



Lifelong Learning (L^2)

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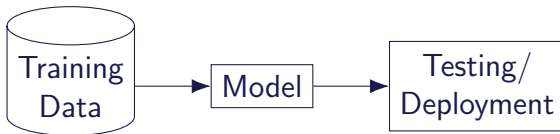


Outline

- Motivation: Why lifelong learning?
 - Classical machine learning
 - Catastrophic forgetting
- Definitions
 - Lifelong Learning
 - Three L^2 settings
- Current L^2 approaches
 - Replay Methods
 - Regularization Methods
 - Architectural Methods
- Evaluation of L^2 methods
- My Research interest



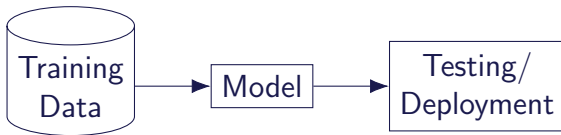
Classical Machine Learning



- **Classical machine learning:** Isolated single-task learning.
- What is a task?



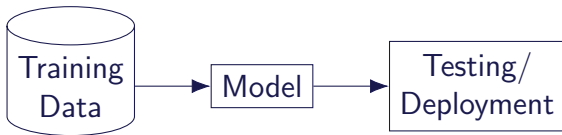
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 - Classification: cars vs truck, MNIST.
 - Regression: stock prices, rainfall.



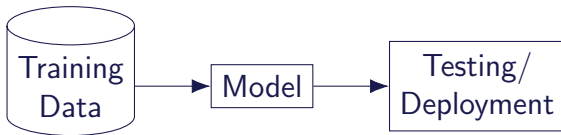
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- Each model performs a single task.
 - Support vector machines, Deep neural networks.



Classical Machine Learning



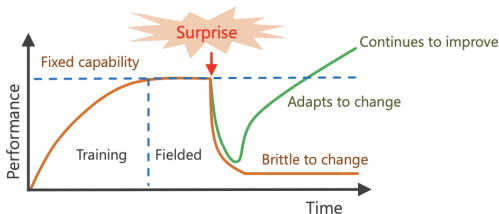
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- What is a task?
 - Classification: cars vs truck, MNIST.
 - Regression: stock prices, rainfall.
- Each model performs a single task.
 - Support vector machines, Deep neural networks.
 - Very effective but there are limitations!



Key issues in classical machine learning

- No lifelong/continual learning
 - Learning occurs in isolation.
 - Knowledge accumulation is not possible.
 - Knowledge transfer is not possible.

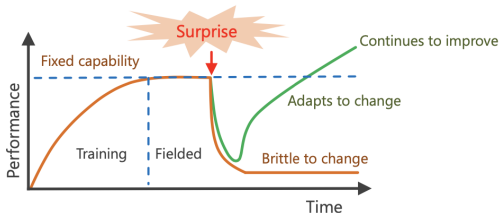
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- No lifelong/continual learning
 - Learning occurs in isolation.
 - Knowledge accumulation is not possible.
 - Knowledge transfer is not possible.
- Assumes stationarity: Can't handle environment changes.
- No more learning is possible after deployment.



Catastrophic Forgetting

Easy Solution

- Train a single model on multiple tasks one after another (in a sequence).



Catastrophic Forgetting

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- Learning requires updating parameters of the **shared** model for each task (like weights in a neural network).



Catastrophic Forgetting

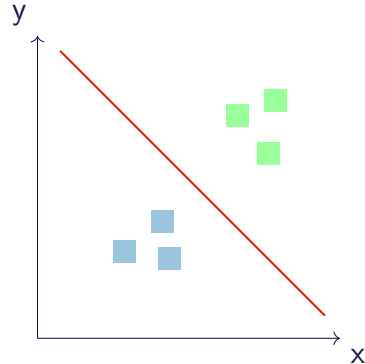
Easy Solution

- Train a single model on multiple tasks one after another (in a sequence).
- Learning requires updating parameters of the **shared** model for each task (like weights in a neural network).
 - Knowledge acquired from previous tasks will be overwritten.
 - Performance on previous tasks deteriorate as we learn new tasks - *Catastrophic forgetting*.



