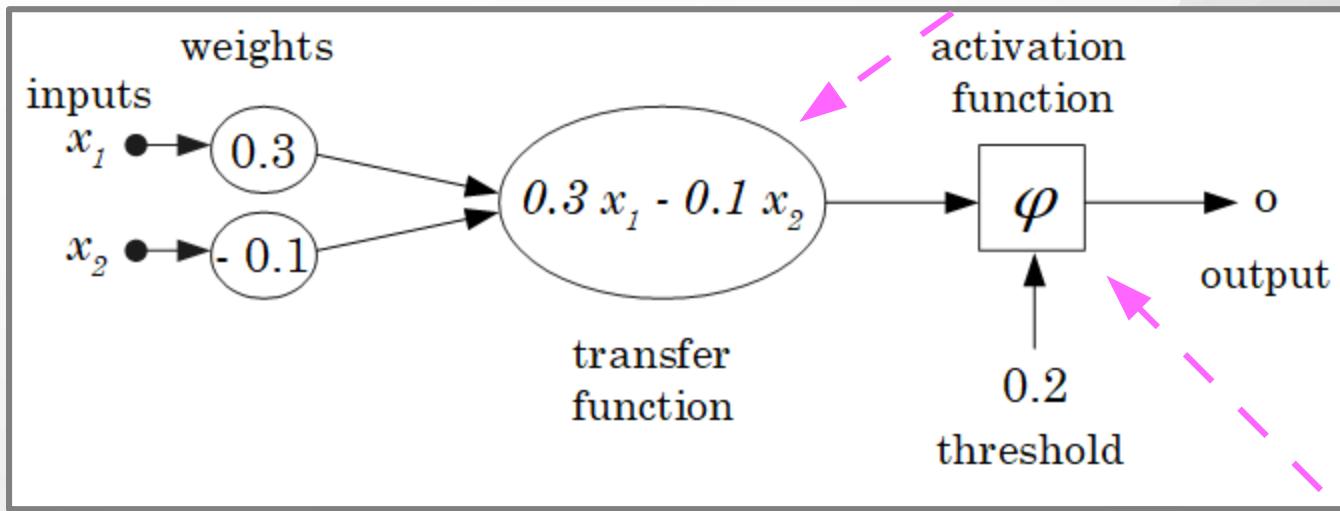
It is the first model of a neuron

- invented by Frank Rosenblatt (1928 – 1971) an American psychologist
- the original perceptron was designed to take a number of binary inputs, and produce one binary output (0 or 1)
- uses different **weights** to represent the importance of each **input**, and that the sum of the values should be greater than a **threshold value** before making a **decision** like true or false (0 or 1)
- the original algorithm:
 1. Set a threshold value
 2. Multiply all inputs with its weights
 3. Sum all the results
 4. Activate the output

Perceptron – example

Consider the parameters: $w_1=0.3$ $w_2=-0.1$ $\theta=0.2$

$$net = \sum_{i=1}^n w_i * x_i$$



For the input: $x=(x_1, x_2)=(1, 0)$

We get the output: $\varphi(0.3 \times 1 - 0.1 \times 0) = \varphi(0.3) = 1$

Activation function

$$\varphi(net) = \begin{cases} 0, & \text{if } net < \theta \\ 1, & \text{if } net \geq \theta \end{cases}$$

threshold function

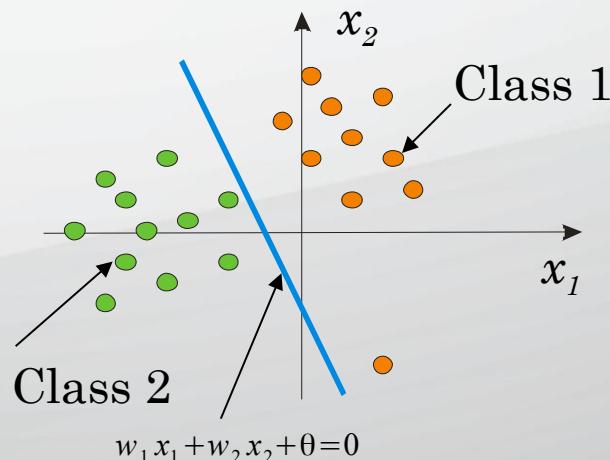
Solving capacity

Observe!

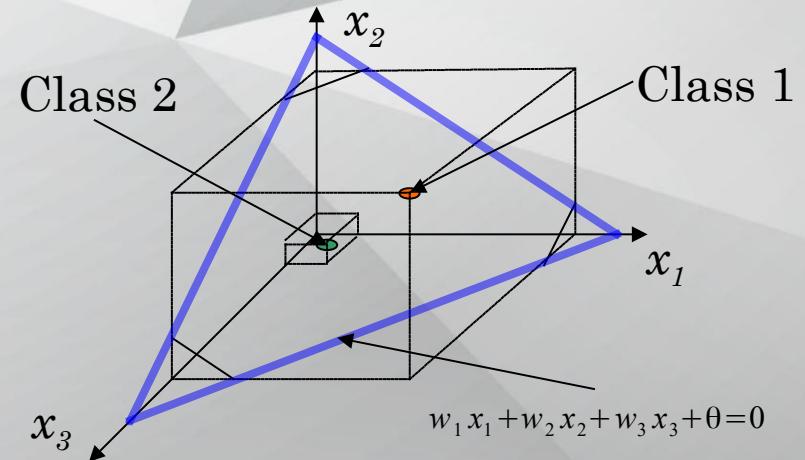
From the transfer function we get

$$y = \sum_{i=1}^n w_i x_i \quad - \text{equation of a hyperplane.}$$

If we compose the transfer function with the threshold function (the activation) we **linear separate** the space \mathbf{R}^n with this hyperplane in two regions.



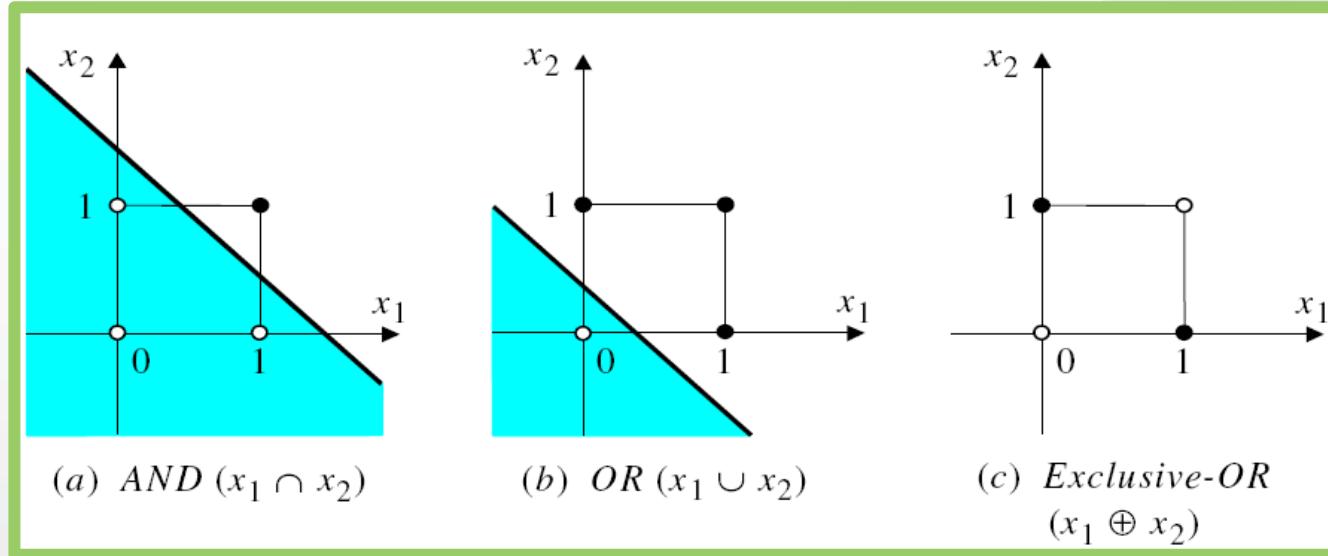
Binary classification with $m=2$ input attributes



Binary classification with $m=3$ input attributes

Perceptron – limits

Non-linear separable data can not be classified.



A perceptron can learn And and OR operations,
but it can not learn XOR operation (it is not linear separable)

Solutions

Neuron with continuous threshold
More neurons

Neuron training

Perceptron's rule → perceptron's algorithm

1. Start by some random weights
2. Determine the quality of the model created for these weights for a **single input data**
3. Re-compute the weights based on the model's quality
4. Repeat (from step 2) until a maximum quality is obtained

Delta's rule → algorithm of gradient descent

1. Start by some random weights
2. Determine the quality of the model created for these weights for **all input data**
3. Re-compute the weights based on the model's quality
4. Repeat (from step 2) until a maximum quality is obtained

Similar to perceptron's rule, but the model's quality is established based on all data (all training data).

The perceptron – learning

Aim:

To identify the optimal weights (w_1, w_2, \dots, w_m) by minimising the errors.

Training data set of n data

$$\{((x_1^d, x_2^d, \dots, x_m^d), t^d) : d = 1, 2, \dots, n\}$$

with m – the number of attributes.

The error is the difference between the real output y and the output o computed by the perceptron for the input (x_1, x_2, \dots, x_m) .

Perceptron's algorithm:

Based on error minimisation associated to an instance of train data

Modify the weights based on error associated to an instance of train data

Perceptron's learning alg.

```
function training_perceptron( $\theta, \eta, m, n, \{(x_1^d, x_2^d, \dots, x_m^d), t^d\} : d = 1, 2, \dots, n\})$ 
     $w_i = \text{random}(-1, 1)$ , where  $i = 1, 2, \dots, m$  # initialise random the perceptron's weights

    do repeat
        for  $d = 1$  to  $n$  do
            activate the neuron and determine the output  $o^d = \varphi\left(\sum_{i=1}^n w_i * x_i^d\right)$ 
            compute the error  $e_d = t^d - o^d$ 
            determine the weight modification  $\Delta w_i = \eta e_d x_i^d$ 
            modify the weights  $w_i = w_i + \Delta w_i$ 
        until there are no incorrect classified examples
    return  $(w_1, w_2, \dots, w_m)$ 
end function
```

Solving *logic AND* problem

AND	0 (False)	1 (True)
0 (False)	0	0
1 (True)	0	1

threshold

$$\theta=0.2$$

learning rate

$$\eta=0.1$$

Epoch	Inputs		Desired output Y_d	Initial weights		Actual output Y	Error e	Final weights	
	x_1	x_2		w_1	w_2			w_1	w_2
1	0	0	0	0.3	-0.1	0	0	0.3	-0.1
	0	1	0	0.3	-0.1	0	0	0.3	-0.1
	1	0	0	0.3	-0.1	1	-1	0.2	-0.1
	1	1	1	0.2	-0.1	0	1	0.3	0.0
2	0	0	0	0.3	0.0	0	0	0.3	0.0
	0	1	0	0.3	0.0	0	0	0.3	0.0
	1	0	0	0.3	0.0	1	-1	0.2	0.0
	1	1	1	0.2	0.0	1	0	0.2	0.0
3	0	0	0	0.2	0.0	0	0	0.2	0.0
	0	1	0	0.2	0.0	0	0	0.2	0.0
	1	0	0	0.2	0.0	1	-1	0.1	0.0
	1	1	1	0.1	0.0	0	1	0.2	0.1
4	0	0	0	0.2	0.1	0	0	0.2	0.1
	0	1	0	0.2	0.1	0	0	0.2	0.1
	1	0	0	0.2	0.1	1	-1	0.1	0.1
	1	1	1	0.1	0.1	1	0	0.1	0.1
5	0	0	0	0.1	0.1	0	0	0.1	0.1
	0	1	0	0.1	0.1	0	0	0.1	0.1
	1	0	0	0.1	0.1	0	0	0.1	0.1
	1	1	1	0.1	0.1	1	0	0.1	0.1

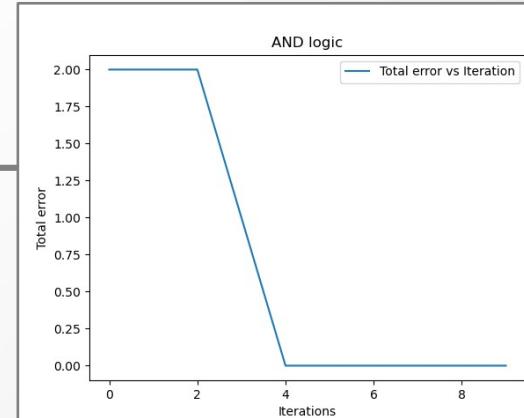
Perceptron use

```
from numpy import random, dot, array
import matplotlib as mpl

def threshold(x):
    if x < 0.2 :
        return 0
    return 1

class Perceptron:
    def __init__(self, noInputs, activationFunction, learningRate):
        self.noInputs = noInputs
        self.weights = random.rand(self.noInputs)
        self.activationFunction = activationFunction
        self.output = 0
        self.learningRate = learningRate
        self.errorVariation = []
    def fire(self, inputs):
        self.output = self.activationFunction(
            inner(array(inputs), self.weights))
        return self.output

    def trainPerceptronRule(self, inputs, output):
        totalError = 0
        for i in range(len(inputs)):
            error = output[i] - self.fire(inputs[i])
            delta = self.learningRate*error*array(inputs[i])
            self.weights += delta
            totalError += error**2
        self.errorVariation.append(totalError)
```



```
def test1():
    # AND logic
    p = Perceptron(2, threshold, 0.1)
    x = [[1,1],[1,0],[0,1],[0,0]]
    t = [1,0,0,0]
    noIterations = 10
    for i in range(noIterations):
        p.trainPerceptronRule(x,t)
    print(p.weights)
    for j in range(len(x)):
        print(x[j], p.fire(x[j]))

    mpl.pyplot.plot(range(noIterations),
                    p.errorVariation, label = 'Total error
                                         vs Iteration')
    mpl.pyplot.xlabel('Iterations')
    mpl.pyplot.ylabel('Total error')
    mpl.pyplot.legend()
    mpl.pyplot.title('AND logic')
    mpl.pyplot.show()
```

Artificial Neural Networks

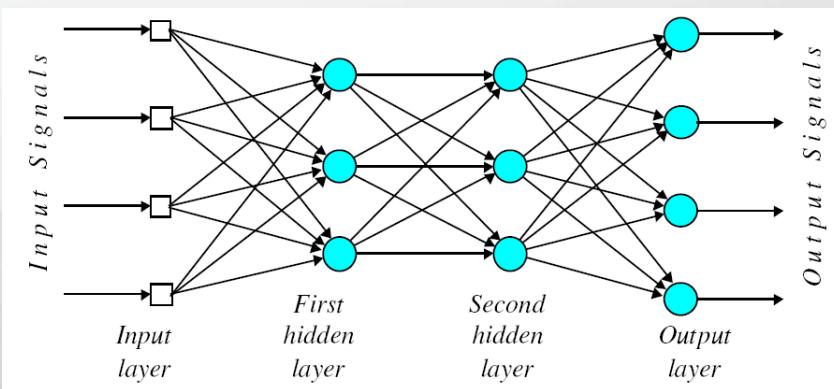
Learning Objectives

By the end of this section you should be able to answer there questions:

1. What is a *feed forward artificial neural network*?
2. How is organized an ANN?
3. What activation functions are used in ANNs?
4. How passes the signal trough an ANN?
5. How to train an ANN?

A structure similar to a biological neural network

- 1943, neurophysiologist Warren McCulloch and mathematician Walter Pitts
- the original ANN was built with electrical circuits
- A set of nodes (units, neurons, processing elements) located in a graph with more layers



In a *feed forward network* the information moves in only one direction, **forward**, from the input nodes, through the hidden nodes (if any) to the output nodes.

– is the most simple type of ANN.

Artificial Neural Networks

Nodes

- Have inputs and outputs
- Perform a simple computing through an activation function
- Connected by weighted links
 - Links between nodes give the network structure
 - Links influence the performed computations

Layers

- Input layer
 - Contains m nodes (m – the number of attributes of a data)
- Output layer
 - Contains r nodes (r – the number of outputs)
- Intermediate layers
 - Different structures
 - Different sizes

Example of a feed forward network structure:

6:4:10:2 → input layer with 6 units (artificial neurons), two hidden layers with 4 and 10 units respectively and an output layer with 2 units.

this structure can be used for a problem with 6 attributes and 2 outputs

each node from the first layer has one input and one output, each unit from the first hidden layer has 6 weights and one output, each unit from the second hidden layer has 4 weights and one output, each node from the output layer has 10 weights and one output.

Artificial Neural Networks

Learning process

A training data set of n data

$$\{((x_1^d, x_2^d, \dots, x_m^d), (t_1^d, t_2^d, \dots, t_r^d)) : d = 1, 2, \dots, n\}$$

where m – number of attributes and r – number of outputs

Form an ANN with m input nodes, r output nodes and an internal structure

- Some hidden layers, each layer having a given number of nodes
- With weighted connections between every 2 nodes of consecutive layers

Determine the optimal weights by minimising the error

- Difference between the real output y and the output computed by the network

Problems solved by an ANN

- Problem data can be represented by pairs (attribute-value)
- Objective function can be:
 - Single or multi-criteria
 - Discrete or continuous (real values)
- Training data can be noised
- A large training time

Neuron processing

Information is transmitted to the neuron → compute the weighted sum of inputs

$$net = \sum_{i=1}^n w_i * x_i$$

Neuron processes the information → by using an activation function

$$o = f(net)$$

- Constant function
- Step function
- Slope function
- Linear function
- Sigmoid function
- Gaussian function

Activation function

Constant function

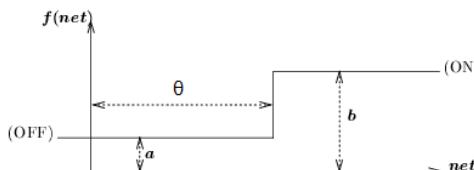
$$f(\text{net}) = \text{const.}$$



Step function

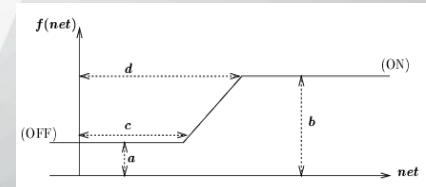
θ - threshold

$$f(\text{net}) = \begin{cases} a, & \text{if } \text{net} < \theta \\ b, & \text{if } \text{net} \geq \theta \end{cases}$$



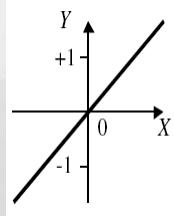
Slope function

$$f(\text{net}) = \begin{cases} a, & \text{if } \text{net} \leq c \\ b, & \text{if } \text{net} \geq d \\ a + \frac{(\text{net} - c)(b - a)}{d - c}, & \text{otherwise} \end{cases}$$



Linear function

$$f(\text{net}) = a * \text{net} + b$$

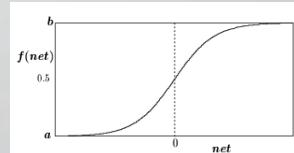


Sigmoid function

$$f(\text{net}) = z + \frac{1}{1 + \exp(-x \cdot \text{net} + y)}$$

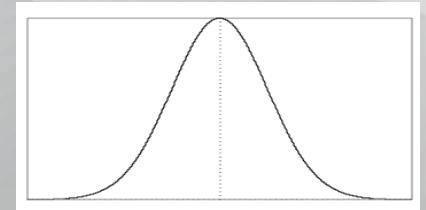
$$f(\text{net}) = \tanh(x \cdot \text{net} - y) + z$$

$$\text{where } \tanh(u) = \frac{e^u - e^{-u}}{e^u + e^{-u}}$$



Gaussian function

$$f(\text{net}) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2}\left(\frac{\text{net} - \mu}{\sigma}\right)^2\right]$$



Attention! Also some other functions are in use – we will see this later!

Gradient descent

- based on the error associated to the entire set of train data
- modify the weights in the direction of the steepest slope of error reduction $E(\mathbf{w})$ for the entire set of train data

$$E(\mathbf{w}) = \frac{1}{2} \sum_{d=1}^n (t^d - o^d)^2$$

- How to determine the steepest slope? → derive E based on w (establish the gradient of error E)

$$\nabla E(\mathbf{w}) = \left(\frac{\partial E}{\partial w_1}, \frac{\partial E}{\partial w_2}, \dots, \frac{\partial E}{\partial w_m} \right)$$

- Error's gradient is computed based on the neuron's activation function (that function must be differentiable → continuous)

➤ linear function $f(\text{net}) = \sum_{i=1}^m w_i x_i^d$

➤ sigmoid function $f(\text{net}) = \frac{1}{1 + e^{-\mathbf{w}\mathbf{x}}} = \frac{1}{1 + e^{-\sum_{i=1}^m w_i x_i^d}}$

- How are modified the weights ? $\Delta w_i = -\eta \frac{\partial E}{\partial w_i}$, where $i = 1, 2, \dots, m$

Compute the error's gradient

- linear function

$$f(\text{net}) = \sum_{i=1}^m w_i x_i^d$$

$$\frac{\partial E}{\partial w_i} = \frac{\partial \frac{1}{2} \sum_{d=1}^n (t^d - o^d)^2}{\partial w_i} = \frac{1}{2} \sum_{d=1}^n \frac{\partial (t^d - o^d)^2}{\partial w_i} = \frac{1}{2} \sum_{d=1}^n 2(t^d - o^d) \frac{\partial (t^d - \mathbf{w}\mathbf{x}^d)}{\partial w_i}$$

$$\frac{\partial E}{\partial w_i} = \sum_{d=1}^n (t^d - o^d) \frac{\partial (t^d - w_1 x_1^d - w_2 x_2^d - \dots - w_m x_m^d)}{\partial w_i} = \sum_{d=1}^n (t^d - o^d) (-x_i^d)$$

$$\Delta w_i = -\eta \frac{\partial E}{\partial w_i} = \eta \sum_{d=1}^n (t^d - o^d) x_i^d$$

- sigmoid function

$$f(\text{net}) = \frac{1}{1 + e^{-\mathbf{w}\mathbf{x}}} = \frac{1}{1 + e^{-\sum_{i=1}^m w_i x_i^d}}$$

$$y = s(z) = \frac{1}{1 + e^{-z}} \Rightarrow \frac{\partial s(z)}{\partial z} = s(z)(1 - s(z))$$

$$\frac{\partial E}{\partial w_i} = \frac{\partial \frac{1}{2} \sum_{d=1}^n (t^d - o^d)^2}{\partial w_i} = \frac{1}{2} \sum_{d=1}^n \frac{\partial (t^d - o^d)^2}{\partial w_i} = \frac{1}{2} \sum_{d=1}^n 2(t^d - o^d) \frac{\partial (t^d - \text{sig}(\mathbf{w}\mathbf{x}^d))}{\partial w_i} = \sum_{d=1}^n (t^d - o^d) (1 - o^d) o^d (-x_i^d)$$

$$\Delta w_i = -\eta \frac{\partial E}{\partial w_i} = \eta \sum_{d=1}^n (t^d - o^d) (1 - o^d) o^d x_i^d$$

Simple and stochastic GDA

Simple GDA

Initialisation of network weights

$$w_i = \text{random}(a, b), \text{ where } i = 1, 2, \dots, m$$

While not stop condition

$$\Delta w_i = 0, \text{ where } i = 1, 2, \dots, m$$

For each train example (\mathbf{x}_d, t_d) , where $d = 1, 2, \dots, n$

Activate the neuron and determine the output o_d

$$\text{Linear activation} \rightarrow o_d = \mathbf{w} \cdot \mathbf{x}_d$$

$$\text{Sigmoid activation} \rightarrow o_d = \text{sig}(\mathbf{w} \cdot \mathbf{x}_d)$$

For each weight w_i , where $i = 1, 2, \dots, m$

Determine the weight modification

$$\Delta w_i = \Delta w_i - \eta \frac{\partial E}{\partial w_i}$$

where η - learning rate

For each weight w_i , where $i = 1, 2, \dots, m$

$$\text{Modify the weights } w_i \quad w_i = w_i + \Delta w_i$$

EndWhile

Stochastic GDA

Initialisation of network weights

$$w_i = \text{random}(a, b), \text{ where } i = 1, 2, \dots, m$$

While not stop condition

$$\Delta w_i = 0, \text{ unde } i = 1, 2, \dots, m$$

For a random sample subset from the training data set
 $(\mathbf{x}_{d_i}, t_{d_i})$, where $d_i \in \{1, 2, \dots, n\}$

Activate the neuron and determine the output o_{d_i}

$$\text{Linear activation} \rightarrow o_{d_i} = \mathbf{w} \cdot \mathbf{x}_{d_i}$$

$$\text{Sigmoid activation} \rightarrow o_{d_i} = \text{sig}(\mathbf{w} \cdot \mathbf{x}_{d_i})$$

For each weight w_i , where $i = 1, 2, \dots, m$

Determine the weight modification

$$\Delta w_i = -\eta \frac{\partial E}{\partial w_i}$$

where η - learning rate

For each weight w_i , where $i = 1, 2, \dots, m$

$$\text{Modify the weights } w_i \quad w_i = w_i + \Delta w_i$$

EndWhile

Neuron learning

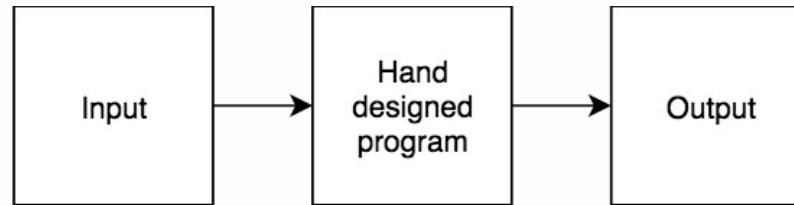
Differences	Perceptron's algorithm	Gradient descent algorithm (delta rule)
What does o^d represent?	$o^d = \text{sign}(\mathbf{w}\mathbf{x}^d)$	$o^d = \mathbf{w}\mathbf{x}^d$ or $o^d = \text{sig}(\mathbf{w}\mathbf{x}^d)$
Convergence	After a finite # of steps (until the perfect separation)	Asymptotic (to minimum error)
Solved problems	With linear separable data	Any data (linear separable or non-linear)
Neuron's output	Discrete and with threshold	Continuous and without threshold

THANK YOU !

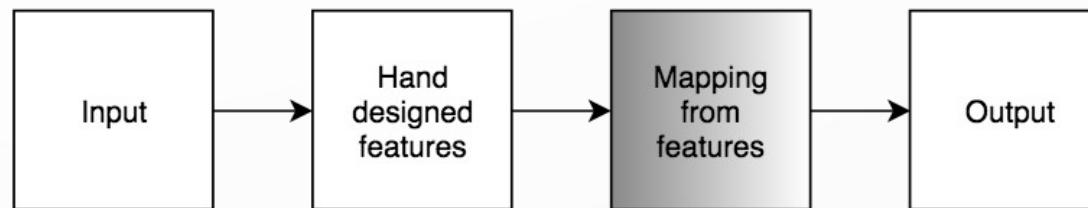
Artificial Neural Networks

Learning multiple components

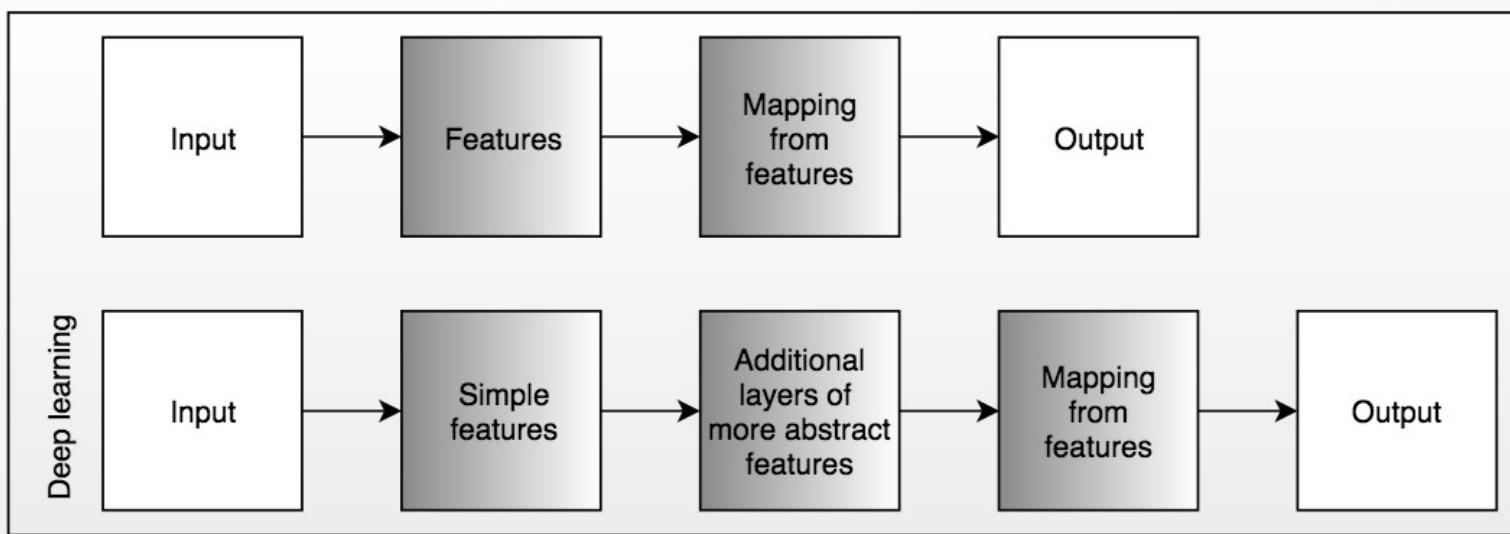
Rule-based systems



Classic machine learning

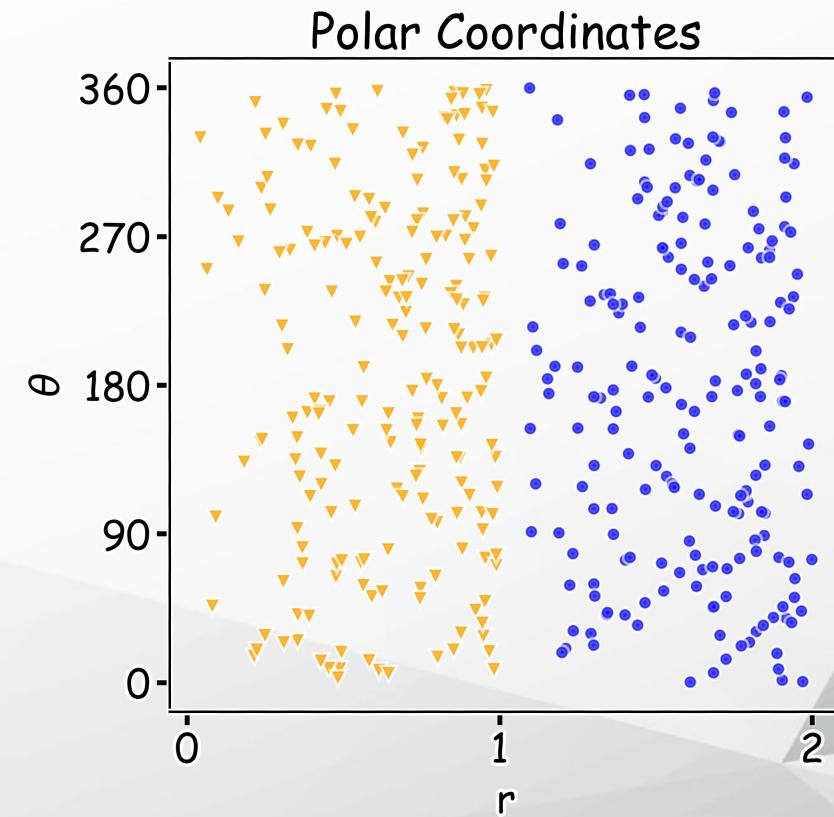
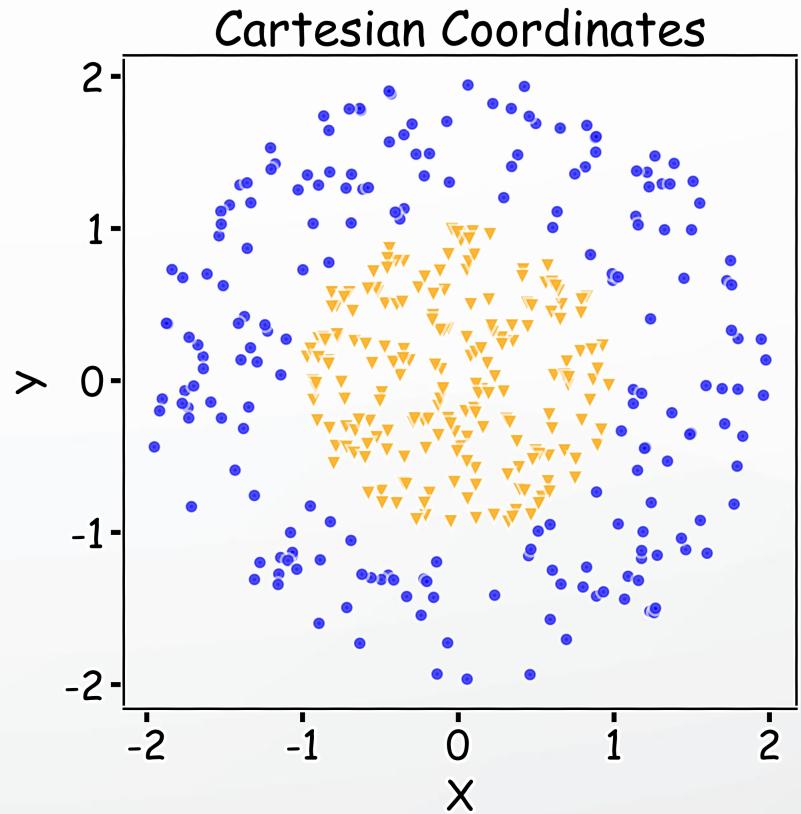


Representation learning

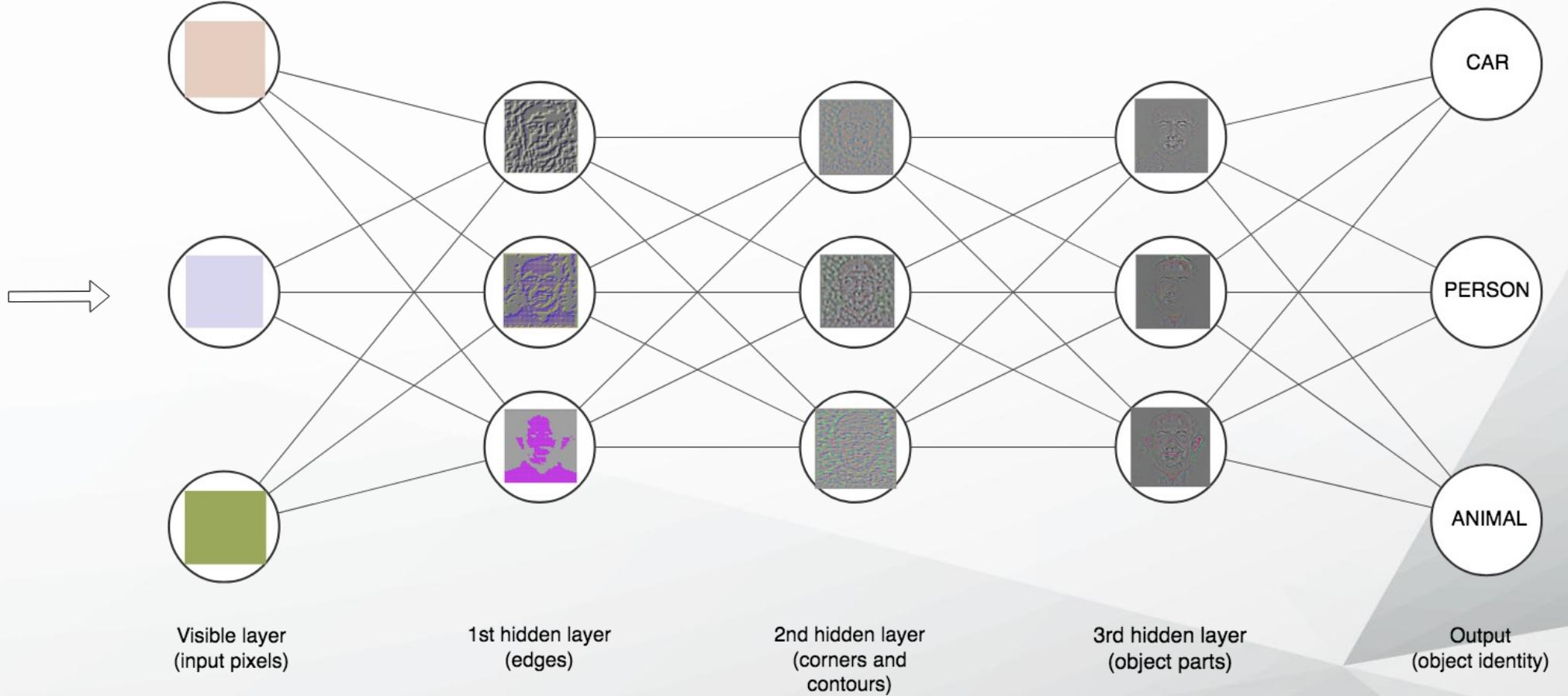


Representation

- First - Representation matters!



Depth – repeated compositions

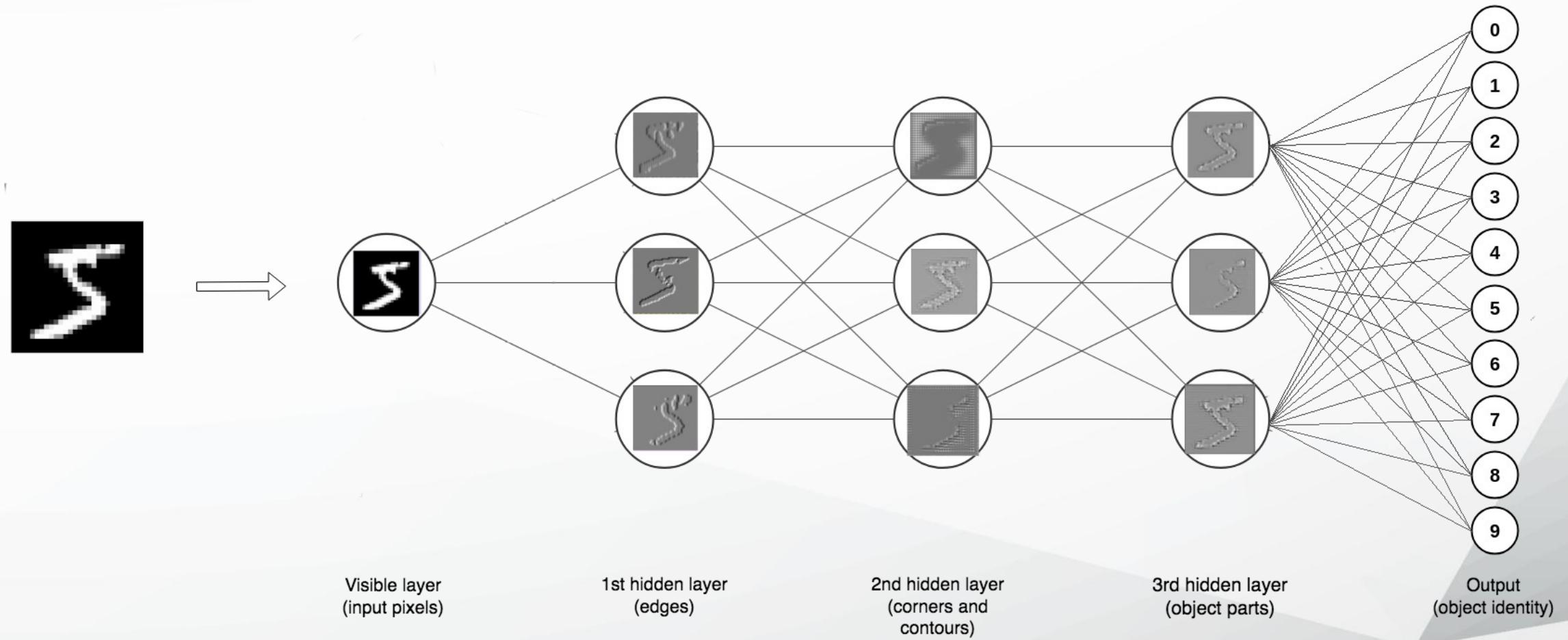


Depth – repeated compositions

MNIST – dataset of hand written digits



Depth – repeated compositions



Common types of Neural Network Architectures

- Feedforward Neural networks
- Convolutional Neural Networks
- Recurrent Neural Networks
- Long Short-term Memory networks
- Autoencoders
- Generative Adversarial Networks

Feed-forward Neural Networks

- Simplest form of ANN:
 - the perceptrons are arranged in layers
 - the first layer is taking the inputs
 - the last layer is producing the outputs
 - between them there are hidden layers
- The data flow goes in one direction:
 - each perceptron is connected with every perceptron on the next layer
 - there is no connection between the perceptrons in the same layer

Features of feed-forward ANNs

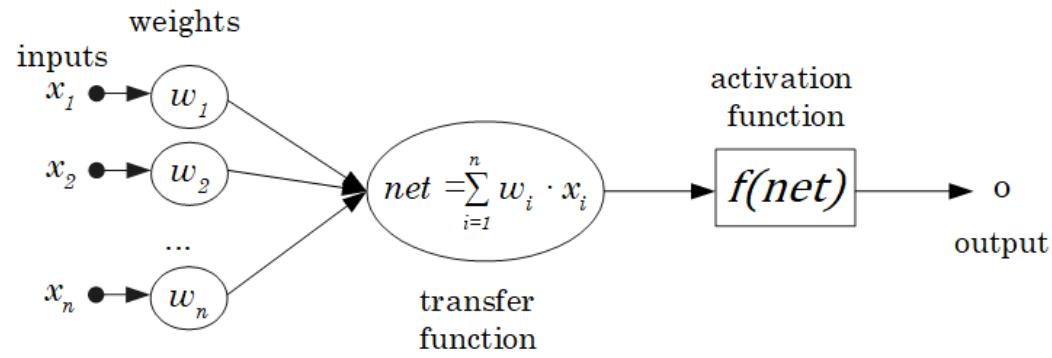
- recall that a single perceptron can classify points into two regions that are linearly separable

Consider a more complex network

- with more perceptrons that are independent of each other in the hidden layer, the points are classified in more pairs of linearly separable regions, each of it having a unique line separating the region.
- by varying the number of nodes in the hidden layer, the number of layers, and the number of input and output nodes, one can classification of points in arbitrary dimension into an arbitrary number of groups
- hence feed-forward networks are commonly used for classification.

Artificial neural network – structure

a node's structure



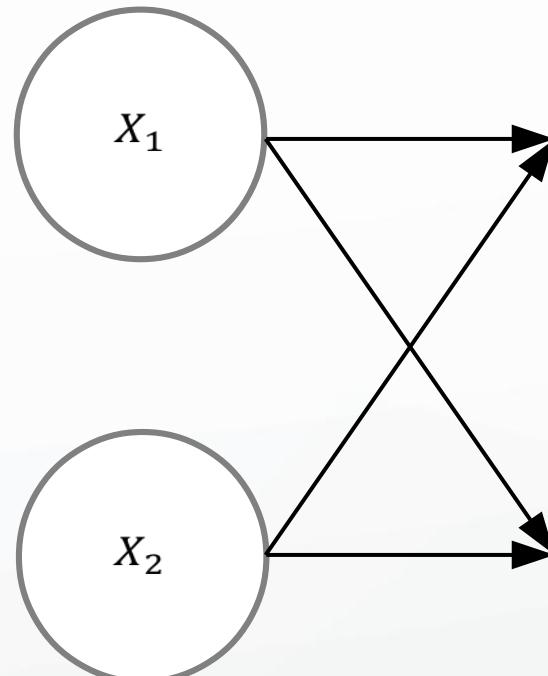
$$\mathbf{X} = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$$

$$\mathbf{W} = \begin{pmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{pmatrix}$$

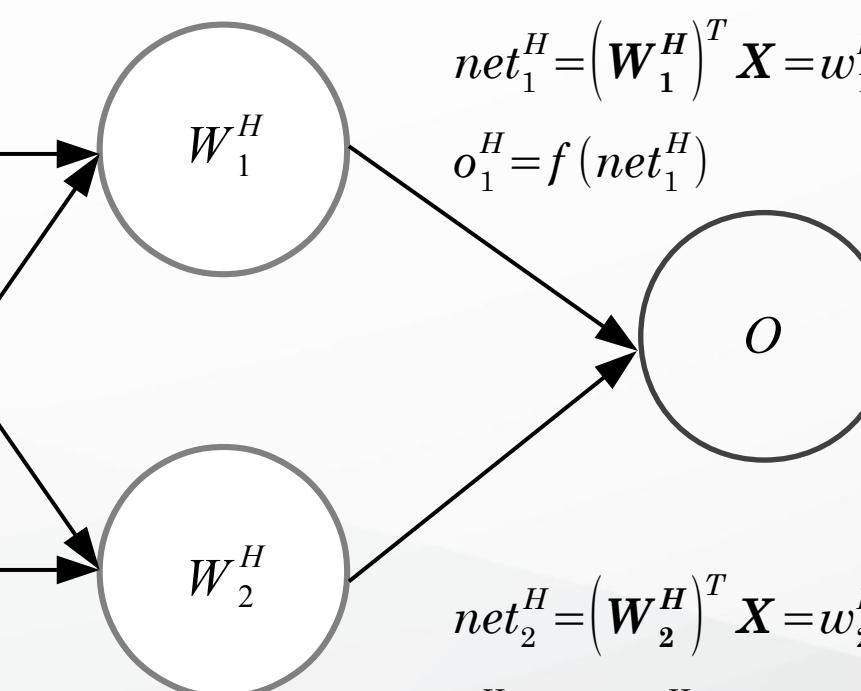
$$\mathbf{o} = f(\mathbf{X}^T \mathbf{W})$$

Artificial neural network – structure

Input layer



Hidden layer



Output layer

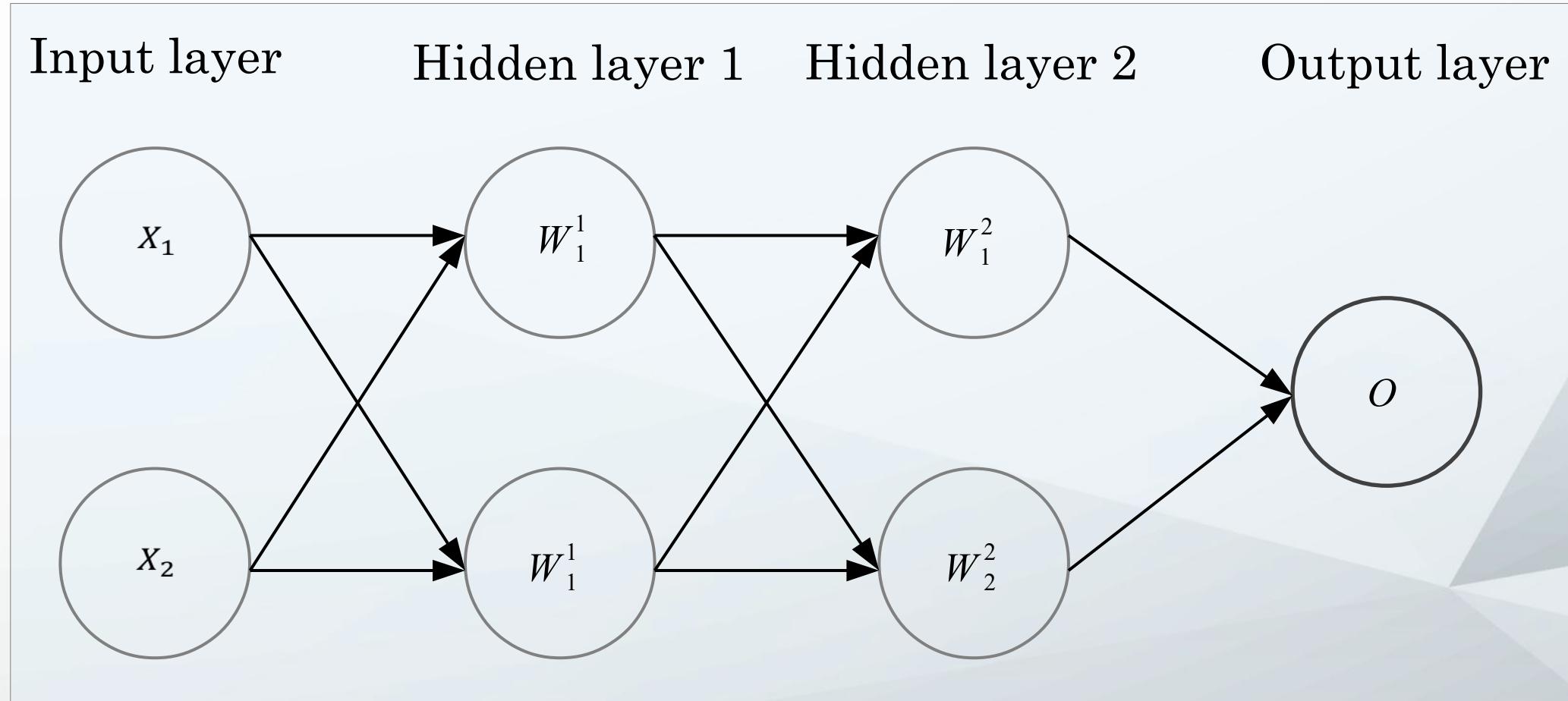
$$\begin{aligned}net_1^H &= (\mathbf{W}_1^H)^T \mathbf{X} = w_{11}^H x_1 + w_{12}^H x_2 \\o_1^H &= f(net_1^H) \\net_2^H &= (\mathbf{W}_2^H)^T \mathbf{X} = w_{21}^H x_1 + w_{22}^H x_2 \\o_2^H &= f(net_2^H)\end{aligned}$$

$$O = g(o_1^H, o_2^H) \longrightarrow Error = E(O, t)$$

Output function **Loss function**

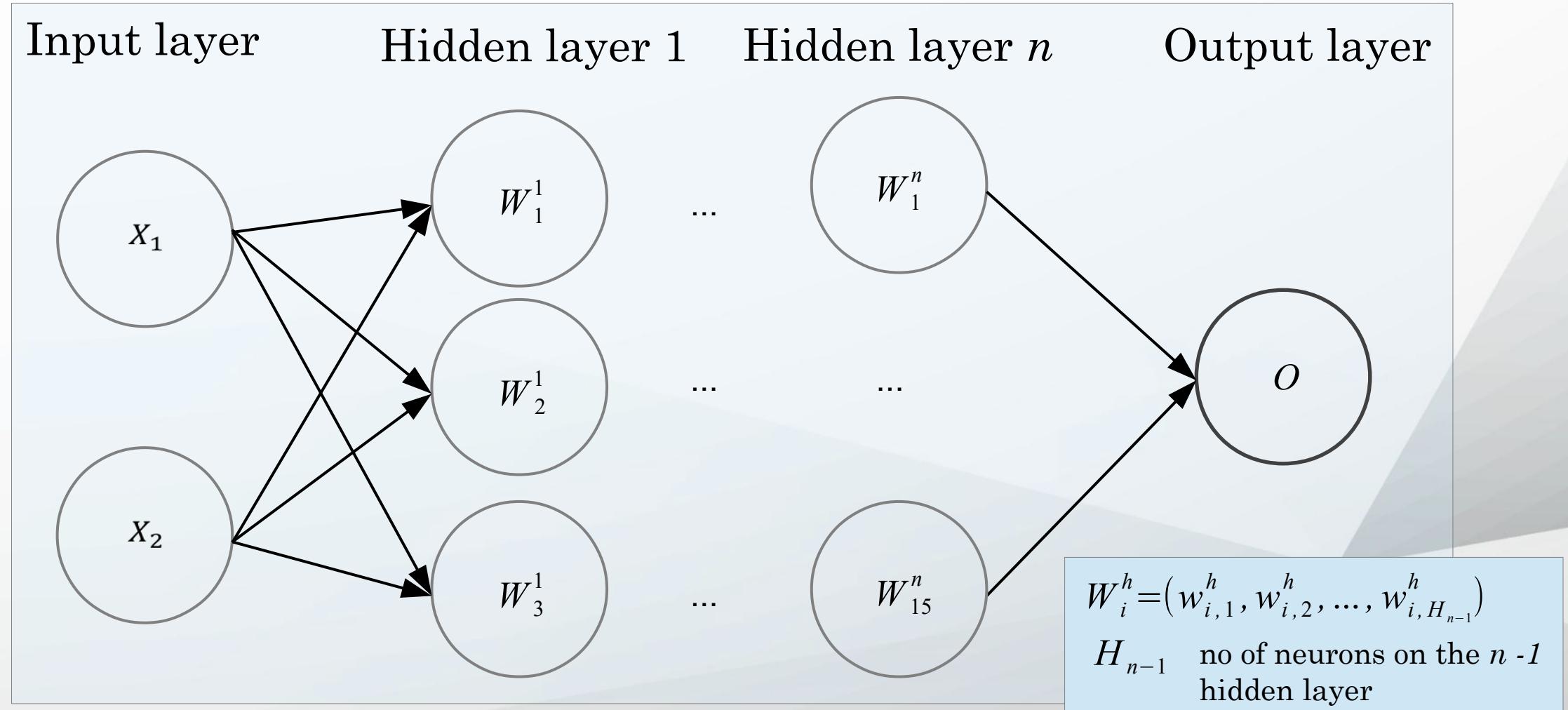
Artificial neural network – structure

Example of a **2 : 2 : 2 : 1** architecture with 2 hidden layers



Artificial neural network – structure

Example of a **2:3: ... :15:1** architecture with n hidden layers



Design choices for feed-forward ANNs

Activation function

Loss function

Output units

Architecture

Linearity versus non-linearity

- Linear models:
 - Can be fit efficiently (via convex optimization)
 - Limited model capacity

- Alternative:

$$f(\mathbf{x}) = \mathbf{W}^T \phi(\mathbf{x})$$

- Where $\phi(\mathbf{x})$ is a *non-linear transform*

Activation functions for ANNs

The activation function should:

- Provide **non-linearity**
- Ensure **gradients remain large** through hidden unit

Common choices are

- Sigmoid
- Relu, leaky ReLU, Generalized ReLU, MaxOut
- Softplus
- Tanh
- Swish

Traditional ANNs (like feed-forward)

- Manually engineer
 - Domain specific, enormous human effort
- Generic transform
 - Maps to a higher-dimensional space
 - Kernel methods: e.g. RBF kernels
 - Over fitting: does not generalize well to test set
 - Cannot encode enough prior information

Deep Learning

- Directly learn ϕ

$$f(\mathbf{x}, \eta) = W^T \phi(\mathbf{x}, \eta)$$

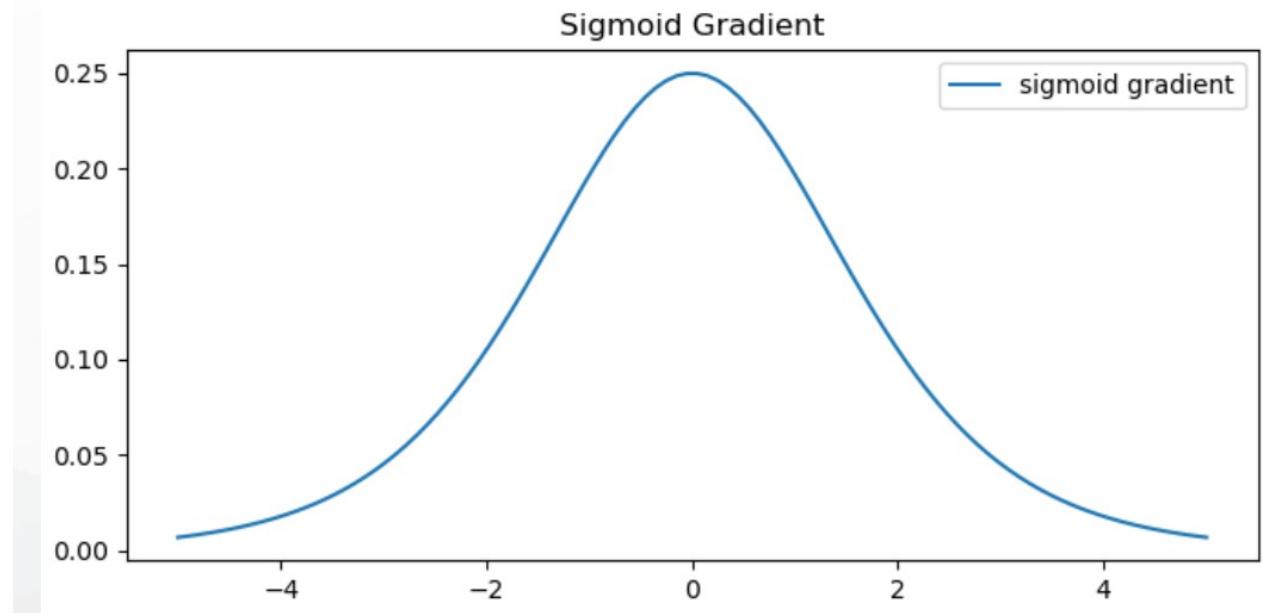
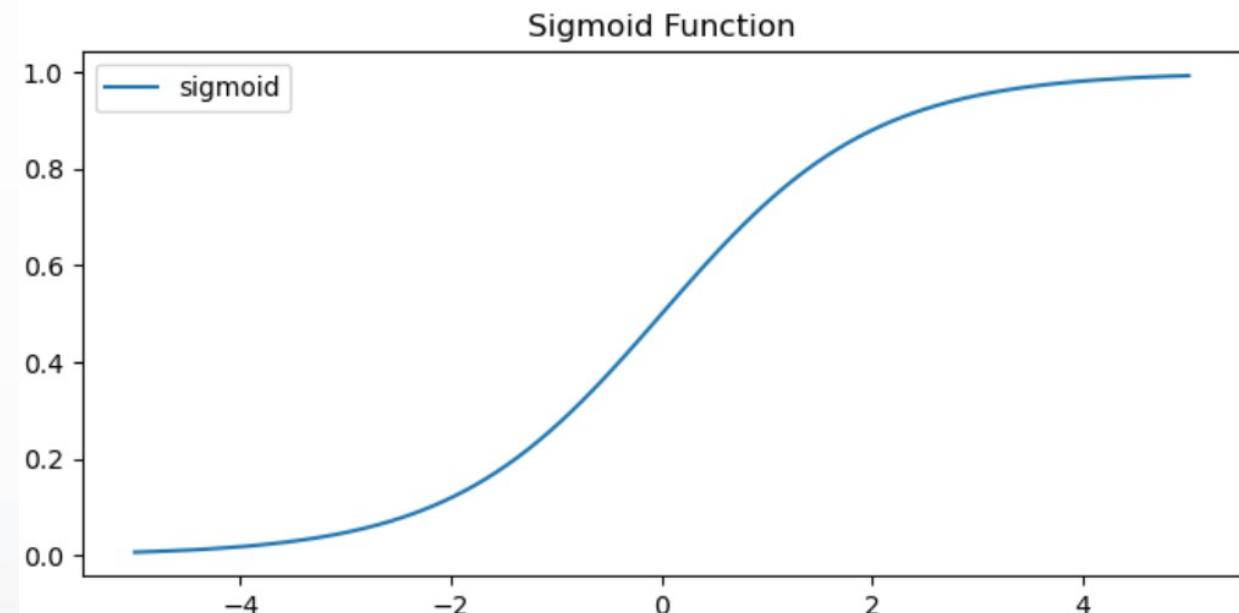
- $\phi(\mathbf{x}, \eta)$ is an automatically-learned **representation** of x
- For **deep networks**, ϕ is the function learned by the **hidden layers** of the network
- η are the learned weights

Non-convex optimization

- Can encode prior beliefs, generalizes well

Sigmoid (aka Logistic)

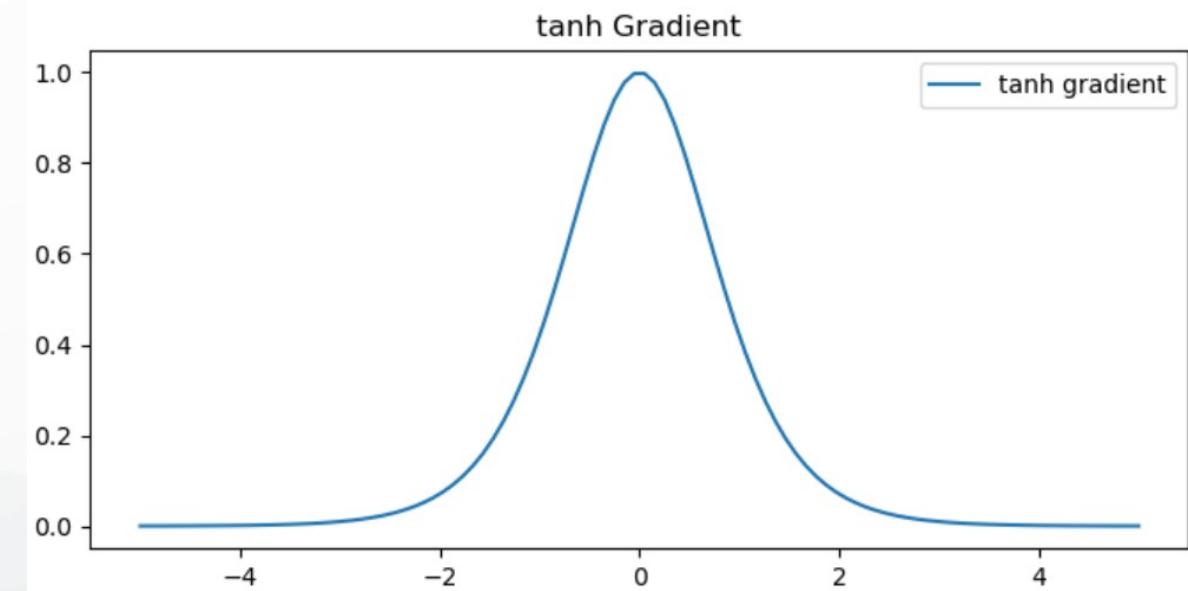
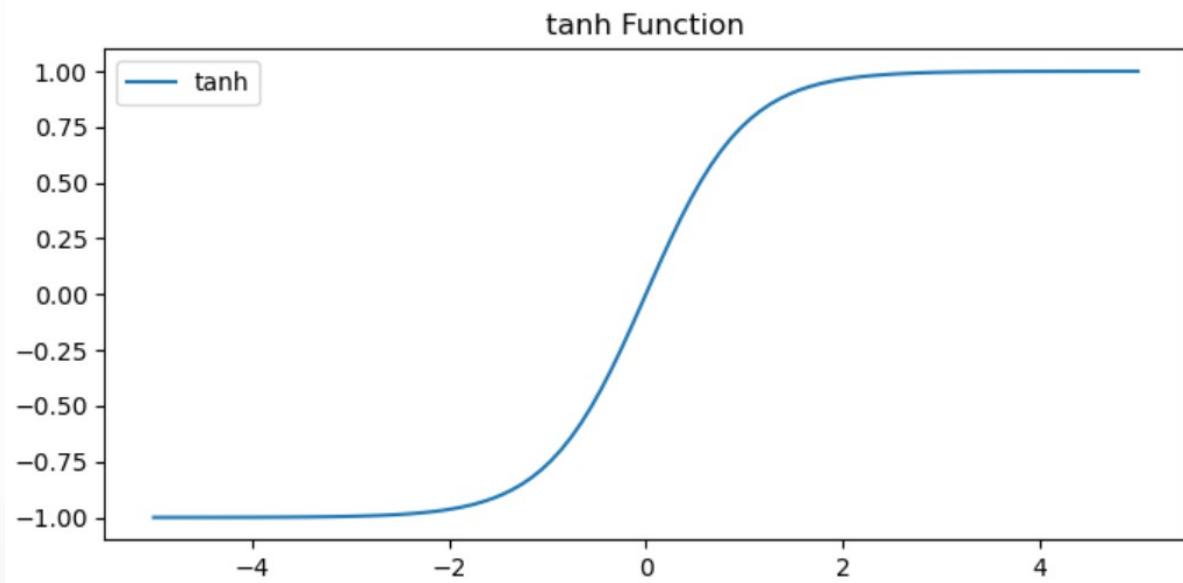
$$y = \frac{1}{1 + e^{-x}}$$



Derivative is **zero** for much of the domain. This leads to “vanishing gradients” in backpropagation.

Hyperbolic tangent (aka tanh)

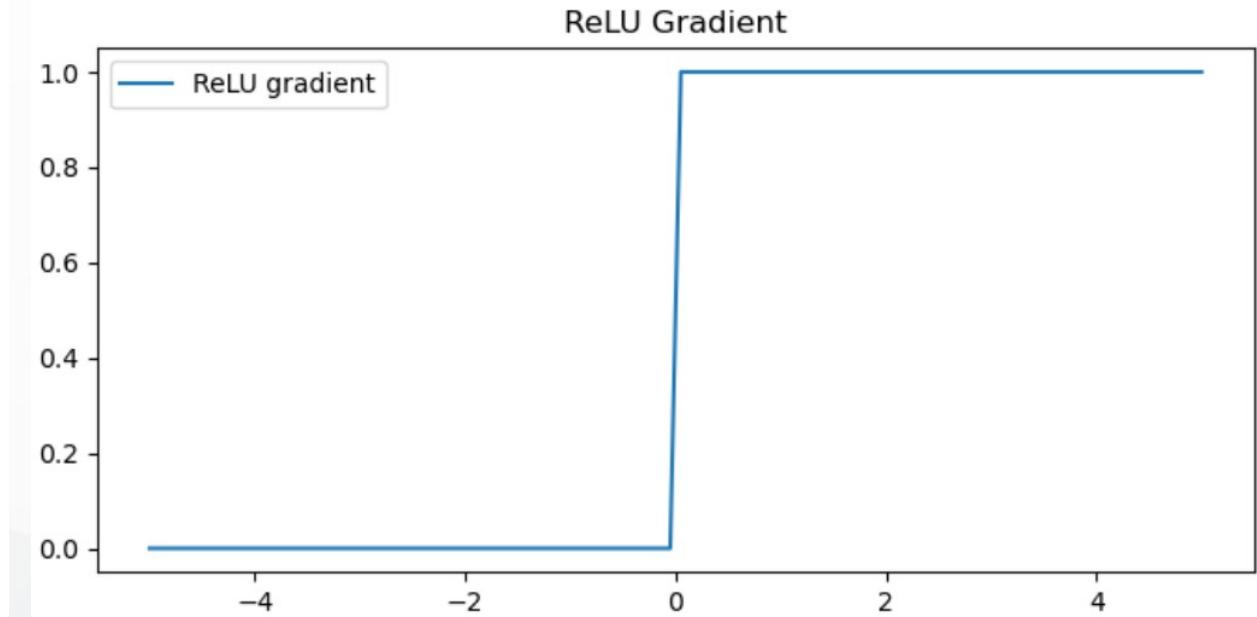
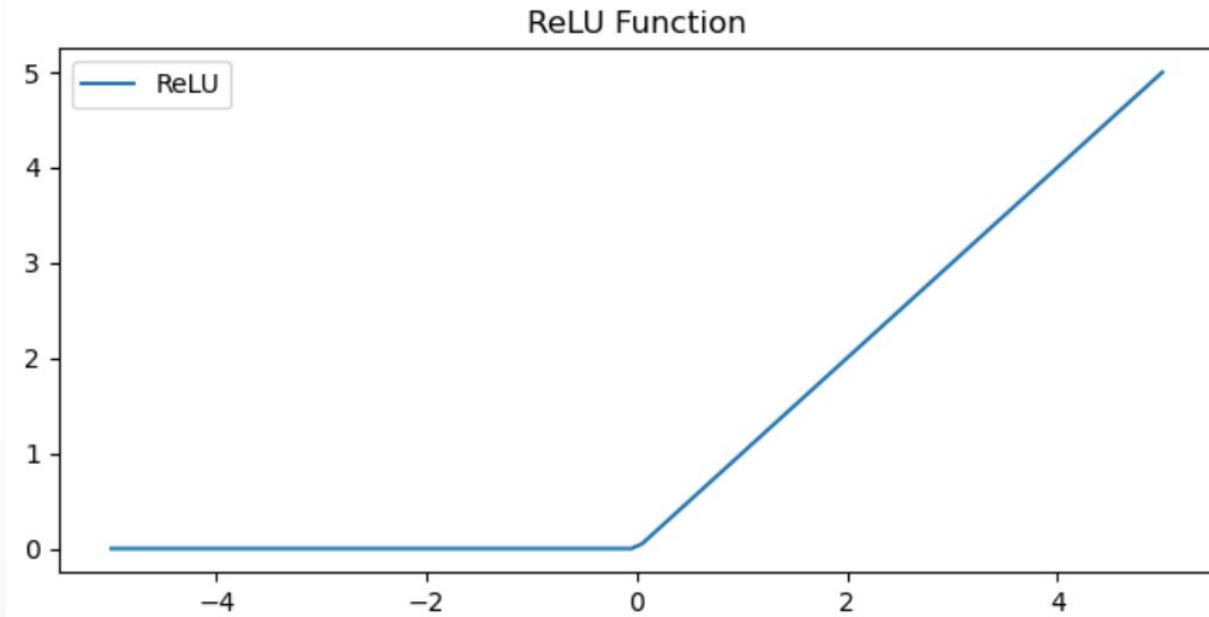
$$y = \frac{e^x - e^{-x}}{e^x + e^{-x}}$$



Derivative is also **zero** for much of the domain.

Rectified Linear Unit (ReLU)

$$y = \max(0, x)$$



Two major advantages:

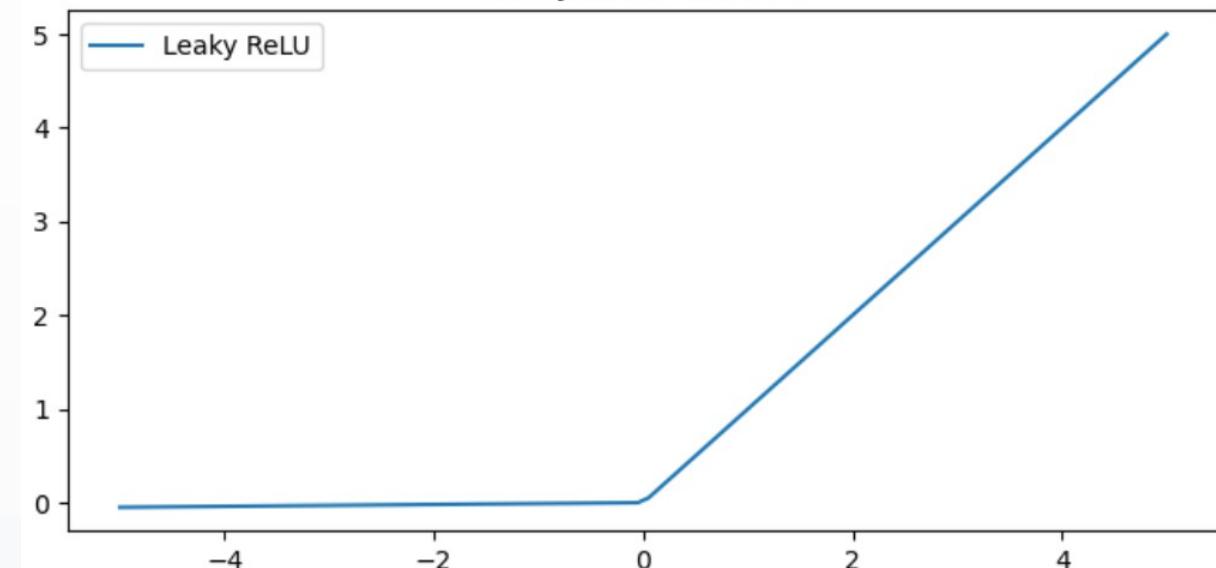
1. No vanishing gradient when $x > 0$
2. Provides sparsity (regularization) since $y = 0$ when $x < 0$

Leaky ReLU

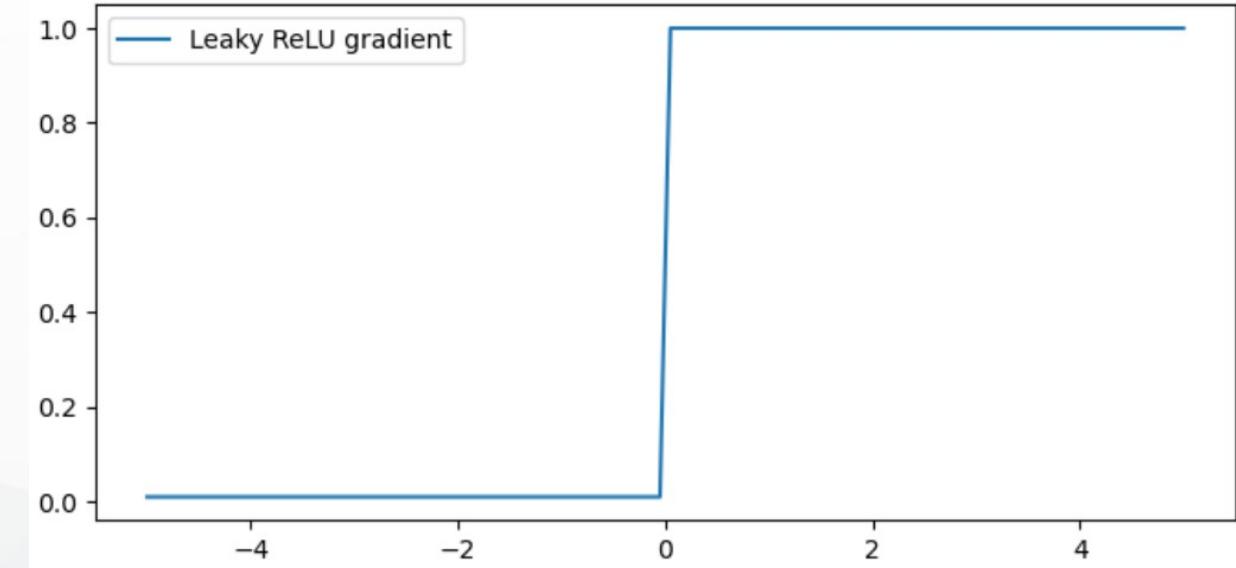
$$y = \max(0, x) + \min(\alpha x, 0)$$

α is a small positive value

Leaky ReLU Function



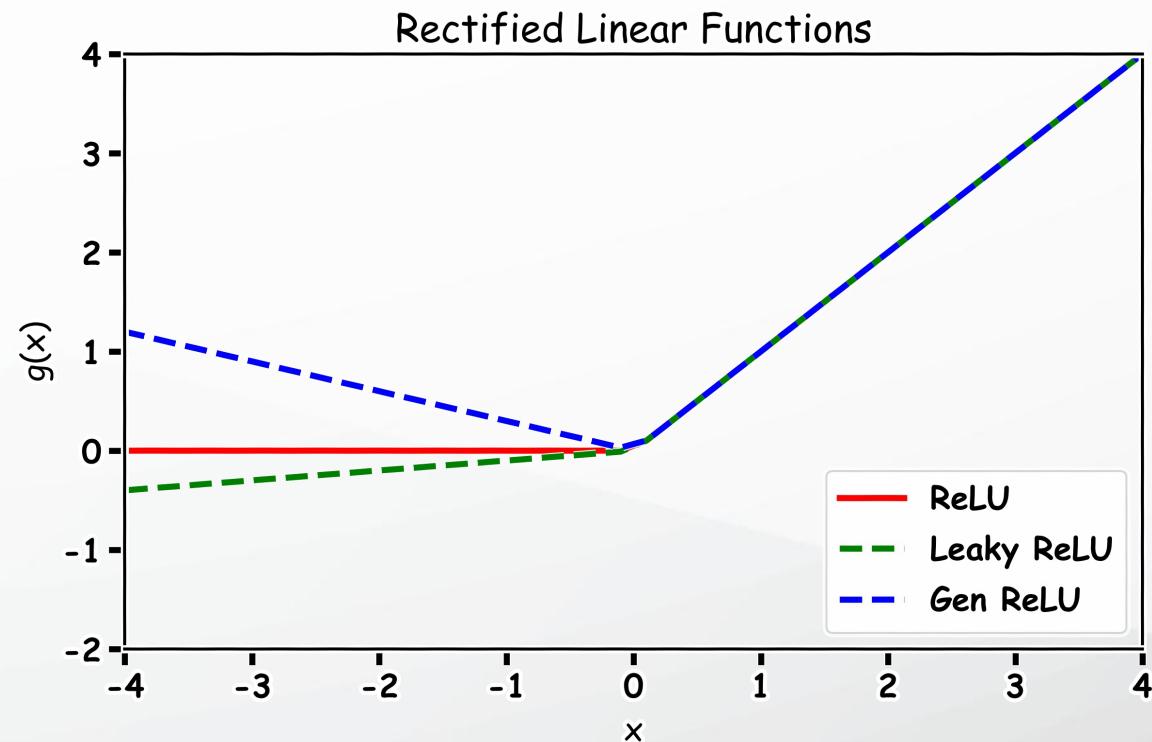
Leaky ReLU Gradient



- Tries to fix “dying ReLU” problem: derivative is non-zero everywhere.
- Some people report success with this form of activation function, but the results are not always consistent

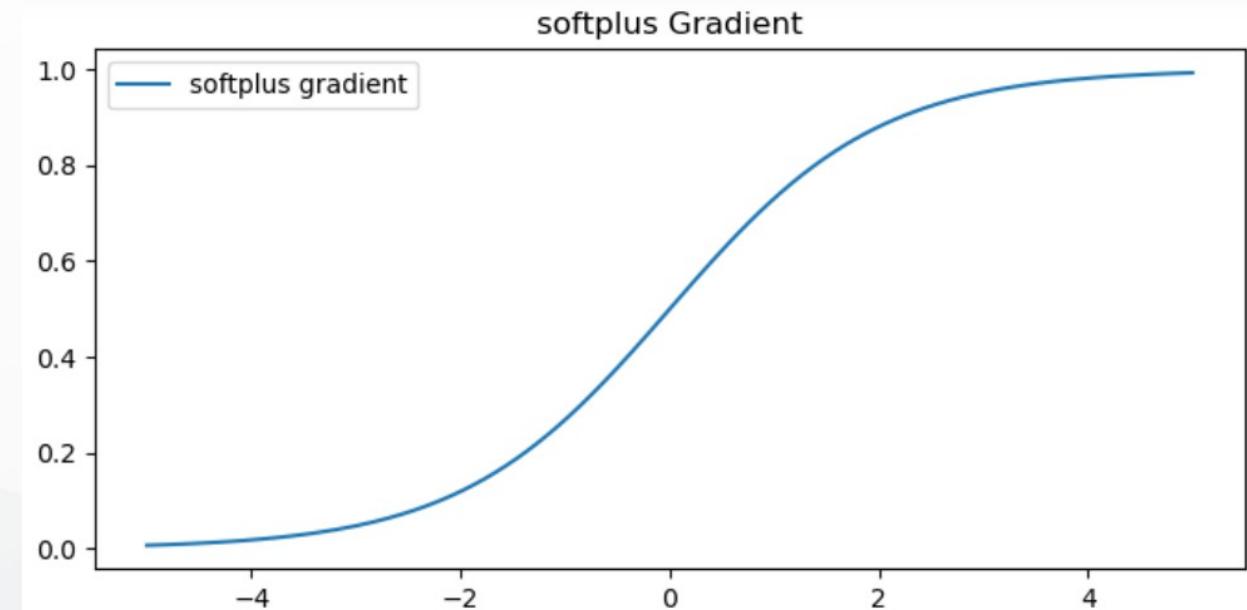
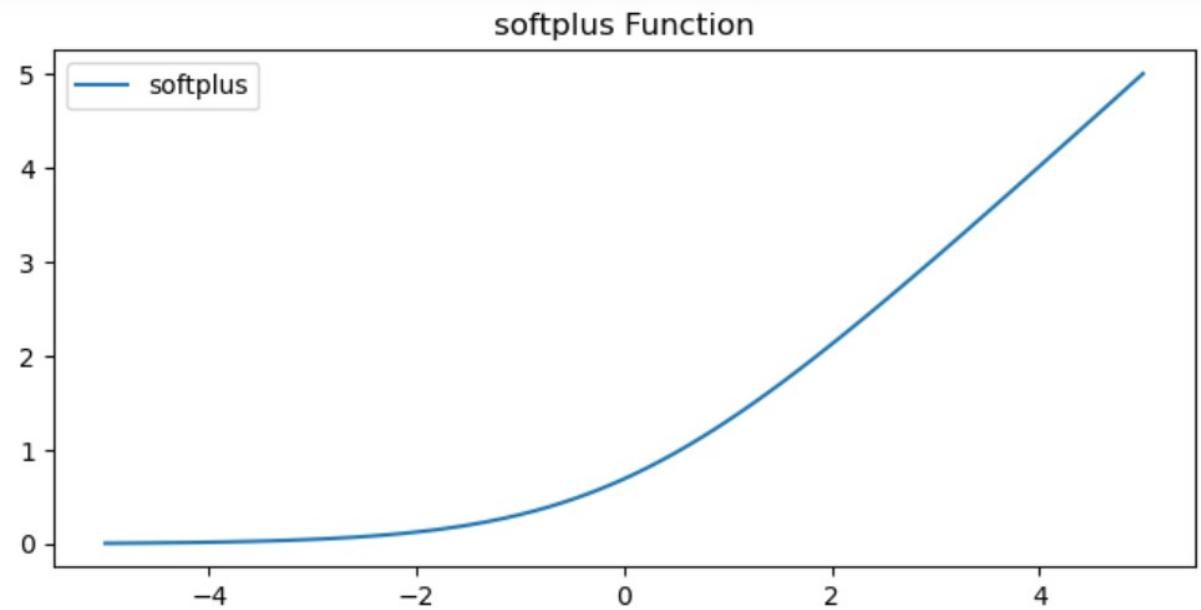
Generalized ReLU

$$y = \max(0, x) + \alpha \min(x, 0)$$



Softplus function

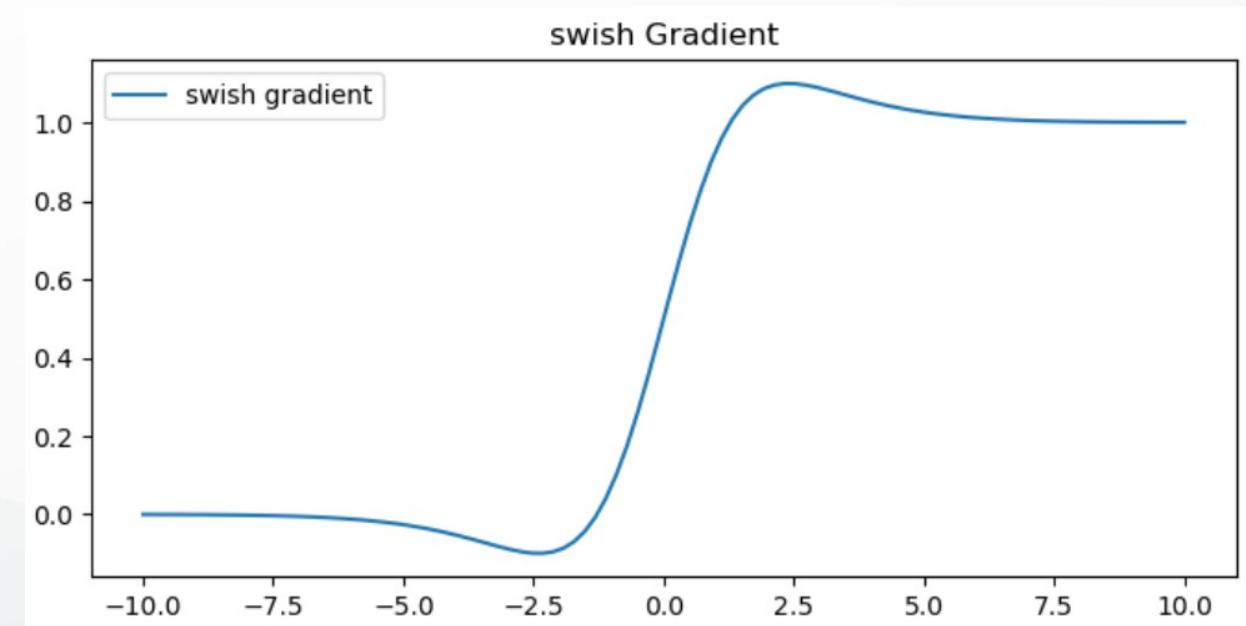
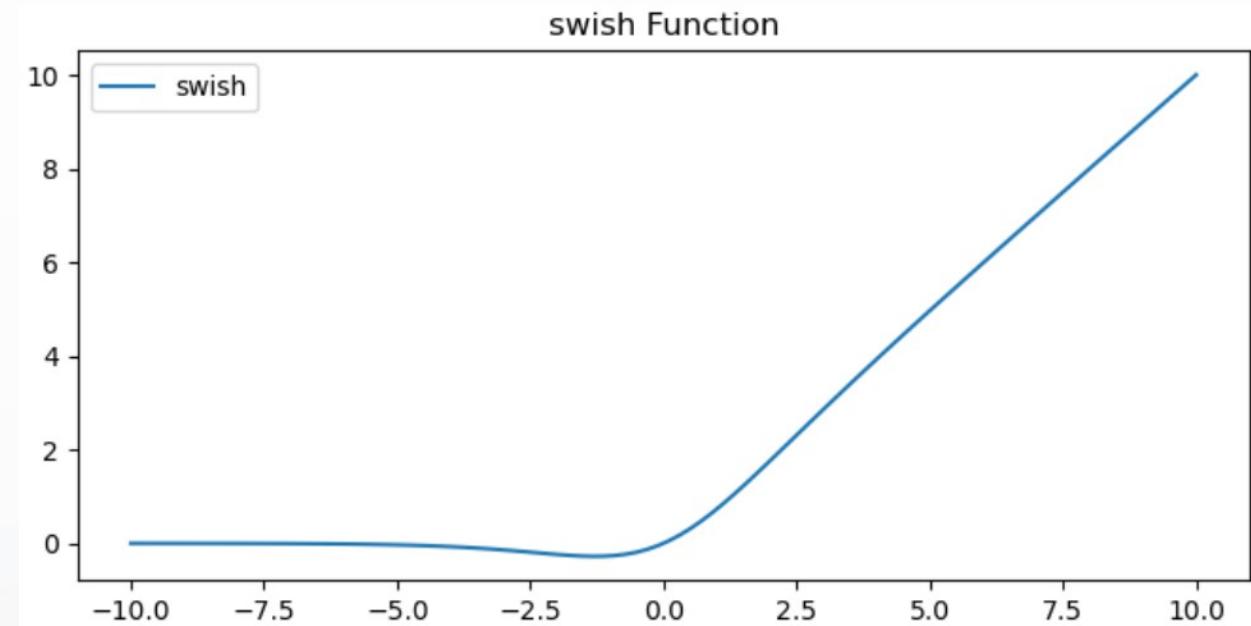
$$y = \log(1 + e^x)$$



Outputs produced by sigmoid and tanh functions have upper and lower limits whereas softplus function produces outputs in scale of $(0, +\infty)$.

Swish function

$$y = x \operatorname{sigmoid}(x)$$



Loss functions for ANNs

- Likelihood for a given point
- Assume independence – likelihood for all measurements
- Maximize the likelihood, or equivalently maximize the log-likelihood
- Turn all this into a loss function

Common loss functions for ANNs

Mean Absolute Error Loss

Mean Squared Error Loss

Negative Log-Likelihood Loss

Cross-Entropy Loss

Hinge Embedding Loss

...

Mean Absolute Error Loss (MAE)

also called L1 Loss

- computes the average of the sum of absolute differences between actual values and predicted values.

$$\text{loss}(x, y) = |x - y|$$

- x represents the actual value and y the predicted value.

used for:

- regression problems
 - especially when the distribution of the target variable has outliers, such as small or big values that are a great distance from the mean value.

Mean Squared Error Loss (MSE)

also called L2 Loss

- computes the average of the squared differences between actual values and predicted values

$$\text{loss}(x, y) = (x - y)^2$$

- x represents the actual value and y the predicted value.

MSE is the default loss function for most regression problems.

Cross-Entropy Loss

Is the difference between two probability distributions for a provided set of occurrences or random variables.

In the discrete setting, given two probability distributions p and q , their cross-entropy is defined as

$$H(p, q) = - \sum_{x \in X} p(x) \log(q(x))$$

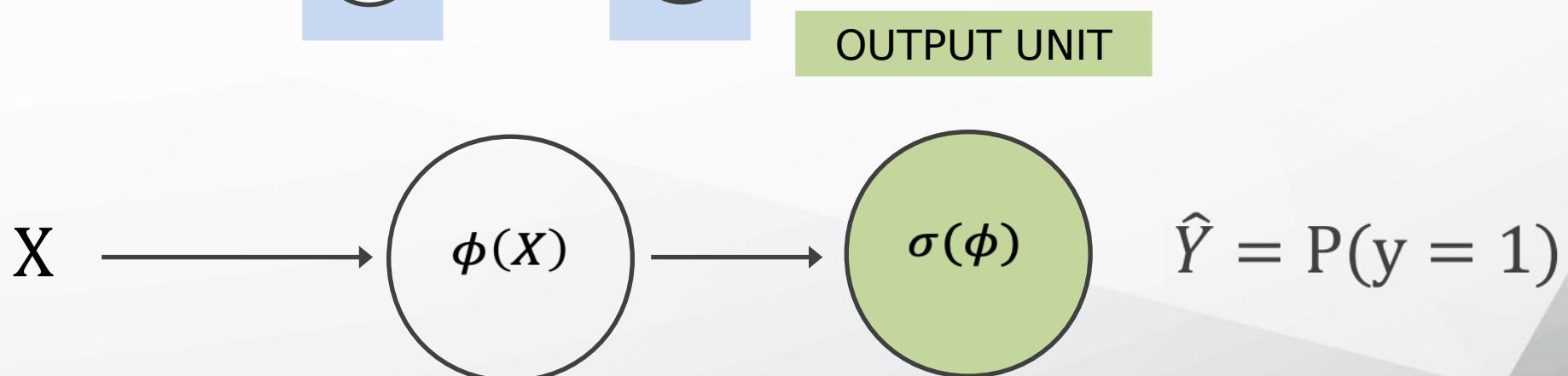
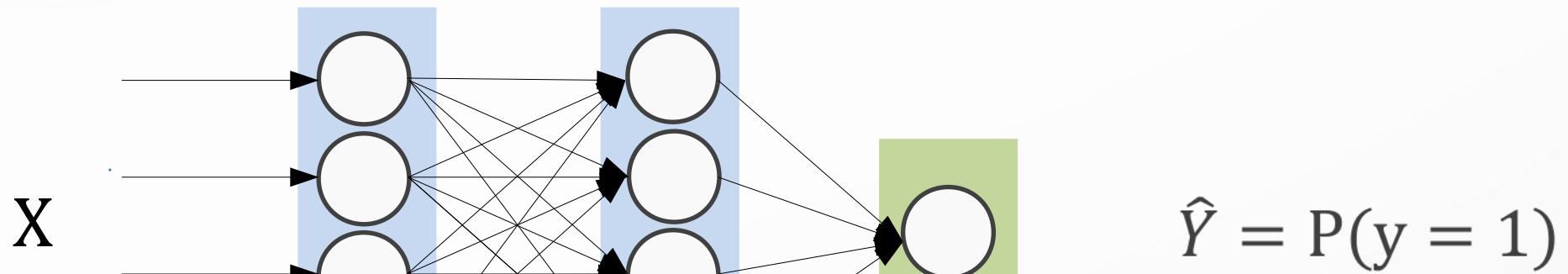
To compute the loss we apply the cross-entropy operator between the desired output and to the real output of our model after we used the softmax operator on the output.

Used in classifications

Output functions

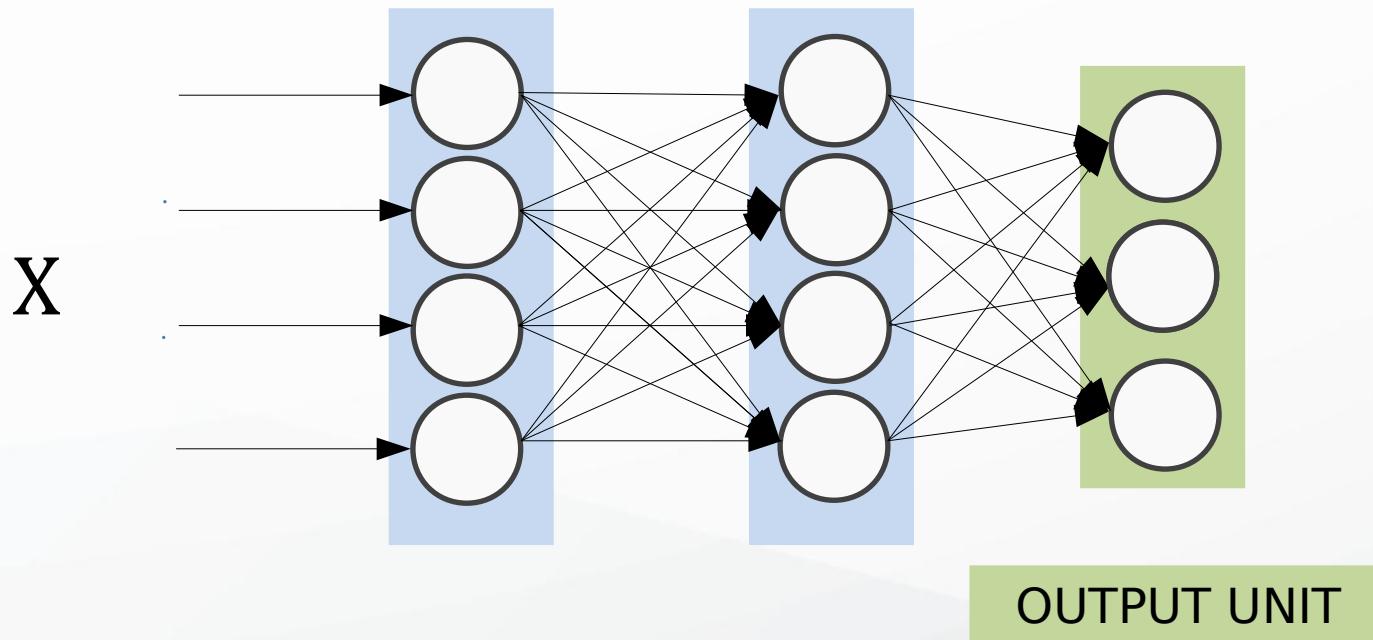
Output Type	Output Distribution	Output layer	Cost Function
Binary	Bernoulli	Sigmoid	Binary Cross Entropy
Discrete	Multinoulli	Softmax	Cross Entropy
Continuous	Gaussian	Linear	MSE
Continuous	Arbitrary	-	GANS

Output unit for binary classification



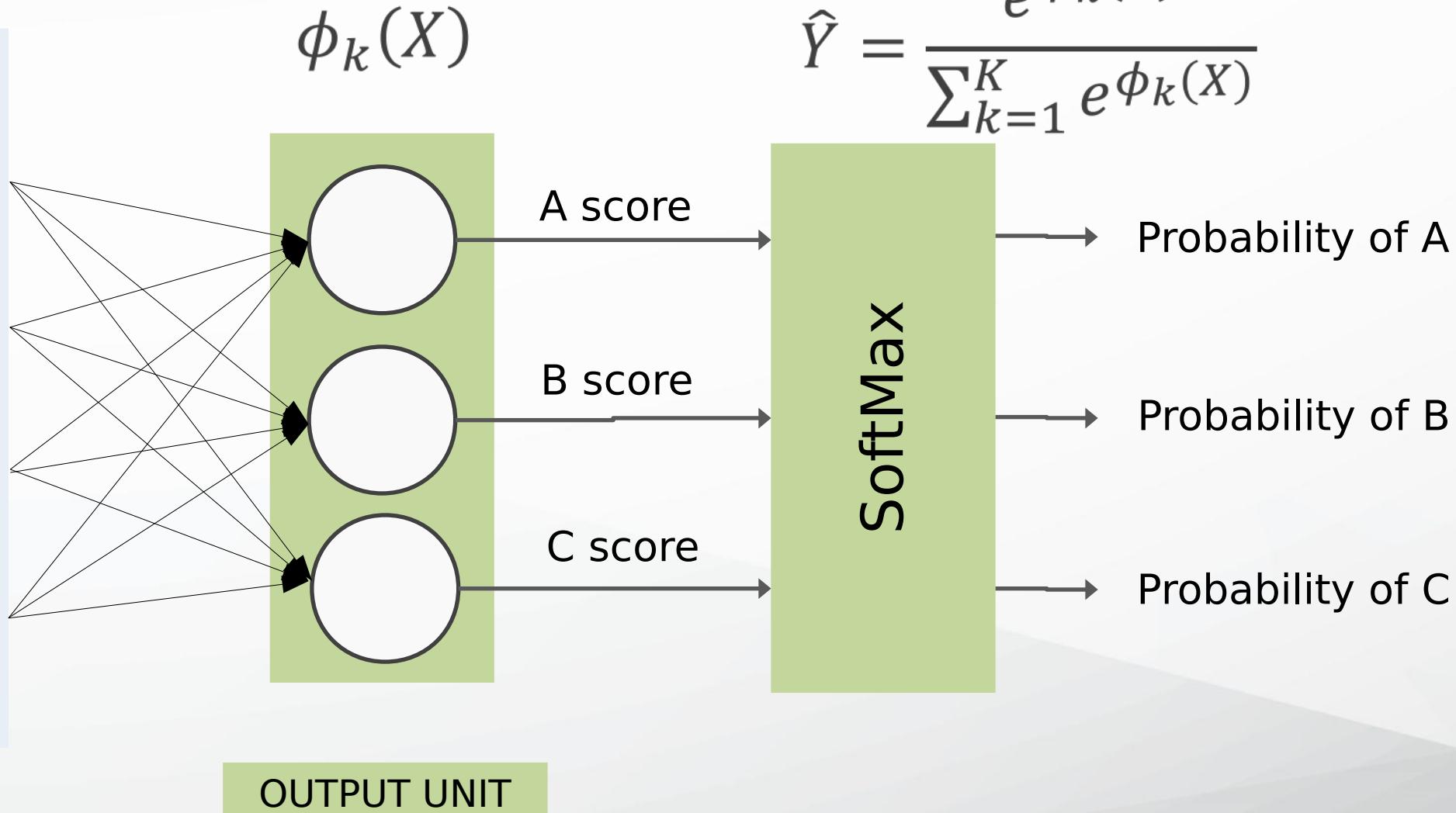
$$X \Rightarrow \phi(X) \Rightarrow P(y = 1) = \frac{1}{1 + e^{-\phi(X)}}$$

Output unit for multi class classification



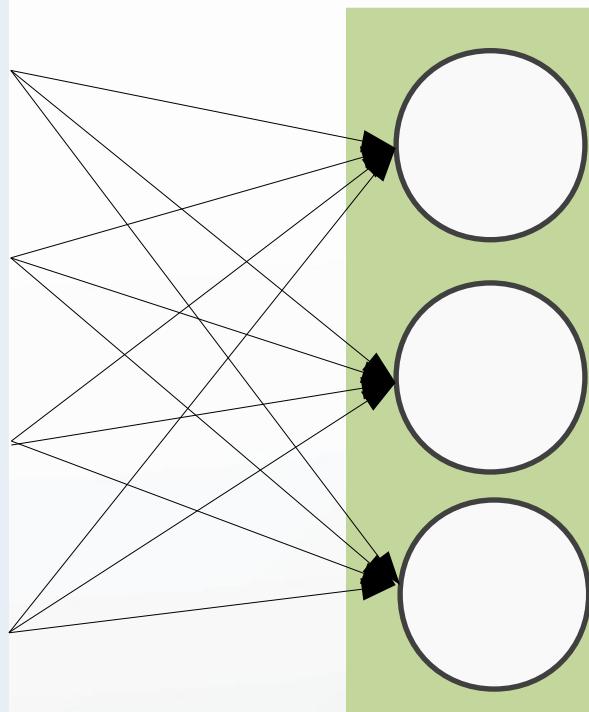
Softmax

rest of the network



Softmax

rest of the network

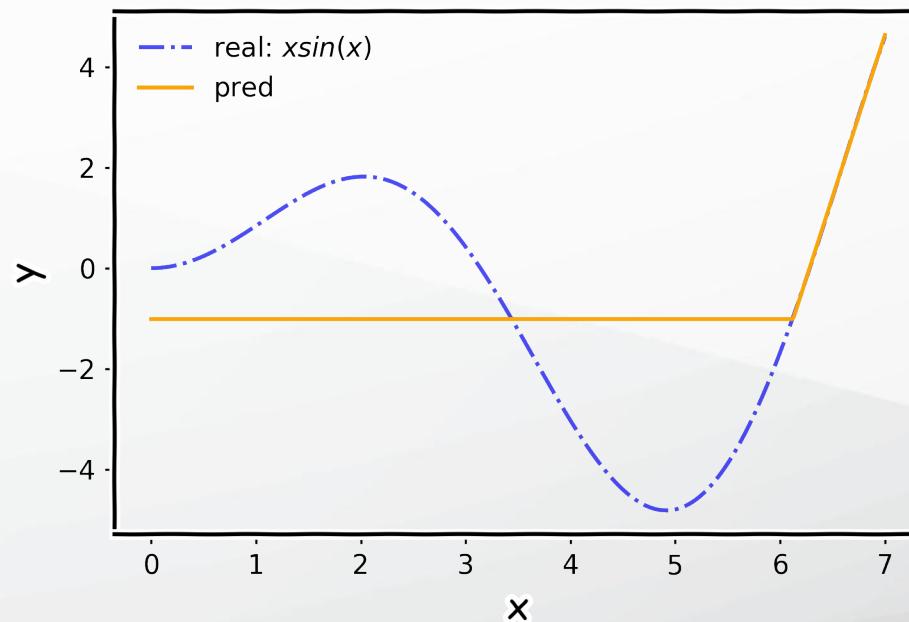
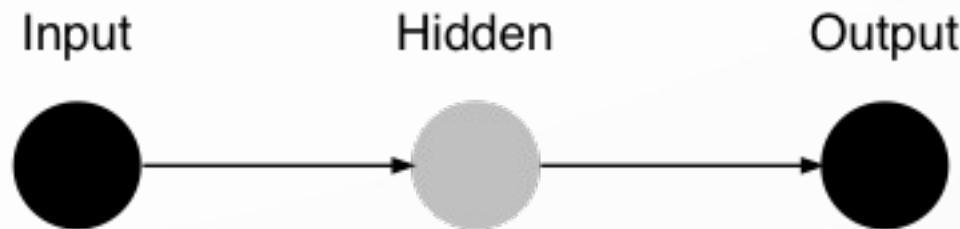


$$\hat{Y} = \frac{e^{\phi_k(X)}}{\sum_{k=1}^K e^{\phi_k(X)}}$$

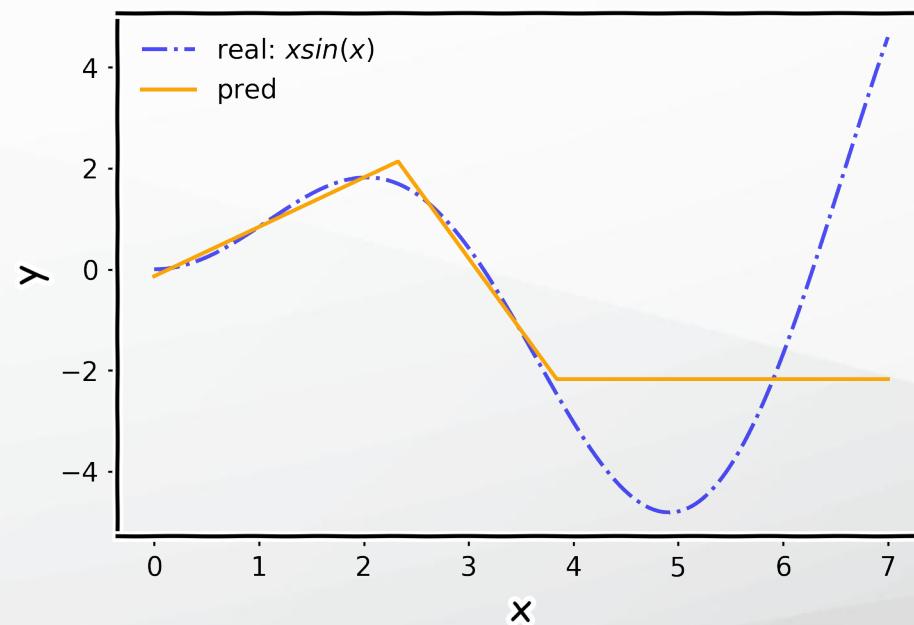
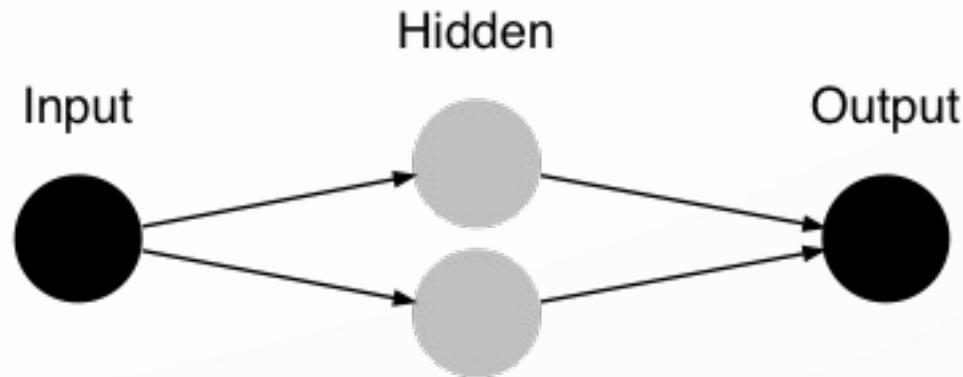
- Probability of A
- Probability of B
- Probability of C

OUTPUT UNIT

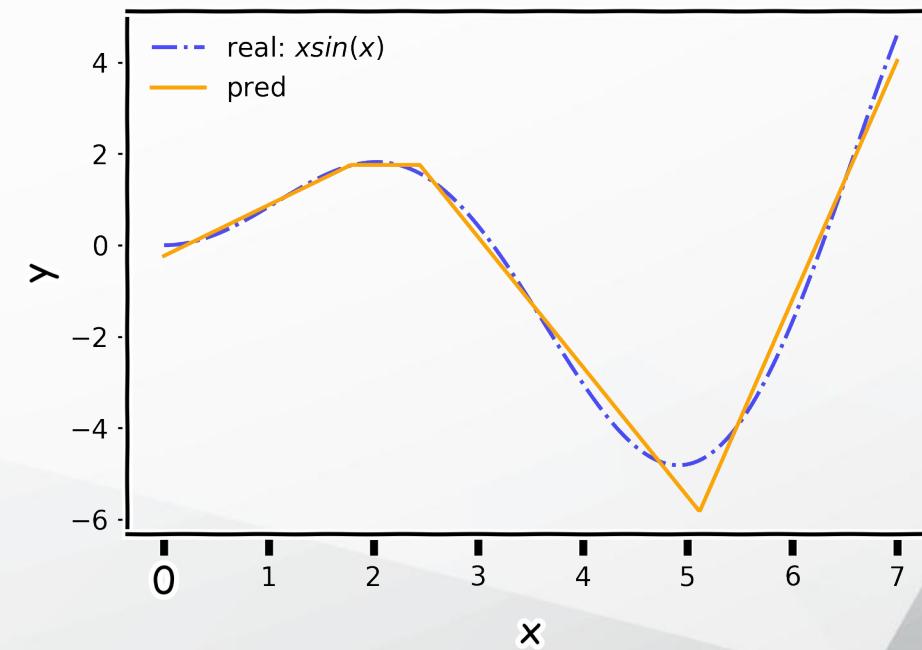
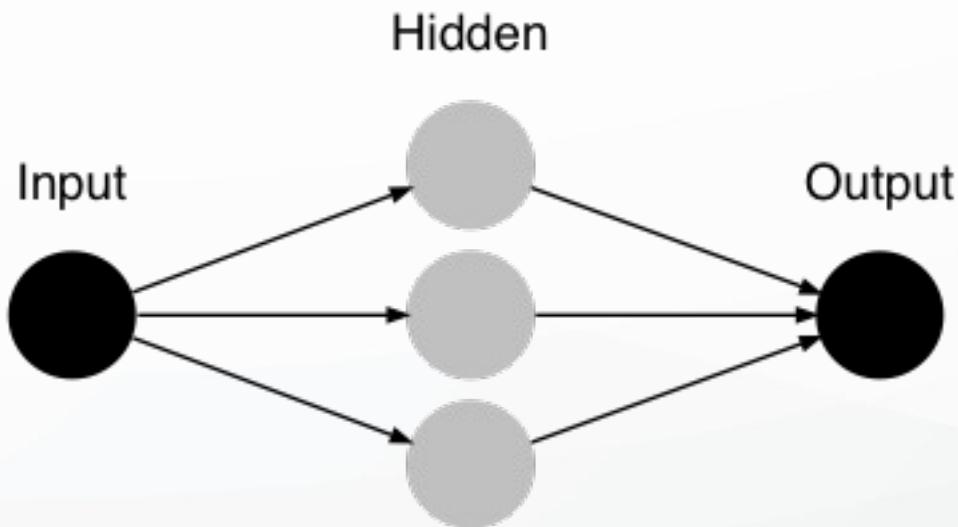
Architecture – performance example



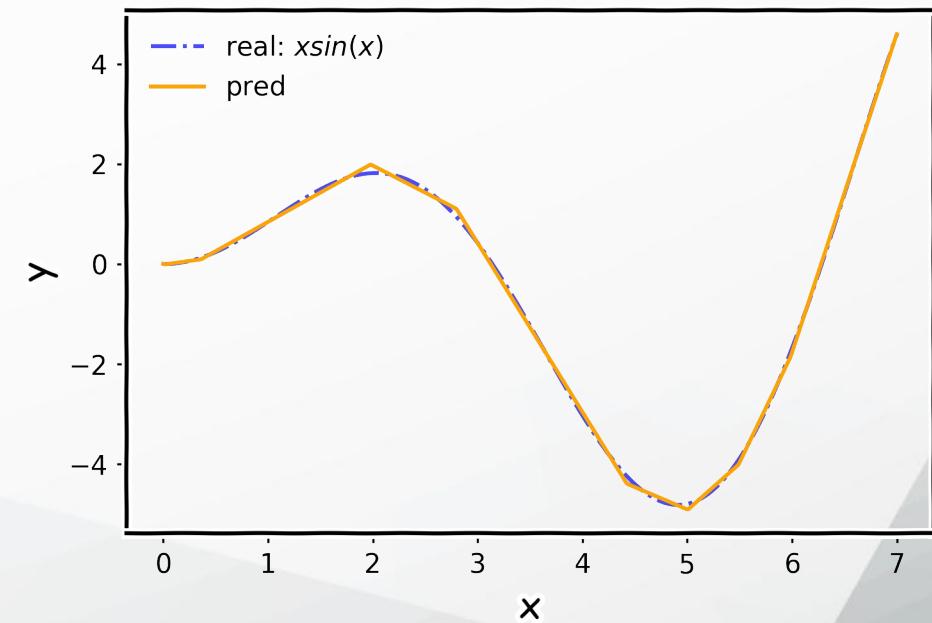
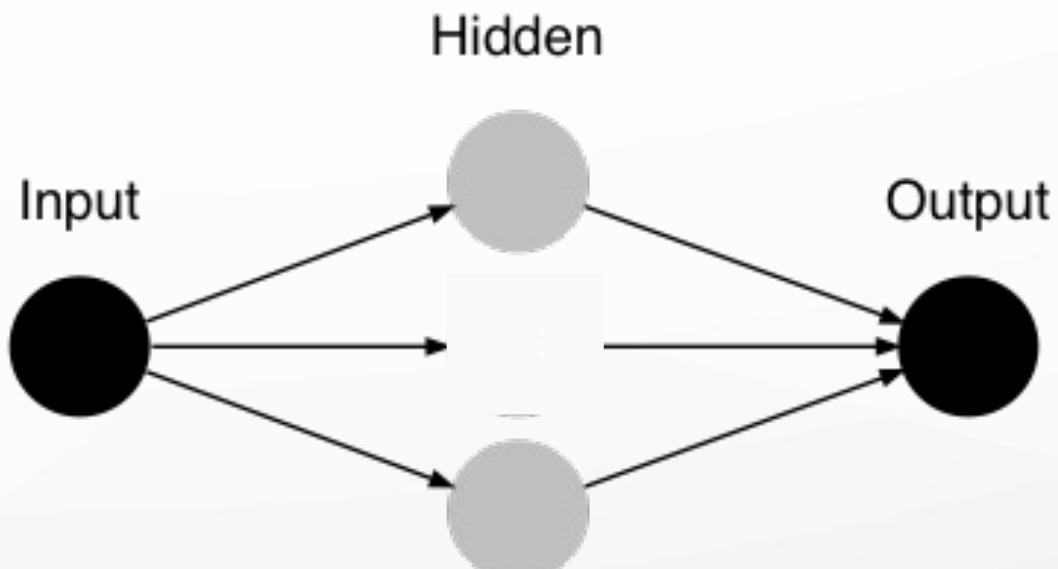
Architecture – performance example



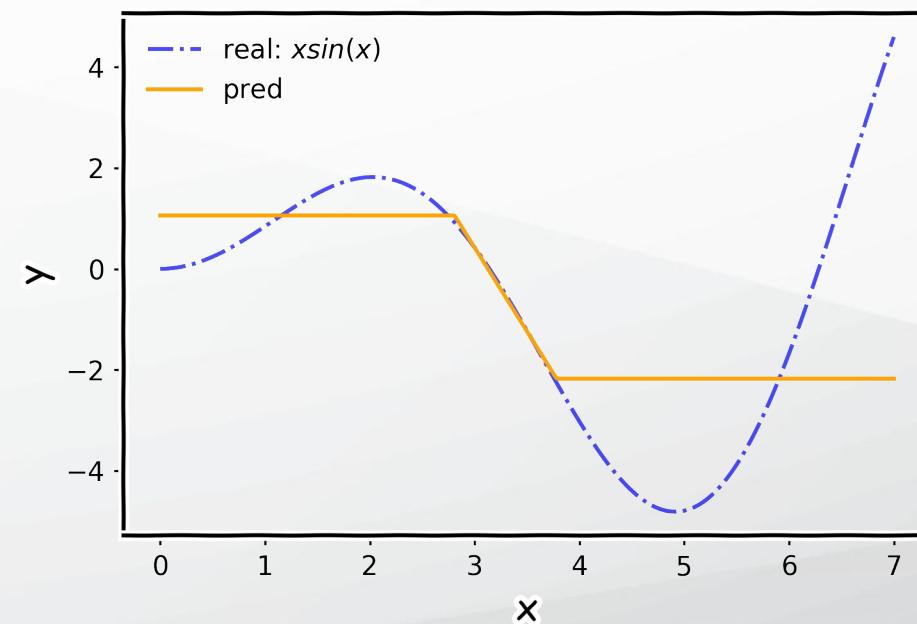
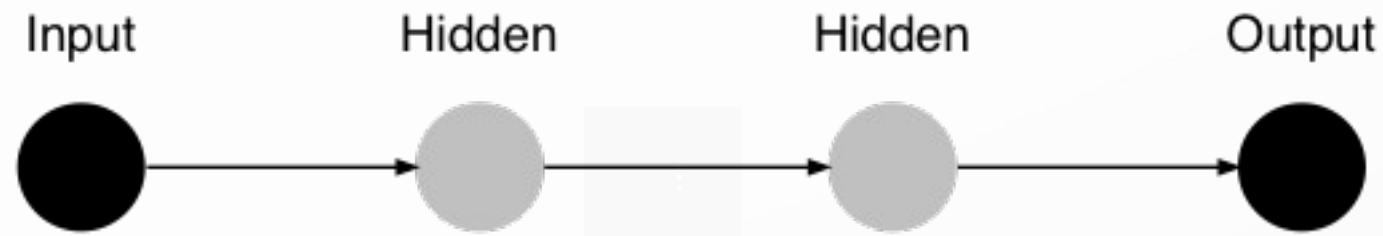
Architecture – performance example



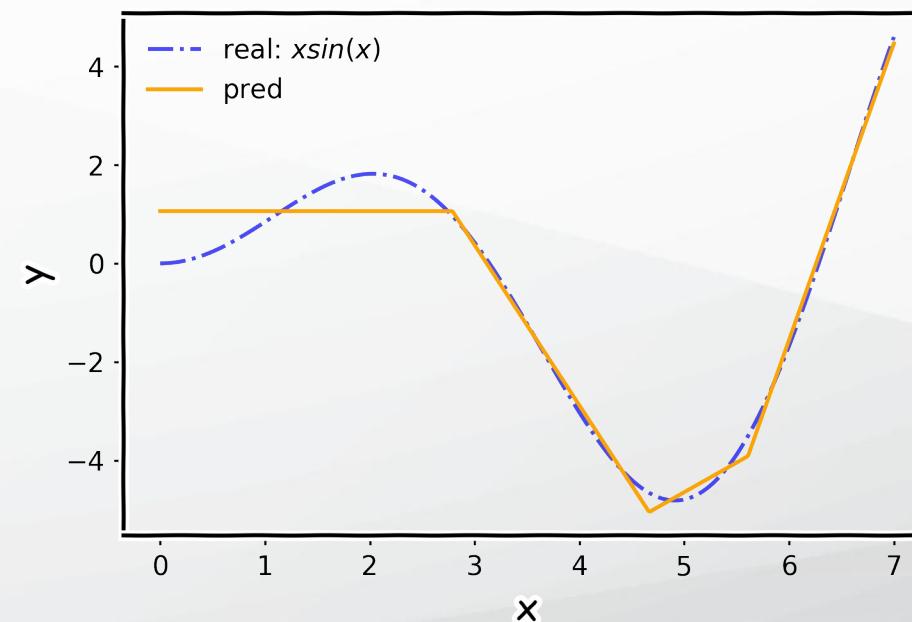
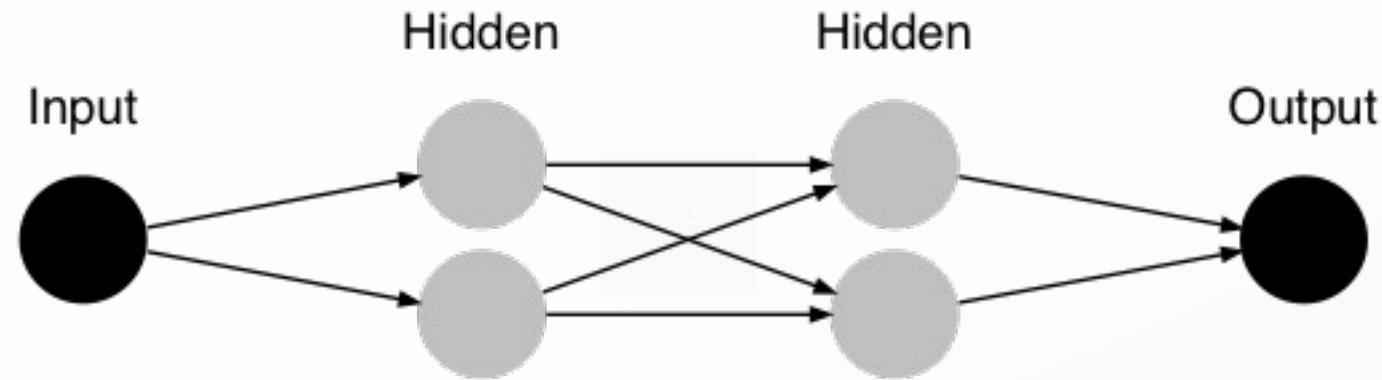
Architecture – performance example



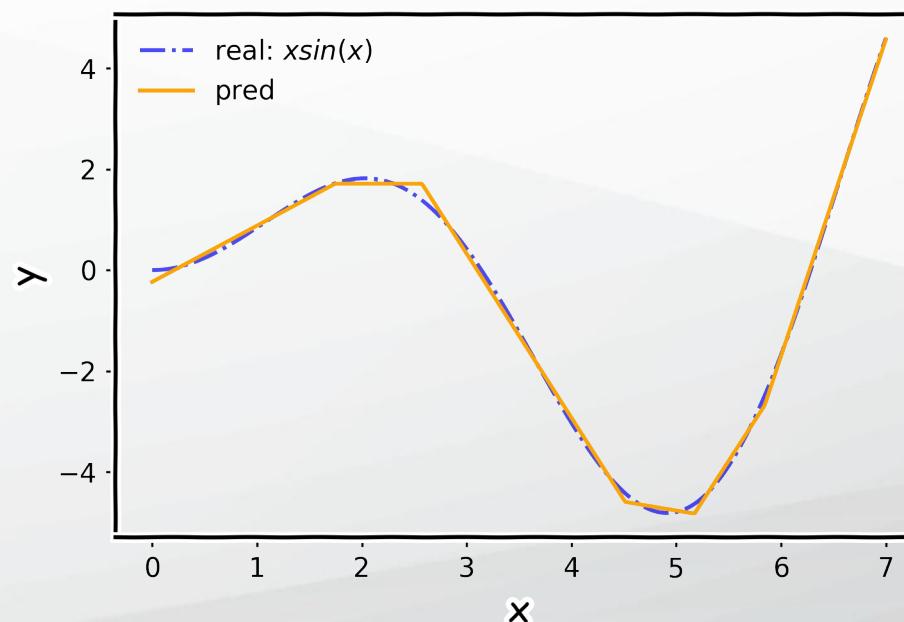
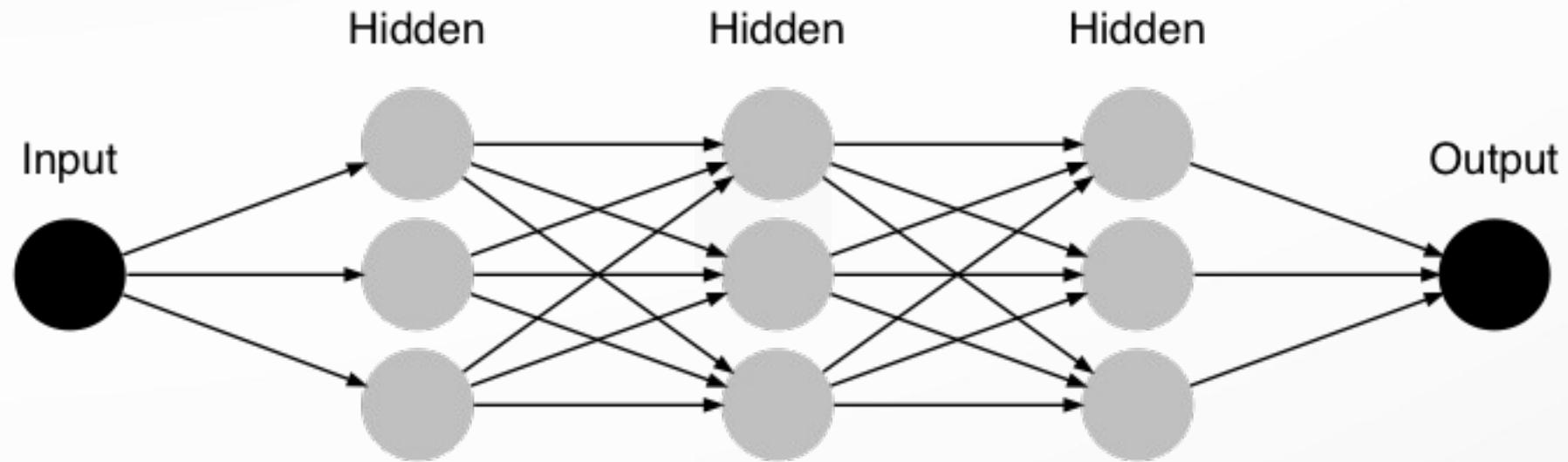
Architecture – performance example



Architecture – performance example



Architecture – performance example



Universal Approximation Theorem

Think of a Neural Network as function approximation.

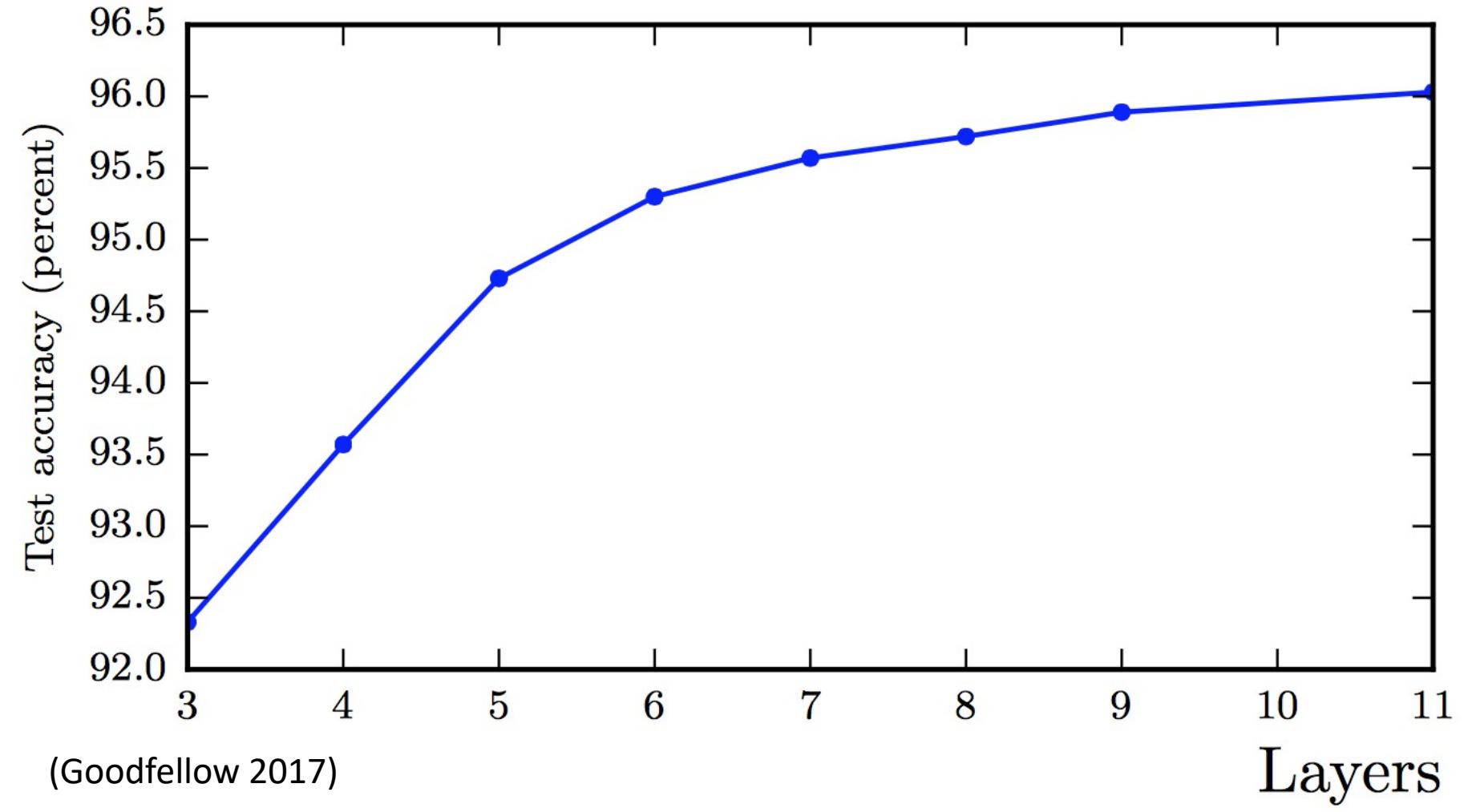
- NN:

One hidden layer is enough to *represent* an approximation of any function to an arbitrary degree of accuracy

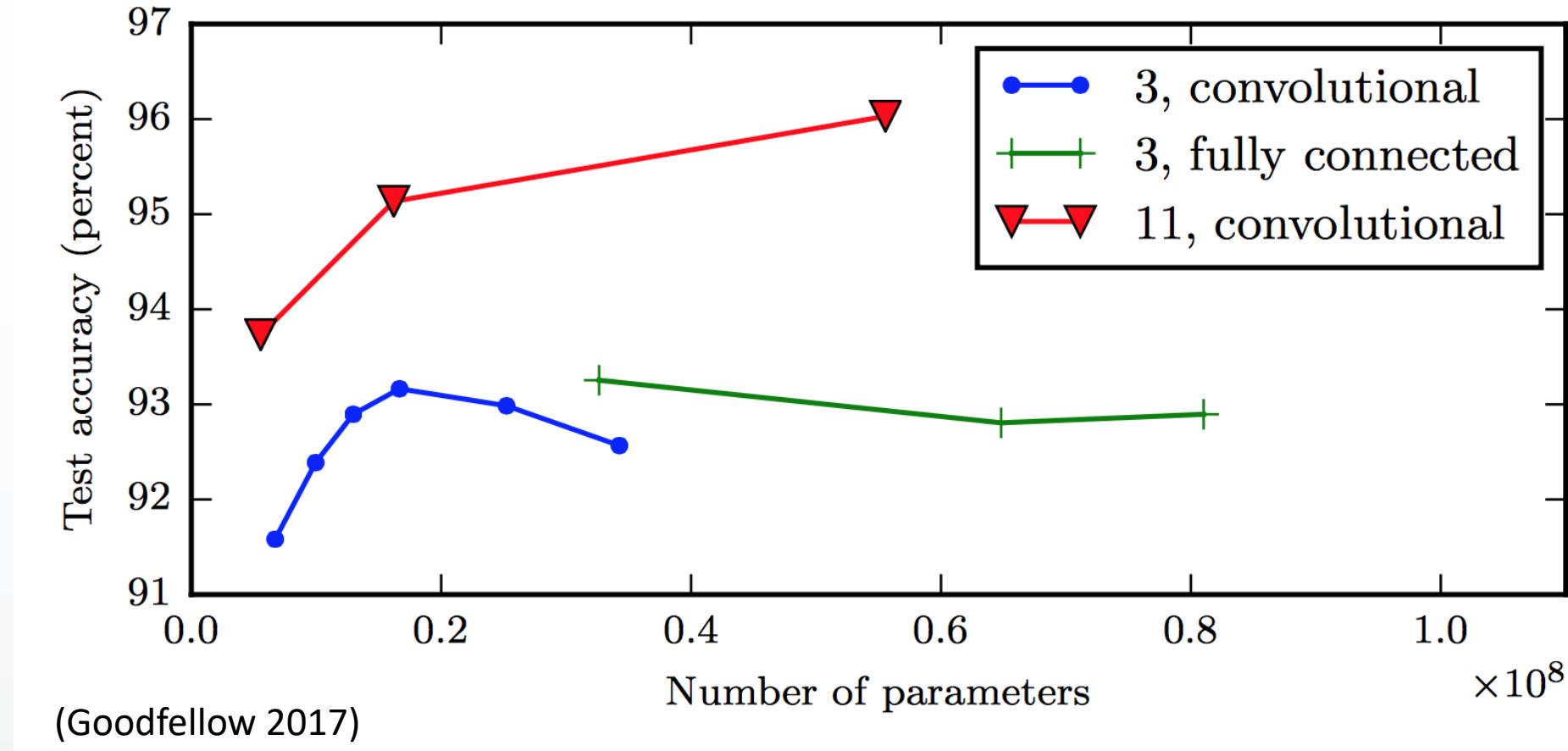
- So why deeper?

- Shallow net may need (exponentially) more width
 - Shallow net may overfit more

Better generalization with depth



Overfitting in shallow nets



The **11-layer net** generalizes better on the test set when controlling for number of parameters.

The 3-layer nets perform worse on the test set, even with similar number of total parameters.

Training a feed-forward ANN

Initialisation of network weights $w_{1,1}^1, w_{1,2}^1, w_{1,3}^1, \dots, w_{1,1}^n, \dots, w_{H_{n-1}, H_n}^n, w_{1,1}^O, w_{1,2}^O, \dots, w_{r, H_n}^O$

While not stop condition

For each train example (x^d, t^d) , where $d = 1, 2, \dots, n$

Activate the network and determine the output o^d :

forward propagate the information and determine the output of each neuron

Modify the weights:

establish and backward propagate the error:

- establish the errors of neurons from the output layer $e_r, r=1, \dots, m$
- backward propagate the errors in the entire network → distribute the errors on all connections of the network
- modify the weights

EndWhile

Back-propagation of errors in an ANN

- One of the first algorithms for fine tuning of the weights in an ANN
- Very popular

Advantages:

- A gradient descent method
- does not require normalization of input vectors (normalization could improve performance)

Limitations:

- is not guaranteed to find the global minimum of the error function, but only a local minimum
- it has trouble crossing plateaus in the error function landscape.
- requires the derivatives of activation functions to be known at network design time.

Computing the derivatives of error

We consider an error function for the model $E(X, W, t)$

Compute the derivative of this function with respect to every weight $w_{j,k}^l$ (the weight from layer l , between neuron j from layer l and neuron k from layer $l-1$).

In general it is:

$$\frac{\partial E}{\partial w_{j,k}^l} = \frac{\partial E}{\partial o_j^l} \frac{\partial o_j^l}{\partial w_{j,k}^l} = \frac{\partial E}{\partial o_j^l} \frac{\partial o_j^l}{\partial \text{net}_j^l(X^l)} \frac{\partial \text{net}_j^l(X^l)}{\partial w_{j,k}^l}$$

Observe that in the last derivative we have a sum, but only one term depends on the weight so:

$$\frac{\partial \text{net}_j^l(X^l)}{\partial w_{j,k}^l} = \frac{\partial}{\partial w_{j,k}^l} \left(\sum_{q=1}^{n_{l-1}} x_q^l w_{j,q}^l \right) = \frac{\partial(x_k^l w_{j,k}^l)}{\partial w_{j,k}^l} = x_k^l = o_k^{l-1}$$

Here: $X^l = (x_1^l, x_2^l, \dots, x_{n_l-1}^l)$ is the input for layer l (aka the output o^{l-1} from the previous layer)

Computing the derivatives of error

For the first hidden layer we have a different situation: the input for this layer is the actual input in the network.

If we evaluate further the partial derivative we get:

$$\frac{\partial o_j^l}{\partial net_j^l(X^l)} = \frac{\partial \phi(net_j^l(X^l))}{\partial net_j^l(X^l)}$$

which is the partial derivative of the activation function ϕ - hence the importance of the derivative

In practice we begin from the last layer because the partial derivatives for this layer are straight forward, and we move backward from layer to layer until we reach the first hidden one.

Thank You!

Deep learning

April 2023

Introduction

Tensors

Convolution

Kernels

Convolutional
Network -
structure

Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

Outline

Introduction

Introduction

Tensors

Tensors

Convolution

Convolution

Kernels

Kernels

Convolutional Network - structure

Convolutional Network -
structure

Convolutional Layer

Convolutional
Layer

Feature learning

Feature learning
Training the
Convolution Layer

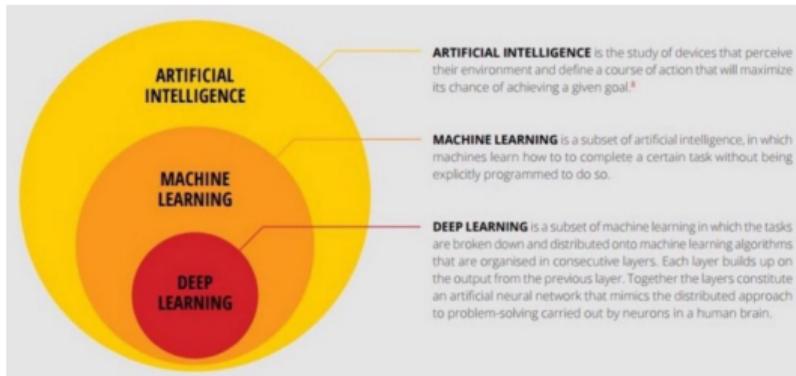
Training the Convolution Layer

Pooling Layer

Pooling Layer

What is deep learning?

- ▶ a sub-field of machine learning dealing with algorithms inspired by the structure and function of the brain called artificial neural networks



- ▶ it mirrors the functioning of our brains
- ▶ similar to how nervous system structured where each neuron connected each other and passing information

Introduction

Tensors

Convolution

Kernels

Convolutional
Network -
structure

Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

Deep Convolutional Neural Networks

(*ConvNets*) are deep artificial neural networks used:

- ▶ to classify images (e.g. name what they see)
- ▶ cluster them by similarity (photo search)
- ▶ perform object recognition within scenes

algorithms that can identify faces, individuals, street signs, tumors, perform optical character recognition (OCR).

Introduction

Tensors

Convolution

Kernels

Convolutional
Network -
structure

Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

Deep Convolutional Neural Networks

- ▶ pre-processing required in a ConvNet is much lower as compared to other classification algorithms
- ▶ architecture of a ConvNet is analogous to that of the connectivity pattern of Neurons in the Human Brain - Visual Cortex
- ▶ a ConvNet captures the spatial and temporal dependencies in an image

[Introduction](#)[Tensors](#)[Convolution](#)[Kernels](#)[Convolutional Network - structure](#)[Convolutional Layer](#)[Feature learning
Training the Convolution Layer](#)[Pooling Layer](#)

Tensors

An n^{th} - rank tensor in m -dimensional space is a mathematical object that has n indices and m^n components and obeys certain transformation rules.

- generalizations of scalars, vectors, and matrices to an arbitrary number of indices.
- used in physics such as elasticity, fluid mechanics, and general relativity.

Introduction

Tensors

Convolution

Kernels

Convolutional
Network -
structure

Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

Notations for tensors

- ▶ $a_{ijk\dots}$, $a^{ijk\dots}$, $a_i^{jk\dots}$, etc., may have an arbitrary number of indices
 - ▶ a tensor (rank $r + s$) may be of mixed type (r, s) :
 r "contravariant" (upper) indices and s "covariant" (lower) indices.
- the positions of the slots in which contravariant and covariant indices are placed are significant!

$$a_{\mu\nu}^{\lambda} \neq a_{\mu}^{\nu\lambda}$$

Introduction

Tensors

Convolution

Kernels

Convolutional
Network -
structure

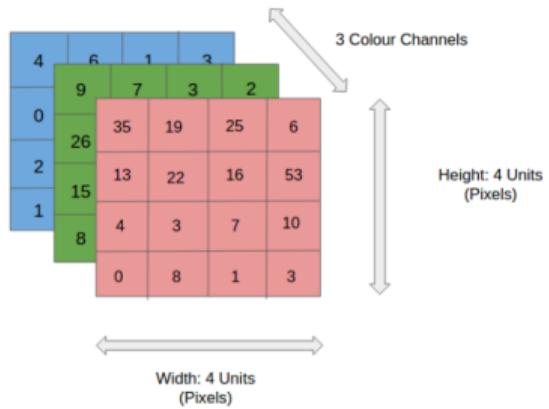
Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

Images as tensors

ConvNets ingest and process images as tensors.



- reduce the images → form easy to process (without losing critical features)

Introduction
Tensors
Convolution
Kernels
Convolutional Network - structure
Convolutional Layer
Feature learning
Training the Convolution Layer

Pooling Layer

Convolution operation

an operation on two functions $x(t)$ (**input**) and $w(t)$ (**kernel**)
of a real - valued argument

$$s(t) = \int x(a)w(t-a)da$$

notation:

$$s(t) = (x \circledast w)(t)$$

if t is discrete the integral turns into a sum

$$s(t) = (x \circledast w)(t) = \sum_{a=-\infty}^{\infty} x(a)w(t-a)$$

Introduction

Tensors

Convolution

Kernels

Convolutional
Network -
structure

Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

Convolution operation

in practice we have two tensors:

- ▶ the input - a multidimensional array of data
 - ▶ the kernel - a multidimensional array of parameters
(adapted by the learning algorithm)
- stored separately → that these functions are zero everywhere but in the finite set of points
 - we can implement the infinite summation as a summation over a finite number of array elements
 - convolutions can be over more than one axis at a time

$$S(i, j) = (I \circledast K)(i, j) = \sum_m \sum_n I(m, n)K(i - m, j - n)$$

Introduction

Tensors

Convolution

Kernels

Convolutional Network - structure

Convolutional Layer

Feature learning
Training the Convolution Layer

Pooling Layer

Using a kernel

we want apply a filter over the image

AIM: **extract the high-level features** (edges, color, gradient orientation)

Example: *Image Dimensions = 5 (Height) x 5 (Breadth) x 1 (Number of channels, eg. RGB)*

Kernel / filter:

$$K = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}$$

Introduction

Tensors

Convolution

Kernels

Convolutional
Network -
structure

Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

Using a kernel

Introduction

Tensors

Convolution

Kernels

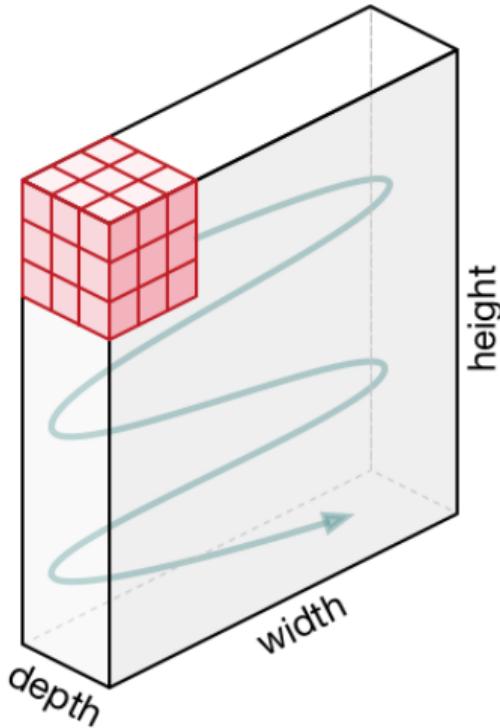
Convolutional
Network -
structure

Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

Using a Kernel - movement of the Kernel



- ▶ kernel shifts
- ▶ every time performing a matrix multiplication operation between K and the portion P of the image over which the kernel is hovering

Introduction
Tensors
Convolution
Kernels
Convolutional Network - structure
Convolutional Layer
Feature learning
Training the Convolution Layer
Pooling Layer

Using a kernel - 3 channels

Introduction

Tensors

Convolution

Kernels

Convolutional
Network -
structure

Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

Layers of a convolutional network

Typical three stages:

- ▶ first: several convolutions
- ▶ second: a nonlinear activation function (ex: rectified linear activation function) - **detector stage**
- ▶ third: **pooling** function to modify the output

Examples: max pooling (Zhou and Chellappa, 1988 - maximum output within a rectangular neighborhood), the average of a rectangular neighborhood, L^2 norm of a rectangular neighborhood, a weighted average based on the distance from the central pixel.

Introduction
Tensors
Convolution
Kernels
Convolutional Network - structure
Convolutional Layer
Feature learning
Training the Convolution Layer
Pooling Layer

Training the network

- ▶ similar with ANN
- ▶ after computing the error, a gradient descent method is applied to all layers

Introduction

Tensors

Convolution

Kernels

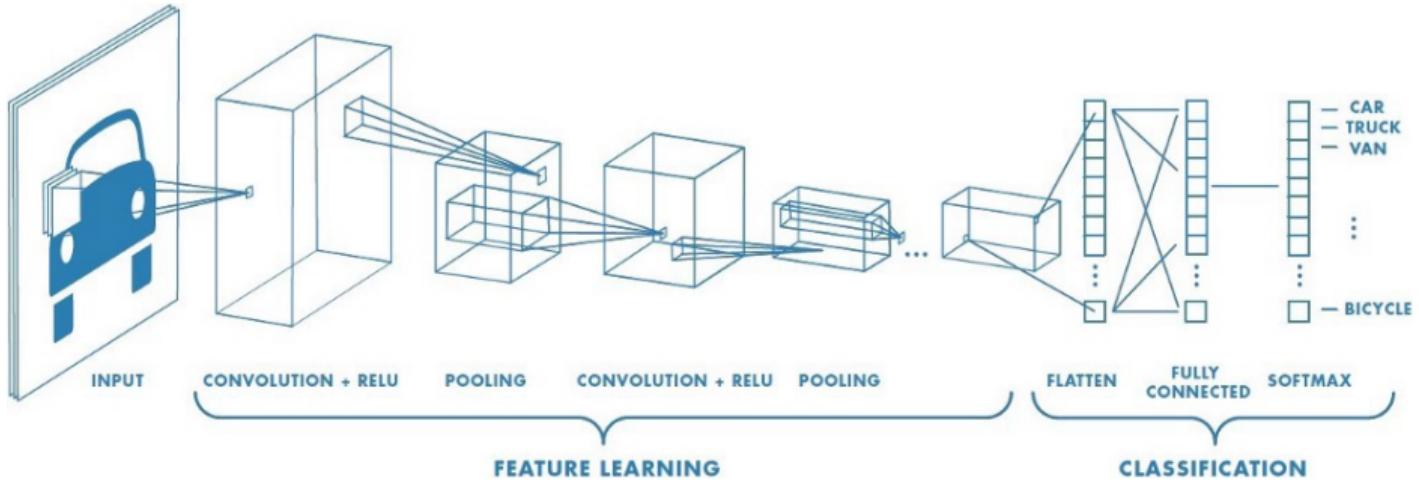
Convolutional
Network -
structure

Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

Feature learning



Feature learning

Applying this filter to an image will result in a feature map that only contains vertical lines. It is a vertical line detector.

1.0	0.0	-1.0
2.0	0.0	-2.0
1.0	0.0	-1.0

Table: A 3x3 element Sobel filter for detecting vertical lines

Dragging this filter systematically across pixel values in an image can only highlight vertical line pixels.

Feature learning

-2.0	-2.0	-4.0	-2.0	-2.0
-1.0	-1.0	-2.0	-1.0	-1.0
0.0	0.0	0.0	0.0	0.0
1.0	1.0	2.0	1.0	1.0
2.0	2.0	4.0	2.0	2.0

Table: A horizontal line detector

Introduction
Tensors
Convolution
Kernels
Convolutional Network - structure
Convolutional Layer
Feature learning
Training the Convolution Layer
Pooling Layer

- ▶ combining the filters' results (combining both feature maps, will result in all of the lines in an image being highlighted)
- ▶ a suite of tens or even hundreds of other small filters can be designed to detect other features in the image

Feature learning

- ★ the values of the filter are weights to be learned during the training of the network
- training under gradient descent

- ▶ the network will learn what types of features to extract from the input
- ▶ the extracted features will be those that minimize the loss function (e. g. extract features that are the most useful for classifying images as dogs or cats)

Introduction

Tensors

Convolution

Kernels

Convolutional
Network -
structure

Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

Gradient descent on Convolution Layer

- ▶ the input $X = \begin{bmatrix} x_{1,1} & x_{1,2} & x_{1,3} \\ x_{2,1} & x_{2,2} & x_{2,3} \\ x_{3,1} & x_{3,2} & x_{3,3} \end{bmatrix}$
- ▶ the filter $F = \begin{bmatrix} f_{1,1} & f_{1,2} \\ f_{2,1} & f_{2,2} \end{bmatrix}$
- ▶ the output is $O = X \circledast F$
- ▶ $\frac{\partial E}{\partial O}$ is the gradient of loss from previous layer

[Introduction](#)[Tensors](#)[Convolution](#)[Kernels](#)[Convolutional Network - structure](#)[Convolutional Layer](#)[Feature learning
Training the Convolution Layer](#)[Pooling Layer](#)

Gradient descent on Convolution Layer

[Introduction](#)[Tensors](#)[Convolution](#)[Kernels](#)[Convolutional Network - structure](#)[Convolutional Layer](#)[Feature learning
Training the Convolution Layer](#)[Pooling Layer](#)

After we apply the convolution on X and F we have:

$$O_{1,1} = x_{1,1} * F_{1,1} + x_{1,2} * F_{1,2} + x_{2,1} * F_{2,1} + x_{2,2} * F_{2,2}$$

$$O_{1,2} = x_{1,2} * F_{1,1} + x_{1,3} * F_{1,2} + x_{2,2} * F_{2,1} + x_{2,3} * F_{2,2}$$

$$O_{2,1} = x_{2,1} * F_{1,1} + x_{2,2} * F_{1,2} + x_{3,1} * F_{2,1} + x_{3,2} * F_{2,2}$$

$$O_{2,2} = x_{2,2} * F_{1,1} + x_{2,3} * F_{1,2} + x_{3,2} * F_{2,1} + x_{3,3} * F_{2,2}$$

Gradient descent on Convolution Layer

we compute the partial derivative of O with respect of F

$$\frac{\partial O_{1,1}}{\partial F_{1,1}} = x_{1,1}, \quad \frac{\partial O_{1,1}}{\partial F_{1,2}} = x_{1,2}, \quad \frac{\partial O_{1,1}}{\partial F_{2,1}} = x_{2,1}, \quad \frac{\partial O_{1,1}}{\partial F_{2,2}} = x_{2,2}$$

similar we compute for $O_{1,2}$, $O_{2,1}$, and $O_{2,2}$

the gradient to update the filter will be

$$\frac{\partial E}{\partial F} = \frac{\partial E}{\partial O} * \frac{\partial O}{\partial F} \tag{1}$$

Introduction
Tensors
Convolution
Kernels
Convolutional Network - structure
Convolutional Layer
Feature learning
Training the Convolution Layer
Pooling Layer

Gradient descent on Convolution Layer

if we expand Equation 1

$$\begin{aligned}\frac{\partial E}{\partial F_{1,1}} &= \frac{\partial E}{\partial O_{1,1}} * \frac{\partial O_{1,1}}{\partial F_{1,1}} + \frac{\partial E}{\partial O_{1,2}} * \frac{\partial O_{1,2}}{\partial F_{1,1}} \\ &\quad + \frac{\partial E}{\partial O_{2,1}} * \frac{\partial O_{2,1}}{\partial F_{1,1}} + \frac{\partial E}{\partial O_{2,2}} * \frac{\partial O_{2,2}}{\partial F_{1,1}} \\ &= \frac{\partial E}{\partial O_{1,1}} * x_{1,1} + \frac{\partial E}{\partial O_{1,2}} * x_{1,2} \\ &\quad + \frac{\partial E}{\partial O_{2,1}} * x_{2,1} + \frac{\partial E}{\partial O_{2,2}} * x_{2,2}\end{aligned}$$

Introduction

Tensors

Convolution

Kernels

Convolutional
Network -
structure

Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

Gradient descent on Convolution Layer

[Introduction](#)[Tensors](#)[Convolution](#)[Kernels](#)[Convolutional Network - structure](#)[Convolutional Layer](#)[Feature learning
Training the Convolution Layer](#)[Pooling Layer](#)

we observe that this is actually a convolution product between the input and the loss gradient

$$\begin{bmatrix} \frac{\partial E}{\partial F_{1,1}} & \frac{\partial E}{\partial F_{1,2}} \\ \frac{\partial E}{\partial F_{2,1}} & \frac{\partial E}{\partial F_{2,2}} \end{bmatrix} = X \circledast \begin{bmatrix} \frac{\partial E}{\partial O_{1,1}} & \frac{\partial E}{\partial O_{1,2}} \\ \frac{\partial E}{\partial O_{2,1}} & \frac{\partial E}{\partial O_{2,2}} \end{bmatrix} \quad (2)$$

Gradient descent on Convolution Layer

[Introduction](#)[Tensors](#)[Convolution](#)[Kernels](#)[Convolutional Network - structure](#)[Convolutional Layer](#)[Feature learning
Training the Convolution Layer](#)[Pooling Layer](#)

similar we get for the derivative of E with respect of X

$$\begin{bmatrix} \frac{\partial E}{\partial x_{1,1}} & \frac{\partial E}{\partial x_{1,2}} & \frac{\partial E}{\partial x_{1,3}} \\ \frac{\partial E}{\partial x_{2,1}} & \frac{\partial E}{\partial x_{2,2}} & \frac{\partial E}{\partial x_{2,3}} \\ \frac{\partial E}{\partial x_{3,1}} & \frac{\partial E}{\partial x_{3,2}} & \frac{\partial E}{\partial x_{3,3}} \end{bmatrix} = \begin{bmatrix} F_{2,2} & F_{2,1} \\ F_{1,2} & F_{1,1} \end{bmatrix} \circledast \begin{bmatrix} \frac{\partial E}{\partial O_{1,1}} & \frac{\partial E}{\partial O_{1,2}} \\ \frac{\partial E}{\partial O_{2,1}} & \frac{\partial E}{\partial O_{2,2}} \end{bmatrix}$$

observe that matrix F is flipped over 180° degrees in this formula.

Pooling

helps to make the representation approximately invariant to small translations of the input.

- useful property if we care more about whether some feature is present than exactly where it is;
- essential for handling inputs of varying size;
- Some guidance as to which kinds of pooling one should use in various situations : Boureau et al., 2010.

Introduction

Tensors

Convolution

Kernels

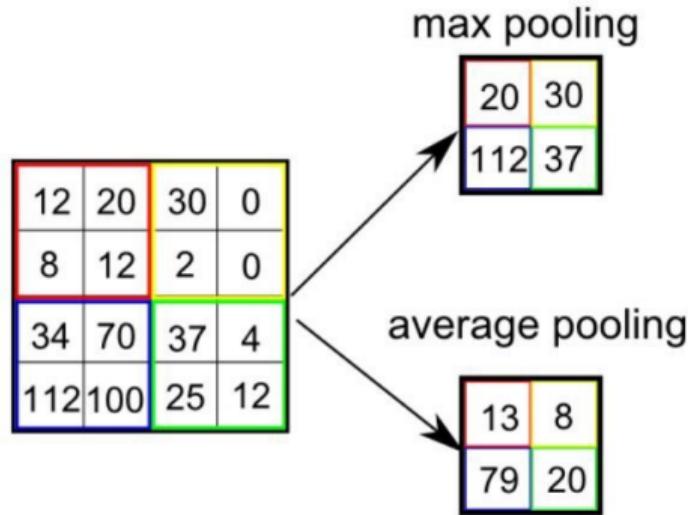
Convolutional
Network -
structure

Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

Pooling



- ▶ Max Pooling - returns the maximum value from the portion of the image covered by the Kernel;
- ▶ Average Pooling returns the average of all the values from the portion of the image covered by the Kernel.

Introduction
Tensors
Convolution
Kernels
Convolutional Network - structure
Convolutional Layer
Feature learning
Training the Convolution Layer
Pooling Layer

Training the Pooling layer

Introduction

Tensors

Convolution

Kernels

Convolutional
Network -
structure

Convolutional
Layer

Feature learning
Training the
Convolution Layer

Pooling Layer

in an $N \times N$ pooling block, backward propagation of error is reduced to a single value - value of the “winning unit”

ARTIFICIAL INTELLIGENCE



Solving search problems

Uninformed search strategies

Content

- ❑ Problems
- ❑ Problem solving
 - Steps of problem solving
- ❑ Solving problem by search
 - Steps of solving problem by search
 - Search strategies

Problems



- Two problem types:
 - Solving in a deterministic manner
 - Computing the sinus of an angle or the square root of a number
 - Solving in a stochastic manner
 - Real-world problems → design of ABS
 - Involve the search of a solution → AI's methods

Problems

□ Tipology

■ Search/optimisation problems

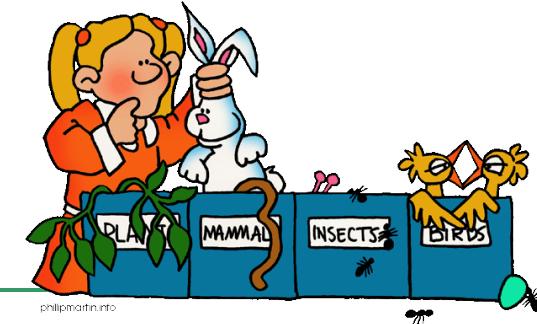
- Planning, satellite's design

■ Modeling problems

- Predictions, classifications

■ Simulation problems

- Game theory

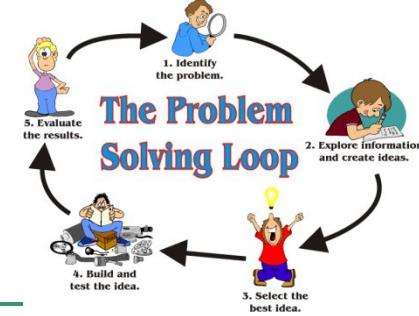




Problem solving

- Identification of a solution
 - In computer science (AI) → search process
 - In engineering and mathematics → optimisation process

- How?
 - Representation of (partial) solutions → points in the search space
 - Design of a search operators → map a potential solution into another one



Steps in problem solving

- Problem definition
- Problem analyses
- Selection of a solving technique
 - Search
 - Knowledge representation
 - Abstraction

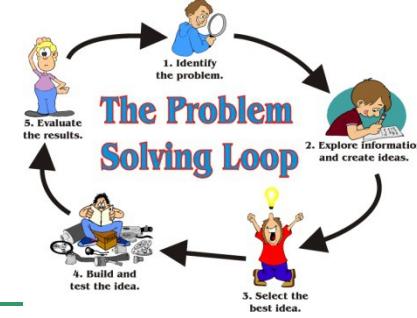


Solving problems by search

- Based on some objectives
- Composed by actions that accomplish the objectives
 - Each action changes a state of the problem
- More actions that map the initial state of problem into a final state

Steps in solving problems by search

Problem definition

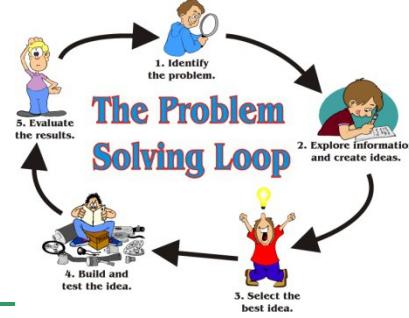


□ Problem definition involves:

- A search space
 - All possible states
 - Representation
 - Explicit – construction of all possible states
 - Default – by using some data structures and some functions (operators)
- One or more initial state
- One or more final states
- One or more paths
 - More successive states
- A set of rules (actions)
 - Successor functions (operators) – next state after a given one
 - Cost functions that evaluate
 - How a state is mapped into another state
 - An entire path
 - Objective functions that check if a state is final or not

Steps in solving problems by search

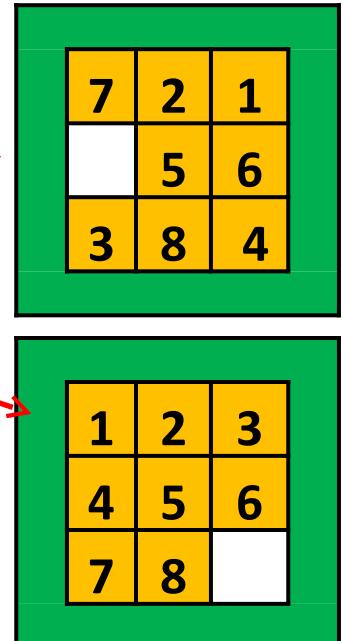
Problem definition

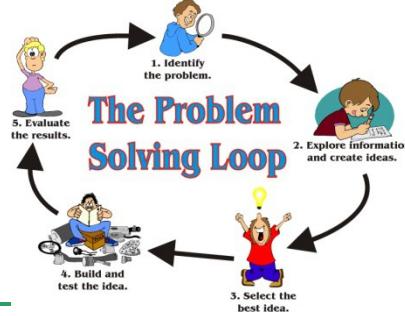


□ Examples

■ Puzzle game with 8 pieces

- State's space – different board configurations for a game with 8 pieces
- Initial state – a random configuration
- Final state – a configuration where all the pieces are sorted in a given manner
- Rules -> white moves
 - conditions: move inside the table
 - Transformations: the white space is moved up, down, to left or to right
- Solution - optimal sequence of white moves





Steps in solving problems by search

Problem definition

□ Examples

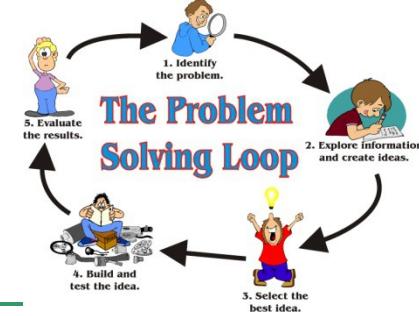
■ Queen's problem

- State's space – different board configurations for a game with n queens
- Initial state – a configuration without queens
- Final state – a configuration n queens so that none of them can hit any other in one move
- Rules -> put a queen on the table
 - conditions: the queen is not hit by any other queen
 - Transformations: put a new queen in a free cell of the table
- Solution - optimal placement of queens

	a	b	c	d	e	f	g	h	
1	Q				Q				1
2				Q				Q	2
3					Q				3
4						Q			4
5		Q							5
6					Q				6
7	Q								7
8						Q			8
	a	b	c	d	e	f	g	h	

Steps in solving problems by search

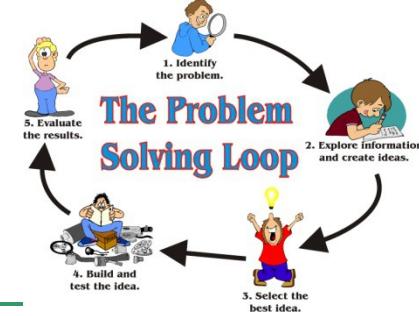
Problem analyse



- The problem can be decomposed?
 - The sub-problems are independent or not?
- The possible state's space is predictable?
- We want a solution or an optimal solution?
- The solution is represented by a single state or by more successive states?
- We require some knowledge for limiting the search or for identifying the solution?
- The problem is conversational or solitary?
 - Human interaction is required for problem solving?

Steps in solving problems by search

Selection of a solving technique

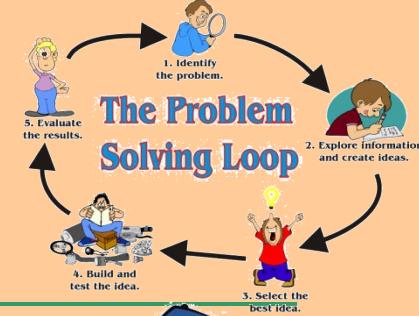


- Solving by moving rules (and control strategy) in the search space until we find a path from the initial state to the final state
- Solving by search
 - Examination of all possible states in order to identify
 - A path from the initial state to the final state
 - An optimal state
 - The search space = all possible states and the operators that maps the states



Steps in solving problems by search

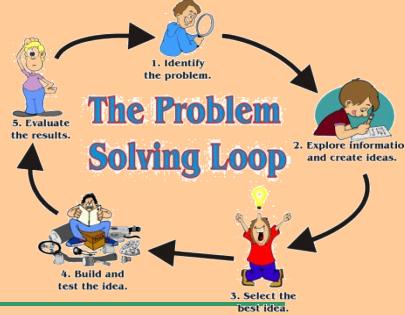
Selection of a solving technique



□ Solving by search

- More searching strategies → how we select one of them?
 - Computational complexity (temporal and spatial)
 - Completeness → the algorithms always ends and finds a solution (if it exists)
 - Optimal → the algorithms finds the optimal solution (the optimal cost of the path from the initial state to the final state)





Steps in solving problems by search

Selection of a solving technique

□ Solving by search

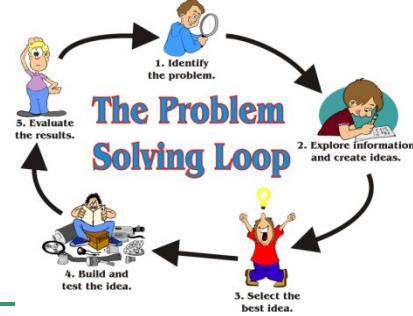
- More searching strategies → how we select one of them? → Computational complexity (temporal and spatial)
 - Strategy's performance depends on
 - Time for running
 - Memory for running
 - Size of input data
 - Computer's performance
 - Compiler's quality
 - Can be evaluated by complexity → computational efficiency
 - Spatial → required memory for solution identification
 - $S(n)$ – memory used by the best algorithms A that solves a decision problem f with n input data
 - Temporal → required time for solution identification
 - $T(n)$ – running time (number of steps) of the best algorithm A that solves a decision problem f with n input data

} Internal factors
}

} External factors

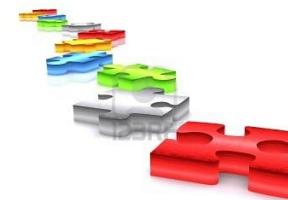
Steps in solving problems by search

Selection of a solving technique



- Problem solving by search can be performed by:

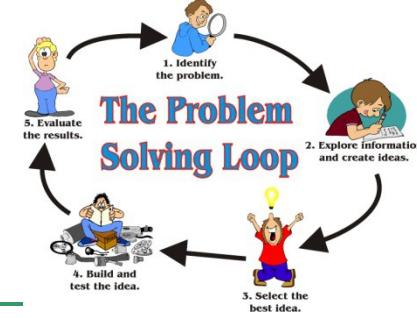
- Step by step construction of solution
- Optimal solution identification



www.shutterstock.com - 36774760

Steps in solving problems by search

Selection of a solving technique



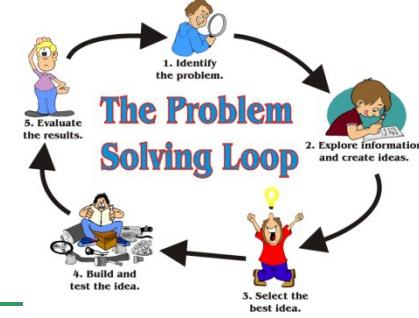
□ Problem solving by search can be performed by:

- Step by step construction of solution
 - ▣ Problem's components
 - Initial state
 - Operators (successor functions)
 - Final state
 - Solution = a path (of optimal cost) from the initial state to the final state
 - ▣ Search space
 - All the states that can be obtained from the initial state (by using the operators)
 - A state = a component of solution
 - ▣ Example
 - Traveling Salesman Problem (TSP)
 - ▣ Algorithms
 - Main idea: start with a solution's component and adding new components until a complete solution is obtained
 - Recurrent → until a condition is satisfied
 - The search's history (path from initial state to the final state) is retained in LIFO/FIFO containers
 - ▣ Advantages
 - Do not require knowledge (intelligent information)



Steps in solving problems by search

Selection of a solving technique



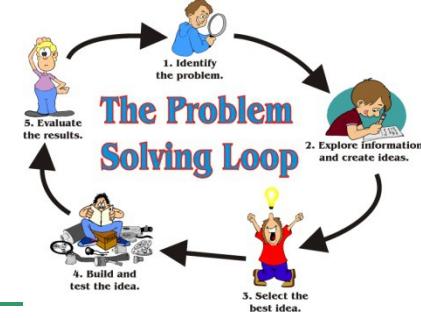
□ Problem solving by search can be performed by:

- Optimal solution identification
 - ▣ Problem's components
 - Conditions (constraints) that must be satisfied by the solution
 - Evaluation function for a potential solution → optimum identification
 - ▣ Search space
 - All possible and complete solutions
 - State = a complete solution
 - ▣ Example
 - Queen's problem
 - ▣ Algorithms
 - Main idea: start with a state that doesn't respect some conditions and change it for eliminating these violations
 - Iterative → a single state is retained and the algorithm tries to improve it
 - The searches history is not retained
 - ▣ Advantages
 - Simple
 - Requires a small memory
 - Can find good solutions in (continuous) search spaces very large (where other algorithms can not be utilised)



Steps in solving problems by search

Selection of a solving technique



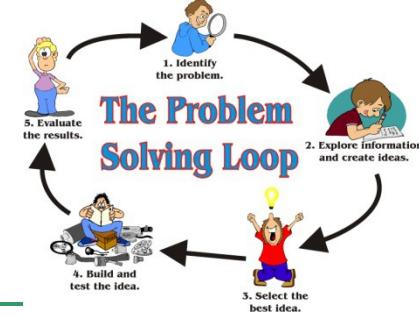
□ Solving problem by search involves:

- Very complex algorithms (NP-complete problems)
- Search in an exponential space



Steps in solving problems by search

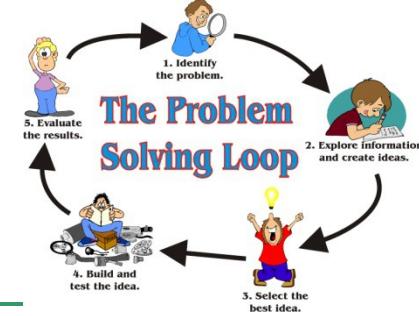
Selection of a solving technique



- Topology of search strategies:
 - Solution **generation**
 - **Constructive** search
 - Solution is identified step by step
 - Ex. TSP
 - **Perturbative** search
 - A possible solution is modified in order to obtain another possible solution
 - Ex. SAT - Propositional Satisfaction Problem
 - Search space **navigation**
 - **Systematic** search
 - The entire search space is visited
 - Solution identification (if it exists) → complete algorithms
 - **Local** search
 - Moving from a point of the search space into a neighbor point → incomplete algorithms
 - A state can be visited more times
 - **Certain** items of the search
 - **Deterministic** search
 - Algorithms that exactly identify the solution
 - **Stochastic** search
 - Algorithms that approximate the solution
 - Search space **exploration**
 - **Sequential** search
 - **Parallel** search

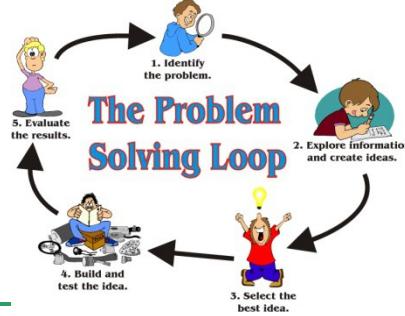
Steps in solving problems by search

Selection of a solving technique



Topology of search strategies:

- **Number of objectives**
 - **Single-objective** search
 - The solution must respect a single condition/constraint
 - **Multi-objective** search
 - The solution must respect more conditions/constraints
- **Number of solutions**
 - **single-modal search**
 - There is a single optimal solution
 - **multi-modal search**
 - There are more optimal solutions
- **Algorithm**
 - Search over a **finite number of steps**
 - **Iterative search**
 - The algorithms converge through the optimal solutions
 - **Heuristic search**
 - The algorithms provide an approximation of the solution
- Search **mechanism**
 - **traditional search**
 - **modern search**
- where the search takes **place**
 - **local search**
 - **global search**



Steps in solving problems by search

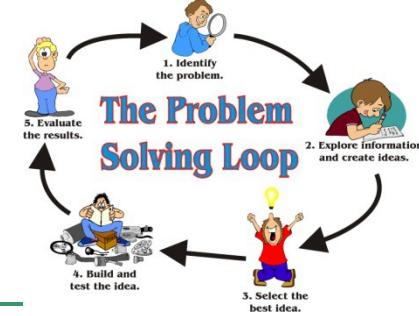
Selection of a solving technique

Topology of search strategies:

- Type (**linearity**) of constraints
 - **Linear search**
 - **non-linear search**
 - Clasical (deterministic)
 - Direct – based on evaluation of the objective function
 - Indirect – based on derivative (I and/or II) of the objective function
 - Enumeration-based
 - How solution is identified
 - Uninformed – the solution is the final state
 - Informed – deals with an evaluation function for a possible solution
 - Search space type
 - Complete – the space is finite (if solution exists, then it can be found)
 - Incomplete – the space is infinite
 - Stochastic search
 - Based on random numbers
- **Agents** involves in search
 - Search by **a single agent** → without obstacle for achieving the objectives
 - **Adversarial search** → the opponent comes with some uncertainty

Steps in solving problems by search

Selection of a solving technique

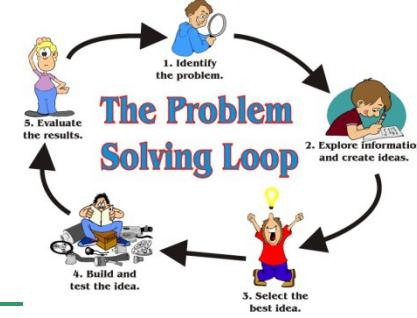


Example

- Topology of search strategies
 - Solution generation
 - **Constructive search**
 - Perturbative search
 - Search space navigation
 - **Systematic search**
 - Local search
 - Certain items of the search
 - **Deterministic search**
 - Stochastic search
 - Search space exploration
 - **Sequential search**
 - Parallel search

Steps in solving problems by search

Selection of a solving technique

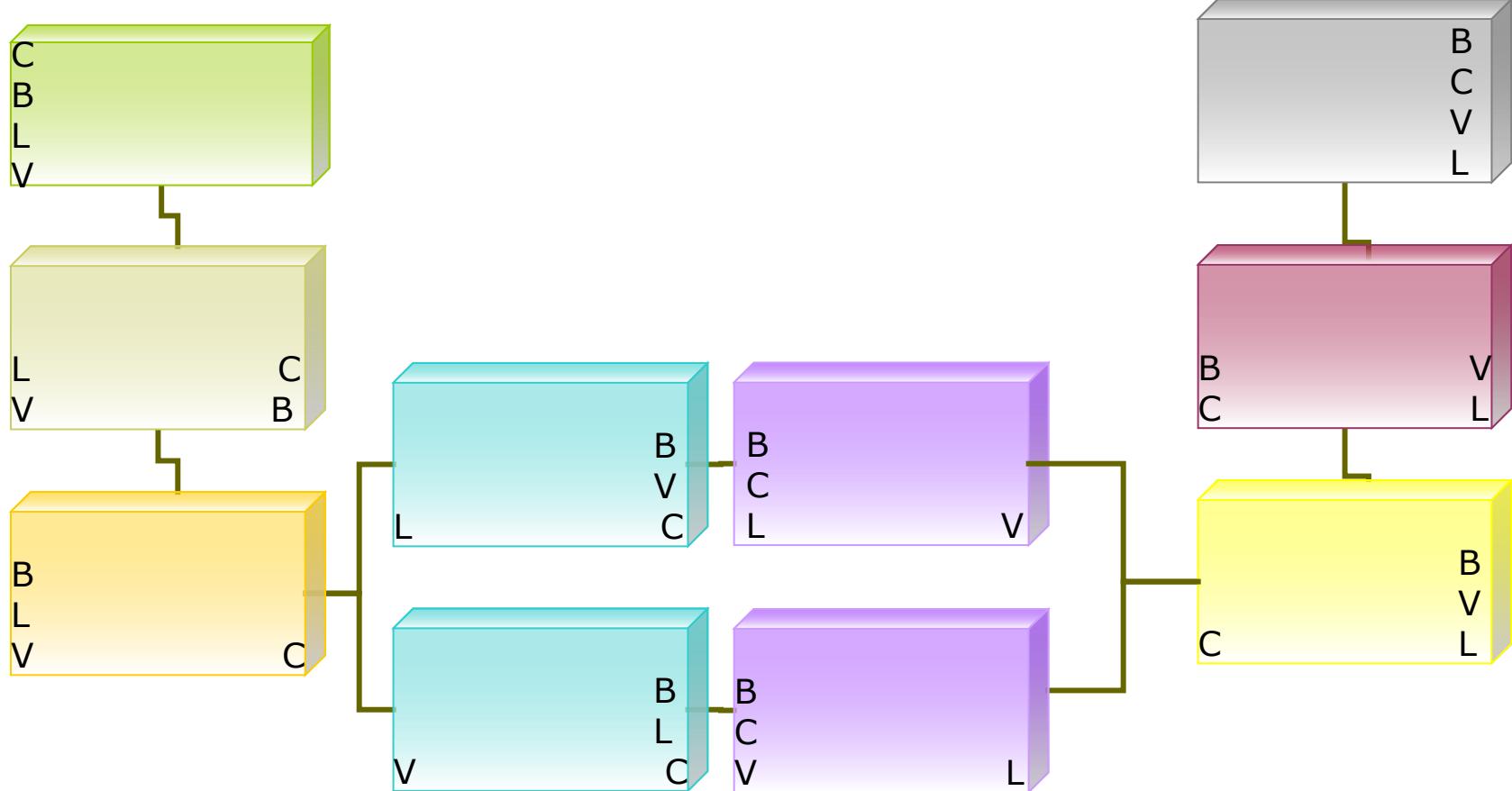
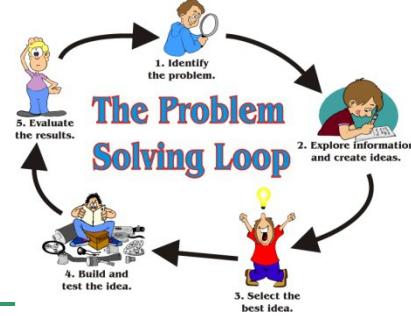


Example

- Constructive, global, deterministic, sequential search
- Problem "capra, varza și lupul"
 - Input :
 - A goat, a cabbage and a wolf on a river-side
 - A boat with a boater
 - Output:
 - Move all the passengers on the other side of the river
 - Taking into account:
 - The boat has only 2 places
 - It is not possible to rest on the same side:
 - The goat and the cabbage
 - The wolf and the goat

Steps in solving problems by search

Selection of a solving technique



Search strategies – Basic elements



- Abstract data types (ADTs)
 - ADT list → linear structure
 - ADT tree → hierachic structure
 - ADT graph → graph-based structure

- ADT
 - Domain and operations
 - Representation



Uninformed search strategies (USS)

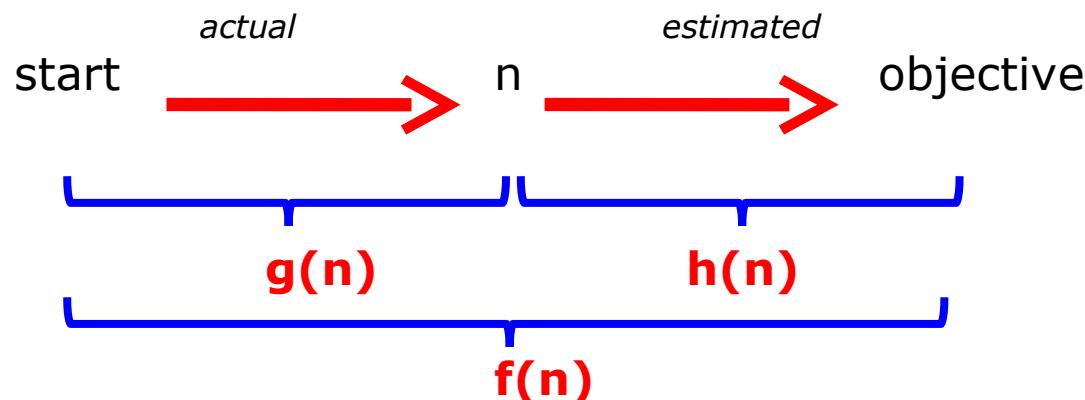
- Characteristics
 - Are NOT based on problem specific information
 - Are general
 - Blind strategies
 - Brute force methods
- Topology
 - Order of node exploration:
 - USS in linear structures
 - Linear search
 - Binary search
 - USS in non-linear structures
 - Breadth-first search
 - Uniform cost search (branch and bound)
 - Depth first search
 - Limited depth first search
 - iterative deepening depth-first search
 - Bidirectional search



SS in tree-based structures

□ Basic elements

- $f(n)$ – evaluation function for estimating the cost of a solution through node (state) n
- $h(n)$ – evaluation function for estimating the cost of a solution path from node (state) n to the final node (state)
- $g(n)$ – evaluation function for estimating the cost of a solution path from the initial node (state) to node (state) n
- $f(n) = g(n) + h(n)$





USS in tree-based structures

Breadth-first search – BFS

□ Basic elements

- All the nodes of depth d are visited before all the nodes of depth $d+1$
- All children of current node are added into a **FIFO** list (**queue**)

□ Example

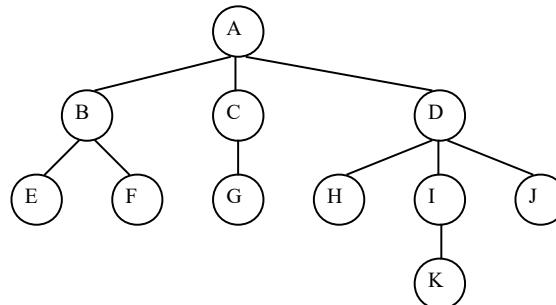
- Visiting order: A, B, C, D, E, F, G, H, I, J, K

□ Algorithm

```

bool BFS(elem, list){
    found = false;
    visited = {};
    toVisit = {start};           //FIFO list
    while((toVisit != {}) && (!found)){
        node = pop(toVisit);
        visited = visited U {node};
        if (node == elem)
            found = true;
        else{
            aux = {};
            for all (unvisited) children of node do
                aux = aux U {child};
        }
        toVisit = toVisit U aux;
    } //while
    return found;
}

```



Vizitate deja	De vizitat
\emptyset	A
A	B, C, D
A, B	C, D, E, F
A, B, C	D, E, F, G
A, B, C, D	E, F, G, H, I, J
A, B, C, D, E	F, G, H, I, J
A, B, C, D, E, F	G, H, I, J
A, B, C, D, E, F, G	H, I, J
A, B, C, D, E, F, G, H	I, J
A, B, C, D, E, F, G, H, I	J, K
A, B, C, D, E, F, G, H, I, J	K
A, B, C, D, E, F, G, H, I, J, K	\emptyset

USS in tree-based structures

Breadth-first search – BFS



□ Search analyse:

- Time complexity:
 - b – ramification factor (number of children of a node)
 - d – length (depth) of solution
 - $T(n) = 1 + b + b^2 + \dots + b^d \Rightarrow O(b^d)$
- Space complexity
 - $S(n) = T(n)$
- Completeness
 - If solution exists, then BFS finds it
- Optimality
 - No

□ Advantages

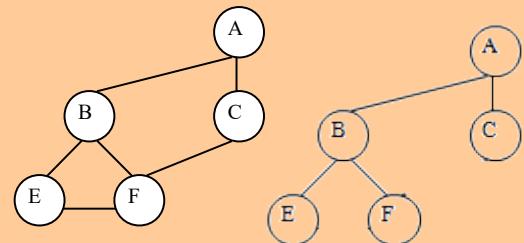
- Finds the shortest path to the objective node (the shallowest solution)

□ Disadvantages

- Generate and retain a tree whose size exponentially increases (with depth of objective node)
- Exponential time and space complexity
- **Russel&Norving experiment**
- Works only for small search spaces

□ Applications

- Identification of connex components in a graph
- Identification of the shortest path in a graph
- Optimisation in transport networks → **algorithm Ford-Fulkerson**
- Serialisation/deserialisation of a binary tree (vs. serialization in a sorted manner) allows efficiently reconstructing of the tree
- Collection copy (garbage collection) → **algorithm Cheney**



Vizitate deja	De vizitat
Φ	B
B	A, E, F
B, A	E, F, C
B, A, E	F, C
B, A, E, F	C
B, A, E, F, C	Φ



USS in tree-based structures

Uniform cost search – UCS

Basic elements

- BFS +special expand procedure (based on the cost of links between nodes)
- All the nodes of depth d are visited before all the nodes of depth $d+1$
- All children of current node are added into a **FIFO ordered** list
 - The nodes of minimum cost are firstly expanded
 - When a path to the final state is obtained, it became a candidate to the optimal solution
- *Branch and bound* algorithm

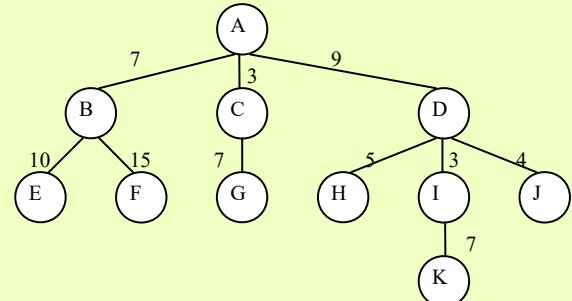
Example

- Visiting order: A, C, B, D, G, E, F, I, H, J, K

Algorithm

```

bool UCS(elem, list){
    found = false;
    visited = {};
    toVisit = {start}; //FIFO sorted list
    while((toVisit != {}) && (!found)){
        node = pop(toVisit);
        visited = visited U {node};
        if (node== elem)
            found = true;
        else
            aux = {};
            for all (unvisited) children of node do{
                aux = aux U {child};
            } // for
            toVisit = toVisit U aux;
            TotalCostSort(toVisit);
    } //while
    return found;
}
  
```



visited	toVisit
{}	A
A	C(3), B(7), D(9)
A, C	B(7), D(9), G(3+7)
A, C, B	D(9), G(10), E(7+10), F(7+15)
A, C, B, D	G(10), I(9+3), J(9+4), H(9+5), E(17), F(22)
A, C, B, D, G	I(12), J(13), H(14), E(17), F(22)
A, C, B, D, G, I	J(13), H(14), E(17), F(22), K(9+3+7)
A, C, B, D, G, I, J	H(14), E(17), F(22), K(19)
A, C, B, D, G, I, J, H	E(17), F(22), K(19)
A, C, B, D, G, I, J, H, E	F(22), K(19)
A, C, B, D, G, I, J, H, E, F	K(19)
A, C, B, D, G, I, J, H, E, F, K	{}



USS in tree-based structures

Uniform cost search – UCS

□ Complexity analyse

- Time complexity
 - b – ramification factor
 - d - length (depth) of solution
 - $T(n) = 1 + b + b^2 + \dots + b^d \Rightarrow O(b^d)$
- Space complexity
 - $S(n) = T(n)$
- Completeness
 - yes – if solutions exists, then UCS finds it
- Optimality
 - Yes

□ Advantages

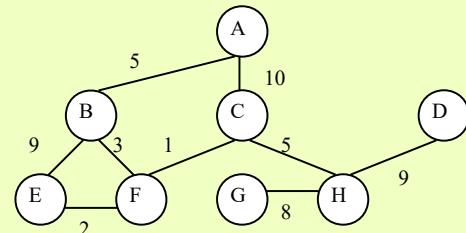
- Finding the minimum cost path to the objective node

□ Disadvantages

- Exponential time and space complexity

□ Applications

- Shortest path → Dijkstra algorithm



Vizitate deja	De vizitat
Φ	A(0)
A(0)	B(5), C(10)
A(0), B(5)	F(8), C(10), E(14)
A(0), B(5), F(8)	C(9), E(10)
A(0), B(5), F(8), C(9)	E(10), H(14)
A(0), B(5), F(8), C(9), E(10)	H(14)



USS in tree-based structures

depth-first search – DFS

□ Basic elements

- Expand a child and depth search until
 - The final node is reached or
 - The node is a leaf
- Coming back in the most recent node that must be explored
- All the children of the current node are added in a **LIFO** list (**stack**)

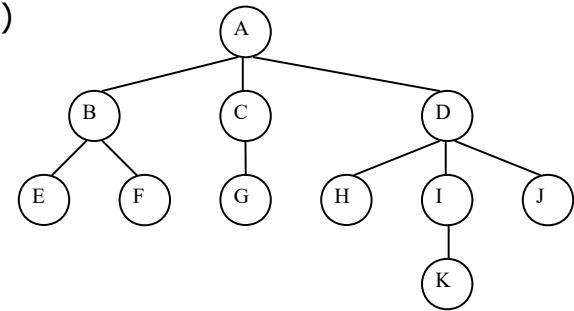
□ Example

- Visiting order: A, B, E, F, C, G, D, H, I, K, J

□ Algorithm

```

bool DFS(elem, list){
    found = false;
    visited = {};
    toVisit = {start};      //LIFO list
    while((toVisit != {}) && (!found)){
        node = pop(toVisit);
        visited = visited U {node};
        if (node== elem)
            found = true;
        else{
            aux = {};
            for all (unvisited) children of node do{
                aux = aux U {child};
            }
            toVisit = aux U toVisit;
        }
    } //while
    return found;
}
  
```



Vizitate deja	De vizitat
{}	A
A	B, C, D
A, B	E, F, C, D
A, B, E	F, C, D
A, B, E, F	C, D
A, B, E, F, C	G, D
A, B, E, F, C, G	D
A, B, E, F, C, G, D	H, I, J
A, B, E, F, C, G, D, H	I, J
A, B, E, F, C, G, D, H, I	K, J
A, B, E, F, C, G, D, H, I, K	J
A, B, E, F, C, G, D, H, I, K, J	{}

USS in tree-based structures

depth-first search – DFS



Complexity analyse

- Time complexity
 - b - ramification factor
 - d_{max} – maximal length (depth) of explored tree
 - $T(n) = 1 + b + b^2 + \dots + b^{d_{max}} \Rightarrow O(b^{d_{max}})$
- Space complexity
 - $S(n) = b * d_{max}$
- Completeness
 - No → the algorithm does not end for infinite paths (there is no sufficient memory for all the nodes that are visited already)
- Optimality
 - No → depth search can find a longer path than the optimal one

Advantages

- Finding the shortest path with minimal resources (recursive version)

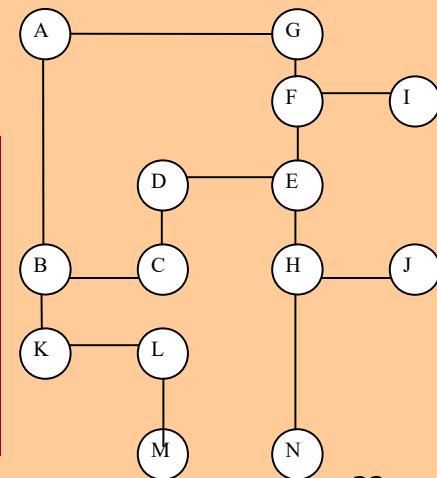
Disadvantages

- Dead paths
 - Infinite cycles
 - Longer solution than the optimal one

Applications

- Maze problem
- Identification of connex components
- Topological sorting
- Testing the graph planarity

A				G	
				F	I
		D		E	
B		C		H	J
K		L			
		M		N	



USS in tree-based structures

depth-first search – DFS



```

bool DFS_edges(elem, list){
    discovered = Φ;
    back = Φ;
    toDiscover = Φ;      //LIFO
    for (all neighbours of start) do
        toDiscover = toDiscover U {(start, neighbour)}
    found = false;
    visited = {start};
    while((toDiscover != Φ) && (!found)){
        edge = pop(toDiscover);
        if (edge.out !e visited){
            discovered = discovered U {edge};
            visited = visited U {edge.out}
            if (edge.out == end)
                found = true;
            else{
                aux = Φ;
                for all neighbours of edge.out do{
                    aux = aux U {(edge.out, neighbour)};
                }
                toDiscover = aux U toDiscover;
            }
        }
        else
            back = back U {edge}
    } //while
    return found;
}

```

Muchia	Muchii vizitare deja	Muchii de vizitat	înapoi	Noduri vizitate
	Φ	AB, AF	Φ	A
AB	AB	BC, BK, AF	Φ	A, B
BC	AB, BC	CD, BK, AF	Φ	A, B, C
CD	AB, BC, CD	DE, BK, AF	Φ	A, B, C, D
DE	AB, BC, CD, DE	EF, EH, BK, AF	Φ	A, B, C, D, E
EF	AB, BC, CD, DE, EF	FI, FG, EH, BK, AF	Φ	A, B, C, D, E, F
FI	AB, BC, CD, DE, EF, FI	FG, EH, BK, AF	Φ	A, B, C, D, E, F, I
FG	AB, BC, CD, DE, EF, FI, FG	GA, EH, BK, AF	Φ	A, B, C, D, E, F, I, G
GA	AB, BC, CD, DE, EF, FI, FG	EH, BK, AF	GA	A, B, C, D, E, F, I, G
EH	AB, BC, CD, DE, EF, FI, FG	HJ, HN, BK, AF	GA	A, B, C, D, E, F, I, G, H
HJ	AB, BC, CD, DE, EF, FI, FG, HJ	HN, BK, AF	GA	A, B, C, D, E, F, I, G, H, J
HN	AB, BC, CD, DE, EF, FI, FG, HI, HN	BK, AF	GA	A, B, C, D, E, F, I, G, H, N



USS in tree-based structures depth-limited search – DLS

□ Basic elements

- DFS + maximal depth that limits the search (d_{lim})
- Solved the completeness problems of DFS

□ Example

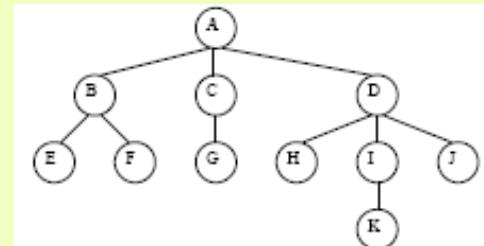
- $d_{lim} = 2$
- Visiting order: A, B, E, F, C, G, D, H, I, J

□ Algorithm

```

bool DLS(elem, list, dlim) {
    found = false;
    visited = Φ;
    toVisit = {start}; //LIFO list
    while((toVisit != Φ) && (!found)) {
        node = pop(toVisit);
        visited = visited ∪ {node};
        if (node.depth <= dlim) {
            if (node == elem)
                found = true;
            else{
                aux = Φ;
                for all (unvisited) children of node do{
                    aux = aux ∪ {child};
                }
                toVisit = aux ∪ toVisit;
            } //if found
        } //if dlim
    } //while
    return found;
}

```



Vizitate deja	De vizitat
Φ	A
A	B, C, D
A, B	E, F, C, D
A, B, E	F, C, D
A, B, E, F	C, D
A, B, E, F, C	G, D
A, B, E, F, C, G	D
A, B, E, F, C, G, D	H, I, J
A, B, E, F, C, G, D, H	I, J
A, B, E, F, C, G, D, H, I	J
A, B, E, F, C, G, D, H, I, K, J	Φ



USS in tree-based structures depth-limited search – DLS

□ Complexity analyse

- Time complexity:
 - b – ramification factor
 - d_{lim} – limit of length (depth) allowed for the explored tree
 - $T(n) = 1 + b + b^2 + \dots + b^{d_{lim}} \Rightarrow O(b^{d_{lim}})$
- Space complexity
 - $S(n) = b * d_{lim}$
- Completeness
 - Yes, but $\Leftrightarrow d_{lim} > d$, where d = length (path) of optimal solution
- Optimality
 - No \rightarrow DLS can find a longer path than the optimal one

□ Advantages

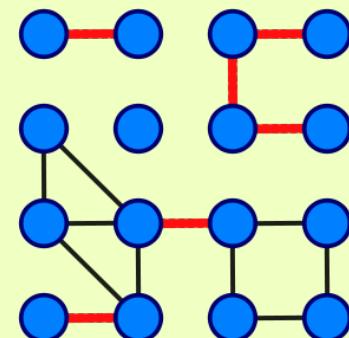
- Solves the completeness problems of DFS

□ Disadvantages

- How to choose a good limit d_{lim} ?

□ Applications

- Identification of bridges in a graph



USS in tree-based structures

iterative deepening depth search – IDDS



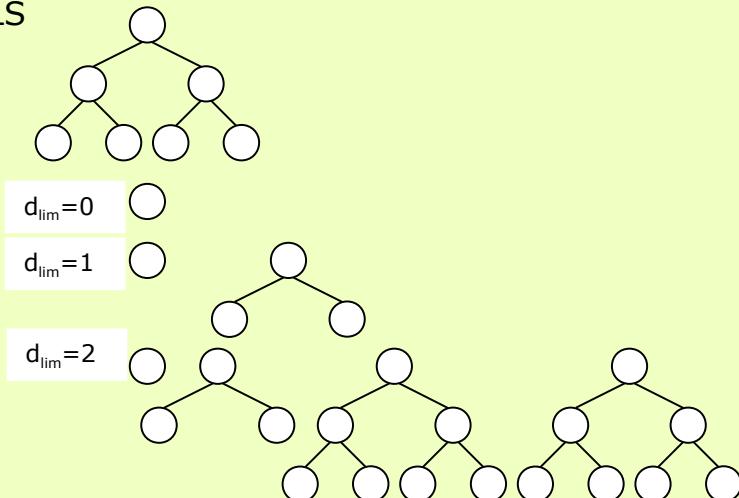
□ Basic elements

- U DLS(d_{lim}), where $d_{lim} = 1, 2, 3, \dots, d_{max}$
 - Solves the identification of the optimal limit d_{lim} from DLS
 - Usually, it works when:
 - The search space is large
 - The length (depth) of solution is known

□ Example

□ Algorithm

```
bool IDS(elem, list){  
    found = false;  
    dlim = 0;  
    while ((!found) && (dlim < dmax)) {  
        found = DLS(elem, list, dlim);  
        dlim++;  
    }  
    return found;  
}
```





USS in tree-based structures

iterative deepening depth search – IDDS

□ Complexity analyse

- Time complexity:
 - $b^{d_{max}}$ nodes at depth d_{max} are expanded once => $1 * b^{d_{max}}$
 - $b^{d_{max}-1}$ nodes at depth $d_{max}-1$ are expanded twice => $2 * (b^{d_{max}-1})$
 - ...
 - b nodes at depth 1 are expanded d_{max} times => $d_{max} * b^1$
 - 1 node (the root) at depth 0 is expanded $d_{max}+1$ times => $(d_{max}+1)*b^0$
- $$T(n) = \sum_{i=0}^{d_{max}} (i+1)b^{d_{max}-i} \Rightarrow O(b^{d_{max}})$$

- Space complexity
 - $S(n) = b * d_{max}$
- Completeness
 - yes
- Optimality
 - yes

□ Advantages

- Requires linear memory
- The goal state is obtained by a minimal path
- Faster than BFS and DFS

□ Disadvantages

- Requires to know the solution depth

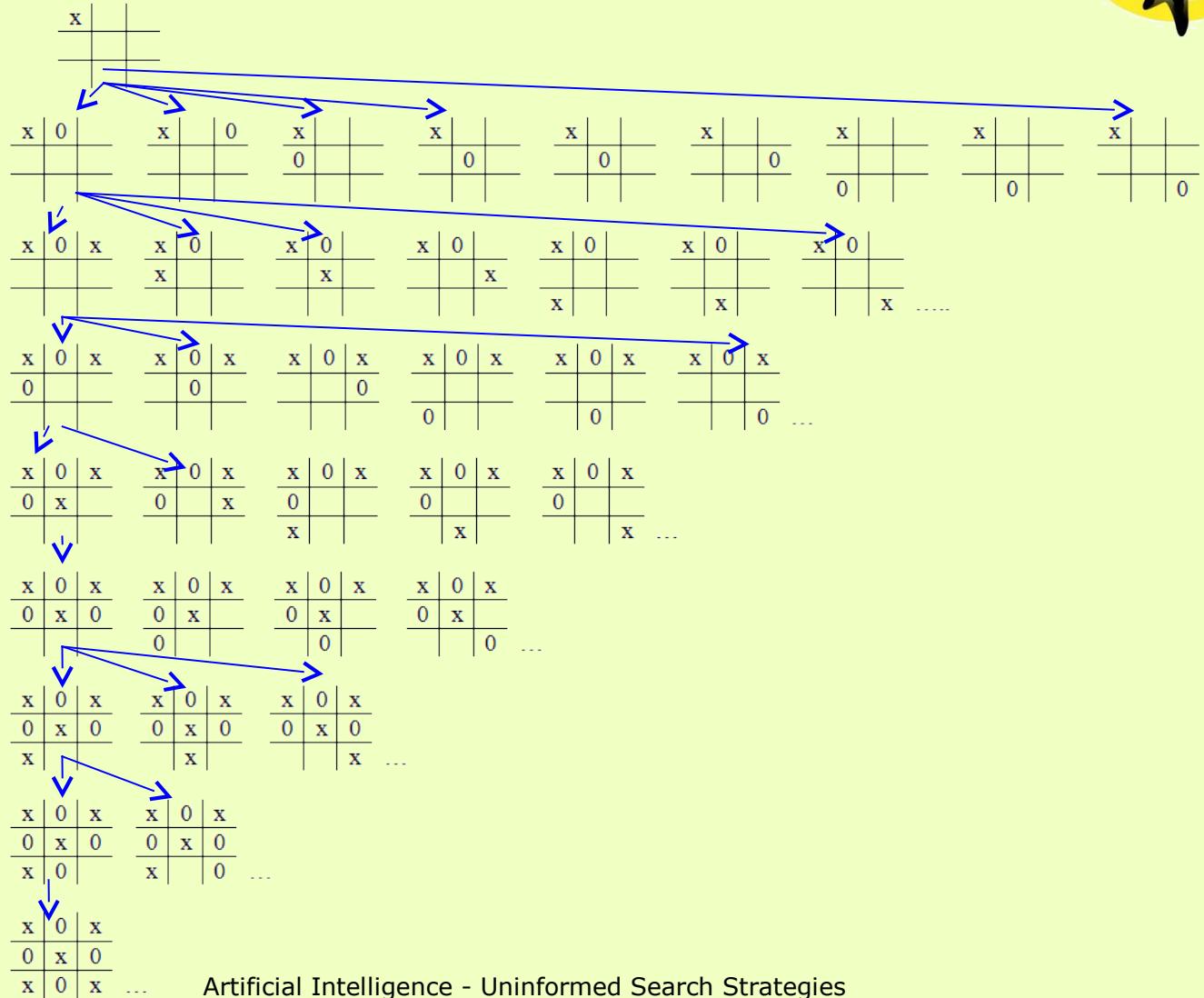
□ Applications

- Tic tac toe game



USS in tree-based structures

iterative deepening depth search – IDDS





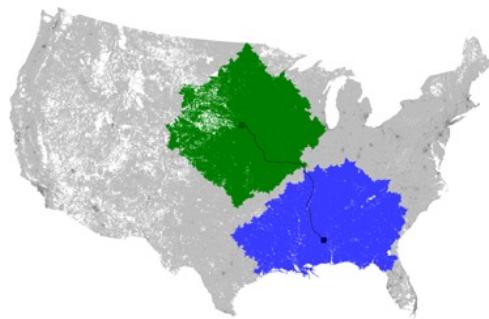
USS in tree-based structures

bi-directional search – BDS

□ Basic elements

- 2 parallel search strategies
 - *forward*: from root to leaves
 - *backward*: from leaves to root
- that end when they meet
- any SS can be used in a direction
- Requires establishing:
 - the parents and the children of each node
 - the meeting point

□ Example



□ Algorithm

- Depend on the SS used



USS in tree-based structures bi-directional search – BDS

□ Complexity analyse

- Time complexity
 - b – ramification factor
 - d – solution length (depth)
 - $O(b^{d/2}) + O(b^{d/2}) \Rightarrow O(b^{d/2})$
- Space complexity
 - $S(n) = T(n)$
- Completeness
 - yes
- Optimality
 - yes

□ Advantages

- Good time and space complexity

□ Disadvantages

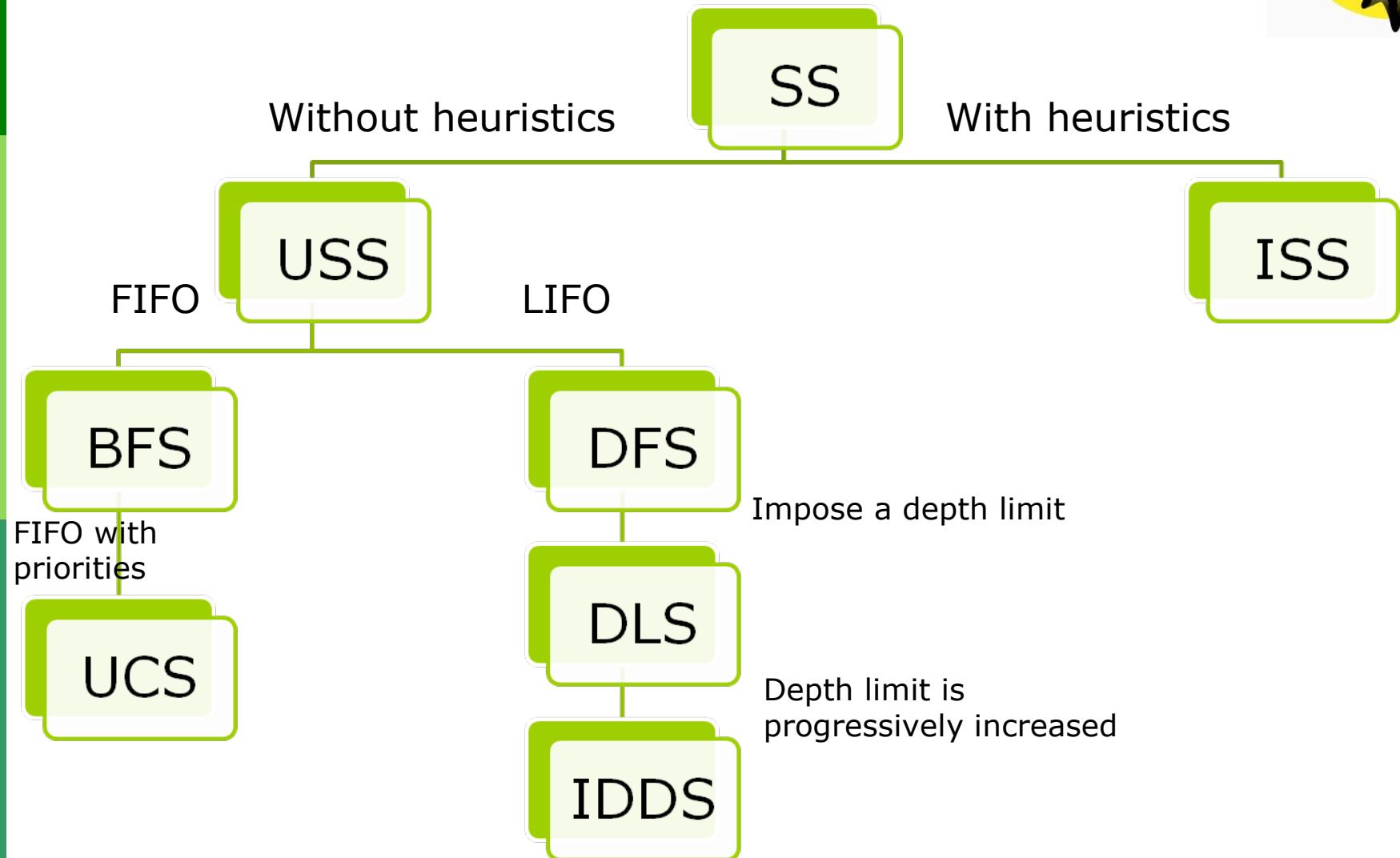
- Each state must be reversed
 - From had to tail
 - From tail to head
- Difficult to implement
- Identification of parents and children for all the nodes
- The final state must be known

□ Applications

- Partitioning problem
- Shortest path



USS in tree-based structures





USS in tree-based structures

Comparison of performances

SS	Time complexity	Space complexity	Completeness	Optimality
BFS	$O(b^d)$	$O(b^d)$	Yes	Yes
UCS	$O(b^d)$	$O(b^d)$	Yes	Yes
DFS	$O(b^{d_{\max}})$	$O(b * d_{\max})$	No	No
DLS	$O(b^{d_{\text{lim}}})$	$O(b * d_{\text{lim}})$	Yes, if $d_{\text{lim}} > d$	No
IDS	$O(b^d)$	$O(b * d)$	Da	Yes
BDS	$O(b^{d/2})$	$O(b^{d/2})$	Yes	Yes

ARTIFICIAL INTELLIGENCE



Solving search problems
Evolutionary Algorithms

Nature-inspired search

Best method for solving a problem

- Human brain
 - Has created the wheel, car, town, etc.
- Mechanism of evolution
 - Has created the human brain

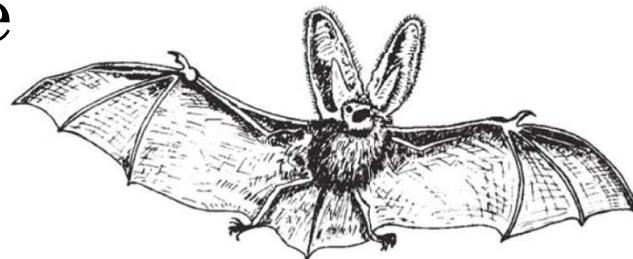
Simulation of nature

- By machines' help → the artificial neural networks simulate the brain
 - Flying vehicles, DNA computers, membrane-based computers
- By algorithms' help
 - Evolutionary algorithms simulate the evolution of nature
 - Particle Swarm Optimisation simulates the collective and social behaviour
 - Ant Colony Optimisation

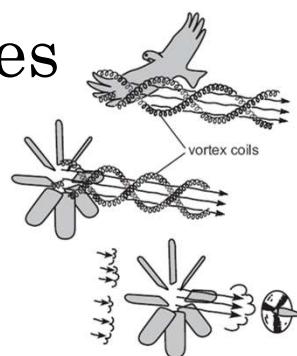
Basic elements

■ Simulation of nature

- Fly of bats
- Leonardo da Vinci – sketch of a flying machine



- Flies of birds and planes
- Flies of birds and wind-turbines



Basic elements

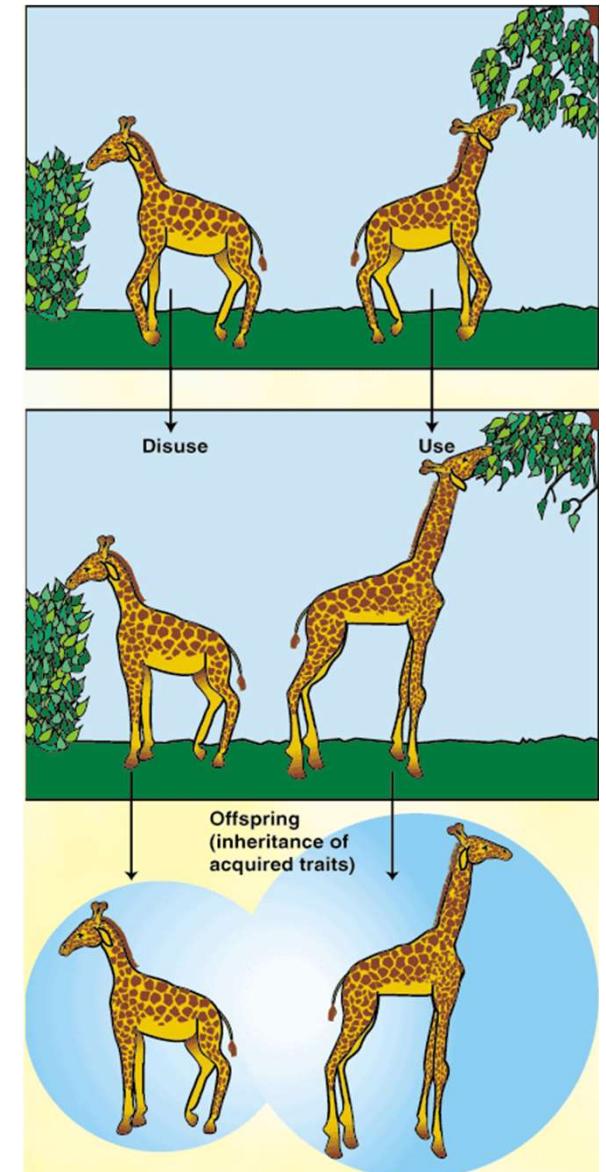
Main characteristics of EAs

- Iterative and parallel processes
- Based on random search
- Bio-inspired – involve mechanisms as:
 - Natural selection
 - Reproduction
 - Recombination
 - Mutation

Basic elements

Historical points

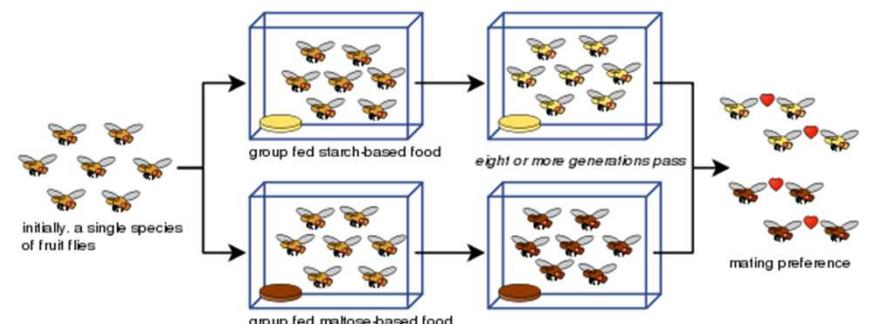
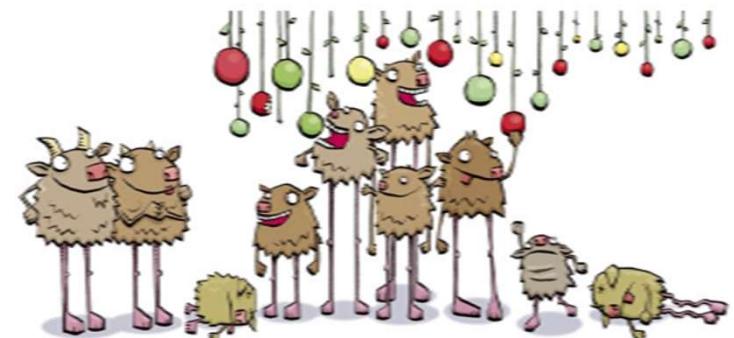
- Jean Baptise de Lamark (1744-1829)
 - Has proposed in 1809 an explanation for origin of species in the book *Zoological Philosophy*:
 - Needs of an organism determine the evolving characteristics
 - Useful characteristics could be transferred to offspring
 - *use and disuse law*



Basic elements

Historical points

- Charles Darwin (1807-1882)
 - In the book *Origin of Species* he proved that all the organisms have evolved based on:
 - Variation
 - Overproduction of offspring
 - Natural selection
 - Competition (generation of constant size)
 - Fitness survival
 - Reproduction
 - Occurrence of new species



Basic elements

Historical points

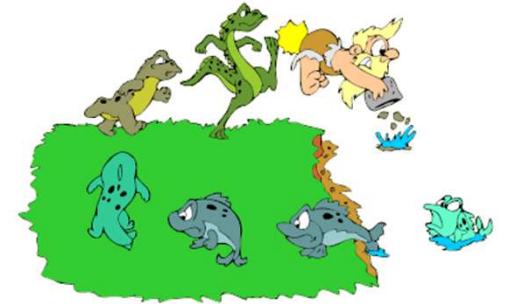
Modern theory of evolution

- Darwin's theory is improved by mechanism of genetic inheritance
- Genetic variance is produced by
 - Mutation and
 - Sexual recombination
- L. Fogel 1962 (San Diego, CA) → *Evolutionary Programming (EP)*
- J. Holland 1962 (Ann Arbor, MI) → *Genetic Algorithms (GAs)*
- I. Rechenberg & H.-P. Schwefel 1965 (Berlin, Germany) → *Evolution Strategies (ESs)*
- J. Koza 1989 (Palo Alto, CA) → *Genetic Programming (GP)*

Basic elements

Evolutionary metaphor

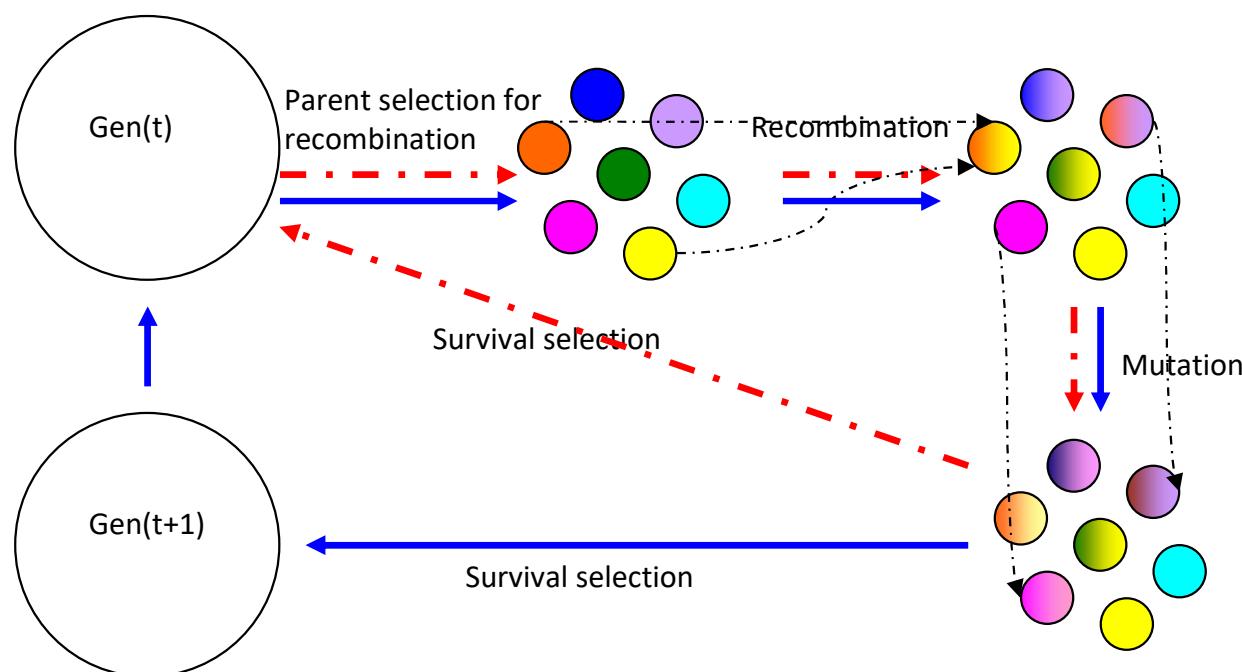
Natural evolution	↔	Problem solving
Individual	↔	Possible solution
Population	↔	Set of possible solutions
Chromosome	↔	Coding of a possible solution
Gene	↔	Part of coding
Fitness	↔	Quality
Crossover and Mutation	↔	Search operators
Environment	↔	Problem



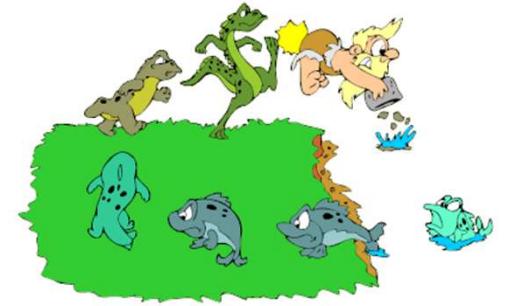
Algorithm

General sketch of an EA

- Generational →
- Steady-state →



Algorithm



④ Design

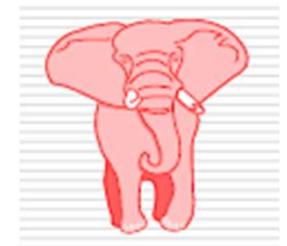
- Chromosome representation
- Population model
- Fitness function
- Genetic operators
 - ④ Selection
 - ④ Mutation
 - ④ Crossover
- Stop condition

Representation

- 2 levels of each possible solution

- External level → phenotype

- Individual – original object in the context of the problem
 - The possible solutions are evaluated here
 - Ant, knapsack, elephant, towns, ...



- Internal level → genotype

- Chromosome – code associated to an object

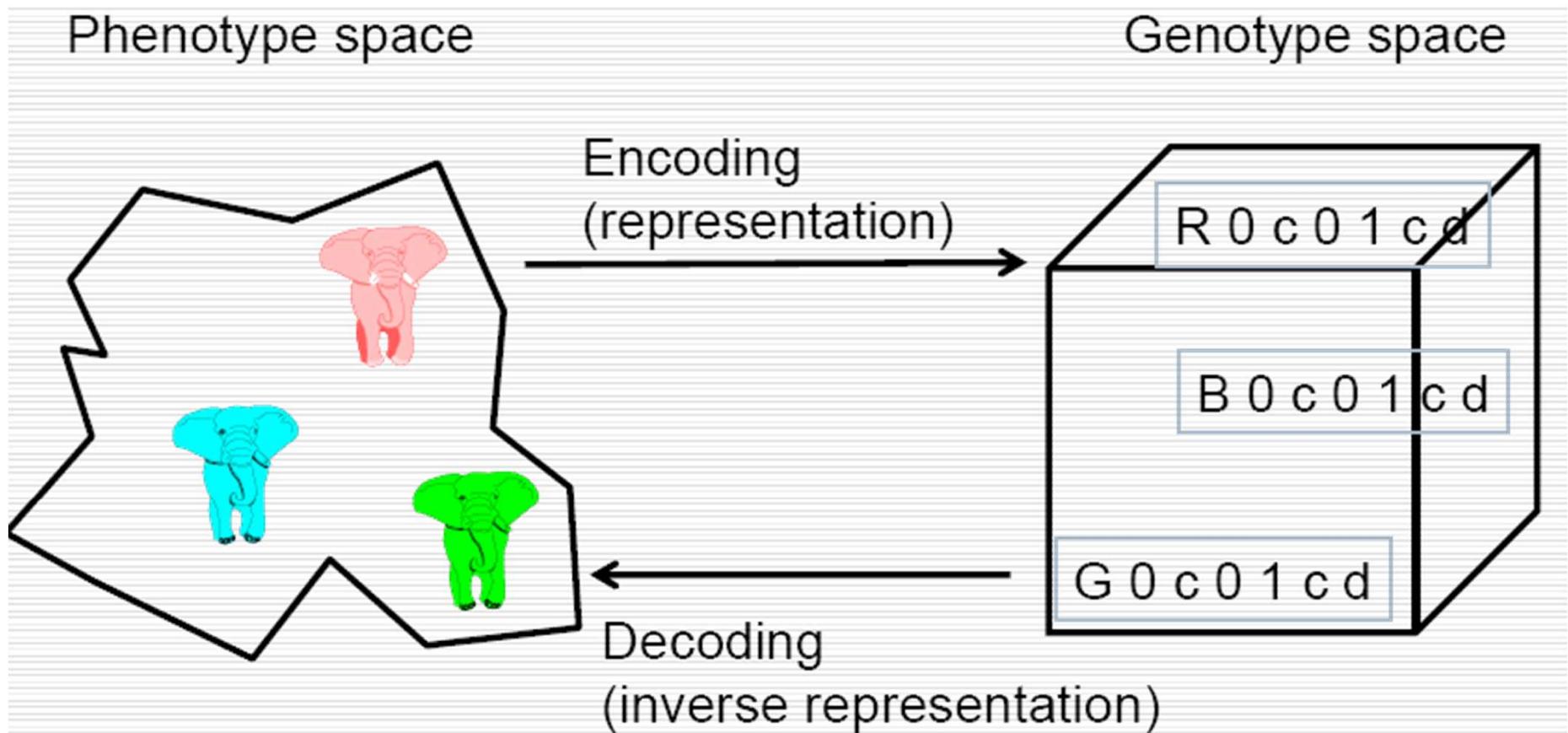
a d c a a c b

- Composed by genes, located in loci (fix positions) and having some values (alleles)
 - The possible solutions are searched here
 - One-dimensional vector (with numbers, bits, characters), matrix, ...

Representation

Representation must be representative for:

- Problem
- Fitness function and
- Genetic operators



Representation

Linear

- Discrete

- Binary → knapsack problem

- Not-binary

- Integers

- Random → image processing

- Permutation → travelling salesman problem (TSP)

- Class-based → map colouring problem

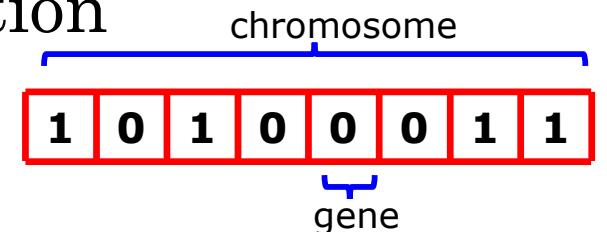
- Continuous (real) → function optimization

Tree-based → regression problems

Representation

Linear discrete and binary representation

- Genotype
Bit-strings



Representation

- Linear discrete and binary representation
 - Genotype
 - Bit-strings
 - Phenotype
 - Boolean elements
 - Ex. Knapsack problem – selected objects for the bag

Genotype	Phenotype
1 0 1 0 0 0 1 1	$ob_1 + ob_3 + ob_7 + ob_8$

Objects 1, 3, 7 and 8 are selected

Representation

- Linear discrete and binary representation
 - Genotype
 - Bit-strings
 - Phenotype
 - Boolean elements
 - Ex. Knapsack problem – selected objects for the bag

- Integers

Genotype	Phenotype	
1 0 1 0 0 0 1 1		= 163

$1 \cdot 2^7 + 0 \cdot 2^6 + 1 \cdot 2^5 + 0 \cdot 2^4 + 0 \cdot 2^3 + 0 \cdot 2^2 + 1 \cdot 2^1 + 1 \cdot 2^0 =$

$128 + 32 + 2 + 1 = 163$

Representation

- Linear discrete and binary representation
 - Genotype
 - Bit-strings
 - Phenotype
 - Boolean elements
 - Ex. Knapsack problem – selected objects for the bag

- Integers
- Real numbers from a range
(ex. [2.5, 20.5])

Genotype	Phenotype								
<table border="1" style="border-collapse: collapse; width: 100%;"><tr><td style="width: 12.5%;">1</td><td style="width: 12.5%;">0</td><td style="width: 12.5%;">1</td><td style="width: 12.5%;">0</td><td style="width: 12.5%;">0</td><td style="width: 12.5%;">0</td><td style="width: 12.5%;">1</td><td style="width: 12.5%;">1</td></tr></table>	1	0	1	0	0	0	1	1	$= 13.9609$
1	0	1	0	0	0	1	1		

$x = 2.5 + \frac{163}{256} (20.5 - 2.5) = 13.9609$

Representation

Transformation of real values from binary representation

- Let be $z \in [x,y] \subseteq \mathbb{R}$ represented as $\{a_1, \dots, a_L\} \in \{0, 1\}^L$
- Function $[x,y] \rightarrow \{0,1\}^L$ must be inversely (a phenotype corresponds to a genotype)
- Function $\Gamma: \{0,1\}^L \rightarrow [x,y]$ defines the representation
$$\Gamma(a_1, \dots, a_L) = x + \frac{y-x}{2^L - 1} \cdot \left(\sum_{j=0}^{L-1} a_{L-j} \cdot 2^j \right) \in [x, y]$$
- Remarks
 - 2^L values can be represented
 - L – maximum precision of solution
 - For a better precision → long chromosomes → slowly evolution

Representation

Linear discrete non-binary integer random representation

- Genotype

Vector of integers from a given range

- Phenotype

Utility of numbers in the problem

- Ex. Pay a sum S by using different n coins

Genotype → vector of n integers from range $[0, S/\text{value of current coin}]$

Phenotype → how many coins of each type must be considered

Representation

Linear discrete non-binary integer permutation representation

- Genotype
 - Permutation of n elements (n – number of genes)
- Phenotype
 - Utility of permutation in problem
- Ex. Traveling Salesman Problem
 - Genotype → permutation of n elements
 - Phenotype → visiting order of towns (each town has associated a number from $\{1,2,\dots,n\}$)

Representation

Linear discrete non-binary integer class-based representation

- Similarly to integer one, but labels are used instead numbers
- Genotype
 - Vector of labels from a given set
- Phenotype
 - Labels' meaning
- Ex. Map colouring problem
 - Genotype → vector of n colours (n – number of countries)
 - Phenotype → what colour has to be used for each country

Representation

Linear continuous (real) representation

- Genotype

Vector of real numbers

- Phenotype

Number meaning

- Ex. Function optimisation $f:R^n \rightarrow R$

Genotype → more real numbers $X=[x_1, x_2, \dots, x_n]$, $x_i \in R$

Phenotype → values of function f arguments

Representation

- Tree-based representation

- Genotype

- Trees than encode S-expressions

- Internal nodes □functions (F)

- Mathematical

- Arithmetic operators

- Boolean operators

- Statements

- Of a given programming language

- Of other language type

- Leaf → terminals (T)

- Real or Boolean values, constants or variables

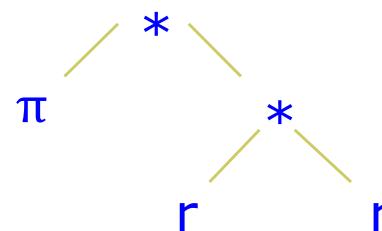
- Sub-programs

- Phenotype

- Meaning of S-expressions

- Ex. Computing the circle area

$$\pi * r^2 \rightarrow$$



Population

Population – concept

- Aim

- Keeps a collection of possible solutions (candidate solutions)

- Repetitions are allowed

- Is entirely utilised during selection for recombination

- Properties

- (usually) fixed dimension μ

- Diversity

- Number of different fitnesses/phenotypes/genotypes

- Remarks

- Represents the basic unit that evolves

- The entire population evolves, not only the individuals!

Population

Population - initialisation

- Uniformly distributed in the search space (if it is possible)

Binary strings

- Randomly generation of 0 and 1 with a 0.5 probability (fifty-fifth)

Arrays of real numbers uniformly generated (in a given range)

Permutations

- Generation of identical permutation and making some changes

Population

Population - initialisation

- Uniformly distributed in the search space (if it is possible)

Trees

- *Full* method – complete trees
 - Nodes of depth $d < D_{\max}$ are randomly initialised by a function from function set F
 - nodes of depth $d = D_{\max}$ are randomly initialised by a terminal from the terminal set T
- *Grow* method – incomplete trees
 - Nodes of depth $d < D_{\max}$ are randomly initialised by an element from $F \cup T$
 - nodes of depth $d = D_{\max}$ are randomly initialised by a terminal from the terminal set T
- *Ramped half and half* method
 - $\frac{1}{2}$ of population is initialised by *Full* methods
 - $\frac{1}{2}$ of population is initialised by *Grow* methods
 - By using different depths

Population

Population model:

- Generational EA

- Each generation creates μ offspring

- Each individual survives a generation only

- Set of parents is totally replaced by set of offspring

- Steady-state EA

- Each generation creates a single offspring

- A single parent (the worst one) is replaced by the offspring

Generation Gap

- Proportion of replaced population
- $1 = \mu/\mu$, for generational model
- $1/\mu$, for steady-state model

Fitness function

Aim

- Reflects the adaptation to environment
- Quality function or objective function
- Associates a value to each candidate solution
 - Consequences over selection → the more different values, the better

Properties

- Costly stage
 - Unchanged individuals could not be re-evaluated

Typology:

- Number of objectives
 - One-objective
 - Multi-objective → Pareto fronts
- Optimisation direction
 - Maximisation
 - Minimisation
- Degree of precision
 - Deterministic
 - Heuristic

Fitness function

Examples

- Knapsack problem

Representation → linear, discrete and binary

Fitness → $\text{abs}(\text{knapsack's capacity} - \text{weight of selected objects}) \rightarrow \text{min}$

- Problem of paying sum s by using different coins

Representation → linear, discrete and integer

Fitness → $\text{abs}(\text{sum to be paid} - \text{sum of selected coins}) \rightarrow \text{min}$

- TSP

Representation → linear, discrete, integer, permutation

Fitness → cost of path → min

- Numerical function optimization

Representation → linear, continuous, real

Fitness → value of function → min/max

- Computing the circle's area

Representation → tree-based

Fitness → sum of square errors (difference between the real value and the computed value for a given set of examples) → min

Selection



❑ Aim:

- Gives more reproduction/survival chances to better individuals
 - ▣ Weaker individuals have chances also because they could contain useful genetic material
- Orients the population to improve its quality

❑ Properties

- Works at population-level
- Is based on fitness only (is independent to representation)
- Helps to escape from local optima (because its stochastic nature)



Selection



- Aim
 - Parent selection (from current generation) for reproduction
 - Survival selection (from parents and offspring) for next generation
- Winner strategy
 - Deterministic – the best wins
 - Stochastic – the best has more chances to win
- Mechanism
 - Selection for recombination
 - Proportional selection (based on fitness)
 - Rank-based selection
 - Tournament selection
 - Survival selection
 - Age-based selection
 - Fitness-based selection

} Based on entire population

→ Based on a part of population



Recombination selection

Proportional selection (fitness-based selection) - PS

Main idea

- Roulette algorithm for entire population
- Estimation of the copies # of an individual (selection pressure)

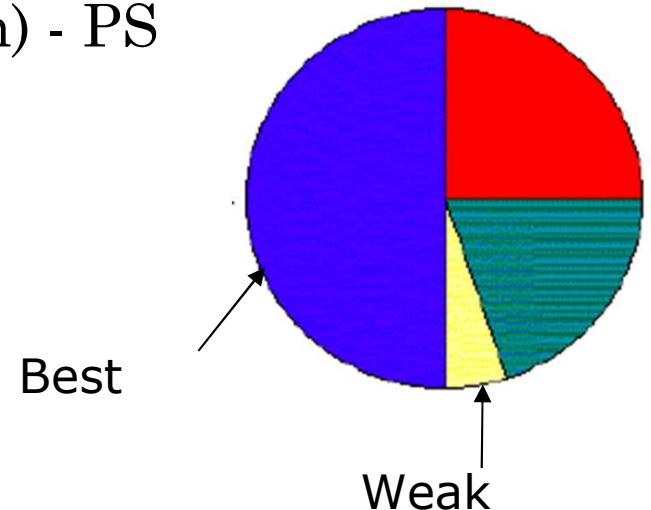
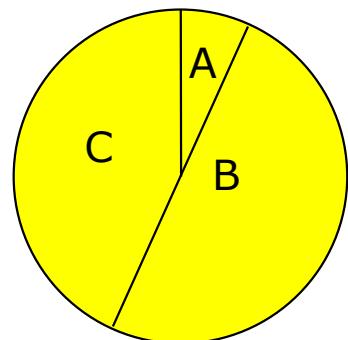
$$E(n_i) = \mu \frac{f(i)}{\langle f \rangle}, \text{ where:}$$

- μ = size of population,
- $f(i)$ = fitness of individual i ,
- $\langle f \rangle$ = mean fitness of population

Better individuals

- Have more space on roulette
- Have more chances to be selected

Ex. A population of $\mu = 3$ individuals



	$f(i)$	$P_{selPS}(i)$
A	1	$1/10=0.1$
B	5	$5/10=0.5$
C	4	$4/10=0.4$
Sum	10	1



Recombination selection

Proportional selection (fitness-based selection) – PS

Advantages

- Simple algorithm

Disadvantages

- Premature convergence

- Best chromosomes predispose to dominate the population

- Low selection pressure when fitness functions are very similar (at the end of a run)

- Real results are different to theoretical probabilistic distribution

- Works at the entire population level

Solutions

- Fitness scaling

- Windowing

- $f(i) = f(i) - \beta^t$, where β is a parameter that depends on evolution history
 - eg. β is the fitness of the weakest individual of current population (the t^{th} generation)

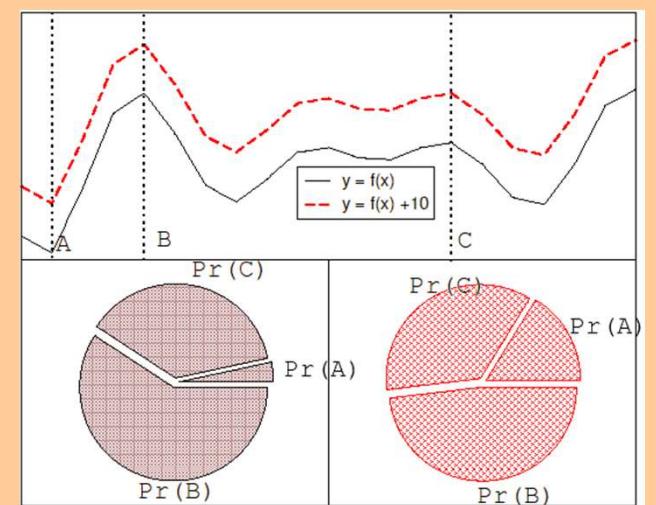
- Sigma scaling (Goldberg type)

- $f(i) = \max\{f(i) - (\langle f \rangle - c * \sigma_f), 0.0\}$, where:
 - C – a constant (usually, 2)
 - $\langle f \rangle$ – average fitness of population
 - σ_f – standard deviation of population fitness

- Normalisation

- Starts by absolute (initial) fitnesses
 - Standardize these fitnesses such as the fitnesses:
 - Belong to $[0,1]$
 - Best fitness is the smallest one (equal to 0)
 - Sum of them is 1

- Another selection mechanism





Selection for recombination

❑ Ranking selection – RS

■ Main idea

- ❑ Sort the entire population based on fitness
 - Increases the algorithm complexity, but it is negligible related to the fitness evaluation
- ❑ Each individual receives a rank
 - Computes the selection probabilities based on these ranks
 - Best individual has rank μ
 - Worst individual has rank 1
- ❑ Tries to solve the problems of proportional selection by using relative fitness (instead of absolute fitness)



Selection for recombination

Ranking selection - RS

Ranking procedures

Linear (LR) $P_{lin_rank}(i) = \frac{2-s}{\mu} + \frac{2i(s-1)}{\mu(\mu-1)}$

- s – selection pressure
 - Measures the advantages of the best individual
 - $1.0 < s \leq 2.0$
 - In the generational algorithm s represents the copies number of an individual
- Ex. For a population of $\mu=3$ individuals

	$f(i)$	$P_{selPS}(i)$	Rank	$P_{selLR}(i)$ for $s=2$	$P_{selRL}(i)$ for $s=1.5$
A	1	$1/10=0.1$	1	0.33	0.33
B	5	$5/10=0.5$	3	1.00	0.33
C	4	$4/10=0.4$	2	0.67	0.33
Sum	10	1			

Exponential (ER) $P_{exp_rank}(i) = \frac{1-e^{-i}}{c}$

- Best individual can have more than 2 copies
- C – normalisation factor
 - Depends on the population size (μ)
 - Must be choose such as the sum of selection probabilities to be 1



Selection for recombination

- Ranking selection - RS
 - Advantages
 - Keep the selection pressure constant
 - Disadvantages
 - Works with the entire population
 - Solutions
 - Another selection procedure

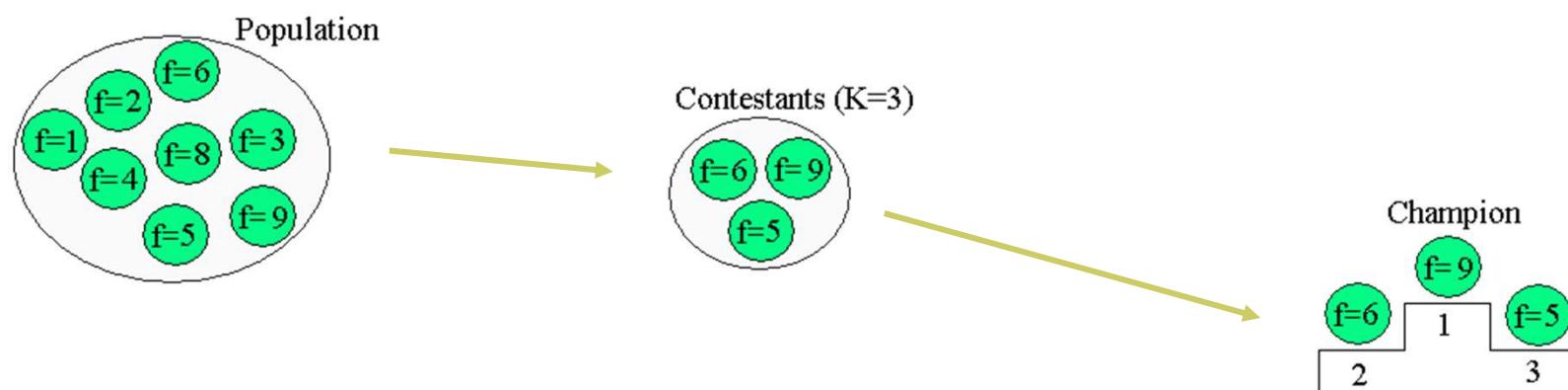


Selection for recombination

■ Tournament selection

■ Main idea

- Chooses k individuals → sample of k individuals (k – tournament size)
- Selects the best individual of the sample
- Probability of sample selection depends on
 - Rank of individual
 - Sample size (k)
 - The larger k is, the greater selection pressure is
- Choosing manner – with replacement (steady-state model) or without replacement
 - Selection without replacement increases the selection pressure
- For $k = 2$ the time required by the best individual to dominate the population is the same to that from linear ranking selection with $s = 2 * p$, p – selection probability of the best individual from population





Selection for recombination

?

Tournament selection

■ Advantages

- Does not work with the entire population
- Easy to implement
- Easy to control the selection pressure by using parameter k

■ Disadvantages

- The real results of this selection are different to theoretical distribution (similarly to roulette selection)

Survival selection



- Survival selection (selection for replacement)
 - Based on age
 - Eliminates the oldest individuals
 - Based on fitness
 - Proportional selection
 - Ranking selection
 - Tournament selection
 - Elitism
 - Keep the best individuals from a generation to the next one (if the offspring are weaker than parents, then keep the parents)
 - GENITOR (replaces the worst individual)
 - Elimination of the worst λ individuals



Variation operators

② Aim :

- Generation of new possible solutions

③ Properties

- Works at individual level
- Is based on individual representation (fitness independent)
- Helps the exploration and exploitation of the search space
- Must produce valid individuals

④ Typology

- Arity criterion
 - ② Arity 1 → mutation operators
 - ② Arity > 1 → recombination/crossover operators



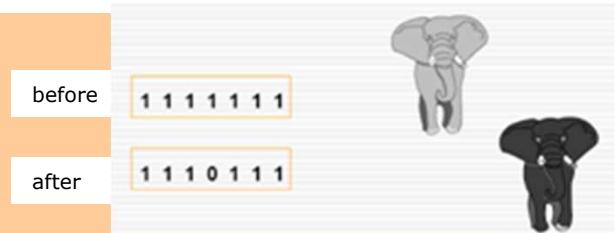
Mutation

¶ Aim

- Reintroduces in population the lost genetic material
- Unary search operator (continuous space)
- Introduces the diversity in population (discrete space)

¶ Properties

- Works at genotype level
- Based on random elements
- Responsible to the exploration of promising regions of the search space
- Responsible to escape from local optima
- Must introduce small and stochastic changes for an individual
- Size of mutation must be controllable
- Can probabilistic take place (by a given probability p_m) at the gene level



Mutation



- Binary representation
 - ▣ Strong mutation – bit-flipping
 - ▣ Weak mutation
- Integer representation
 - ▣ Random resetting
 - ▣ Creep mutation
- Permutation representation
 - ▣ Insertion mutation
 - ▣ Swap mutation
 - ▣ Inverse mutation
 - ▣ scramble mutation
 - ▣ K-opt mutation
- Real representation
 - ▣ Uniform mutation
 - ▣ Non-uniform mutation
 - Gaussian mutation
 - Cauchy mutation
 - Laplace mutation
- Tree-based representation → future lecture
 - ▣ Grow mutation
 - ▣ Shrink mutation
 - ▣ Switch mutation
 - ▣ Cycle mutation
 - ▣ Koza mutation
 - ▣ Mutation for numerical terminals



Mutation (binary representation)

- A chromosome $c = (g_1, g_2, \dots, g_L)$ becomes $c' = (g'_1, g'_2, \dots, g'_L)$, where $g_i, g'_i \in \{0, 1\}$, for $i = 1, 2, \dots, L$.
- Strong mutation – *bit flipping*
 - Main idea
 - Changes by probability p_m (mutation rate) all the genes in their complement
 - $1 \rightarrow 0$
 - $0 \rightarrow 1$
 - Ex. A chromosome of $L = 8$ genes, $p_m = 0.1$





Mutation (binary representation)

- ❑ A chromosome $c = (g_1, g_2, \dots, g_L)$ becomes $c' = (g'_1, g'_2, \dots, g'_L)$, where $g_i, g'_i \in \{0,1\}$, for $i = 1, 2, \dots, L$

- Weak mutation

- Main idea

- Changes by probability p_m (mutation rate) some of the genes in 0 or 1

- $1 \rightarrow 0/1$

- $0 \rightarrow 1/0$

- Eg. A chromosome of $L = 8$ genes, $p_m = 0.1$





Mutation (integer representation)

- ❑ A chromosome $c = (g_1, g_2, \dots, g_L)$ becomes $c' = (g'_1, g'_2, \dots, g'_L)$, where $g_i, g'_i \in \{val_1, val_2, \dots, val_k\}$ for $i = 1, 2, \dots, L$.

- ❑ Random resetting mutation

- Main idea

- ❑ The value of a gene is changed (by probability p_m) into another value (from the definition domain)





Mutation (integer representation)

- ❑ A chromosome $c = (g_1, g_2, \dots, g_L)$ becomes $c' = (g'_1, g'_2, \dots, g'_L)$, where $g_i, g'_i \in \{val_1, val_2, \dots, val_k\}$, for $i = 1, 2, \dots, L$.

❑ *Creep* mutation

- Main idea
 - ❑ The value of a gene is changed (by probability p_m) by adding a positive/negative value
 - New value follows a 0 symmetric distribution
 - The performed change is very small





Mutation (permutation representation)

- A chromosome $c = (g_1, g_2, \dots, g_L)$ with $g_i \neq g_j$ for all $i \neq j$ becomes
 $c' = (g'_1, g'_2, \dots, g'_L)$, where $g_i, g'_i \in \{val_1, val_2, \dots, val_L\}$,
for $i = 1, 2, \dots, L$ s. a. $g'_i \neq g'_j$ for all $i \neq j$.

□ Swap mutation

- Main idea
 - Randomly choose 2 genes and swap their values





Mutation (permutation representation)

- A chromosome $c = (g_1, g_2, \dots, g_L)$ with $g_i \neq g_j$ for all $i \neq j$ becomes $c' = (g_1', g_2', \dots, g_L')$, where $g_i, g_i' \in \{val_1, val_2, \dots, val_L\}$, for $i = 1, 2, \dots, L$ s. a. $g_i' \neq g_j'$ for all $i \neq j$.

□ Insertion mutation

■ Main idea

- Randomly choose 2 genes g_i and g_j with $j > i$
- Insert gene g_j after gene g_i s.a. $g_i' = g_i, g_{i+1}' = g_j, g_{k+2}' = g_{k+1}$, for $k = i, i+1, i+2, \dots$





Mutation (permutation representation)

- A chromosome $c = (g_1, g_2, \dots, g_L)$ with $g_i \neq g_j$ for all $i \neq j$ becomes $c' = (g'_1, g'_2, \dots, g'_L)$, where $g_i, g'_i \in \{val_1, val_2, \dots, val_L\}$, for $i = 1, 2, \dots, L$ s.a. $g'_i \neq g'_j$ for all $i \neq j$.
- Inversion mutation
 - Main idea
 - Randomly choose 2 genes and inverse the order of genes between them (sub-string of genes)





Mutation (permutation representation)

- A chromosome $c = (g_1, g_2, \dots, g_L)$ with $g_i \neq g_j$ for all $i \neq j$ becomes $c' = (g_1', g_2', \dots, g_L')$, where $g_i, g_i' \in \{val_1, val_2, \dots, val_L\}$, for $i = 1, 2, \dots, L$ s.a. $g_i' \neq g_j'$ for all $i \neq j$.

- *scramble mutation*

- Main idea

- Randomly choose a (continuous or discontinuous) subarray of genes and re-organise that genes





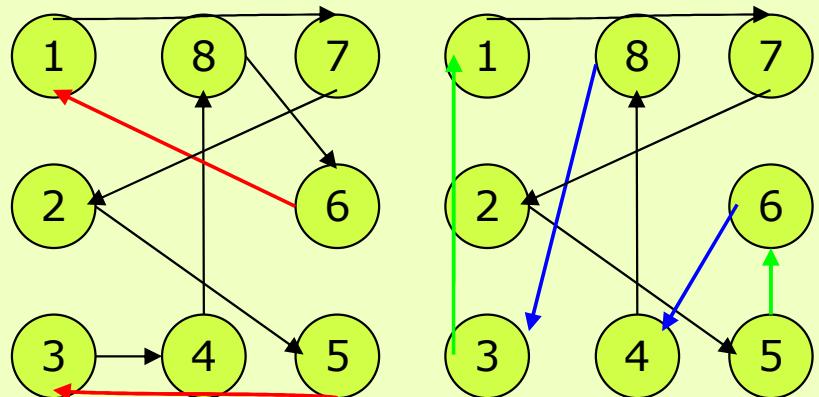
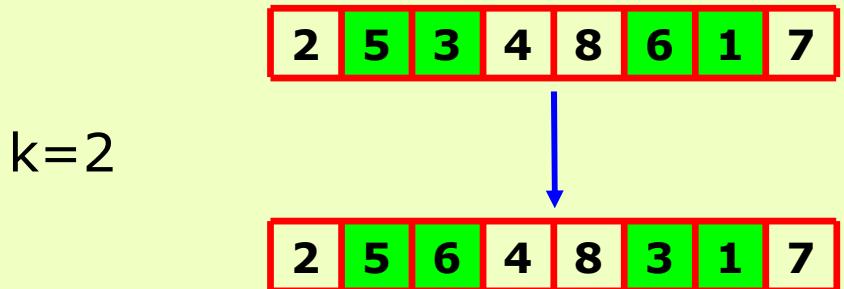
Mutation (permutation representation)

- A chromosome $c = (g_1, g_2, \dots, g_L)$ with $g_i \neq g_j$ for all $i \neq j$ becomes $c' = (g'_1, g'_2, \dots, g'_L)$, where $g_i, g'_i \in \{val_1, val_2, \dots, val_L\}$,
for $i = 1, 2, \dots, L$ s.a. $g'_i \neq g'_j$ for all $i \neq j$.

□ K-opt mutation

■ Main idea

- Choose 2 disjoint sub-strings of length k
- Interchange 2 elements of these sub-strings





Mutation (real representation)

- A chromosome $c = (g_1, g_2, \dots, g_L)$ becomes $c' = (g'_1, g'_2, \dots, g'_L)$, where $g_i, g'_i \in [a_i, b_i]$, for $i=1, 2, \dots, L$.

□ Uniform mutation

- Main idea
 - g'_i is changed by probability p_m into a new value that is randomly uniform generated in $[a_i, b_i]$ range



Mutation (real representation)

- ❑ A chromosome $c = (g_1, g_2, \dots, g_L)$ becomes $c' = (g'_1, g'_2, \dots, g'_L)$, where $g_i, g'_i \in [a_i, b_i]$, for $i = 1, 2, \dots, L$.

❑ Non-uniform mutation

■ Main idea

- ❑ The value of a gene is probabilistically (p_m) changed by adding a positive/negative value
 - The added value belongs to a distribution of type
 - $N(\mu, \sigma)$ (Gaussian) with $\mu = 0$
 - Cauchy (x_0, γ)
 - Laplace (μ, b)
 - And it is re-introduced in $[a_i, b_i]$ range (if it is necessary) – *clamping*

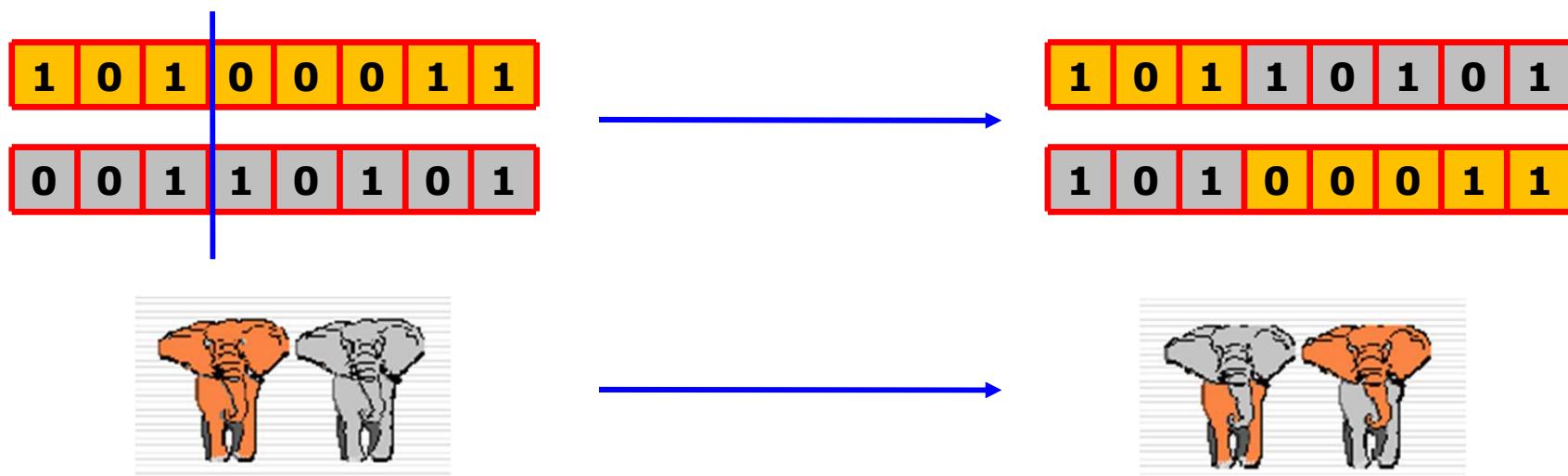
Recombination



- Aim
 - Mix the parents' information

Properties

- The offspring has to inherit something from both parents
 - Selection of mixed information is randomly performed
- Operator for exploitation of already discovered possible solutions
- The offspring can be better, the same or weaker than their parents
- Its effects are reducing while the search converges



Recombination



- Types
 - Binary and integer representation
 - With cutting points
 - Uniforme
 - Permutation representation
 - Order crossover (version 1 and version 2)
 - Partially Mapped Crossover
 - Cycle crossover
 - Edge-based crossover
 - Real representation
 - Discrete
 - Arithmetic
 - Singular
 - Simple
 - Complete
 - Geometric
 - Shuffle crossover
 - Simulated binary crossover
 - Tree-based representation
 - Sub-tree based crossover → future lecture



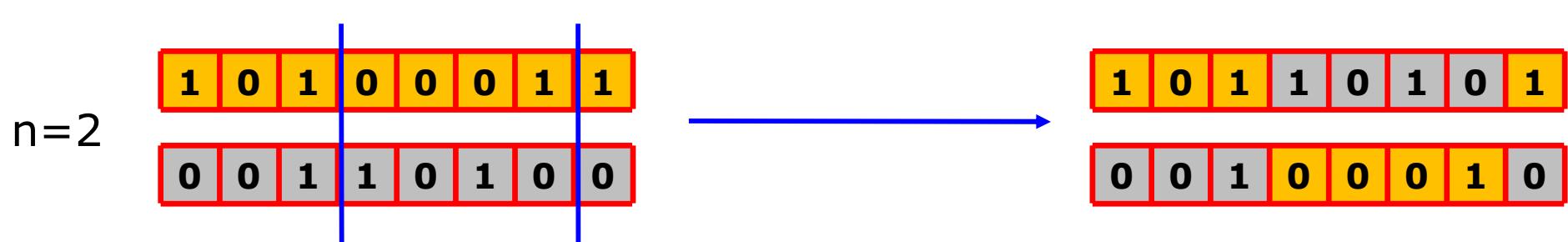
Recombination (binary and integer representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - where $g_i^1, g_i^2, g_i', g_i'' \in \{0, 1\} / \{val_1, val_2, \dots, val_k\}$, for $i = 1, 2, \dots, L$

□ N-cutting point crossover

- Main idea

- Choose n cutting-points ($n < L$)
- Cut the parents through these points
- Put together the resulted parts, by alternating the parents





Recombination (binary and integer representation)

□ N cutting point crossover

■ Properties

- Average of values encoded by parents = average of values encoded by offspring
 - Eg binary representation on 4 bits of integer numbers – XO with $n = 1$ after second bit
 - $p_1 = (1, 0, 1, 0), p_2 = (1, 1, 0, 1)$
 - $c_1 = (1, 0, 0, 1), c_2 = (1, 1, 1, 0)$
 - $val(p_1) = 10, val(p_2) = 13 \rightarrow (val(p_1) + val(p_2)) / 2 = 23 / 2 = 11.5$
 - $val(c_1) = 9, val(c_2) = 14 \rightarrow (val(c_1) + val(c_2)) / 2 = 23 / 2 = 11.5$
 - Eg. Binary representation on 4 bits for knapsack problem ($K=10$, 4 items of weight and value: (2,7), (1,8), (3,1), (2,3))
 - $p_1 = (1, 0, 1, 0), p_2 = (1, 1, 0, 1)$
 - $c_1 = (1, 0, 0, 1), c_2 = (1, 1, 1, 0)$
 - $val(p_1) = 8, val(p_2) = 18 \rightarrow (val(p_1) + val(p_2)) / 2 = 26 / 2 = 13$
 - $val(c_1) = 10, val(c_2) = 16 \rightarrow (val(c_1) + val(c_2)) / 2 = 26 / 2 = 13$

- Probability of $\beta \approx 1$ is the largest one

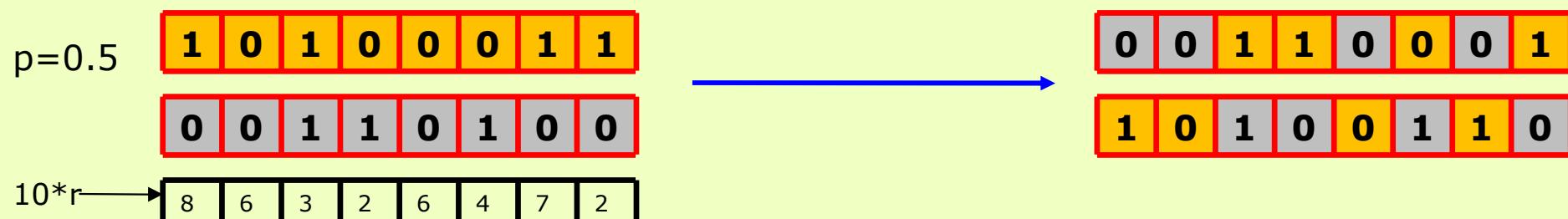
$$\beta = \left| \frac{val(d_1) - val(d_2)}{val(p_1) - val(p_2)} \right|$$

- Contracting crossover $\beta < 1$
 - Offspring values are between parent values
- Expanding crossover $\beta > 1$
 - Parent values are between offspring values
- Stationary crossover $\beta = 1$
 - Offspring values are equal to parent values



Recombination (binary and integer representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - where $g_i^1, g_i^2, g_i', g_i'' \in \{0, 1\} / \{val_1, val_2, \dots, val_k\}$, for $i = 1, 2, \dots, L$
- Uniform crossover
 - Main idea
 - Each gene of an offspring comes from a randomly and uniform selected parent:
 - For each gene a uniform random number r is generated
 - If $r < probability p$ (usually, $p=0.5$), c_1 will inherit that gene from p_1 and c_2 from p_2 ,
 - otherwise, c_1 will inherit p_2 and c_2 will inherit p_1

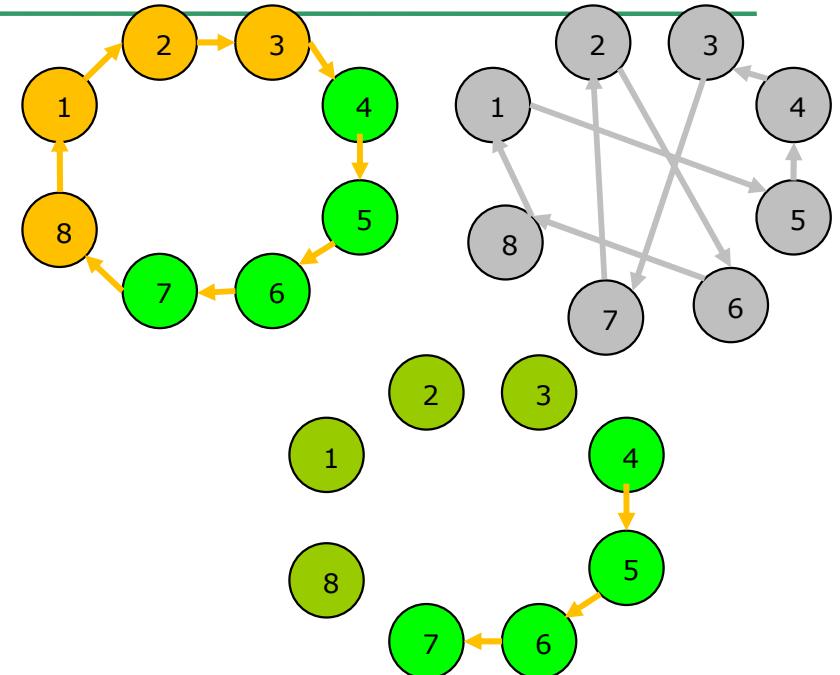
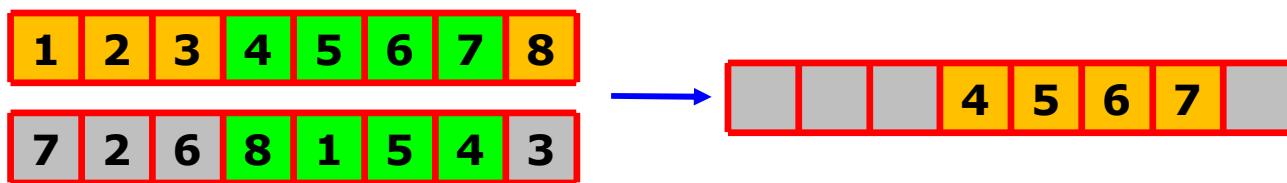




Recombination (permutation representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [1, L] \cap \mathbb{Z}$, for $i = 1, 2, \dots, L$.

- Order crossover
 - Main idea
 - Offspring keep the order of genes from parents
 - Choose a substring of genes from the parent p_1
 - Copy the substring from p_1 into offspring d_1 (on corresponding positions)

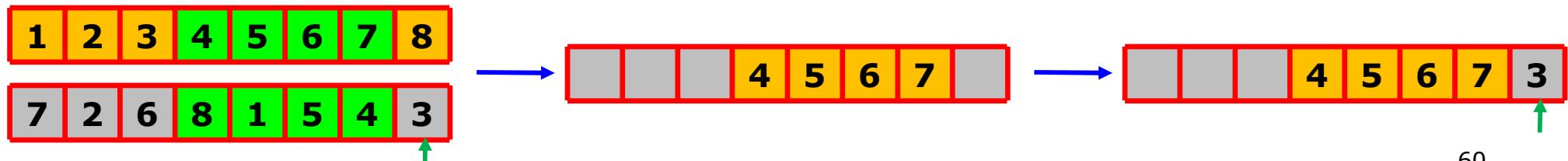
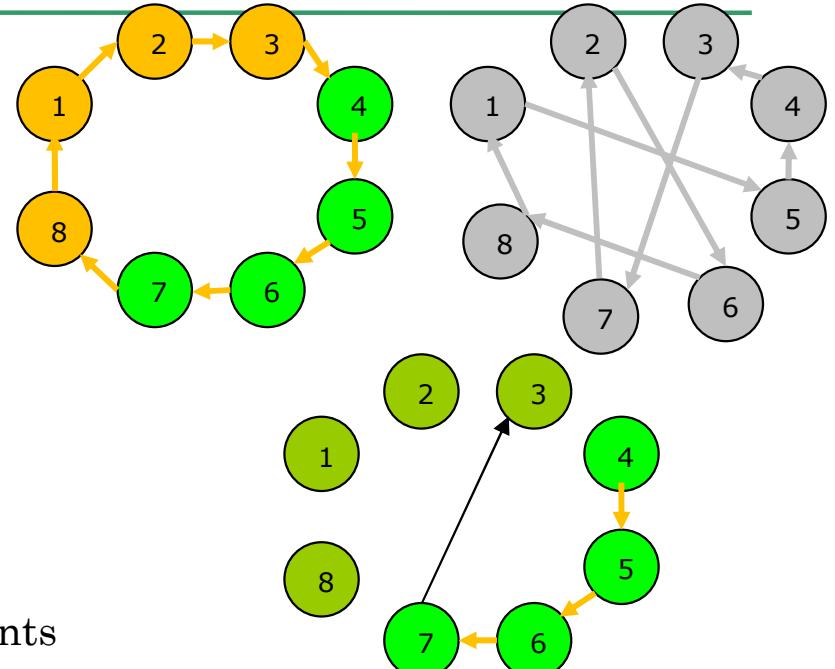




Recombination (permutation representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [1, L] \cap \mathbb{Z}$, for $i = 1, 2, \dots, L$.

- Order crossover
 - Main idea
 - Offspring keep the order of genes from parents
 - Choose a substring of genes from the parent p_1
 - Copy the substring from p_1 into offspring d_1 (on corresponding positions)
 - Copy the genes of p_2 in offspring d_1 :
 - Starting with the first position after sub-string
 - Respecting gene's order from p_2 and
 - Re-loading the genes from start (if the end of chromosome is reached)

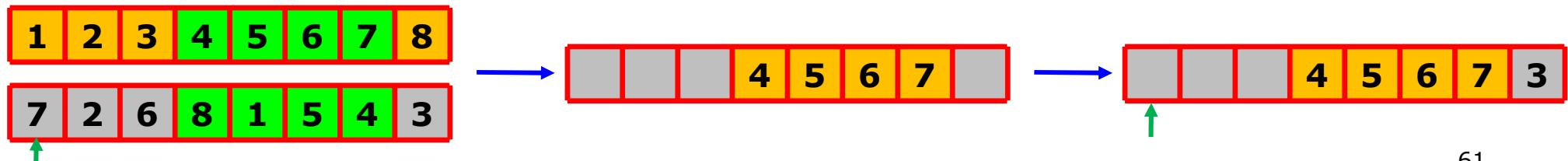
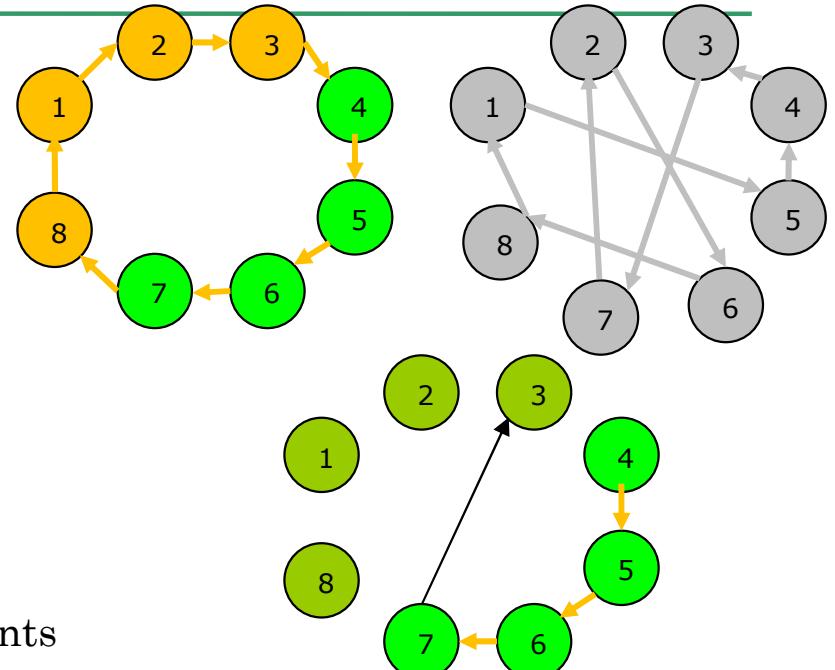




Recombination (permutation representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [1, L] \cap \mathbb{Z}$, for $i = 1, 2, \dots, L$.

- Order crossover
 - Main idea
 - Offspring keep the order of genes from parents
 - Choose a substring of genes from the parent p_1
 - Copy the substring from p_1 into offspring d_1 (on corresponding positions)
 - Copy the genes of p_2 in offspring d_1 :
 - Starting with the first position after sub-string
 - Respecting gene's order from p_2 and
 - Re-loading the genes from start (if the end of chromosome is reached)

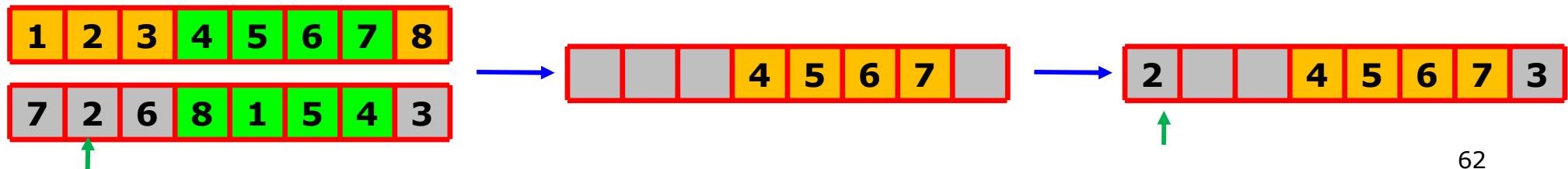
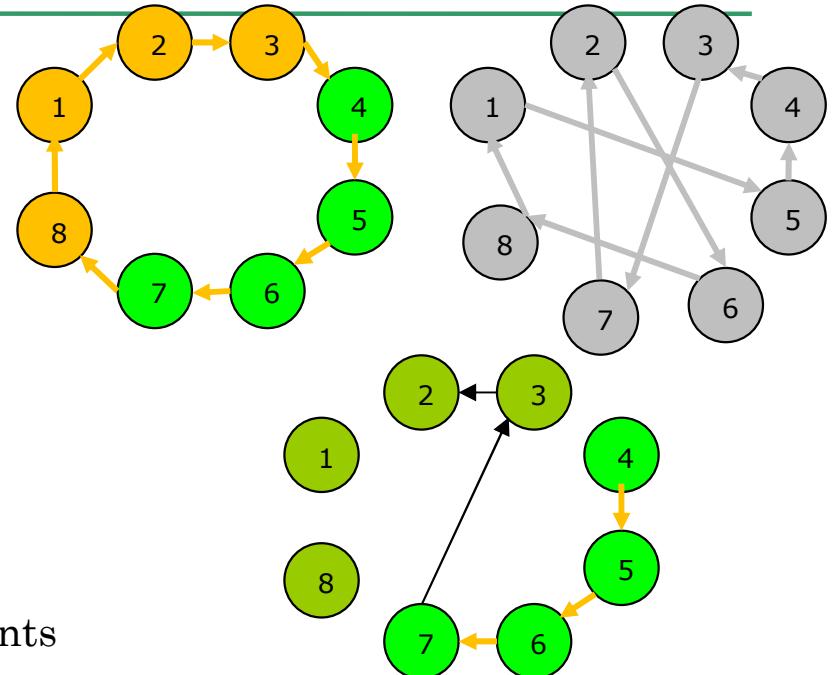




Recombination (permutation representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [1, L] \cap \mathbb{Z}$, for $i = 1, 2, \dots, L$.

- Order crossover
 - Main idea
 - Offspring keep the order of genes from parents
 - Choose a substring of genes from the parent p_1
 - Copy the substring from p_1 into offspring d_1 (on corresponding positions)
 - Copy the genes of p_2 in offspring d_1 :
 - Starting with the first position after sub-string
 - Respecting gene's order from p_2 and
 - Re-loading the genes from start (if the end of chromosome is reached)

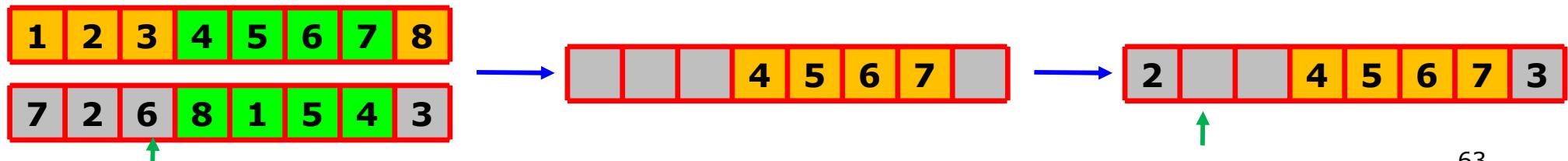
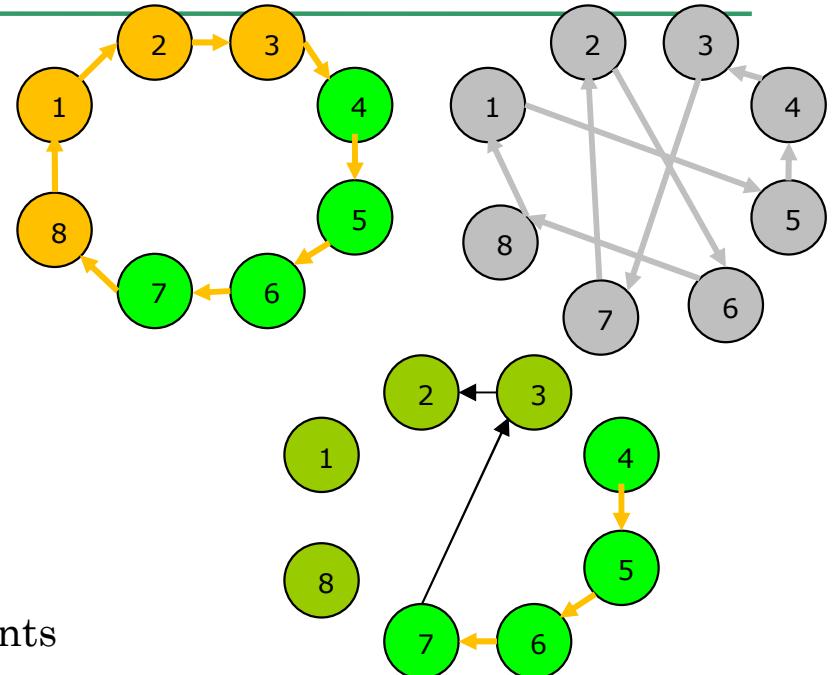




Recombination (permutation representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [1, L] \cap \mathbb{Z}$, for $i = 1, 2, \dots, L$.

- Order crossover
 - Main idea
 - Offspring keep the order of genes from parents
 - Choose a substring of genes from the parent p_1
 - Copy the substring from p_1 into offspring d_1 (on corresponding positions)
 - Copy the genes of p_2 in offspring d_1 :
 - Starting with the first position after sub-string
 - Respecting gene's order from p_2 and
 - Re-loading the genes from start (if the end of chromosome is reached)

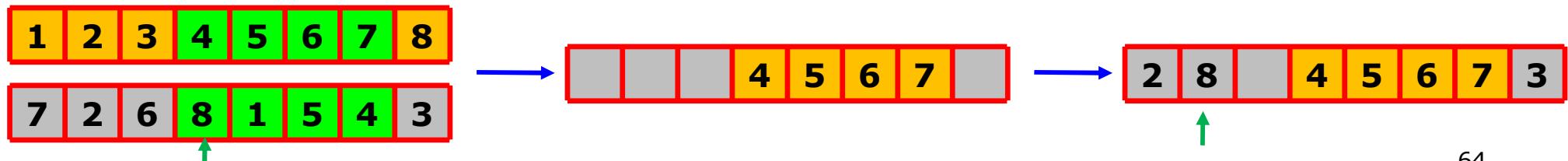
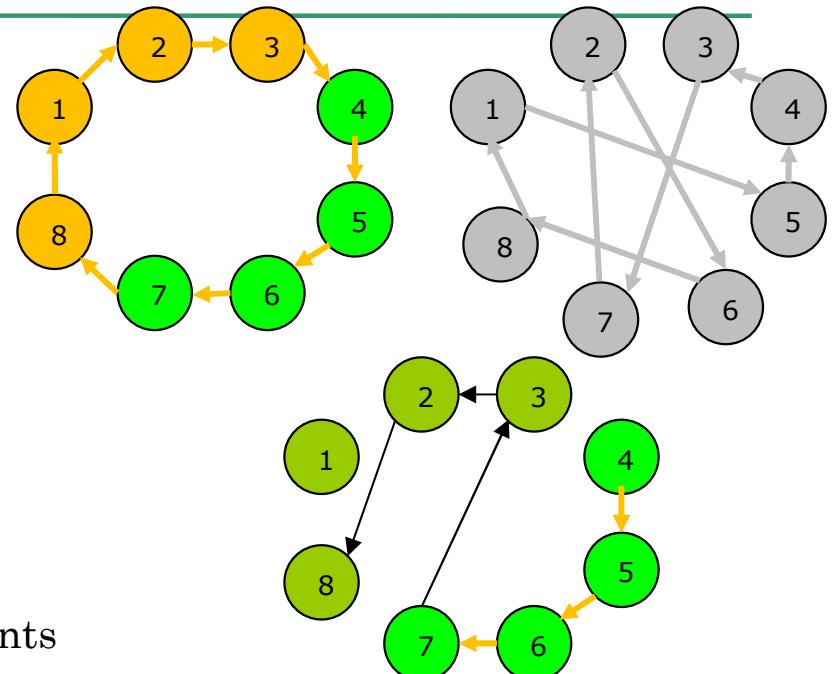




Recombination (permutation representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [1, L] \cap \mathbb{Z}$, for $i = 1, 2, \dots, L$.

- Order crossover
 - Main idea
 - Offspring keep the order of genes from parents
 - Choose a substring of genes from the parent p_1
 - Copy the substring from p_1 into offspring d_1 (on corresponding positions)
 - Copy the genes of p_2 in offspring d_1 :
 - Starting with the first position after sub-string
 - Respecting gene's order from p_2 and
 - Re-loading the genes from start (if the end of chromosome is reached)

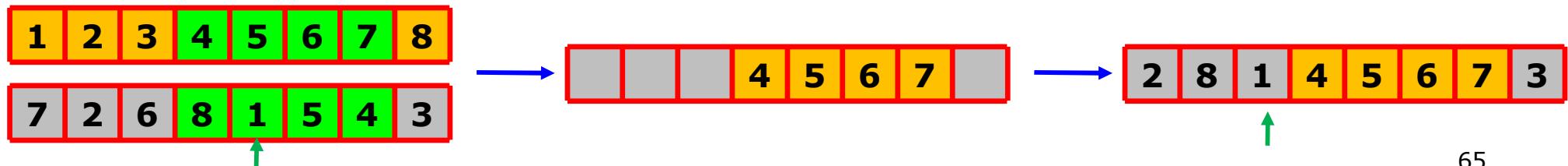
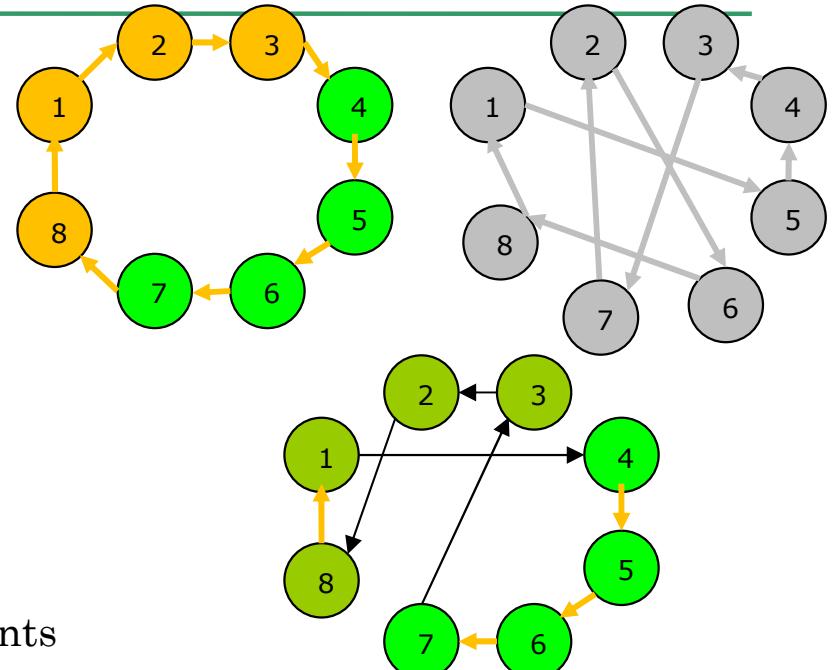




Recombination (permutation representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [1, L] \cap \mathbb{Z}$, for $i = 1, 2, \dots, L$.

- Order crossover
 - Main idea
 - Offspring keep the order of genes from parents
 - Choose a substring of genes from the parent p_1
 - Copy the substring from p_1 into offspring d_1 (on corresponding positions)
 - Copy the genes of p_2 in offspring d_1 :
 - Starting with the first position after sub-string
 - Respecting gene's order from p_2 and
 - Re-loading the genes from start (if the end of chromosome is reached)

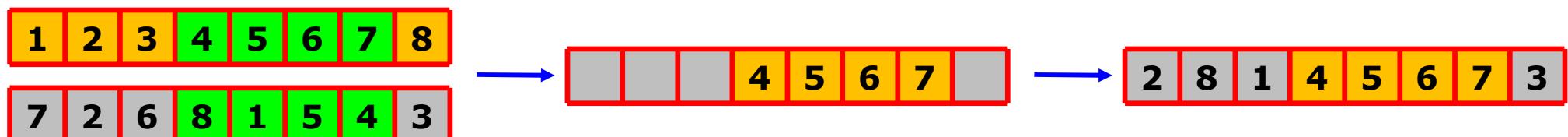
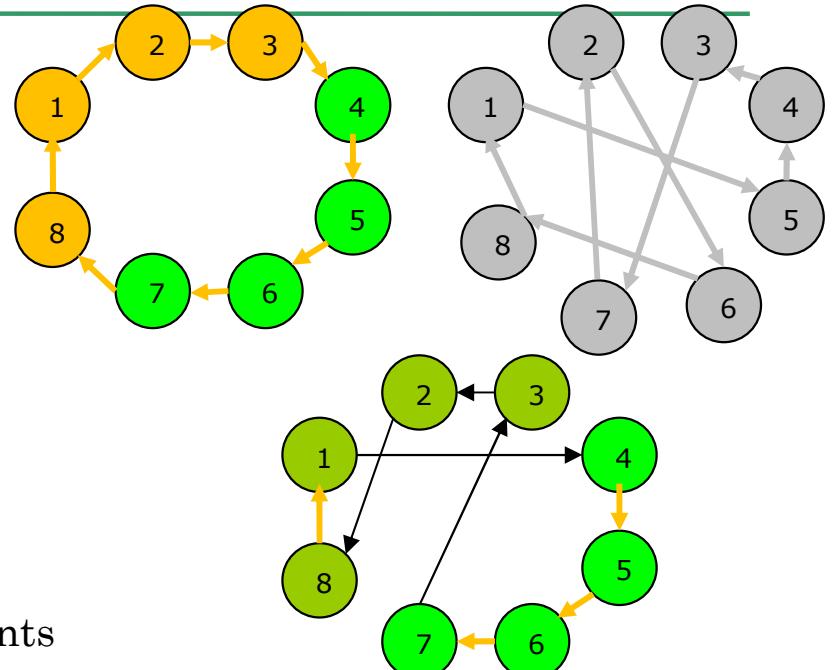




Recombination (permutation representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [1, L] \cap \mathbb{Z}$, for $i = 1, 2, \dots, L$.

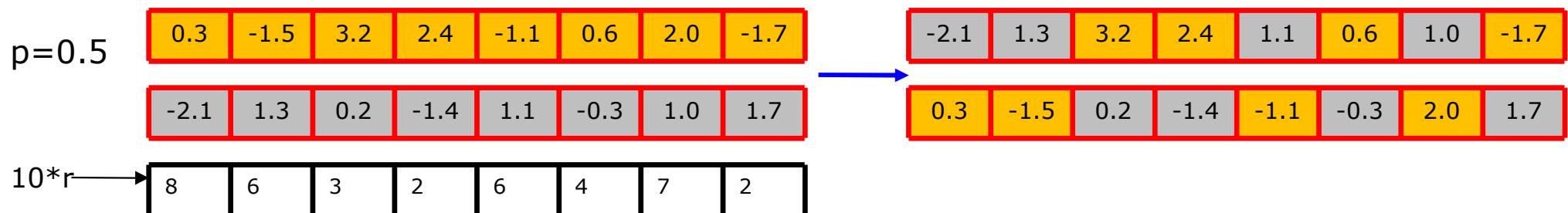
- Order crossover
 - Main idea
 - Offspring keep the order of genes from parents
 - Choose a substring of genes from the parent p_1
 - Copy the substring from p_1 into offspring d_1 (on corresponding positions)
 - Copy the genes of p_2 in offspring d_1 :
 - Starting with the first position after sub-string
 - Respecting gene's order from p_2 and
 - Re-loading the genes from start (if the end of chromosome is reached)





Recombination (real representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [a_i, b_i]$, for $i = 1, 2, \dots, L$
- Discrete crossover
 - Main idea
 - Each gene offspring is taken (by the same probability, $p = 0.5$) from one of the parents
 - Similarly to uniform crossover for binary/integer representation
 - The absolute values of genes are not changed (no new information is created)





Recombination (real representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [a_i, b_i]$, for $i = 1, 2, \dots, L$

□ Arithmetic crossover

- Main idea
 - Create offspring between parents → arithmetic crossover
 - $z_i = a x_i + (1 - a) y_i$ where $0 \leq a \leq 1$.
 - Parameter a can be:
 - Constant → uniform arithmetic crossover
 - Variable → eg. Depends on the age of population
 - Random → generated for each new XO that is performed
 - New values of a gene can appear

- Types:
 - Singular arithmetic crossover
 - Simple arithmetic crossover
 - Complete arithmetic crossover



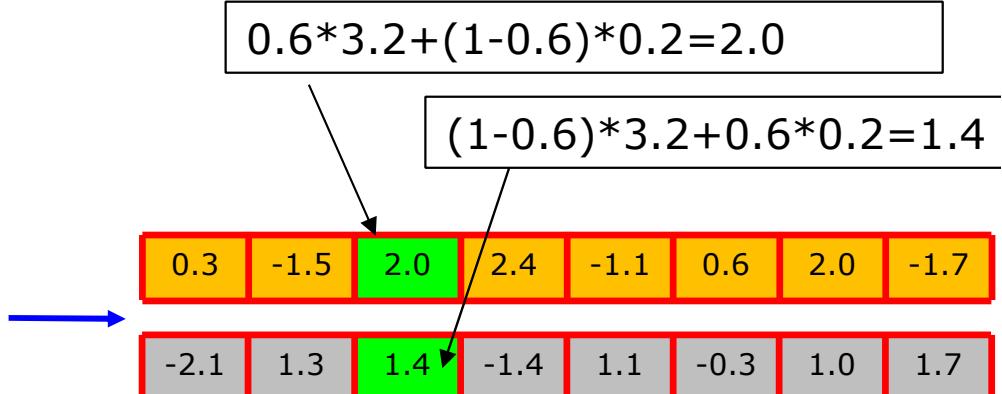
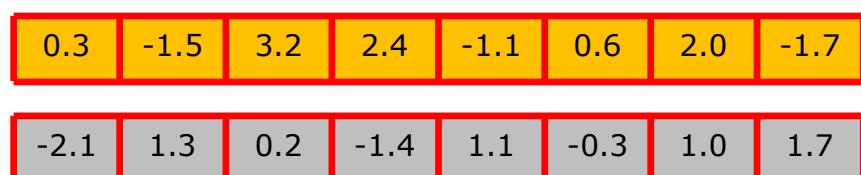
Recombination (real representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [a_i, b_i]$, for $i = 1, 2, \dots, L$
- Singular arithmetic crossover
 - Choose one gene from two parents (of the same position k) and combine them
 - $g_k' = a g_k^1 + (1 - a) g_k^2$
 - $g_k'' = (1 - a) g_k^1 + a g_k^2$
 - The rest of genes are unchanged
 - $g_i' = g_i^1$
 - $g_i'' = g_i^2$, for $i = 1, 2, \dots, L$ and $i \neq k$

$$[a, b] = [-2.5, +3]$$

$$k = 3$$

$$\alpha = 0.6$$





Recombination (real representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [a_i, b_i]$, for $i = 1, 2, \dots, L$

- Simple arithmetic crossover
 - Select a position k and combine all the genes after that position
 - $g_i' = a g_i^1 + (1 - a) g_i^2$
 - $g_i'' = (1 - a) g_i^1 + a g_i^2$, for $i = k, k + 1, \dots, L$
 - Genes from positions $< k$ rest unchanged
 - $g_i' = g_i^1$
 - $g_i'' = g_i^2$, for $i = 1, 2, \dots, k - 1$

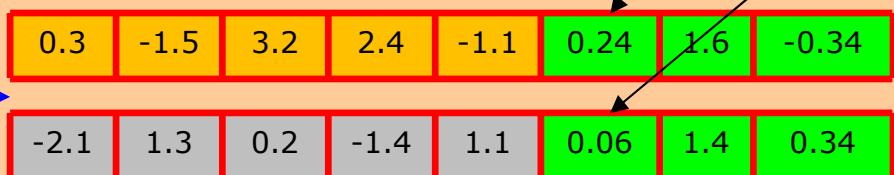
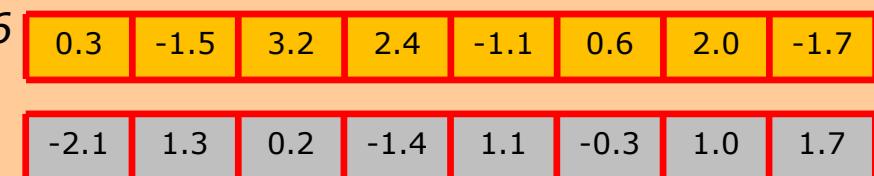
$$0.6 * 0.6 + (1 - 0.6) * (-0.3) = 0.24$$

$$(1 - 0.6) * 0.6 + 0.6 * (-0.3) = 0.06$$

$$[a, b] = [-2.5, +3]$$

$$k = 6$$

$$\alpha = 0.6$$





Recombination (real representation)

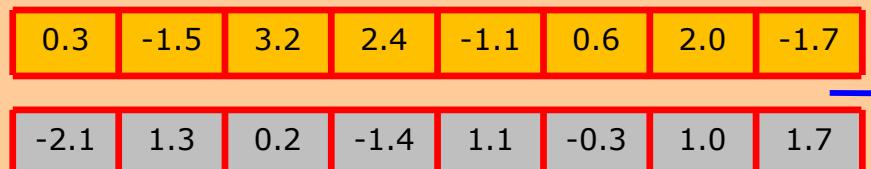
- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [a_i, b_i]$, for $i = 1, 2, \dots, L$

□ Complete arithmetic crossover

- All of the genes are combined
 - $g_i' = a g_i^1 + (1 - a) g_i^2$
 - $g_i'' = (1 - a) g_i^1 + a g_i^2$, for $i = 1, 2, \dots, L$

$$0.6 * 0.3 + (1 - 0.6) * (-2.1) = -0.66$$

$$[a, b] = [-2.5, +3]$$
$$\alpha = 0.6$$



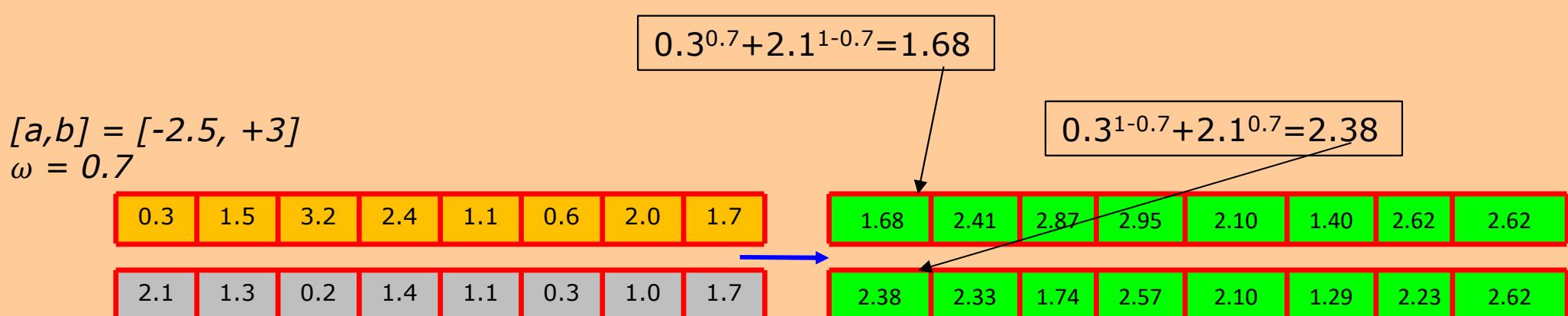
$$(1 - 0.6) * 0.3 + 0.6 * (-2.1) = -1.14$$



Recombination (real representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [a_i, b_i]$, for $i = 1, 2, \dots, L$

- Geometric crossover
 - Main idea
 - Each gene of an offspring represents the product between parent's genes, each of them by a given exponent ω and $1-\omega$, respectively (where ω is a real positive number ≤ 1)
 - $g_i' = (g_i^1)^\omega (g_i^2)^{1-\omega}$
 - $g_i'' = (g_i^1)^{1-\omega} (g_i^2)^\omega$





Recombination (real representation)

- From 2 parent chromosomes
 - $p_1 = (g_1^1, g_2^1, \dots, g_L^1)$ and $p_2 = (g_1^2, g_2^2, \dots, g_L^2)$
- 2 offspring are obtained
 - $c_1 = (g_1', g_2', \dots, g_L')$ and $c_2 = (g_1'', g_2'', \dots, g_L'')$,
 - Where $g_i^1, g_i^2, g_i', g_i'' \in [a_i, b_i]$, for $i = 1, 2, \dots, L$
- Blend crossover – BLX
 - Main idea
 - A single offspring is created
 - Offspring's genes are randomly generated from $[Min_i - I * a, Max_i + I * a]$ range, where:
 - $Min_i = min\{g_i^1, g_i^2\}$, $Max_i = max\{g_i^1, g_i^2\}$
 - $I = Max - Min$, a – parameter from $[0, 1]$

$$[a, b] = [-2.5, +3]$$

$$a = 0.7$$

0.3	1.5	3.2	2.4	1.1	0.6	2.0	1.7
2.1	1.3	0.2	1.4	1.1	0.3	1.0	1.7



1.25	1.45	-1.11	2.37	1.10	0.11	0.70	1.70
------	------	-------	------	------	------	------	------

Min	0.3	1.3	0.2	1.4	1.1	0.3	1.0	1.7
Max	2.1	1.5	3.2	2.4	1.1	0.6	2.0	1.7
I	0.8	0.2	3.0	1.0	0	0.3	1.0	0.0

Min-Ia	-0.26	1.16	-1.90	0.70	1.10	0.09	0.30	1.70
Max+Ia	2.66	1.50	3.20	2.40	1.10	0.60	2.00	1.70

Recombination or mutation?

□ Intense debates

- Questions:
 - Which is the best operator?
 - Which is the most necessary operator?
 - Which is the most important operator?
- Answers:
 - Depend on problem, but,
 - In general, is better to use both operators
 - Each of them having another role (purpose).
 - EAs with mutation only are possible, but EAs with crossover only are not possible

□ Search aspects:

- Exploration → discovering promising regions in the search space (accumulating useful information about the problem)
- Exploitation → optimising in a promising region of the search space (by using the existent information)
- Cooperation and competition mut exist between these 2 aspects

□ Recombination

- Exploitation operator → performs a large jump into a region somewhere between the regions associated to parents
 - Effects of exploitation decrease while AE is converging
- Binary/n-ary operator that can combine information from 2/more parents
- Operator that does not change the frequency of values from chromosome at the population level

□ Mutation

- Exploration operator → performs small random diversions, remaining in a neighbourhood of parent
 - Local optima escape
- Operator that can introduce new genetic information
- Operator that change the frequency of values from chromosome at the population level



Stop condition

- Choosing a stop condition
- An optimal solution was found
- The physical resources were ended
 - A given number of fitness evaluation has been performed
- The user resources (time, patience) were ended
 - Several generation without improvements have been born



Evaluation

- Performance evaluation of an EA
 - After more runs
 - Statistical measures are computed
 - Average of solutions
 - Median of solutions
 - Best solution
 - Worst solution
 - Standard deviation of solutions – for comparisons
 - The number of independent runs must be large enough

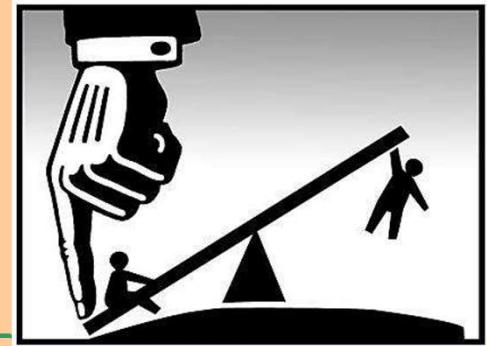
EAs



Analyse of complexity

- The most costly part → fitness evaluation

EAs



Advantages

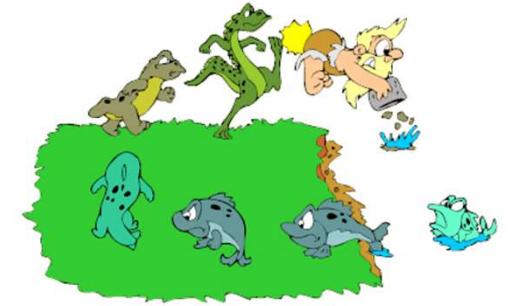
- AEs have a general sketch for all the problems
 - Only
 - representation
 - fitness function
 - are changed
- AEs are able to give better results than classical optimisation methods because
 - They do not require linearization
 - They are not based on some presumptions
 - They do not ignore some possible solutions
- AEs are able to explore more possible solutions than human can

AES



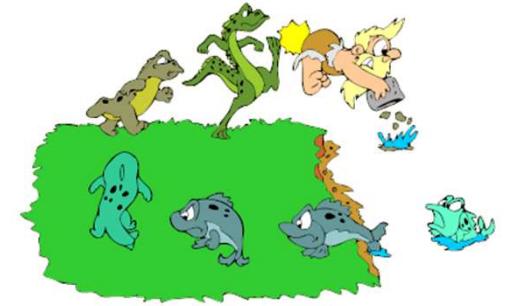
Disadvantages

- Large running time



Applications

- Vehicle design
 - Material composition
 - Vehicle shape
- Engineering design
 - Structural and organisational optimisation of constructions (buildings, robots, satellites, turbines)
- Robotics
 - Design and components optimisation
- Hardware evolution
 - Digital circuits optimisation
- Telecommunication optimisation
- Cross-word game generation
- Biometric inventions (inspired by natural architectures)
- Traffic and transportation routing
- PC games
- Cryptography
- Genetics
- Chemical analysis of kinematics
- Financial and marketing strategies



Types

- Evolutionary strategies
- Evolutionary programming
- Genetic algorithms
- Genetic programming

Thank you for your attention!

ARTIFICIAL INTELLIGENCE



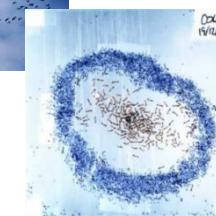
**Particle Swarm Optimization
Ant Colony Optimization**

Local search

- Simple local search – a single neighbour state is retained
 - Hill climbing → selects the best neighbour
 - Simulated annealing → selects probabilistically the best neighbour
 - Tabu search → retains the list of visited solutions
- Beam local search – more states are retained (a population of states)
 - Evolutionary algorithms
 - Particle swarm optimisation
 - Ant colony optimization

Nature-inspired algorithms

- Swarm intelligence (collective intelligence)
 - A group of individuals that interact in order to achieve some objectives by collective adaptation to a global or local environment
 - A computational metaphor inspired by
 - Birds' flying (V shape)
 - Ants that are searching food
 - Bees' swarms that are constructing their nest
 - Schools of fish
 - Because:
 - Control is distributed among more individuals
 - Individuals local communicate
 - system behaviour transcends the individual behaviour
 - System is robust and can adapt to environment changes
- Social insects (2% of total)
 - Ants
 - 50% of social insects
 - 1 ant has \sim 1mg \rightarrow total weight of ants \sim total weight of humans
 - Live for over 100 millions of years (humans live for over 50 000 years)
 - Termites
 - Bees



Nature-inspired algorithms

- Swarm (Group)
 - More individuals, apparently un-organised, that are moving in order to form a group, but each individual seems to move in a particular direction
 - Inside the group can appear some social processes
 - The collection is able to do complex tasks
 - Without a guide or an external control
 - Without a central coordination
 - The collection can have performances better than the independent individuals
- Collective adaptation → self-organisation
 - Set of dynamic mechanisms that generates a global behaviour as a result of interaction among individual components
 - Rules that specify this interaction are executed based on local information only, without global references
 - Global behaviour is an emergent property of the system (and not one external imposed)

PSO

- ❖ Theoretical aspects
- ❖ Algorithm
- ❖ Example
- ❖ Properties
- ❖ Applications

PSO – theoretical aspects

- Proposed by
 - ◆ Kennedy and Eberhart in 1995
 - ◆ Inspired by social behaviour of bird swarms and school of fish
- Search is
 - ◆ **Cooperative**, guided by the relative quality of individuals
- Search operators
 - ◆ A kind of mutation

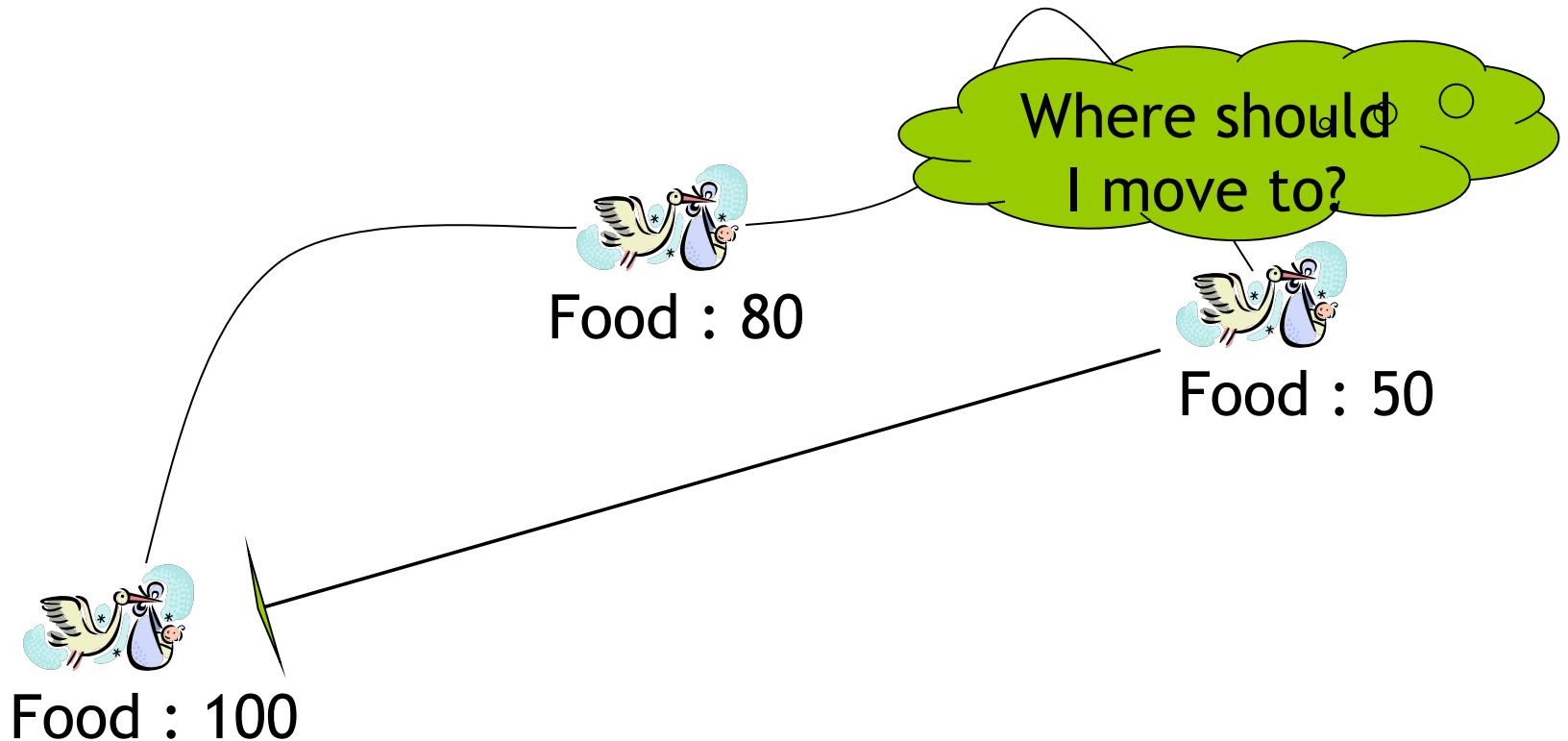
PSO – theoretical aspects

□ Special elements

- Optimisation method based on:
 - Populations (\approx EAs) of particles (\approx chromosomes) that search the optimal solution
 - Cooperation (instead of concurrence, like in EAs case)
- Each particle
 - moves (in the search space) and has a velocity (velocity \approx movement, because the time is discrete)
 - Retains the place where it has obtained the best results
 - Has associated a neighbourhood of particles
- Particles cooperate
 - Exchange information among them (regarding the discovering performed in the places already visited)
 - Each particle knows the fitness of neighbours such as it can use the position of the best neighbour for adjusting its velocity

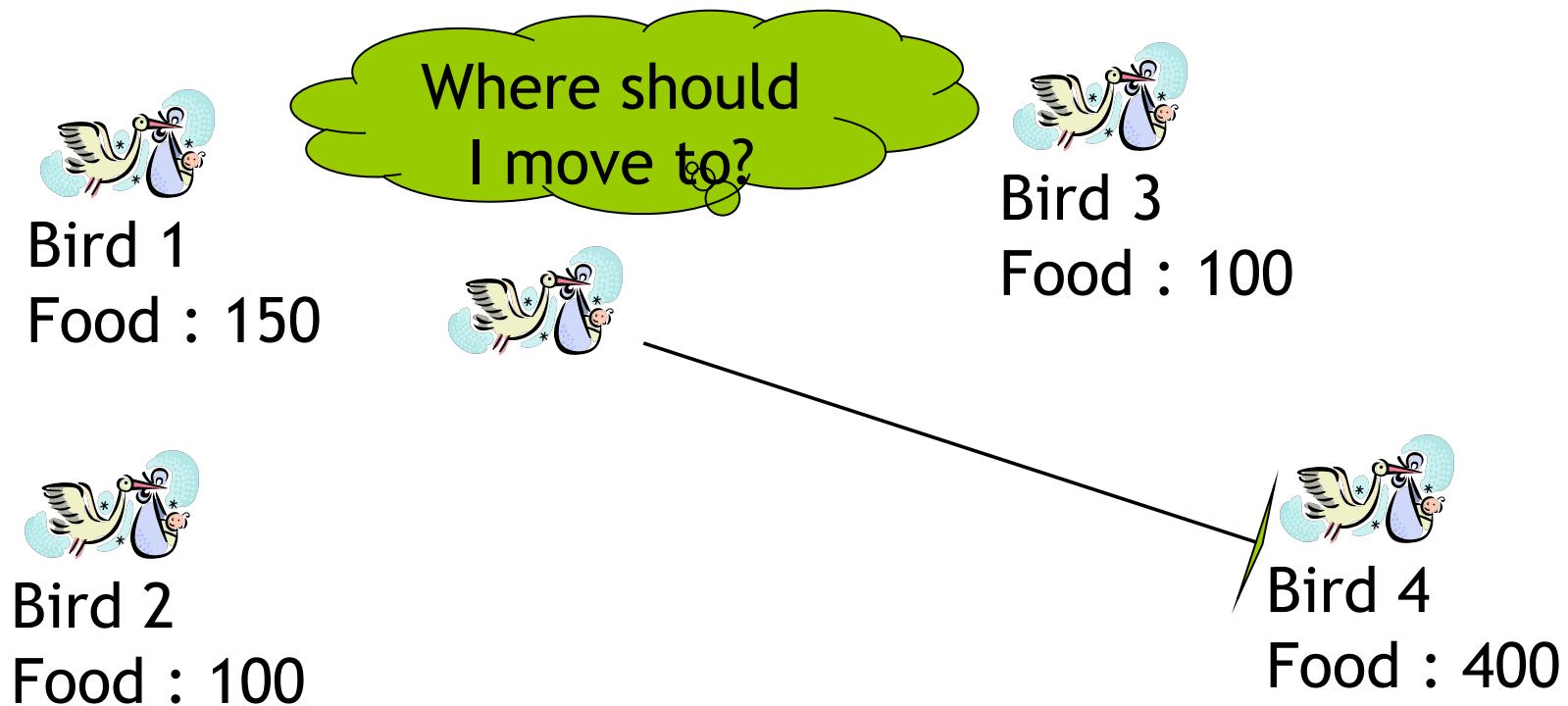
PSO – theoretical aspects

Main idea: cognitive behaviour → an individual remembers past knowledge (has memory)



PSO – theoretical aspects

Main idea: social behaviour → an individual relies on the knowledge of other members of the group



PSO – algorithm

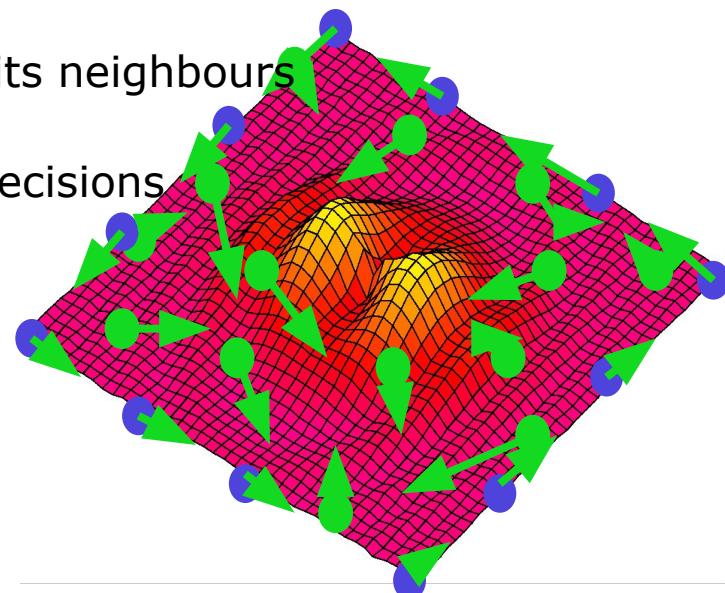
□ General sketch

1. Creation of the initial population of particles
 1. Random positions
 2. Null/random velocities
2. Evaluation of particles
3. For each particle
 - Update the memory
 - Identify the best particle of the swarm (g_{Best}) / of the current neighbourhood (I_{Best})
 - Identify the best position (with the best fitness) reached until now – p_{Best}
 - Update the velocity
 - Update the position
5. If the stop conditions are not satisfied, go back to step 2; otherwise STOP.

PSO – algorithm

1. Creation of the initial population of particles

- Each particle has associated
 - A position – possible solution of the problem
 - A velocity – changes a position into another position
 - A quality function (fitness)
- Each particle has to:
 - Interact (exchange information) with its neighbours
 - Memorise a previous position
 - Use the information in order to take decisions
- Initialisation of particles
 - Random positions
 - Null/random velocities



PSO – algorithm

2. Evaluation of particles

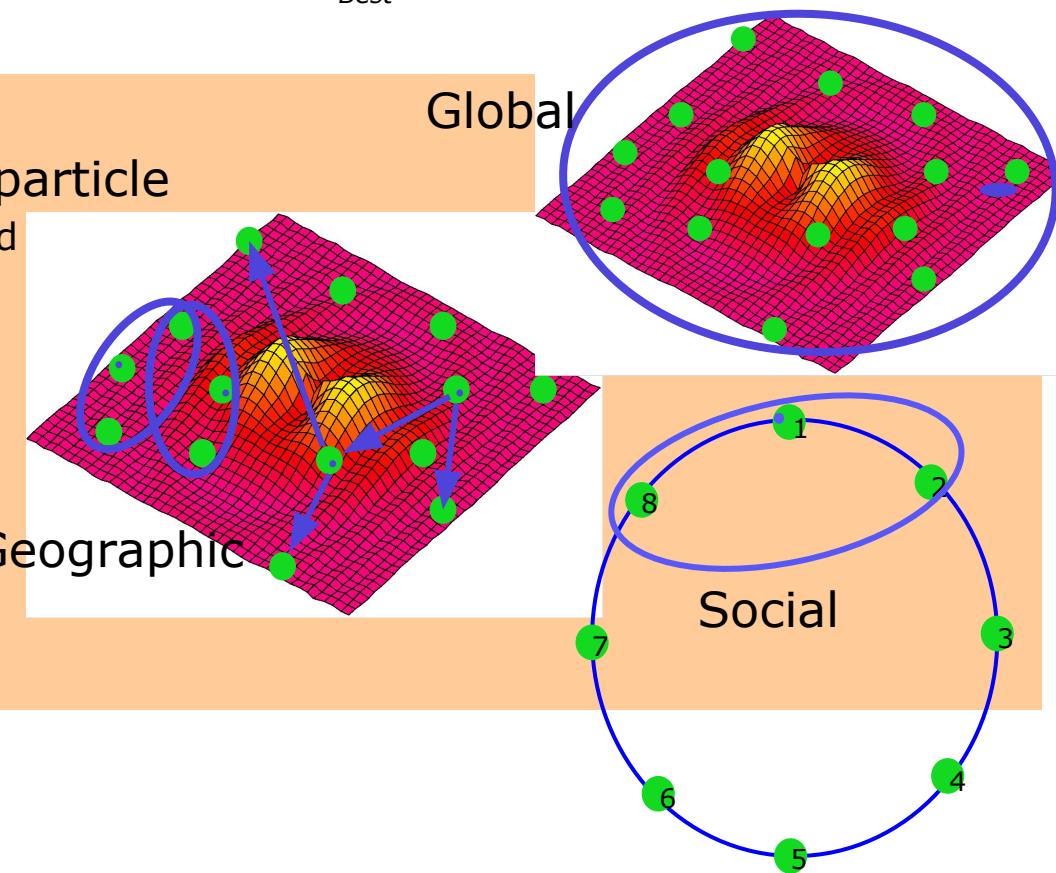
- Depends on problem

PSO – algorithm

3. For each particle p_i

- Update the memory
 - Identify the best particle of the swarm (g_{Best}) / of the current neighbourhood (I_{Best})

- Neighbourhood for a particle
 - Neighbourhood's spread
 - Global
 - Local
 - Neighbourhood's type
 - Geographic
 - Social
 - Circular

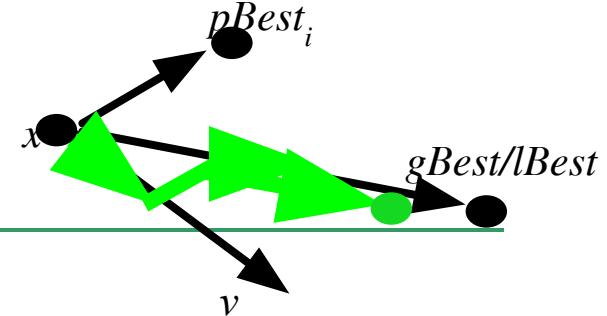


PSO – algorithm

3. For each particle p_i

- Update the memory
 - Identify the best particle of the swarm (g_{Best}) / of the current neighbourhood (I_{Best})
 - Identify the best position (with the best fitness) reached until now – p_{Best}

PSO – algorithm



3. For each particle p_i
 - Update the velocity \mathbf{v}_i and position $\mathbf{x}_i = (x_{i1}, x_{i2}, \dots, x_{iD})$ (on each dimension)
 - $v_{id} = w * v_{id} + c_1 * rand() * (p_{Best_d} - x_{id}) + c_2 * rand() * (g_{Best_d} - x_{id})$
 - $x_{id} = x_{id} + v_{id}$
 - where:
 - $i=1,N$ (N – total number of particles/swarm size);
 - $d = 1,D$
 - w – inertia coefficient (Shi, Eberhart)
 - $w * v_{id}$ inertial factor → forces the particle to move in the same direction until now (*audacious*)
 - Balance the search between global exploration (large w) and local exploration (small w)
 - Can be constant or descending (while the swarm is getting old)
 - c_1 - cognitive learning coefficient
 - $c_1 * rand() * (p_{Best_d} - x_{id})$ – cognitive factor → forces the particle to move towards its best position (*conservation*)
 - c_2 - social learning coefficient
 - $c_2 * rand() * (g_{Best_d} - x_{id})$ – social factor → forces the particle to move towards the best neighbour (*follower*)
 - c_1 and c_2 can be equal or different ($c_1 > c_2 \text{ si } c_1 + c_2 < 4$ – Carlisle, 2001)
 - Each component of velocity vector must belong to a given range $[-v_{max}, v_{max}]$ in order to keep the particles inside the search space

PSO – properties

- PSO principles:
 - Proximity – the group has to perform computing in space and time
 - Quality – the group has to be able of answering to the quality of environment
 - Stability – the group has not to change its behaviour at each environment change
 - Adaptability – the group has to be able of changing its behaviour when the cost on change is not prohibit
- Differences from EAs:
 - There is no recombination operator – information exchange takes place based on particle's experience and based on the best neighbour (not based on the parents selected based on quality only)
 - Position update ~ mutation
 - Selection is not utilized – survival is not based on quality (fitness)
- PSO versions
 - PSO binary and discrete
 - PSO with more social learning coefficients
 - PSO with heterogeneous particles
 - Hierarchical PSO

PSO – properties

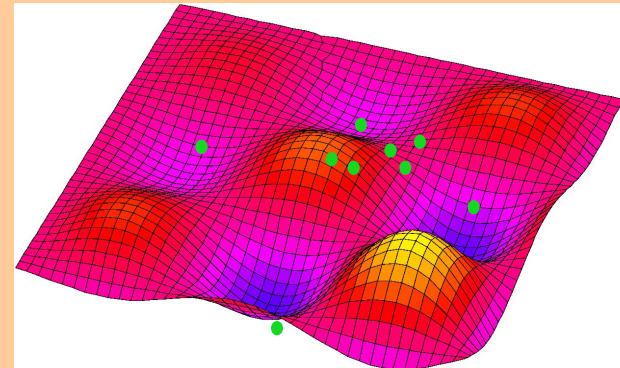
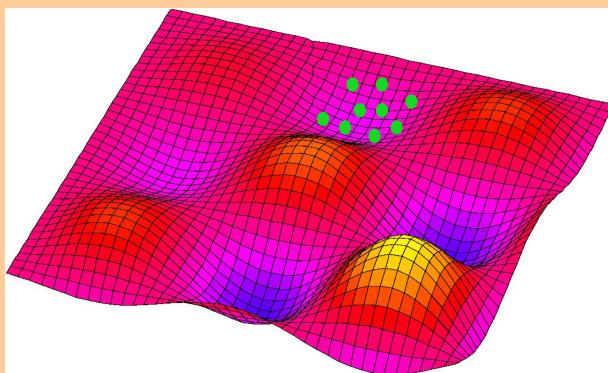
- PSO discrete (binary)
 - PSO version for a discrete search space
 - Position of a particle
 - Possible solution of the problem → binary string
 - Changes based on the velocity of particle
 - Velocity of a particle
 - Element from a continuous space
 - Changes based on standard PSO principles
 - Can be viewed as changing probability of the corresponding bit from the particle's position

$$x_{ij} = \begin{cases} 1, & \text{if } \tau < s(v_{ij}) \\ 0, & \text{otherwise} \end{cases}, \text{ where } s(v_{ij}) = \frac{1}{1 + e^{-v_{ij}}}$$

PSO – properties

□ Risks

- Particles has the trend to group in the same place
 - To rapid convergence and the impossibility to escape from local optima
 - Solution:
 - Re-initialisation of some particles



- Particles move through infeasible regions

PSO – properties

□ Analysis of PSO algorithm

- Dynamic behaviour of the swarm can be analysed by 2 index:

- Dispersion index

- Measures the spreading degree of particle around the best particle of the swarm
 - Average of absolute distances (on each dimension) between each particle and the best particle of the swarm
 - Explains the cover degree (small or spread) of the search space

- Velocity index

- Measures the moving velocity of the swarm into a iteration
 - Average of absolute velocities
 - Explain how the swarm moves (aggressive or slow)

PSO – applications

- Control and design of antenna
- Biological, medical and pharmaceutical applications
 - Analysis of tremor in Parkinson's disease
 - Cancer Classification
 - Prediction of protein structure
- Network communication
- Combinatorial optimisation
- Financial optimisation
- Image and video analyse
- Robotics
- Planning
- Network security, intrusion detection, cryptography
- Signal processing

ACO

- ❖ Theoretical aspects
- ❖ Algorithm
- ❖ Example
- ❖ Properties
- ❖ Applications

ACO – theoretical aspects

- Proposed
 - By Colorni and Dorigo in 1991 for solving discrete optimisation problems – TSP – as a comparison for EAs
 - Inspired by social behaviour of ants that search a path from their nest and food
 - Why ants?
 - Colony system (from several ants to millions of ants)
 - Labor division
 - Social behaviour is very complex
- Search
 - **Cooperative**, guided by the **relative** quality of individuals
- Search operators
 - Constructive ones, adding elements in solution

ACO – theoretical aspects

❖ Special elements

- The optimisation problem must be transformed into a problem of identifying the optimal path in an oriented graph
- Ants construct the solution by walking through the graph and put pheromones on some edges
- Optimisation method based on
 - Ant colonies (\approx EAs) that search the optimal solution
 - Cooperation (instead of concurrence like in EAs)
- Each ant:
 - Moves (in the search space) and put some pheromones on its path
 - Memorises the path
 - Selects the path based on
 - The existing pheromones on that path
 - Heuristic information associated to that path
 - Cooperates with other ants through the pheromone trail (that corresponds to a path) that
 - Depends on the solution quality
 - Evaporates while the time is passing

ACO – theoretical aspects

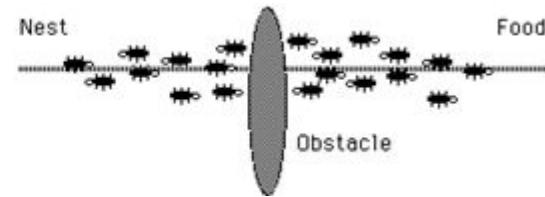
- Natural ants
 - An ant colony start to search some food



ACO – theoretical aspects

□ Natural ants

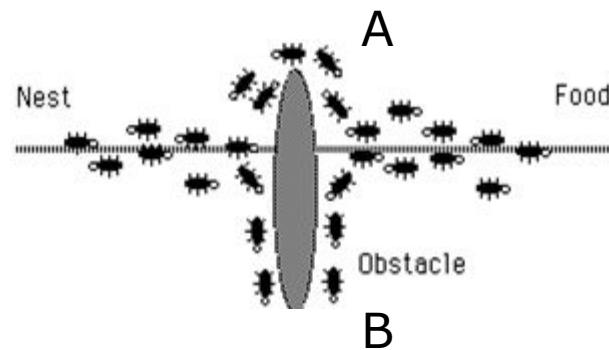
- An ant colony start to search some food
- At a moment, an obstacle appears



ACO – theoretical aspects

□ Natural ants

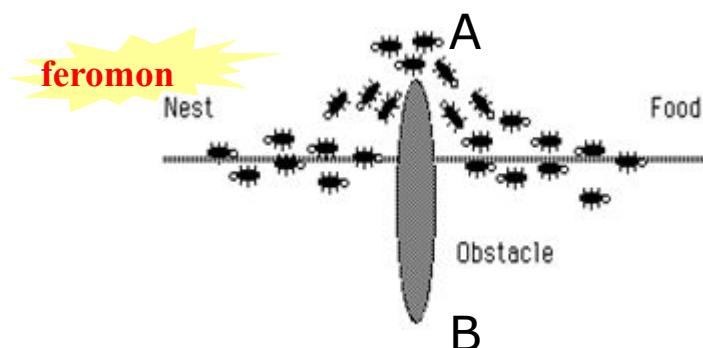
- An ant colony start to search some food
- At a moment, an obstacle appears
- The ants will surround the obstacle either on path A or path B



ACO – theoretical aspects

□ Natural ants

- An ant colony start to search some food
- At a moment, an obstacle appears
- The ants will surround the obstacle either on path A or path B
- Because the path A is shorter, the ants of this path will performed more rounds and, therefore, will put more pheromones
- Pheromone concentration will quickly increase on path A (relative to path B) such as the ants from path B will re-oriented to path A
- Because the ants do not follow path B and because the pheromone trail evaporates, the trail of ants from path B will disappear
- Therefore, the ants will take the shortest path (path A)



ACO – theoretical aspects

- Artificial ants look like natural ants
 - Walk from their nest towards food
 - Discover the shortest path based on pheromone trail
 - Each ant performed random moves
 - Each ant put some pheromone on its path
 - Each ant detects the path of “boss ant” and tends to follow it
 - Increasing the pheromone of a path will determine to increase the probability to follow that path by more ants
- But they have some improvements:
 - Has memory
 - Retains performed moves → has a proper state (retaining the history of decisions)
 - Can come back to their nest (based on pheromone trail)
 - Are not completely blind – can appreciate the quality of their neighbour space
 - Perform move in a discrete space
 - Put pheromone based on the identified solution, also

ACO – theoretical aspects

- Pheromone trail plays the role of
 - A collective, dynamic and distributed memory
 - A repository of the most recent ants' experiences of searching food

- Ants can indirectly communicate and can influence each-other
 - By changing the chemical repository
 - In order to identify the shortest path from nest to food

ACO – algorithm

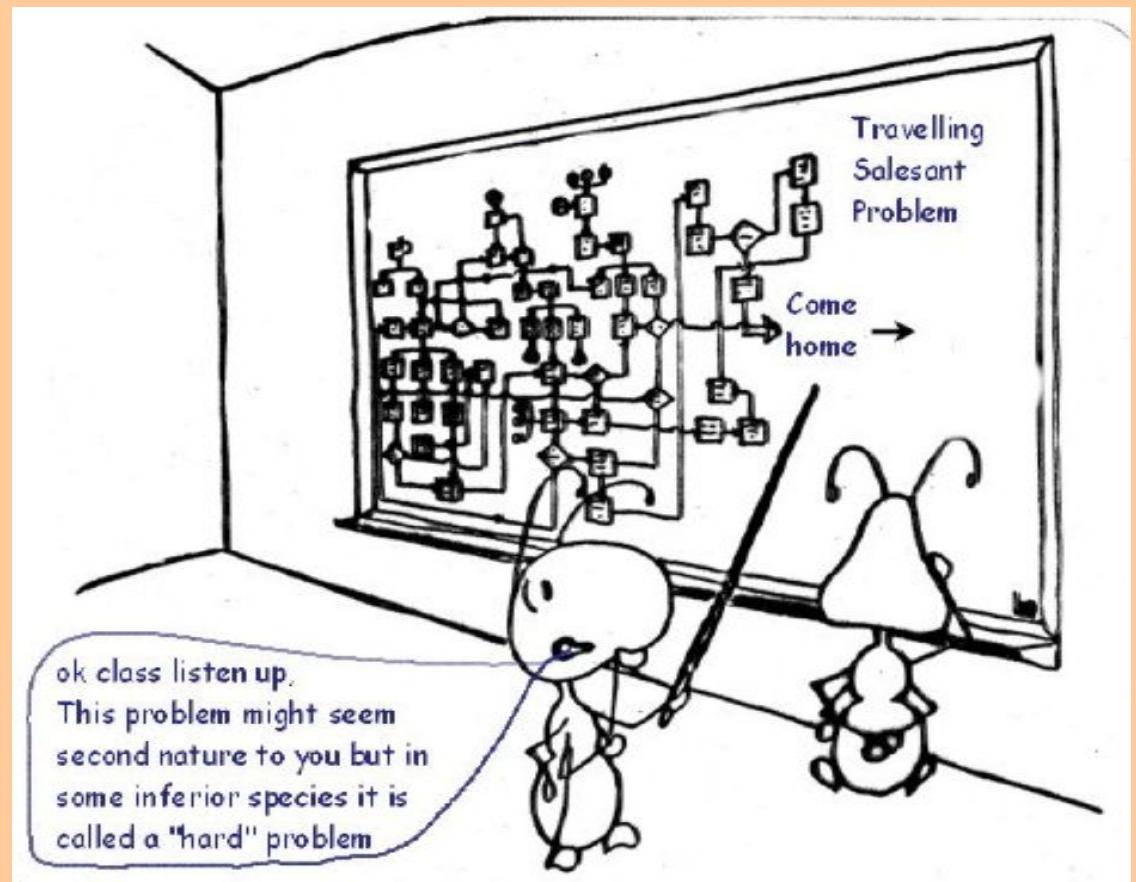
- While iteration < maximum # of iterations
 - 1. Initialisation
 - 2. While # of steps required to identify the optimal solution is not performed
 - For each ant of the colony
 - Increase the partial solution by an element (ant moves one step)
 - Change locally the pheromone trail based on the last element added in solution
 - 3. Change the pheromone trail on the paths traversed by
 - all ants/the best ant
 - 4. Return the solution identified by the best ant

ACO – algorithm

- 3 versions – differences:
 - Rules for transforming a state into another state (moving rules for ants)
 - Moment when the ants deposit pheromones
 - While the solution is constructed
 - At the end of solution's construction
 - Which ant deposits pheromones
 - All the ants
 - The best ant only
- Versions :
 - Ant system (AS)
 - **All** the ants deposit pheromones **after** a solution is **complete** constructed (global collective update)
 - MaxMin Ant System (MMAS) \approx AS, but
 - The **best** ant only deposits pheromones **after** a solution is **complete** constructed (global update of the leader)
 - Deposited pheromones is **limited** to a given range
 - Ant Colony System (ACO) \approx AS, but
 - **All** the ants deposit pheromones at **each step** of solution construction (collective local update)
 - The **best** ant only deposits pheromone after the solution is complete constructed (global update of the leader)

ACO – example

- Travelling salesman problem - TSP
 - Finds the shortest path that visits only once all the n given cities.



ACO – example

1. Initialization:

- t := 0 (time)
- For each edge (i,j) 2 elements are initialised:
 - $\tau_{ij}^{(t)} = c$ (intensity of pheromone trail on edge (I,j) at time t)
 - $\Delta\tau_{ij} = 0$ (quantity of pheromone deposited on edge (i,j) by all the ants)
- m ants are randomly places in n city-nodes ($m \leq n$)
- Each ant updates its memory (list of visited cities)
 - Adds in the list the starting city

ACO – example for TSP

1. While # of steps required to identify the optimal solution is not performed (# of steps = n)

- For each ant of the colony

- Increase the partial solution by an element (ant moves one step)

- Each ant k (from city i) selects the next city j:

$$j = \begin{cases} \arg \max_{l \in \text{permis}_k} \{\tau_{il}\}^\alpha [\eta_{il}]^\beta \}, & \text{if } q \leq q_0 \\ J, & \text{otherwise} \end{cases}$$

Random proportional rule

- where:

- q – random uniform number from [0,1]
- q_0 – parameter, $0 \leq q_0 \leq 1$ ($q_0 = 0 \rightarrow$ AS/MMAS, otherwise ACO)
- J is a city selected by probability

$$p_{ij}^k(t) = \begin{cases} \frac{[\tau_{ij}^{(t)}]^\alpha [\eta_{ij}]^\beta}{\sum_{s=allowed_k(t)} [\tau_{is}^{(t)}]^\alpha [\eta_{is}]^\beta}, & j - allowed \\ 0, & otherwise \end{cases}$$

Pseudo-random proportional rule

- where:

- p_{ij}^k – probability of transition of ant k from city i to city j
- $\eta_{ij} = \frac{1}{d_{ij}}$ – visibility from city I towards city j (attractive choice of edge (i,j))
- $allowed_k$ – cities that can be visited by ant k at time t
- α – controls the trail importance (how many ants have visited that edge)
- β – controls the visibility importance (how close is the next city)

ACO – example for TSP

1. While # of steps required to identify the optimal solution is not performed
 - For each ant of the colony
 - Increase the partial solution by an element (ant moves one step)
 - Change locally the pheromone trail based on the last element added in solution

$$\tau_{ij}^{(t+1)} = (1 - \varphi)\tau_{ij}^{(t)} + \varphi * \tau_0$$

- where:
 - φ – pheromone degradation coefficient; $\varphi \in [0, 1]$; for $\varphi = 0 \rightarrow$ AS/MMAS, otherwise ACO
 - τ_0 – initial value of pheromone
 - (i, j) – last edge visited by ant

ACO – example for TSP

3. Change the pheromone trail from
 - **Paths covered by all ants (AS)**

- For each edge
 - Compute the unit quantity of pheromones put by the k^{th} ant on edge (i,j)
 - $\Delta\tau_{ij}^k = \begin{cases} Q & \text{if the } k^{\text{th}} \text{ ant used the edge } (i,j) \\ L_k & \\ 0 & \end{cases}$
 - Q – quantity of pheromone deposited by an ant.
 - L_k – length (cost) of tour performed by the k^{th} ant
 - Compute the total quantity of pheromone from edge (ij) $\Delta\tau_{ij} = \sum_{k=1}^m \Delta\tau_{ij}^k$
 - Compute the intensity of pheromone trail as a sum of old pheromone evaporation and the new deposited pheromone
$$\tau_{ij}^{(t+n)} = (1 - \rho) * \tau_{ij}^{(t)} + \Delta\tau_{ij}$$
 - Where ρ ($0 < \rho < 1$) – evaporation coefficient of pheromone trail from a complete tour to another complete tour

ACO – example for TSP

3. Change the pheromone trail from
 - **The best path (ACO)**
 - **The best path of the best ant (MMAS)**
 - For each edge of the best path
 - Compute the unit quantity of pheromone deposited by the best ant on edge (ij)
 - $$\Delta\tau_{ij} = \frac{1}{L_{best}}$$
 - L_{best} – length (cost) of the best path
 - Of current iteration
 - Over all executed iteration (until that time)
 - Compute the intensity of pheromone trail as sum of old pheromone evaporation and the new deposited pheromone
 - Where ρ ($0 < \rho < 1$) – – evaporation coefficient of pheromone trail from a complete tour to another complete tour
 - τ_{min} și τ_{max} – limits (inferior and superior) of pheromone;
 - For $\tau_{min} = -\infty$ and $\tau_{max} = +\infty \rightarrow$ ACO, otherwise MMAS

$$\tau_{ij}^{(t+1)} = [(1-\rho) * \tau_{ij}^{(t)} + \rho * \Delta\tau_{ij}^{best}]_{\tau_{min}}^{\tau_{max}}$$

ACO – properties

□ Properties

- Iterative algorithm
- Algorithm that progressively constructs the solution based on
 - Heuristic information
 - Pheromone trail
- Stochastic algorithm

□ Advantages

- Run continuous and real-time adaptive change input
 - Ex. for TSP the graph can be dynamically changed
- Positive feedback helps to quickly discovering of solution
- Distributed computing avoids premature convergence
- Greedy heuristic helps to identify an acceptable solution from the first stages of search
- Collective interaction of individuals

□ Disadvantages

- Slowly convergence vs other heuristic search
- For TSP instances with more than 75 cities it finds weak solutions
- In AS there is no central process to guide the search towards good solutions

ACO – applications

- Optimal paths in graphs
 - Ex. Traveling Salesman Problem
- Problems of quadratic assignments
- Problems of network optimisation
- Transport problems



Review

□ PSO

- Beam local search
- Possible solutions → particles that have:
 - A position in the search space
 - A velocity
- Cooperative and perturbative search based on:
 - Position of the best particle of the swarm
 - Best position of particle (particle has memory)

□ ACO

- Beam local search
- Possible solutions → ants that have:
 - Memory – retain steps of solution construction
 - Smell – take decisions based on pheromones deposited by other ants (social, collective, collaborative behaviour)
- Cooperative and constructive search

Thank you!



BABEŞ-BOLYAI UNIVERSITY
Faculty of Computer Science and Mathematics



ARTIFICIAL INTELLIGENCE

Intelligent systems

Machine learning

Support Vector Machines

K-means

Intelligent Systems – Support Vector Machines

□ Support Vector Machines (SVMs)

- Definition
- Solved problems
- Advantages
- Difficulties
- Tools

Intelligent Systems – Support Vector Machines

□ Definition

- Developed by Vapnik in 1970
- Popularised after 1992
- Linear classifiers that identify the hyperplane that separates the positive and negative classes
- Have a theoretical foundation
- Work very well for large data (text mining, image analysis)

■ **Remember**

- Supervised learning problem – a data set:
 - (x^d, t^d) , with:
 - $x^d \in \mathbb{R}^m \quad \square x^d = (x^d_1, x^d_2, \dots, x^d_m)$
 - $t^d \in \mathbb{R} \quad \square t^d \in \{1, -1\}$, 1 \square positive class, -1 \square negative class
 - where $d = 1, 2, \dots, n, n+1, n+2, \dots, N$
- First n data (x^d and t^d are known) are used as training data
- Last $N-n$ data (x^d is known, t^d is unknown) are used as testing data

Intelligent Systems – Support Vector Machines

□ Definition

- SVM finds a linear function $f(\mathbf{x}) = \langle \mathbf{w} \cdot \mathbf{x} \rangle + b$, (\mathbf{w} -weight vector) such as

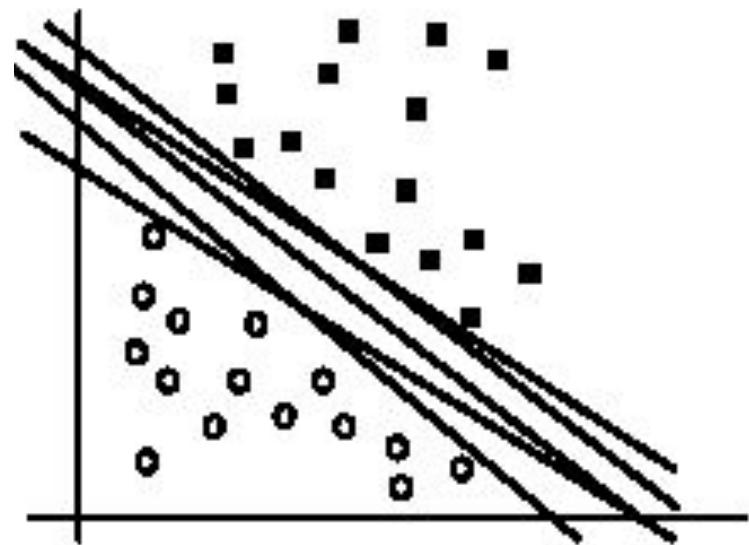
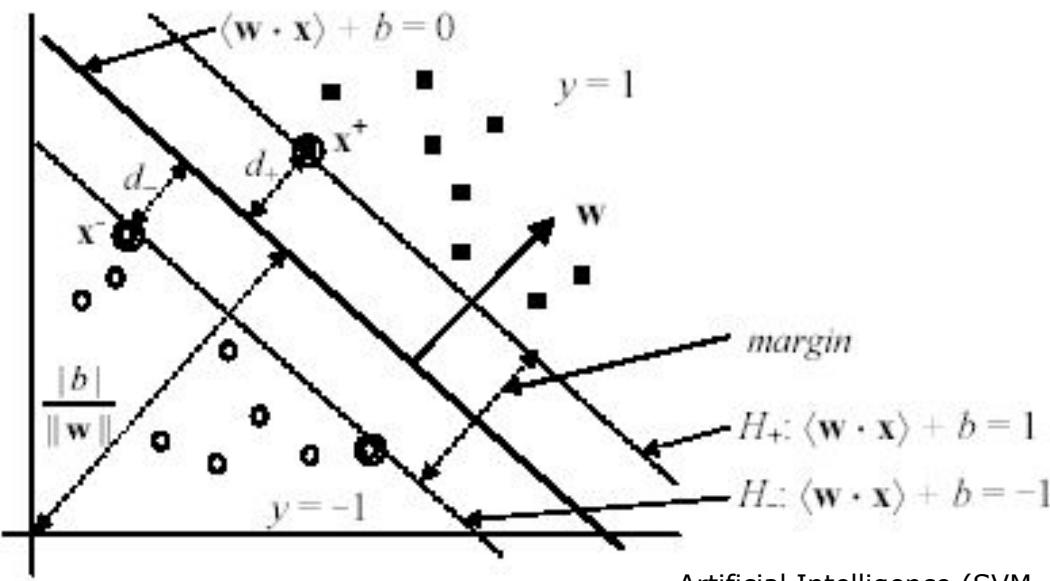
$$y_i = \begin{cases} 1 & \text{if } \langle \mathbf{w} \cdot \mathbf{x}_i \rangle + b \geq 0 \\ -1 & \text{if } \langle \mathbf{w} \cdot \mathbf{x}_i \rangle + b < 0 \end{cases}$$

- $\langle \mathbf{w} \cdot \mathbf{x} \rangle + b = 0$ □ decision hyperplane that separates the two classes

Intelligent Systems – Support Vector Machines

□ Definition

- There are more hyper-planes
 - Which is the best hyper-plane?
- SVM searches the hyper-plane with the largest margin (that minimises the generalisation error)
 - SMO (*Sequential minimal optimization*) algorithm

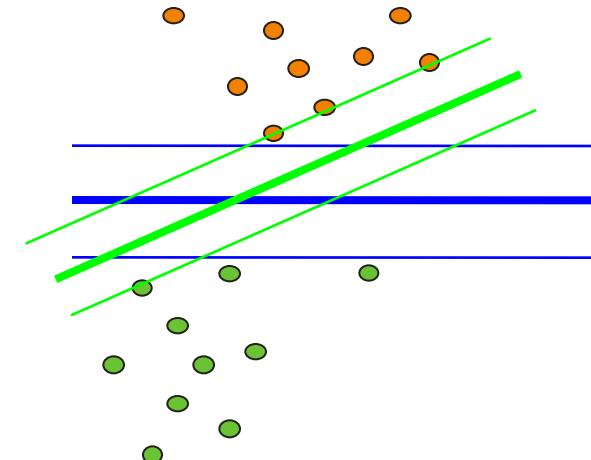


Intelligent Systems – Support Vector Machines

□ Solved problems

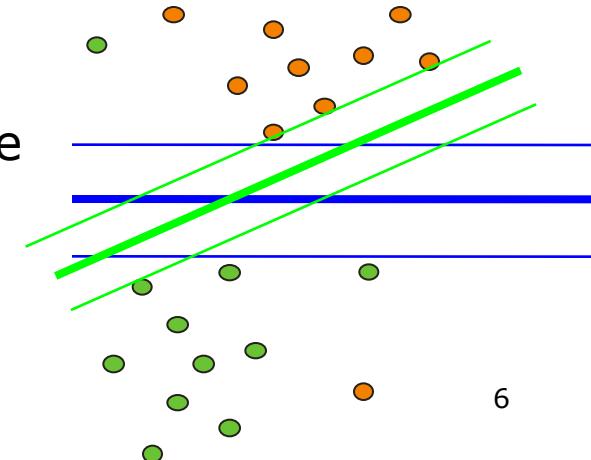
- Classification problems □ more cases
(based on the data type):

- Linear separable



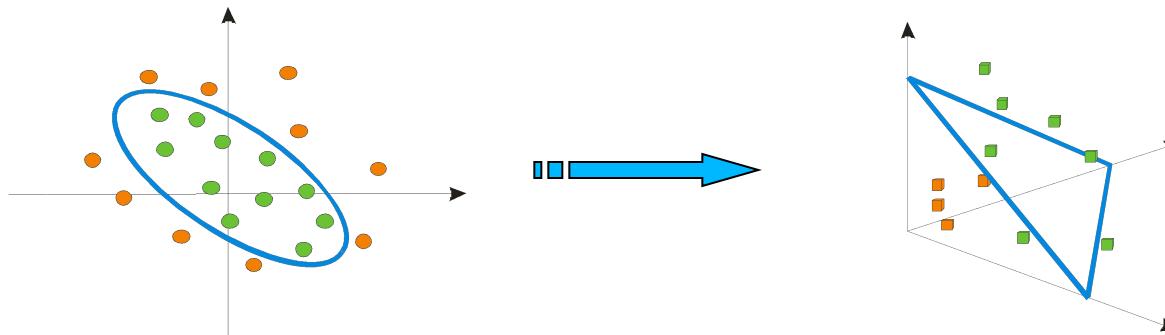
- Separable
 - Error = 0

- Non-separable
 - Constraints are relaxed □ some error are allowed
 - C – penalisation coefficient



Intelligent Systems – Support Vector Machines

- Solved problems □ classification problems □ data cases:
 - Non-linear separable
 - Input space is transformed (mapped) into a space of more dimensions (feature space) by using kernel function – in this new space the data becomes linear separable
 - In SVMs the kernel function computes the distance among 2 points
 - □ kernel ~ similarity function



Intelligent Systems – Support Vector Machines

□ Solved problems □ classification problems □ data cases:

■ Non-linear separable □ possible kernels

□ Classic kernels

- Polynomial kernel: $K(\mathbf{x}^{d1}, \mathbf{x}^{d2}) = (\mathbf{x}^{d1}, \mathbf{x}^{d2} + 1)^p$
- RBF kernel: $K(\mathbf{x}^{d1}, \mathbf{x}^{d2}) = \exp(-||\mathbf{x}^{d1} - \mathbf{x}^{d2}||^2/2\sigma^2)$

□ Multiple Kernels

- Linear : $K(\mathbf{x}^{d1}, \mathbf{x}^{d2}) = \sum w_i K_i(\mathbf{x}^{d1}, \mathbf{x}^{d2})$
- Non-linear
 - Without coefficients: $K(\mathbf{x}^{d1}, \mathbf{x}^{d2}) = K_1(\mathbf{x}^{d1}, \mathbf{x}^{d2}) + K_2(\mathbf{x}^{d1}, \mathbf{x}^{d2}) * \exp(K_3(\mathbf{x}^{d1}, \mathbf{x}^{d2}))$
 - With coefficients: $K(\mathbf{x}^{d1}, \mathbf{x}^{d2}) = K_1(\mathbf{x}^{d1}, \mathbf{x}^{d2}) + c_1 * K_2(\mathbf{x}^{d1}, \mathbf{x}^{d2}) \exp(c_2 + K_3(\mathbf{x}^{d1}, \mathbf{x}^{d2}))$

□ Kernels for strings

□ Kernels for images

□ Kernels for graphs

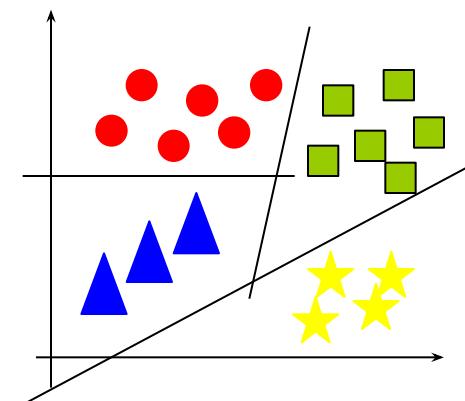
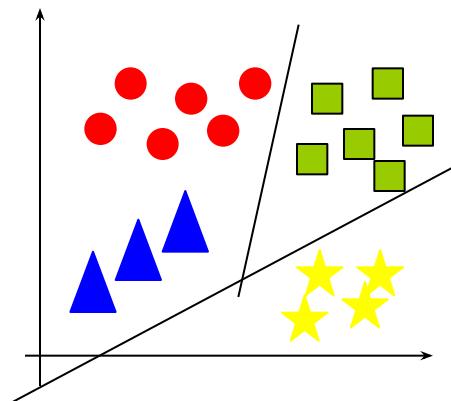
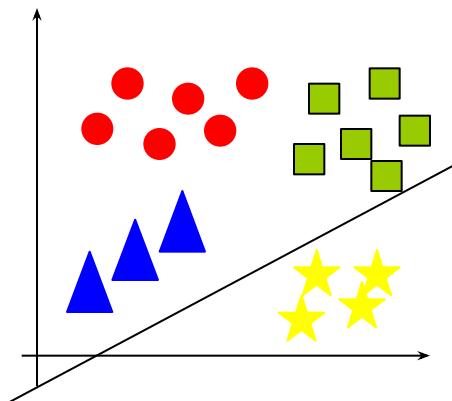
Intelligent Systems – Support Vector Machines

SVM parameters setting:

- Penalisation coefficient C
 - C – small \square slowly convergence
 - C – large \square fast convergence
- Kernel parameters
 - If m (# of attributes) is larger than n (# of data)
 - SVM with a linear kernel (SVM without kernel) \square
$$K(\mathbf{x}^{d1}, \mathbf{x}^{d2}) = \mathbf{x}^{d1} \cdot \mathbf{x}^{d2}$$
 - If m (# of attributes) is large and n (# of data) is medium
 - SVM with Gaussian kernel
$$K(\mathbf{x}^{d1}, \mathbf{x}^{d2}) = \exp(-|\|\mathbf{x}^{d1} - \mathbf{x}^{d2}\||^2 / 2\sigma^2)$$
 - σ – dispersion of training data
 - Attributes must be normalised (scaled to (0,1))
 - If m (# of attributes) is small and n (# of data) is large
 - Add new attributes and use SVM with linear kernel

Intelligent Systems – Support Vector Machines

- SVM for multi-class classification problems (more than 2 classes)
 - one vs. all



Intelligent Systems – Support Vector Machines

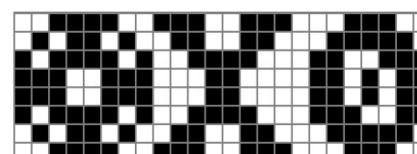
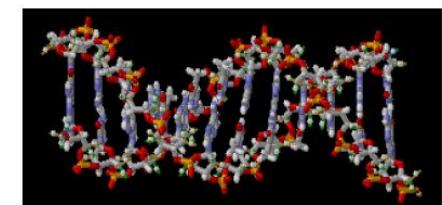
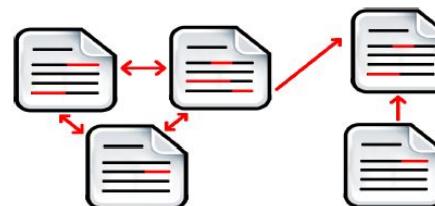
□ Structured SVMs

■ Machine Learning

- Simple SVM $f: \mathcal{X} \rightarrow \mathbb{R}$
 - Any type of inputs
 - Numerical outputs (natural numbers, integers, real numbers)
- Structured SVM: $\mathcal{X} \rightarrow \mathcal{Y}$
 - Any type of inputs
 - Any type of outputs (numerical or structured outputs)

■ Structured information

- Texts and hyper-texts
- Molecules and molecular structures
- Images



Intelligent Systems – Support Vector Machines

□ Structured SVMs

■ Applications

- Natural Language Processing
 - Automatic translation (outputs □ sentences)
 - Syntactic and/or morphologic analysis of sentences (outputs □ syntactic and/or morphologic tree)
- Bioinformatic
 - Prediction of secondary structures (outputs □ bi=partite graphs)
 - Prediction of enzyme function (outputs □ paths in trees)
- Speech processing
 - Automatic transcriptions (outputs □ sentences)
 - Transformation of texts in voice (outputs □ audio signal)
- Robotics
 - Planning (outputs □ sequences of actions)

Intelligent Systems – Support Vector Machines

□ Advantages

- Can work with any type of data (linear or non-linear separable, uniform distributed or not, with known or unknown distribution)
 - Kernel function that creates new attributes (features)
 - hidden layers of an ANN
- If the problem is convex SVM finds a unique solution □ global optima
 - ANNs can associates more solutions □ local optima
- Automatic selection of the learnt model (by support vectors)
 - In ANNs hidden layers have to be configured apriori
- Avoid overfitting
 - ANNs have overfitting problems even the cross-validation is involved

□ Difficulties

- Real attributes only
- Binary classification problems only
- Difficult mathematical background

□ Tools

- LibSVM □ <http://www.csie.ntu.edu.tw/~cjlin/libsvm/>
- Weka □ SMO
- SVMLight □ <http://svmlight.joachims.org/>
- SVMTorch □ <http://www.torch.ch/>
- <http://www.support-vector-machines.org/>

Intelligent systems – Machine Learning

□ Typology

- Experience criteria:

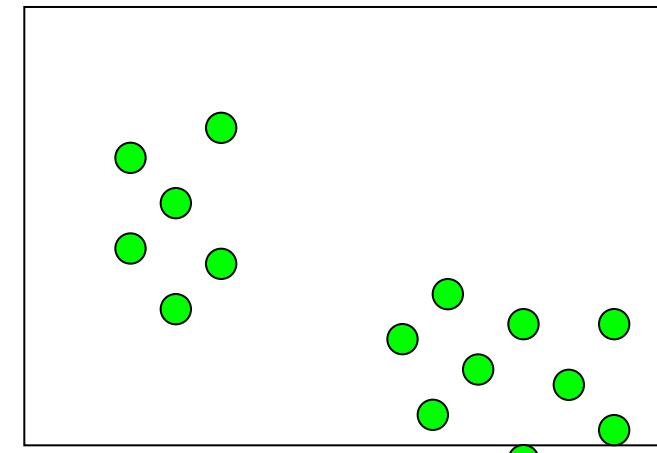
- Supervised learning
 - Unsupervised learning
 - Active learning
 - Reinforcement learning

- Algorithm criteria

- Decision trees
 - Artificial Neural Networks
 - Evolutionary Algorithms
 - Support Vector Machines
 - Hidden Markov Models
 - **K-means**

Unsupervised learning

- Aim
 - to find a model or a structure of data
- Solved problems
 - Identification of groups (clusters)
 - Analysis of genes
 - Image processing
 - Analysis of social networks
 - Market segmentation
 - Analysis of astronomical data
 - Clusters of computers
 - Dimension reduction
 - Identification of causes (explanations) for data
 - Modelling the data densities
- Specific
 - **Data are not annotated** (labelled)



Unsupervised learning – definition

Separates the un-labelled examples in disjoint subsets (clusters) such as:

- Examples of the same cluster are similar
- Examples of different clusters are different

Definition

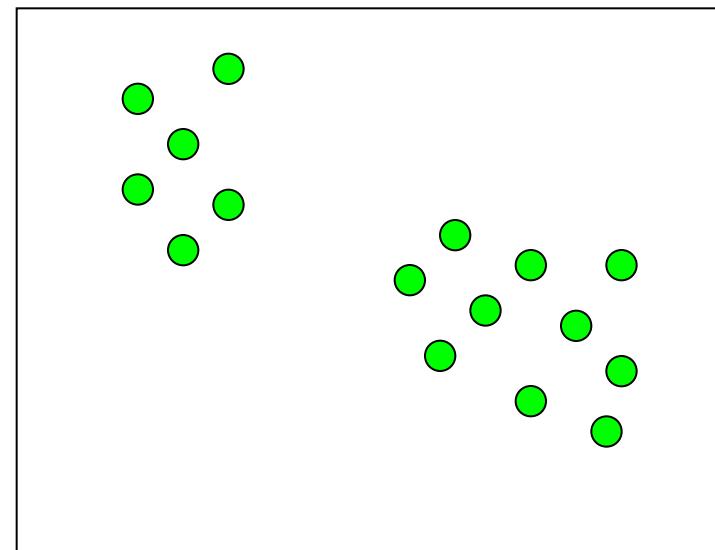
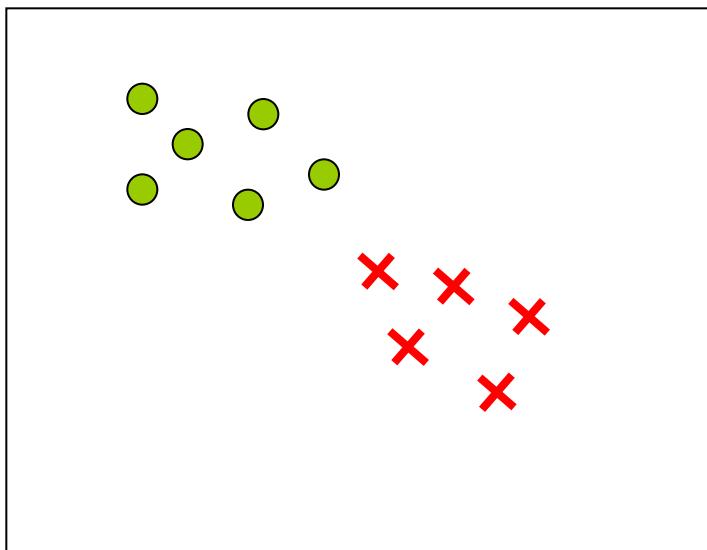
- Given
 - A set of data (examples, instances, cases)
 - Training data
 - As **attribute_data_i**, where
 - $i = 1, N$ ($N = \#$ of training data)
 - $\text{attribute_data}_i = (atr_{i1}, atr_{i2}, \dots, atr_{im})$, $m = \#$ of attributes (characteristics, properties) of data
 - Testing data
 - As $(\text{attribute_data}_i)$, $i = 1, n$ ($n = \#$ of testing data)
- Determine
 - An unknown function that groups the training data in more classes
 - # of classes can be pre-defined (k) or unknown
 - Data of the same class are similar
 - The class of a new testing data by using the learnt grouping (on training data)

Other names

- Clustering

Unsupervised learning – definition

- Supervised vs. unsupervised



Unsupervised learning – definition

- Distance between 2 elements \mathbf{p} and $\mathbf{q} \in R^m$
 - Euclid distance
 - $d(\mathbf{p}, \mathbf{q}) = \sqrt{\sum_{j=1,2,\dots,m} (p_j - q_j)^2}$
 - Manhattan distance
 - $d(\mathbf{p}, \mathbf{q}) = \sum_{j=1,2,\dots,m} |p_j - q_j|$
 - Mahalanobis distance
 - $d(\mathbf{p}, \mathbf{q}) = \sqrt{(\mathbf{p} - \mathbf{q}) S^{-1} (\mathbf{p} - \mathbf{q})^T}$,
 - Where S is the covariance matrix ($S = E[(\mathbf{p} - E[\mathbf{p}])(\mathbf{q} - E[\mathbf{q}])^T]$)
 - Internal product
 - $d(\mathbf{p}, \mathbf{q}) = \sum_{j=1,2,\dots,m} p_j q_j$
 - Cosine distance
 - $d(\mathbf{p}, \mathbf{q}) = \sum_{j=1,2,\dots,m} p_j q_j / (\sqrt{\sum_{j=1,2,\dots,m} p_j^2} * \sqrt{\sum_{j=1,2,\dots,m} q_j^2})$
 - Hamming distance
 - # of differences between \mathbf{p} and \mathbf{q}
 - Levenshtein distance
 - Minimal # of operations required for transforming \mathbf{p} in \mathbf{q}
- Distance vs. similarity
 - Distance □ minimisation
 - Similarity □ maximisation

Unsupervised learning – definition

Application

- Gene clustering
- Market segmentation (for client clustering)
- news.google.com

Unsupervised learning – process

Process

- 2 steps:
 - Learning
 - Determine (learn), by using an algorithm, the existing clusters
 - Testing
 - Include a new data in one of the identified (during training) clusters

Learning quality (clustering validation)

- Internal criteria
 - Large similarity inside the cluster and reduce similarity between clusters
- External criteria
 - Using benchmarks composed of *apriori* grouped data

Unsupervised learning – evaluation

Performance measures:

- Internal criteria
 - Distance inside the cluster
 - Distance between clusters
 - Davies-Bouldin index
 - Dunn index
- External criteria
 - Comparison with known data – impossible in real-world applications
 - Precision
 - Recall
 - F-measure

Unsupervised learning – evaluation

Internal criteria

- Distance inside cluster c_j that contains n_j instances
 - Average distance (among instances)
 - $D_a(c_j) = \sum_{x_{i1}, x_{i2} \in c_j} \|x_{i1} - x_{i2}\| / (n_j(n_j - 1))$
 - Nearest neighbour distance
 - $D_{nn}(c_j) = \sum_{x_{i1} \in c_j} \min_{x_{i2} \notin c_j} \|x_{i1} - x_{i2}\| / n_j$
 - Distance to centroids
 - $D_c(c_j) = \sum_{x_i \in c_j} \|x_i - \mu_j\| / n_j$ where $\mu_j = 1/n_j \sum_{x_i \in c_j} x_i$

Unsupervised learning – evaluation

Internal criteria

- Distance between two clusters c_{j1} and c_{j2}

- Simple link

- $d_s(c_{j1}, c_{j2}) = \min_{x_{i1} \in c_{j1}, x_{i2} \in c_{j2}} \{||x_{i1} - x_{i2}||\}$

- Complete link

- $d_{co}(c_{j1}, c_{j2}) = \max_{x_{i1} \in c_{j1}, x_{i2} \in c_{j2}} \{||x_{i1} - x_{i2}||\}$

- Average link

- $d_a(c_{j1}, c_{j2}) = \sum_{x_{i1} \in c_{j1}, x_{i2} \in c_{j2}} \{||x_{i1} - x_{i2}||\} / (n_{j1} * n_{j2})$

- Link between centroids

- $d_{ce}(c_{j1}, c_{j2}) = ||\mu_{j1} - \mu_{j2}||$

Unsupervised learning – evaluation

Internal criteria

- Davies-Bouldin index □ min □ compact clusters
 - $DB = 1/nc * \sum_{i=1,2,\dots,nc} \max_{j=1, 2, \dots, nc, j \neq i} ((\sigma_i + \sigma_j)/d(\mu_i, \mu_j))$
 - where:
 - nc – # of clusters
 - μ_i – centroid of cluster i
 - σ_i – average of distances between elements from cluster i and the centroid μ_i
 - $d(\mu_i, \mu_j)$ – distance between centroid μ_i and centroid μ_j
- Dunn index
 - Identifies the dense clusters and well separated
 - $D=d_{min}/d_{max}$
 - where:
 - d_{min} – minimal distance between 2 elements from different clusters - intra-cluster distance
 - d_{max} – maximal distance between 2 elements from the same cluster - inter-cluster distance

Unsupervised learning – typology

- How the clusters are forming
 - Hierarchic clustering
 - Non-hierarchical (partitioned) clustering
 - Clustering based on data density
 - Clustering based on a grid

Unsupervised learning – typology

□ How the clusters are forming

■ Hierarchic clustering

- Creates a dendrogram (taxonomic tree)
 - Creates the clusters (recursively)
 - k (# of clusters) is unknown
- Agglomerative clustering (bottom-up) □ small clusters to large clusters
- Divisive clustering (top-down) □ large clusters to small clusters
- Eg.
 - Clustering hierarhic agglomerative

Unsupervised learning – typology

How the clusters are formed

- Non-hierarchical
 - Partitional □ determine a data separation □ all the clusters in the same time
 - Optimises an objective function defined
 - Locally – by using some features only
 - Globally – by using all attributes
- that can be:
 - squared error – sum of squared distances between data and the cluster's centroid □ min
 - Ex. *K-means*
 - Graph-based
 - Ex. Clustering based in minimum spanning tree
 - Based on probabilistic models
 - Ex. Identify the data distribution □ expectation maximisation
 - Based on the nearest neighbour
- Required to fix k apriori □ fix the initial clusters
 - Algorithm is run more times with different parameters and the most efficient version is selected
- Ex. *K-means, ACO*

Unsupervised learning – typology

How the clusters are forming

- Based on data densities
 - Data density and data connectivity
 - Cluster formation is based on data density from a given region
 - Cluster formation is based on data connectivity from a given region
 - Function of data density
 - Tries to model the data distribution
 - Advantage:
 - Modeling of clusters of any shape

Unsupervised learning – typology

□ How the cluster are forming

■ Based on a grid

- Is not a distinct approach
 - Can be hierachic, partitional or density-based
- Involves data space segmentation in regular areas
- Objects are placed on a multi-dimensional grid
- Eg. ACO

Unsupervised learning – typology

□ How the algorithms work

- Agglomerative clustering
 - 1. Initially, each instance form a cluster
 - 2. Compute the distance between any 2 clusters
 - 3. Reunion the closest 2 clusters
 - 4. Repeat steps 3 and 4 until a single cluster is obtained or other stop criterion is satisfied
- Divisive clustering
 - 1. Establish the number of clusters (k)
 - 2. Initialise the centre of each cluster
 - 3. Determine a data separation
 - 4. Re-compute the centre of each cluster
 - 5. Repeat steps 3 and 4 until the partition is unchanged (algorithm converges)

□ How the algorithm takes into account the attributes (features)

- Monotonic – attributes are taken into account one-by-one
- Polytonic – attributes are simultaneous taken into

Unsupervised learning – typology

□ How the data belong to clusters

- Exact clustering (hard clustering)
 - Each instance x_i has associated a label (class) c_j
- Fuzzy clustering
 - Associates to each input \mathbf{x}_i , a degree (probability) of membership f_{ij} to a certain class c_j □ an instance \mathbf{x}_i that can belong to several clusters

Unsupervised learning – algorithms

- Agglomerative hierarchical clustering
- K-means
- AMA
- Probabilistic models
- Nearest neighbour
- Fuzzy
- Artificial Neural Network
- Evolutionary algorithms
- ACO

Unsupervised learning – algorithms

Agglomerative hierarchical clustering

- a. Consider a distance between 2 instances $d(x_{i1}, x_{i2})$
- b. Form N clusters, each of them containing an instance
- c. Repeat
 - Determine the closest 2 clusters
 - Reunion the 2 clusters \square a cluster

Until a single cluster is obtained

Unsupervised learning – algorithms

Agglomerative hierarchical clustering

Distance between 2 clusters c_i and c_j :

- Simple link □ minimal distance between the objects of 2 clusters
 - $d(c_i, c_j) = \min_{x_{i1} \in c_i, x_{i2} \in c_j} sim(\mathbf{x}_{i1}, \mathbf{x}_{i2})$
- Complete link □ maximal distance between the objects of 2 clusters
 - $d(c_i, c_j) = \max_{x_{i1} \in c_i, x_{i2} \in c_j} sim(\mathbf{x}_{i1}, \mathbf{x}_{i2})$
- Average link □ mean of distances between the objects of 2 clusters
 - $d(c_i, c_j) = 1 / (n_i * n_j) \sum_{x_{i1} \in c_i} \sum_{x_{i2} \in c_j} d(\mathbf{x}_{i1}, \mathbf{x}_{i2})$
- Average link over group □ distance between the means (centroids) of 2 clusters
 - $d(c_i, c_j) = \rho(\boldsymbol{\mu}_i, \boldsymbol{\mu}_j)$, ρ – *distance*, $\boldsymbol{\mu}_j = 1/n_j \sum_{x_i \in c_j} \mathbf{x}_i$

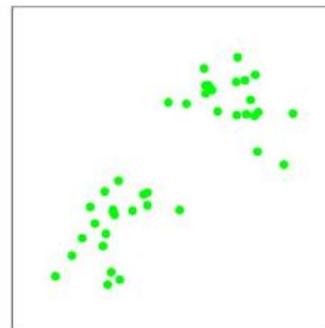
Unsupervised learning – algorithms

K-means (Lloyd algorithm / Voronoi iteration)

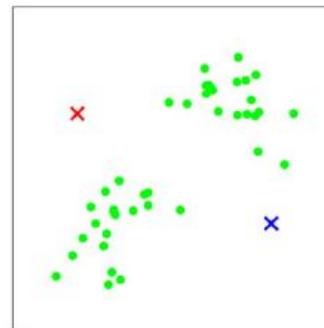
- Suppose that k clusters will form
- Initialise k centroids $\boldsymbol{\mu}_1, \boldsymbol{\mu}_2, \dots, \boldsymbol{\mu}_k$
 - A centroid $\boldsymbol{\mu}_j$ ($j=1, 2, \dots, k$) is a vector of m values (m - # of features)
- Repeat until convergence
 - Associated to each instance the nearest centroid □ for each instance \mathbf{x}_i , $i = 1, 2, \dots, N$
 - $c_i = \arg \min_{j=1, 2, \dots, k} \|\mathbf{x}_i - \boldsymbol{\mu}_j\|^2$
 - Re-compute the centroids by moving them in the mean of instances associated to it □ for each cluster c_j , $j = 1, 2, \dots, k$
 - $\boldsymbol{\mu}_j = \sum_{i=1, 2, \dots, N} \mathbf{1}_{c_i=j} \mathbf{x}_i / \sum_{i=1, 2, \dots, N} \mathbf{1}_{c_i=j}$

Unsupervised learning – algorithms

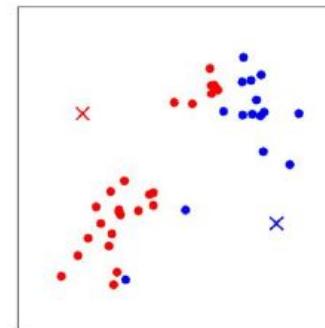
□ K-means



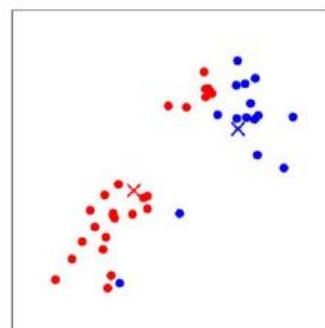
(a)



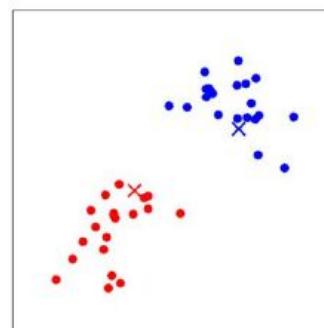
(b)



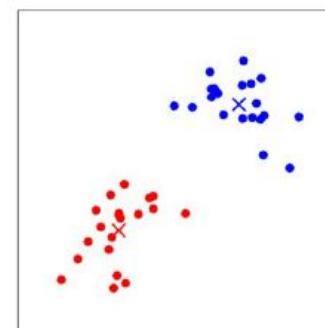
(c)



(d)



(e)



(f)

Unsupervised learning – algorithms

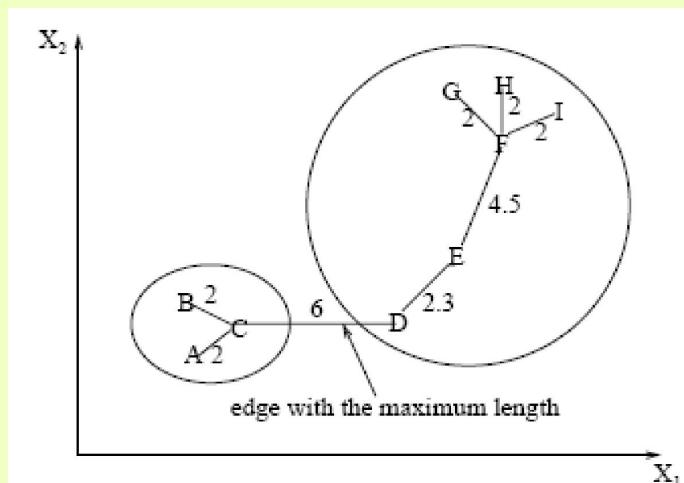
K-means

- Initialisation of k centroids $\boldsymbol{\mu}_1, \boldsymbol{\mu}_2, \dots, \boldsymbol{\mu}_k$
 - With random values (in the definition domain of the problem)
 - With k instances of N (randomly selected)
- Does the algorithm always converge?
 - Yes, because of distortion function J
 - $$J(c, \mu) = \sum_{i=1,2,\dots,N} \|\mathbf{x}_i - \boldsymbol{\mu}_{c_i}\|^2$$
which is decreasing
 - Converges in a local optima
 - Finding the global optima □ NP-difficult problem

Unsupervised learning – algorithms

Clustering based on minimum spanning tree (AMA)

- Construct the minimum spanning tree of data
- Eliminate from the tree the longest edges and form clusters



Unsupervised learning - algorithms

Probabilistic models

- <http://www.gatsby.ucl.ac.uk/~zoubin/courses04/ul.pdf>
- <http://learning.eng.cam.ac.uk/zoubin/nipstudent.pdf>

Unsupervised learning - algorithms

Nearest neighbor

- Some of the instances are labeled
- It is repeated until all instances are labeled
 - An unlabeled instance will be included in the closest instance cluster
 - if the distance between the unlabeled instance and the labeled one is less than a threshold

Unsupervised learning - algorithms

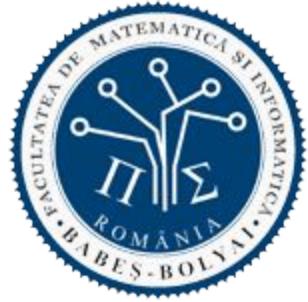
Fuzzy clustering

- An initial fuzzy partitioning is established
 - The membership degrees matrix U , is constructed, where u_{ij} – the degree of membership of instance \mathbf{x}_i ($i=1,2, \dots, N$) to the cluster c_j ($j = 1, 2, \dots, k$) ($u_{ij} \in [0,1]$)
 - The higher u_{ij} is, the higher the confidence that instance \mathbf{x}_i is part of cluster c_j
- An objective function is established
 - $E^2(U) = \sum_{i=1,2, \dots, N} \sum_{j=1,2, \dots, k} u_{ij} \|\mathbf{x}_i - \boldsymbol{\mu}_j\|^2,$
 - where $\boldsymbol{\mu}_j = \sum_{i=1,2, \dots, N} u_{ij} \mathbf{x}_i$ – the center of the j^{th} fuzzy cluster
 - which is optimized (min) by re-assigning instances (in new clusters)
- Fuzzy Clustering Hard Clustering
 - imposing a threshold on the membership function u_{ij}

Thank you for your attention!



BABEŞ-BOLYAI UNIVERSITY
Faculty of Computer Science and Mathematics



ARTIFICIAL INTELLIGENCE



Intelligent systems

Rule-based systems – uncertainty

Content

□ Intelligent systems

■ Knowledge-based systems

□ Rule-based systems in uncertain environments



Intelligent systems – knowledge-based systems(KBS)

- Computational systems – composed of 2 parts:
 - Knowledge base (KB)
 - Specific information of the domain
 - Inference engine (IE)
 - Rules for generating new information
 - Domain-independent algorithms

Intelligent systems - KBS

Knowledge base

Content

- Information (in a given representation) about environment
- Required information for problem solving
- Set of propositions that describe the environment

Classification

- Perfect information
 - Classical logic
 - *IF A is true THEN A is \neg false*
 - *IF B is false THEN B is \neg true*
- Imperfect information
 - Non-exact
 - Incomplete
 - Incommensurable

Intelligent systems - KBS

- Sources of uncertainty
 - Imperfection of rules
 - Doubt of rules
 - Using a vague (imprecise) language
- Modalities to express the uncertainty
 - Probabilities
 - Fuzzy logic
 - Bayes theorem
 - Theory of Dempster-Shafer
- Modalities to represent the uncertainty
 - By using a single value □ certainty factors, confidence, truth value
 - How sure we are that the given facts are valid
 - By using more values □ logic based on ranges
 - Min □ lower limit of uncertainty (confidence, necessity)
 - Max □ upper limit of uncertainty (plausibility, possibility)

Intelligent systems – KBS – Fuzzy systems

- Theory of possibility
- Content and design
- Classification
- Tools
- Advantages and limits

Intelligent systems – KBS – Fuzzy systems

Why fuzzy?

- Problem: translate in C++ code the following sentences:

Georgel is tall.

It is cold outside.

When fuzzy is important?

- Natural queries
- Knowledge representation for a KBS
- Fuzzy control – then we deal by imprecise phenomena (noisy phenomena)

Theory of possibility – a little bit of history

- Parminedes (400 B.C.)
- Aristotle
 - "Law of the Excluded Middle" – every sentence must be True or False
- Plato
 - A third region, between True and False
 - Forms the basis of fuzzy logic
- Lukasiewicz (1900)
 - Has proposed an alternative and systematic approach related to bi-valent logic of Aristotle – trivalent logic: true, false or possible
- Lotfi A. Zadeh (1965)
 - Mathematical description of fuzzy set theory and fuzzy logic: truth functions takes values in $[0,1]$ (instead of $\{\text{True}, \text{False}\}$)
 - He has proposed new operations in fuzzy logic
 - He has considered the fuzzy logic as a generalisation of the classic logic
 - He has written the first paper about fuzzy sets

Theory of possibility

Fuzzy logic

- Generalisation of Boolean logic
- Deals by the concept of partial truth

Classical logic – all things are expressed by binary elements

- 0 or 1, white or black, yes or no

Fuzzy logic – gradual expression of a truth

- Values between 0 and 1

Logic vs. algebra

- Logical operators are expressed by using mathematical terms (George Boole)
 - Conjunction = minimum $a \wedge b = \min(a, b)$
 - Disjunction = maximum $a \vee b = \max(a, b)$
 - Negation = difference $\neg a = 1 - a$

Content and design

Main idea

Cf. to certainty theory:

- *Popescu is tall*

Cf. to uncertainty theory

- Cf. to probability theory
 - *There is 80% chance that Popescu is young*
- Cf. fuzzy logic

Cf. teoriei informațiilor certe

- *Popescu este Tânăr*

Cf. teoriei informațiilor incerte

- Cf. teoriei probabilităților:
 - *Există 80% șanse ca Popescu să fie Tânăr*
- Cf. logicii fuzzy:
 - *Popescu's degree of membership to the group of young people is 0.80*

Necessity

Real phenomena involve fuzzy sets

Example

*The room's temperature can be:
low,
Medium or
high*

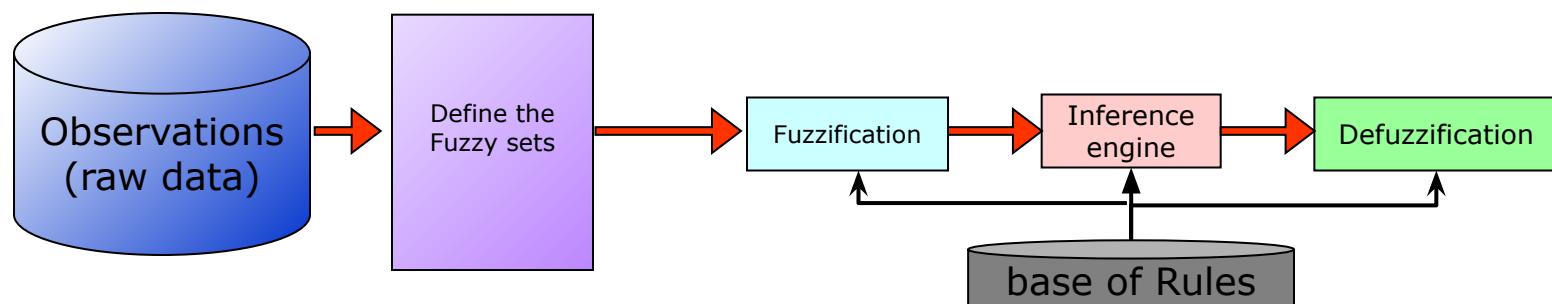
These sets of possible temperatures can overlap !

A temperature can belong to more classes (groups) depends on the person that evaluates that temperature

Content and design

□ Steps for constructing a fuzzy system

- Define the inputs and the outputs – by an expert
 - Raw inputs and outputs
 - Fuzzification of inputs and outputs
 - Fix the fuzzy variables and fuzzy sets based on membership functions
- Construct a base of rules – by an expert
 - Decision matrix
- Evaluate the rules
 - Inference – transform the fuzzy inputs into fuzzy outputs by applying all the rules
- Aggregate the results
- Defuzzification of the result
- Interpret the result



Elements from probability theory (fuzzy logic)

Fuzzy facts (fuzzy sets)

- Definition
- Representation
- Operations – complements, containment, intersection, reunion, equality, algebraic product, algebraic sum
- Properties – associativity, commutativity, distributivity, transitivity, idempotency, identity, involution
- Hedges

Fuzzy variables

- Definition
- Properties

Establish the fuzzy variables and the fuzzy sets based on membership functions

Fuzzy sets

Set definition – 2 possibilities:

- By enumeration of elements
 - Ex. Set of students = {Ana, Maria, Ioana}
- By specifying a property of elements
 - Ex. Set of even numbers = {x | x = 2n, where n = 2k}

Characteristic function μ for a set

- Let X a universal set and x an element of this set ($x \in X$)
- Classical logic
 - Let R a subset of X: $R \subseteq X$, R – regular set
 - Every element x belong to set R
- $\mu_R : X \rightarrow \{0, 1\}$, where $\mu_R(x) = \begin{cases} 1, & x \in R \\ 0, & x \notin R \end{cases}$

Fuzzy logic

- Let F a subset of X (a universe) : $F \subseteq X$, F – fuzzy set
- Every element x belongs to F by a given degree of membership $\mu_F(x)$
- $\mu_F : X \rightarrow [0, 1]$, $\mu_F(x) = g$, where $g \in [0, 1]$ – membership degree of x to F
- $g = 0 \rightarrow$ not-belong
- $g = 1 \rightarrow$ belong
- A fuzzy set = a pair (F, μ_F) , where

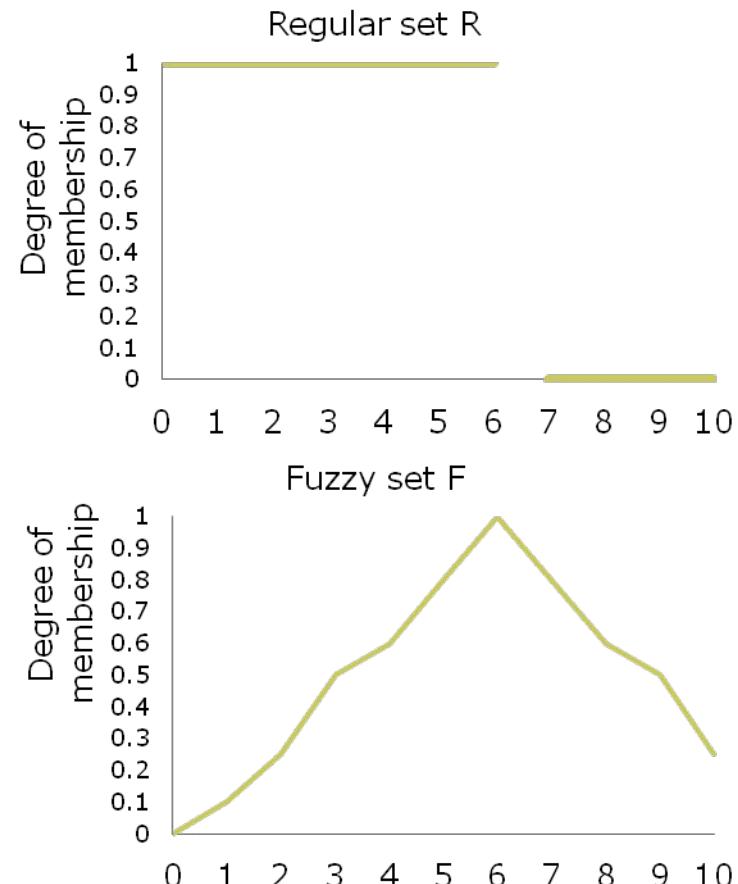
$$\mu_F(x) = \begin{cases} 1, & \text{if } x \text{ is totally in } F \\ 0, & \text{if } x \text{ is not in } F \\ \in (0,1) & \text{if } x \text{ is part of } F (x \text{ is a fuzzy number)} \end{cases}$$

Fuzzy sets

Example 1

- X – set of natural numbers < 11
- R – set of natural numbers < 7
- F – set of natural numbers that are neighbours of 6

x	$\mu_R(x)$	$\mu_F(x)$
0	1	0
1	1	0.1
2	1	0.25
3	1	0.5
4	1	0.6
5	1	0.8
6	1	1
7	0	0.8
8	0	0.6
9	0	0.5
10	0	0.25

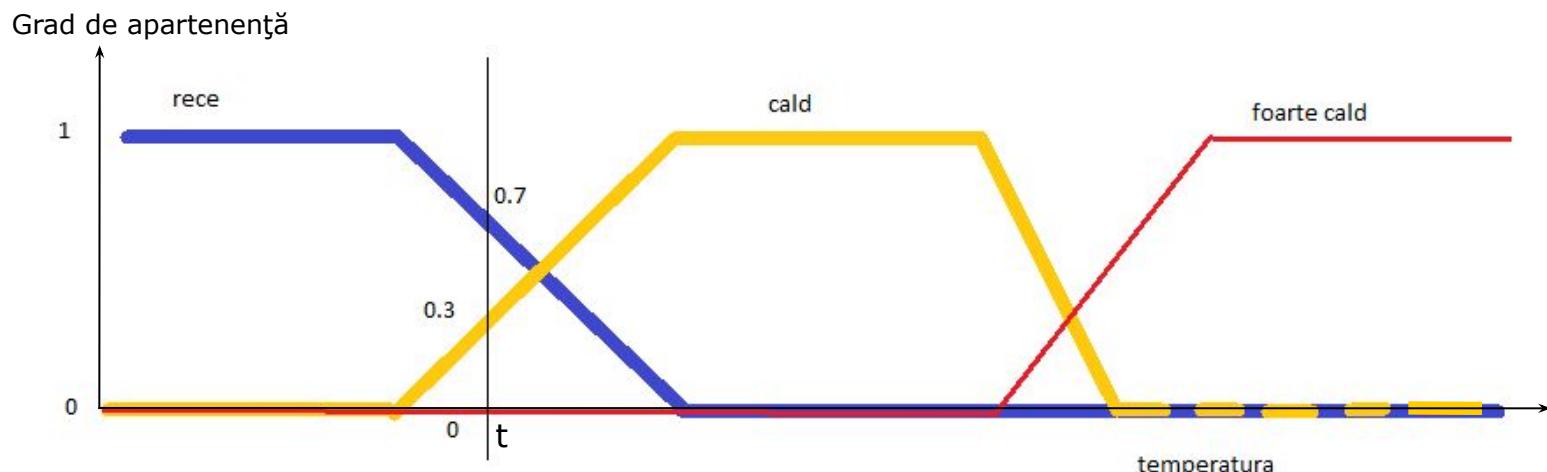


Fuzzy sets

Example 2

A temperature t can have 3 truth values:

- Red (0): is not hot
- Orange (0.3): warm
- Blue (0.7): cold

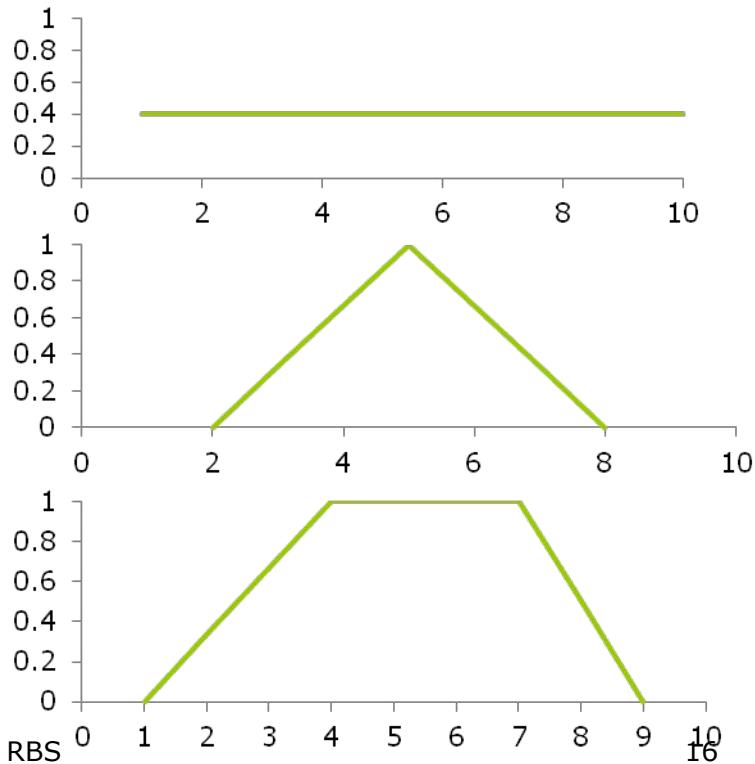


Fuzzy sets

Representation:

Gradual limits ☐ representations based on membership functions

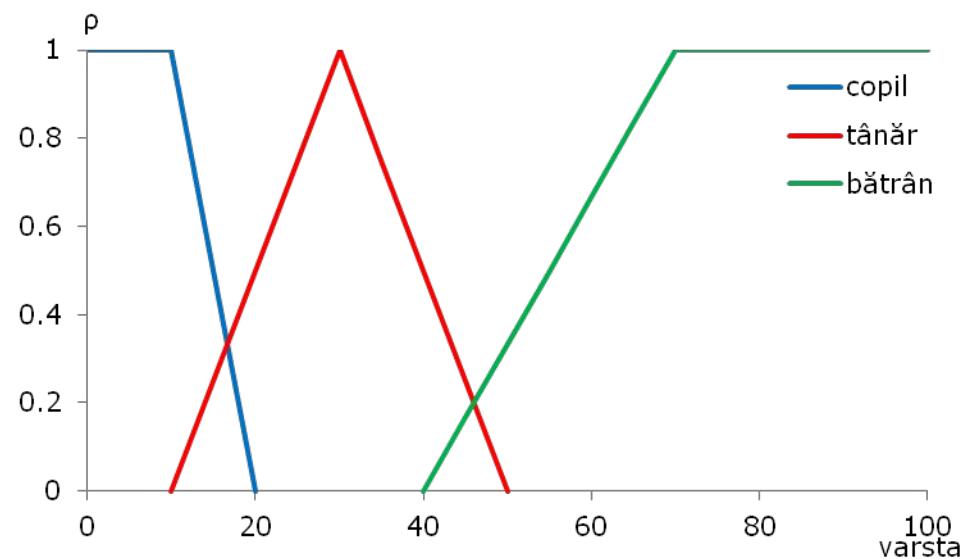
- Singular
 - $\mu(x) = s$, where s is a scalar
- Triangular
 - $$\mu(x) = \max\left\{0, \min\left\{\frac{x-a}{b-a}, 1, \frac{c-x}{c-b}\right\}\right\}$$
- Trapezoidal
 - $$\mu(x) = S(x) = \max\left\{0, \min\left\{\frac{x-a}{b-a}, 1, \frac{d-x}{d-c}\right\}\right\}$$
- Z function
 - $\mu(x) = 1 - S(x)$
- Π function
 - $$\mu(x) = \Pi(x) = \begin{cases} S(x), & \text{if } x \leq c \\ Z(x), & \text{if } x > c \end{cases}$$



Fuzzy sets

Example:

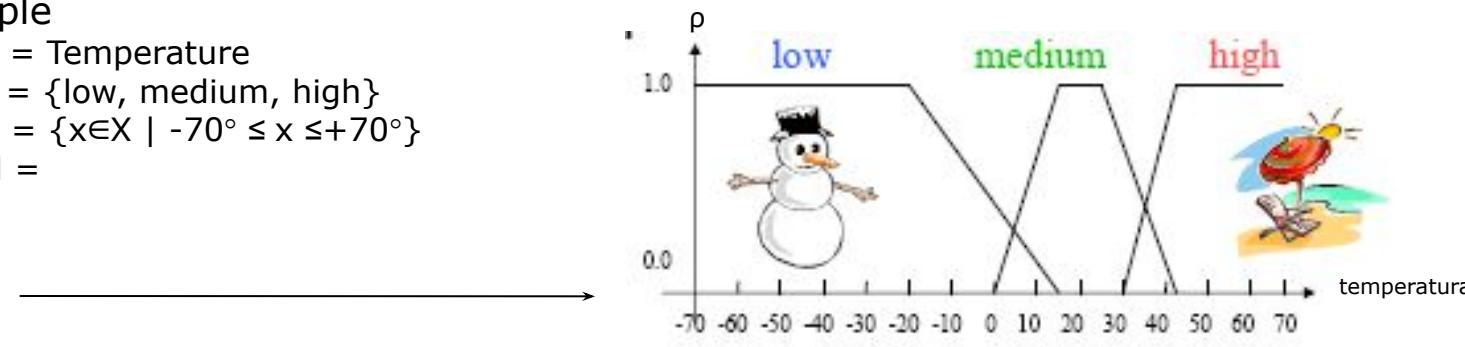
Age of a person



Fuzzy variable

Definitions

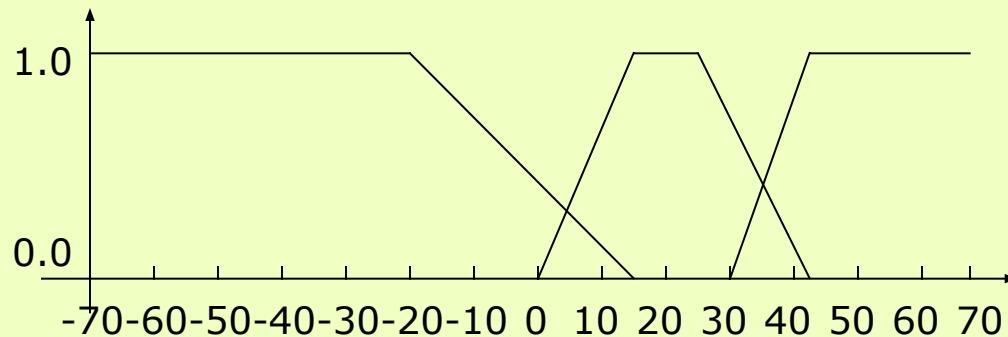
- A fuzzy variable is defined by $V = \{x, L, u, m\}$, where:
 - x – name of symbolic variable
 - L – set of possible labels for variable x
 - U – universe of the variable
 - M – semantic regions that define the meaning of labels from L (membership functions)
- Membership functions
 - Subjective assessment
 - The shape of functions is defined by experts
 - Ad-hoc assessment
 - Simple functions that can solve the problem
 - Assessment based on distributions and probabilities of information extracted from measurements
 - Adapted assessment
 - By testing
 - Automated assessment
 - Algorithms utilised for defining functions based on some training data
- Example
 - $X = \text{Temperature}$
 - $L = \{\text{low}, \text{medium}, \text{high}\}$
 - $U = \{x \in X \mid -70^\circ \leq x \leq +70^\circ\}$
 - $M =$



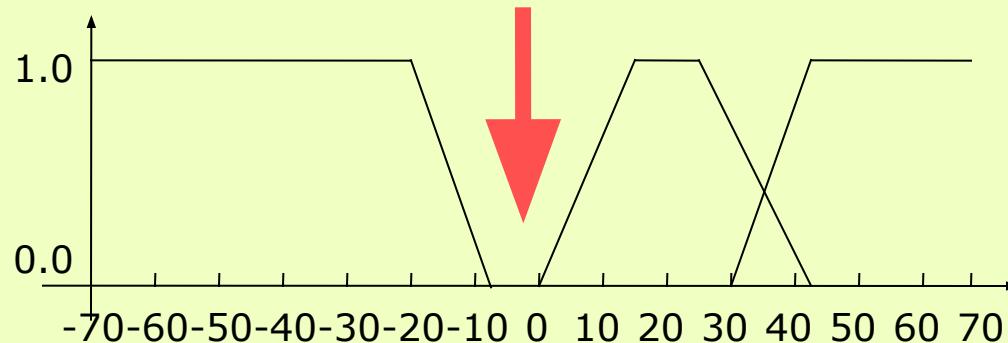
Fuzzy variable

Properties

- Completeness
 - A fuzzy variable V is complete if for all $x \in X$ there is a fuzzy set A such as $\mu_A(x) > 0$



Complete



Incomplete

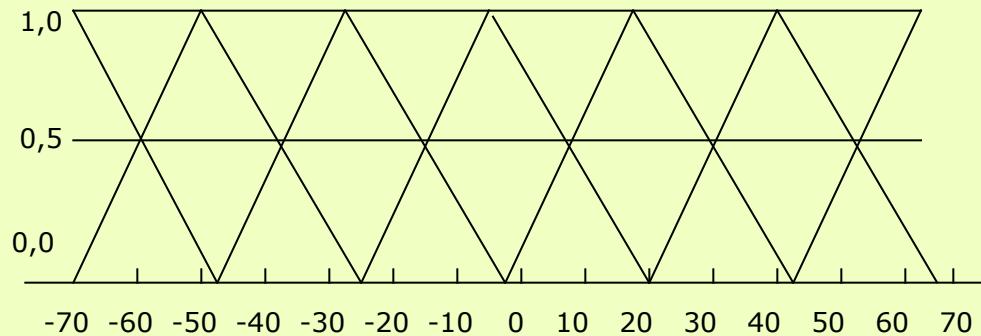
Fuzzy variable

Properties

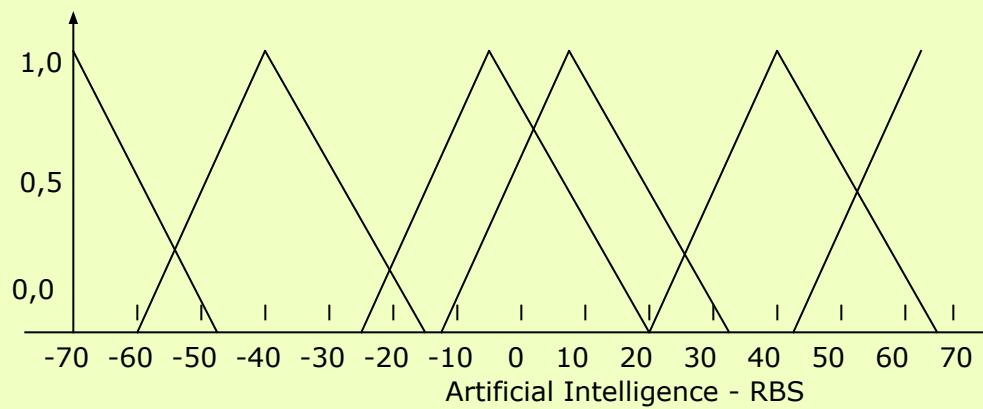
Unit partition

- A fuzzy variable V forms a unit partition if for all input values x we have $\sum_{i=1}^p \mu_{A_i}(x) = 1$
- where p is the number of sets that x belongs to
- There are no rules for defining 2 neighbour sets
 - Usually, the overlap is between 25% și 50%

$$\sum_{i=1}^p \mu_{A_i}(x) = 1$$



Unit partition



Non-unit partition

Fuzzy variable

Properties

- Unit partition

A complete fuzzy variable can be transformed into a unit partition:

$$\mu_{\hat{A}_i}(x) = \frac{\mu_{A_i}(x)}{\sum_{j=1}^p \mu_{A_j}(x)} \text{ for } i = 1, \dots, p$$

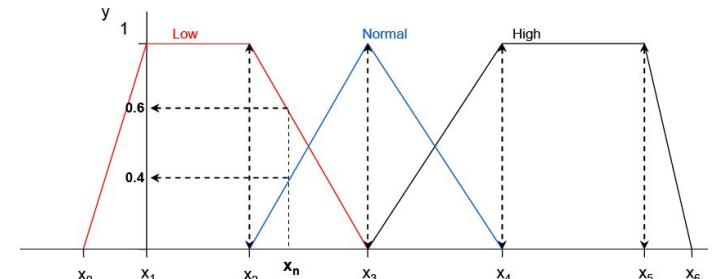
Fuzzification of input data

Establish the fuzzy variables and the fuzzy sets based on membership functions

Fuzzification of input data

Mechanism

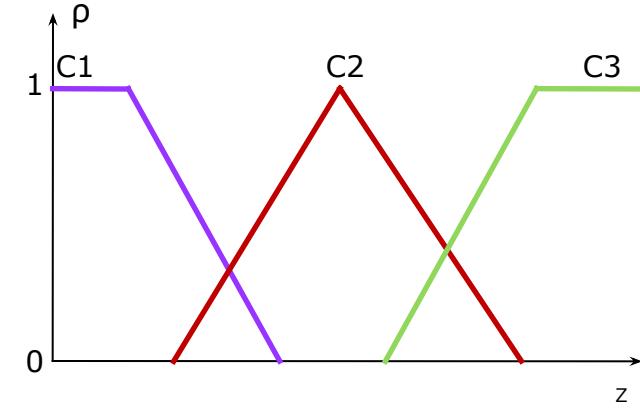
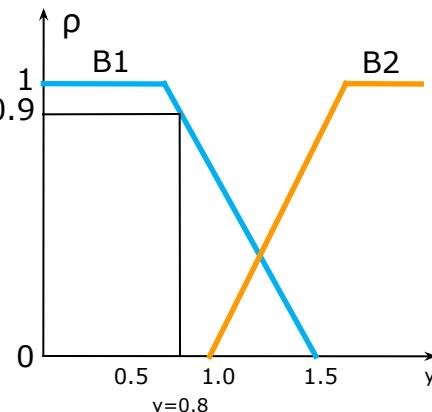
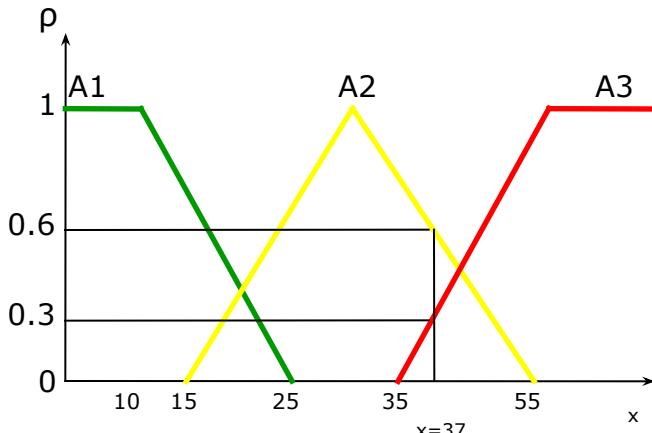
- Establish the raw (input and output) data of the system
- Define membership functions for each input data
 - Each membership function has associated a quality label – linguistic variable
 - A raw variable can have associated one or more linguistic variables
 - Example
 - Raw variable: temperature T
 - Linguistic variable: low $\sqcap A_1$, medium $\sqcap A_2$, high $\sqcap A_3$
- Transform each raw input data into a linguistic data \sqcap fuzzification
 - Establish the fuzzy set of that raw input data
 - How?
 - For a given raw input determine the membership degree for each possible set
 - Example
 - $T (=x_n) = 5^\circ$
 - $A_1 \sqcap \mu_{A_1}(T) = 0.6$
 - $A_2 \sqcap \mu_{A_2}(T) = 0.4$



Fuzzification of input data

- Example - air conditioner device

- Inputs :
 - x (temperature – cold, normal, hot) and
 - y (humidity – small, large)
- Outputs:
 - z (machine power – low, medium, high)
- Input data:
 - Temperature $x = 37$
 - $\mu_{A_1}(x)=0, \mu_{A_2}(x)=0.6, \mu_{A_3}(x)=0.3$
 - Humidity $y = 0.8$
 - $\mu_{B_1}(y)=0.9, \mu_{B_2}(y)=0$



Base of rules

Construct a base of rules – by an expert

Rules

- Definition
 - Linguistic constructions
 - Affirmative sentences: A
 - Conditional sentences: if A then B
 - Where A and B are (collections of) sentences that contain linguistic variables
 - A – premise of the rule
 - B – consequence of the rule
- Typology
 - Non-conditional
 - $x \text{ is (in) } A_i$
 - Eg. *Save the energy*
 - Conditional
 - If $x \text{ is (in) } A_i$ then $z \text{ is (in) } C_k$
 - If $x \text{ is (in) } A_i$ and $y \text{ is (in) } B_j$, then $z \text{ is (in) } C_k$
 - If $x \text{ is (in) } A_i$ or $y \text{ is (in) } B_j$, then $z \text{ is (in) } C_k$

Base of rules -example

	Rules of classical logic	Rules of fuzzy logic
R_1	<i>If temperature is -5, then is cold</i>	<i>If temperature is law, then is cold</i>
R_2	<i>If temperature is 15, then is warm</i>	<i>If temperature is medium, then is warm</i>
R_3	<i>If temperature is 35, then is hot</i>	<i>If temperature is high, then is hot</i>

Base of rules

Rules

■ Database of fuzzy rules

- R_{11} : if x is A_1 and y is B_1 then z is C_u
- R_{12} : if x is A_1 and y is B_2 then z is C_v
- ...
- R_{1n} : if x is A_1 and y is B_n then z is C_x

- R_{21} : if x is A_2 and y is B_1 then z is C_x
- R_{22} : if x is A_2 and y is B_2 then z is C_z
- ...
- R_{2n} : if x is A_2 and y is B_n then z is C_v

- ...

- R_{m1} : if x is A_m and y is B_1 then z is C_x
- R_{m2} : if x is A_m and y is B_2 then z is C_v
- ...
- R_{mn} : if x is A_m and y is B_n then z is C_u

Base of rules

Decision matrix of the knowledge database

- Example – air conditioner device
 - Inputs :
 - x (temperature – cold, normal, hot) and
 - y (humidity – small, large)
 - Outputs:
 - z (machine power – low, constant, high)
 - Rules:
 - *If temperature is normal and humidity is small then the power is constant*

		Input data y	
		Small	Large
Input data x	Cold	Low	Constant
	Normal	Constant	High
	Hot	High	High

Rule evaluation (fuzzy inference)

Which rules are firstly evaluated?

Fuzzy inference

- Rules are evaluated in **parallel**, each rules contributing to the shape of the final result
- Resulted fuzzy sets are defuzzified **after all the rules** have been evaluated

Rule evaluation (fuzzy inference)

Evaluation of causes

- For each premise of a rule (*if s is (in) A*) establish the membership degree of raw input data to all fuzzy sets
- A rule can have more premises linked by logic operators *AND*, *OR* or *NOT* □ use fuzzy operators
 - Operator *AND* □ intersection (minimum) of 2 sets
 - $\mu_{A \cap B}(x) = \min\{\mu_A(x), \mu_B(x)\}$
 - Operator *OR* □ union (maximum) of 2 sets
 - $\mu_{A \cup B}(x) = \max\{\mu_A(x), \mu_B(x)\}$
 - Operator *NOT* □ negation (complement) of a set
 - $\mu_{\neg A}(x) = 1 - \mu_A(x)$
- The result of premise's evaluation
 - Degree of satisfaction
 - Other names:
 - Rule's firing strength
 - Degree of fulfillment

Rule evaluation (fuzzy inference)

Determine the results

- Establish the membership degree of variables (involved in the consequences) to different fuzzy sets

Each output region must be de-fuzzified in order to obtain crisp value

Based on the consequence's type

- **Mamdani model** – consequence of rule: “output variable belongs to a fuzzy set”
- **Sugeno model** – consequence of rule: “output variable is a crisp function that depends on inputs”
- **Tsukamoo model** – consequence of rule: “output variable belongs to a fuzzy set following a monotone membership function”

Mamdani model

Main idea:

- consequence of rule: “output variable belongs to a fuzzy set”
- Result of evaluation is applied for the membership function of the consequence
- Example
 - ***if x is in A and y is in B, then z is in C***

Classification based on how the results is applied on the membership function of the consequence:

- Clipped fuzzy sets
- Scaled fuzzy sets

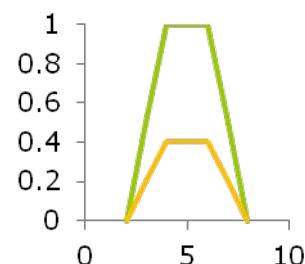
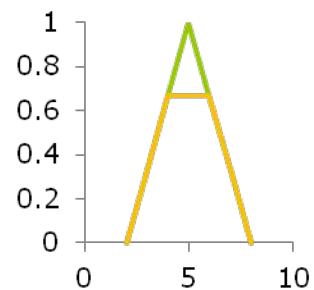
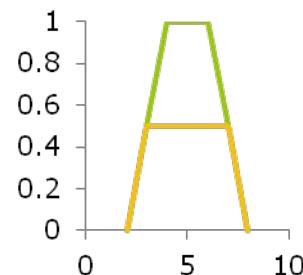
Mamdani model - Classification

Clipped fuzzy sets

- Membership function of the consequence is cut at the level of the result's truth value
- Advantage □ easy to compute
- Disadvantage □ some information are lost

Scaled fuzzy sets

- Membership function of the consequence is adjusted by scaling (multiplication) at the level of the result's truth value
- Advantage □ few information is lost
- Disadvantage □ complicate computing



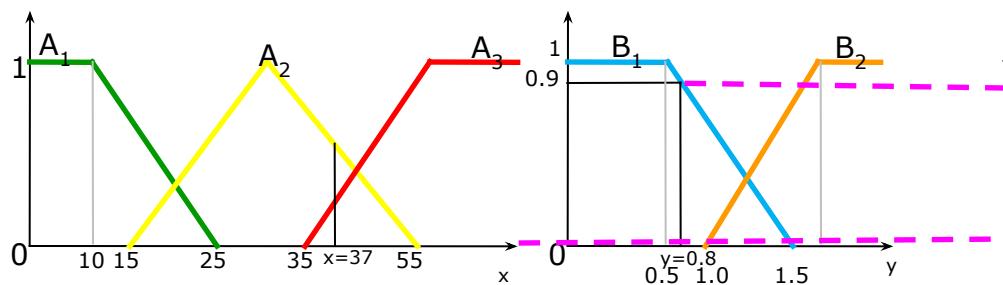
Mamdani model

- Example – air conditioner device
 - Inputs :
 - x (temperature – cold, normal, hot) and
 - y (humidity – small, large)
 - Outputs:
 - z (machine power – law, constant, high)
 - Input data:
 - Temperature x = 37
 - $\mu_{A1}(x)=0$, $\mu_{A2}(x)=0.6$, $\mu_{A3}(x)=0.3$
 - Humidity y = 0.8
 - $\mu_{B1}(x)=0.9$, $\mu_{B2}(x)=0$

		Input data y	
		Small	Large
Input data x	Cold	Law	Constant
	Normal	Constant	High
	Hot	High	High

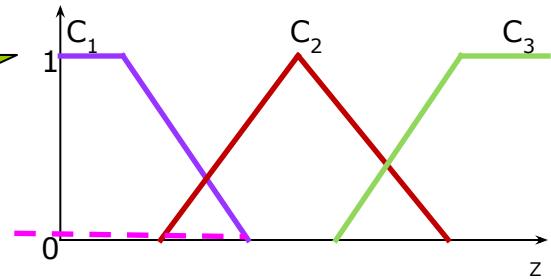
Mamdani model

R1: if x is in A_1 and y is in B_1 then z is in C_1
 $\mu_{A_1}(x) = 0$ $\mu_{B_1}(y)=0.9$

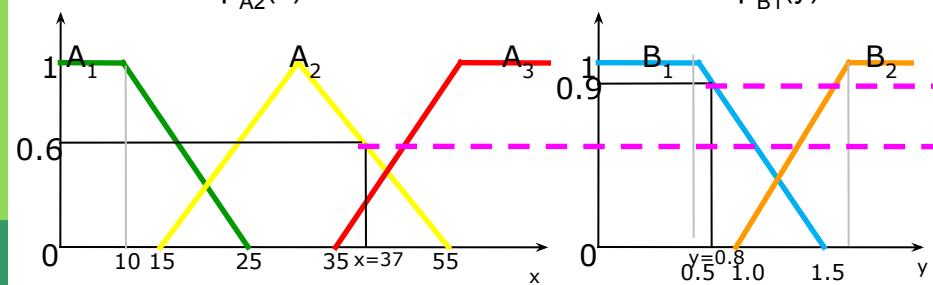


AND
(min)

$$\mu_{C_1}(z)=0$$

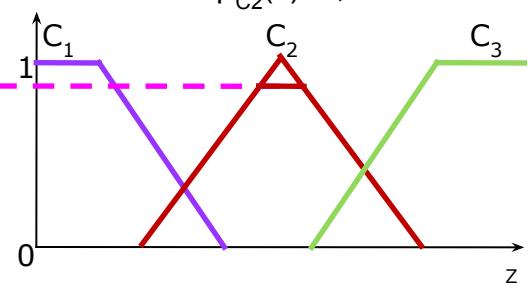


R2: if x is in A_2 or y is in B_1 then z is in C_2
 $\mu_{A_2}(x) = 0.6$ $\mu_{B_1}(y)=0.9$

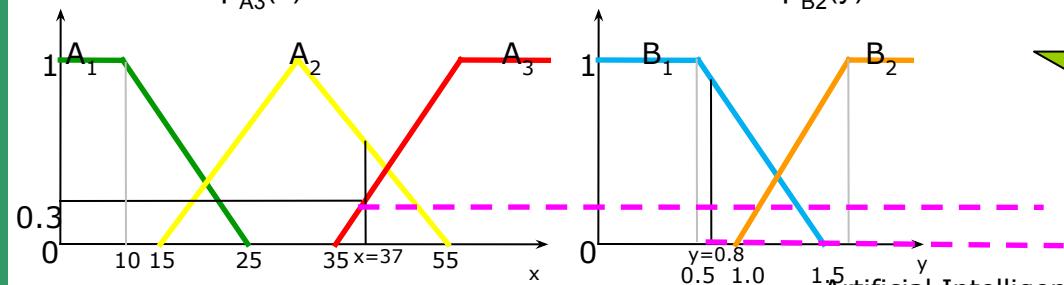


OR
(max)

$$\mu_{C_2}(z)=0.9$$

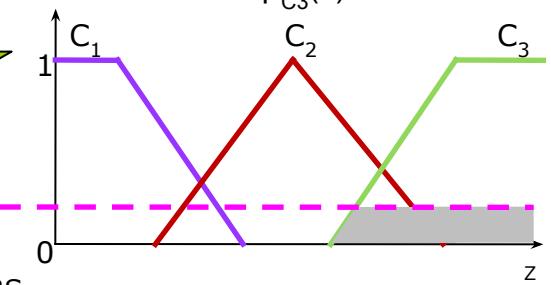


R3: if x is in A_3 or y is in B_2 then z is in C_3
 $\mu_{A_3}(x) = 0.3$ $\mu_{B_2}(y)=0$



OR
(max)

$$\mu_{C_3}(z)=0.3$$



Sugeno model

Main idea

- consequence of rule: “output variable is a crisp function that depends on inputs”

Example

If x is in A and y is in B then z is f(x,y)

Classification based on characteristics of $f(x,y)$

Sugeno model of degree 0

if $f(x,y) = k$ – constant (membership function of the consequences are singleton – a fuzzy set whose membership functions have value 1 for a single (unique) point of the universe and 0 for all other points)

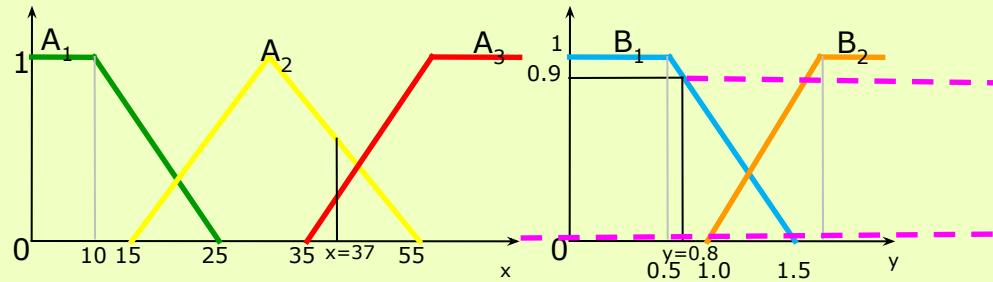
Sugeno model of degree 1

if $f(x,y) = ax + by + c$

Sugeno model

R1: if x is in A_1 and y is in B_1 then z is in C_1

$$\mu_{A_1}(x) = 1 \quad \mu_{B_1}(y) = 0.9$$

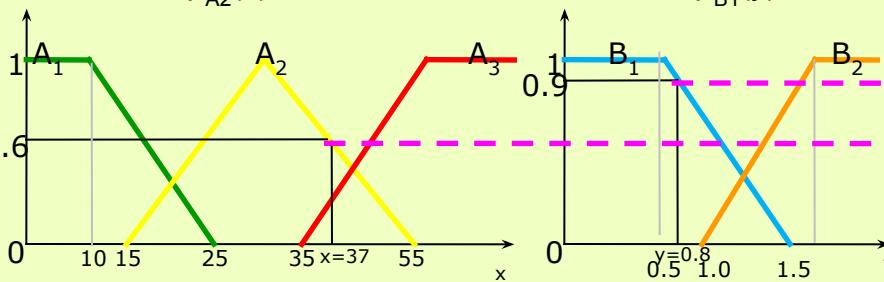


AND
(min)

$$\mu_{C_1}(z) = 0$$

R2: if x is in A_2 or y is in B_1 then z is in C_2

$$\mu_{A_2}(x) = 0.6$$

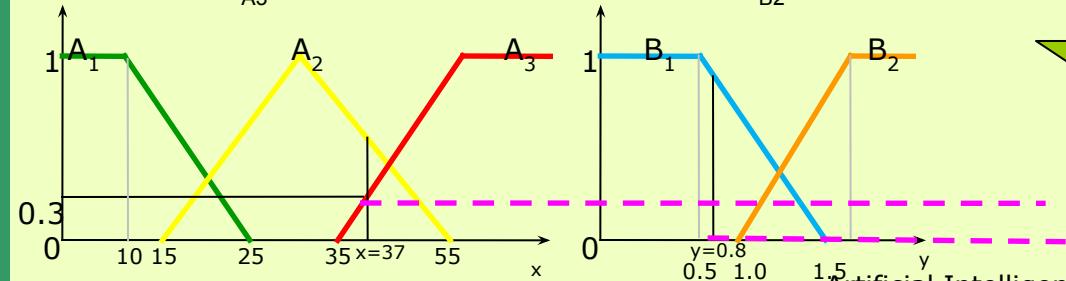


OR
(max)

$$\mu_{C_2}(z) = 0.9$$

R3: if x is in A_3 or y is in B_2 then z is in C_3

$$\mu_{A_3}(x) = 0.3$$



OR
(max)

$$\mu_{C_3}(z) = 0.3$$

Tsukamoto model

Main idea

- consequence of rule:

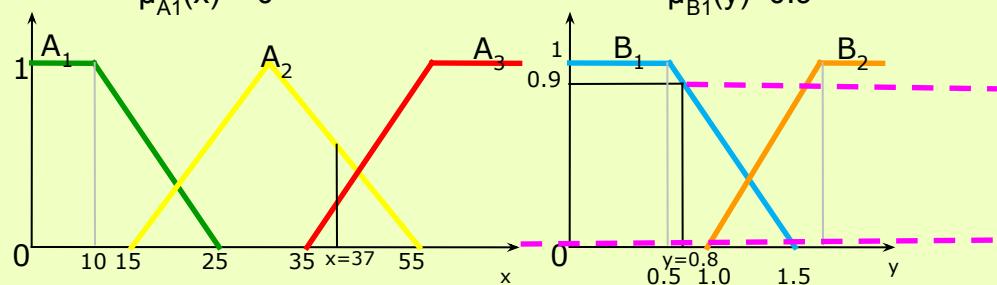
output variable belongs to a fuzzy set following a monotone membership function

A crisp value is obtained as output □ rule's firing strength

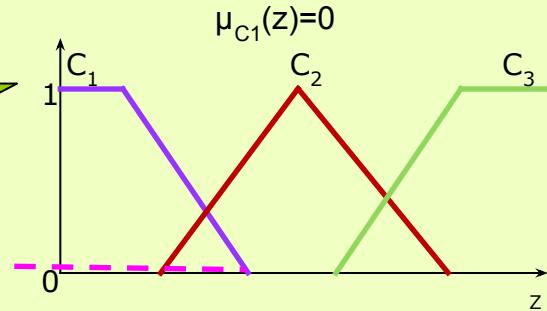
Tsukamoto model

Content and design □ rule evaluation □ Evaluation of consequences □ Tsukamoto model

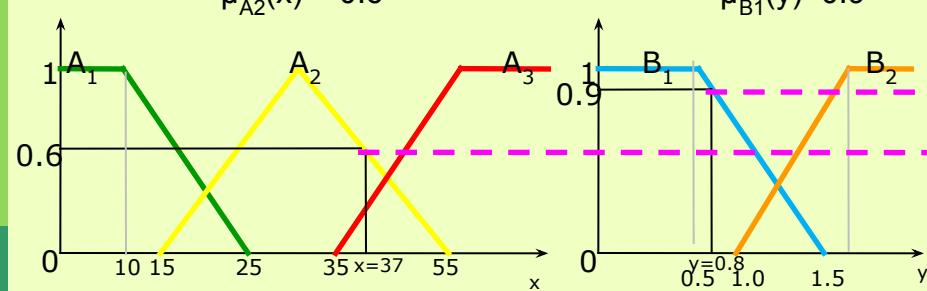
R1: if x is in A_1 and y is in B_1 then z is in C_1



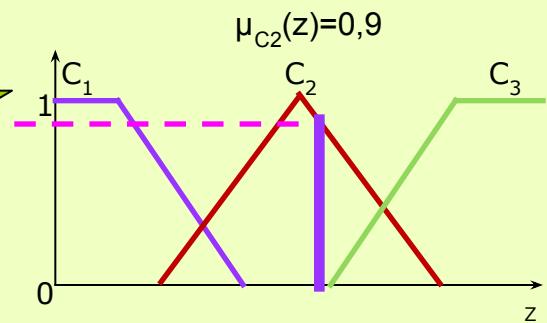
AND
(min)



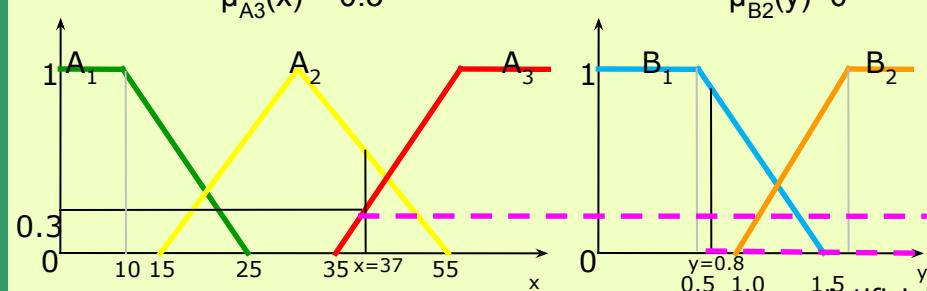
R2: if x is in A_2 or y is in B_1 then z is in C_2



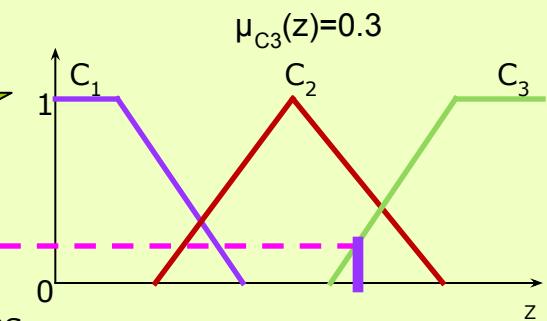
OR
(max)



R3: if x is in A_3 or y is in B_2 then z is in C_3



OR
(max)

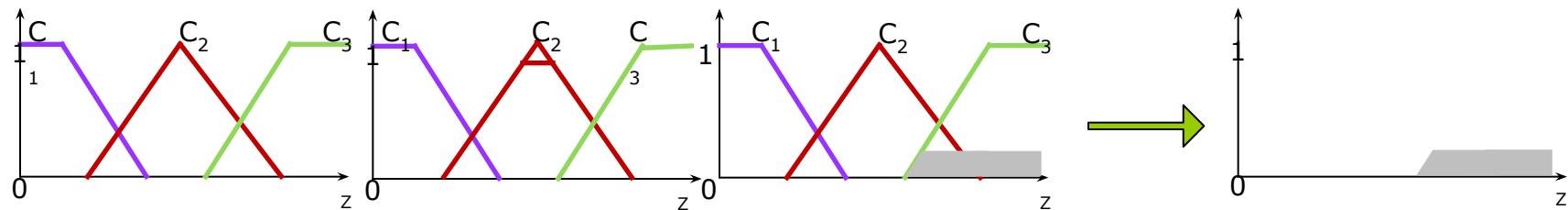


Aggregate the results

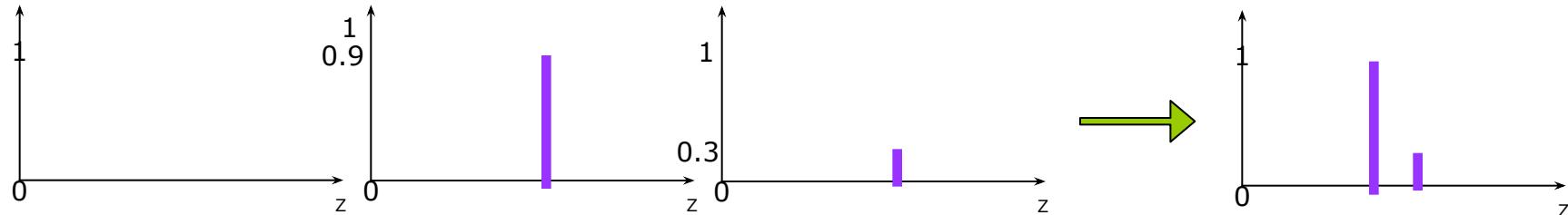
- Union of outputs for all the applied rules
- Consider the membership functions for all the consequences and combine them into a single fuzzy set (a single result)
- Aggregation process have as
 - Inputs □ membership functions (clipped or scaled) of the consequences
 - Outputs □ a fuzzy set of the output variable

Example

Mamdani



Sugeno



Defuzzification

- Transform the fuzzy result into a crisp (raw) value
- Inference □ obtain some fuzzy regions for each output variable
- Defuzzification □ transform each fuzzy region into a crisp value

Methods

- Based on the gravity center
 - COA – Centroid Area
 - BOA – *Bisector of area*
- Based on maximum of membership function
 - MOM - *Mean of maximum*
 - SOM - *Smallest of maximum*
 - LOM - *Largest of maximum*

Defuzzification

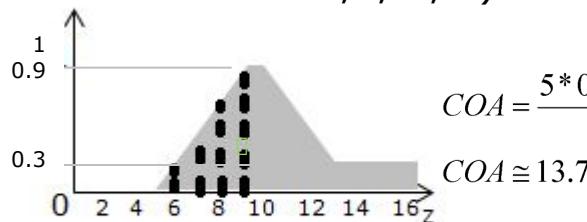
COA – Centroid Area

- Identify the z point from the middle of aggregated set

$$COG = \frac{\sum_{i=0}^n x_i \mu_A(x_i)}{\sum_{i=0}^n \mu_A(x_i)} \text{ sau } COG = \frac{\int x_i \mu_A(x_i) dx}{\int \mu_A(x_i) dx}$$

- Example

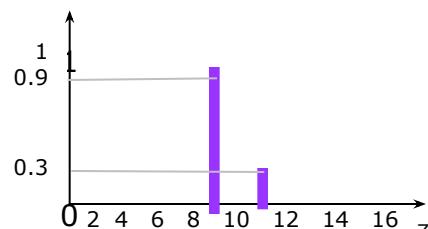
- Mamdani model □ estimation of COA by using a sample of n points (x_i , $i = 1, 2, \dots, n$) of the resulted fuzzy set



$$COA = \frac{5*0 + 6*0.3 + 7*0.5 + 8*0.7 + 9*0.9 + 10*0.9 + 11*0.7 + 12*0.5 + 13*0.3 + 14*0.3 + 15*0.3 + 16*0.3}{0 + 0.3 + 0.5 + 0.7 + 0.9 + 0.9 + 0.7 + 0.5 + 0.3 + 0.3 + 0.3 + 0.3}$$

$$COA \approx 13.7$$

- Sugeno or Tsukamoto model □ COA becomes a weighted average of m crisp values obtained by applying all m rules



$$COA = \frac{9*0.9 + 11*0.3}{0.9 + 0.3}$$

$$COA \approx 9.5$$

Defuzzification

BOA – Bisector of area

Identify the point z that determine the splitting of aggregated set in 2 parts of equal area

$$BOA = \int_{\alpha}^z \mu_A(x)dx = \int_z^{\beta} \mu_A(x)dx,$$

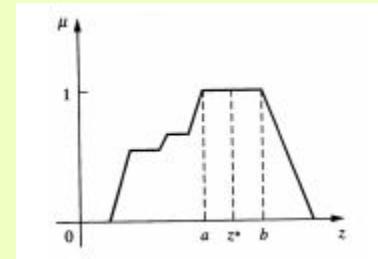
where $\alpha = \min\{x \mid x \in A\}$ and $\beta = \max\{x \mid x \in A\}$

Defuzzification

➤ MOM - *Mean of maximum*

- Identify the point z that represents the mean of that points (from the aggregated set) that have a maximum membership function

$$MOM = \frac{\sum_{x_i \in \max \mu} x_i}{|\max \mu|}, \text{ where } \max \mu = \mu^* = \{x \mid x \in A, \mu(x) = \max\}$$



➤ SOM - *Smallest of maximum*

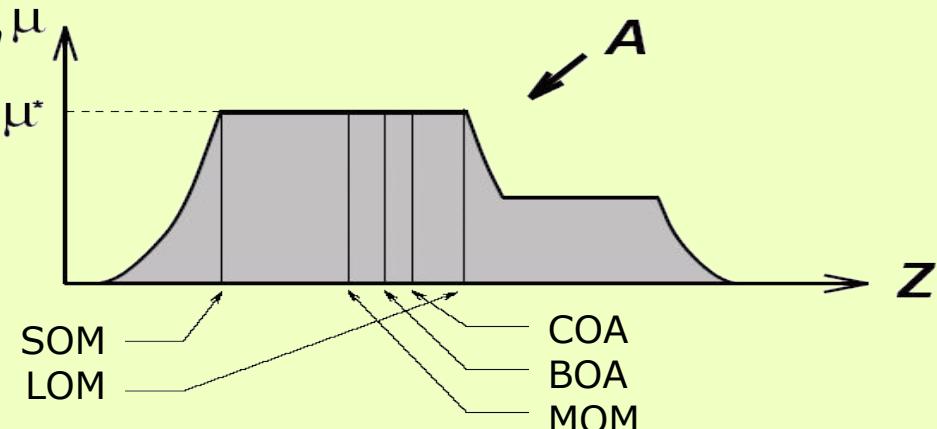
- Identify the smallest point z (from the aggregated set) that have a maximum membership function

➤ LOM - *Largest of maximum*

- Identify the largest point z (from the aggregated set) that have a maximum membership function

Defuzzification

- Main idea
 - Transform the fuzzy result into a crisp (raw) value
 - Inference □ obtain some fuzzy regions for each output variable
 - Defuzzification □ transform each fuzzy region into a crisp value
- Methods
 - Based on the gravity center
 - COA – Centroid Area
 - BOA – *Bisector of area*
 - Based on maximum of membership function
 - MOM - *Mean of maximum*
 - SOM - *Smallest of maximum*
 - LOM - *Largest of maximum*



Intelligent systems – KBS – Fuzzy systems

Advantages

- Imprecision and real-world approximations can be expressed through some rules
- Easy to understand, to test and to maintain
- Robustness can operate when rules are not so clear
- Require few rules than other KBSs
- Rules are evaluated in parallel

Disadvantages

- Require many simulations and tests
- Do not automatically learn
- It is difficult to identify the most correct rules
- There is not mathematical model

Applications

Space control

- Altitude of satellites, Setting the planes

Auto-control

- Automatic transmission, traffic control, anti-braking systems

Business

- Decision systems, personal evaluation, fond management, market predictions, etc

Industry

- Energy exchange control, water purification control
- pH control, chemical distillation, polymer production, metal composition

Electronic devices

- Camera exposure, humidity control. Air conditioner, shower setting, Freezer setting, Washing machine setting

Applications

Nourishment

- Cheese production

Military

- Underwater recognition, infrared image recognition, vessel traffic decision

Navy

- Automatic drivers, route selection

Medical

- Diagnostic systems, pressure control during anesthesia, modeling the neuropathology results of Alzheimer patients

Robotics

- Kinematics (arms)