Catastrophic Forgetting

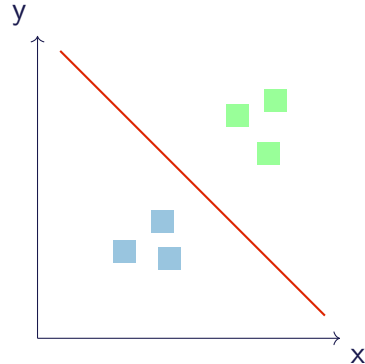
- **Task 1**
 - 2 classes: blue and green squares.





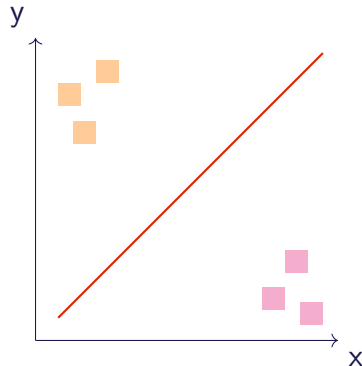
Catastrophic Forgetting

- **Task 1**
 - 2 classes: blue and green squares.
- Find a line that separates two classes.
 - $y = mx + c$
 - Model = Finding m and c .



Catastrophic Forgetting

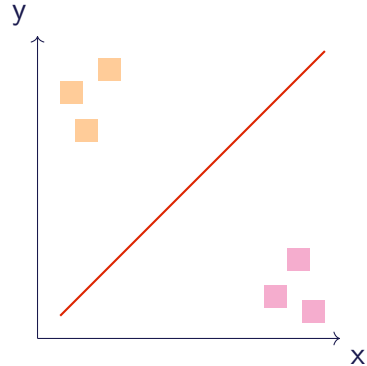
- Apply the easy solution
 - Continue training the model on Task 2.
- **Task 2**
 - 2 classes: orange and magenta squares.
 - Find a line that separates two classes.





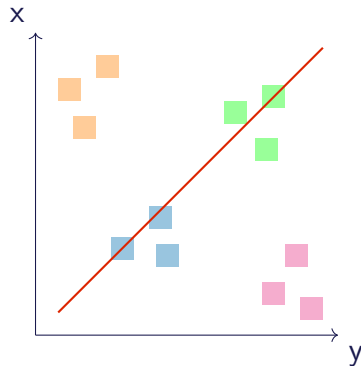
Catastrophic Forgetting

- Apply the easy solution
 - Continue training the model on Task 2.
- **Task 2**
 - 2 classes: orange and magenta squares.
 - Find a line that separates two classes.
- Red line is our model now.



Catastrophic Forgetting

- We wanted a **single shared model** for all tasks.
- New model (line) doesn't work for Task 1.
- Learning Task 2 made model forget Task 1.
 - Catastrophic forgetting.
- Catastrophic forgetting is the most fundamental problem in L^2 .





Definitions



Lifelong Learning (L^2)

- Learn a sequence of tasks, $T_1, T_2, \dots, T_N, \dots$ sequentially.
- Each task t has a dataset for training, $\mathcal{D}_t = \{(\mathbf{x}_i, y_i)\}_{i=1}^n$



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- **Assumption:** Once a task is learned, its data is no longer accessible (at least majority of it).



Lifelong Learning (L^2)

Three L^2 settings [Van de Ven, 2022]

1. Task incremental learning
 - Models are *partially* shared across tasks.
 - Task identity is required during testing.



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 - E.g. Classifying objects under different lightning conditions.








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Three L^2 settings [Van de Ven, 2022]

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 - Task identity is required during testing.
2. Domain incremental learning
 - All tasks have the same set of classes.
 - Task identity is not required during testing.
 - E.g. Classifying objects under different lightning conditions.
3. Class incremental learning
 - Produce a single model from all tasks.
 - All classes in all tasks are handled by one model.

Three L^2 Settings

| | | | | |
|--|--|--|--|--|
| <p>Task 1</p>  <p>first class second class</p> | <p>Task 2</p>  <p>first class second class</p> | <p>Task 3</p>  <p>first class second class</p> | <p>Task 4</p>  <p>first class second class</p> | <p>Task 5</p>  <p>first class second class</p> |
|--|--|--|--|--|

Task-IL

With task given, is it the 1st or 2nd class?
(e.g., 0 or 1)

Domain-IL

With task unknown, is it a 1st or 2nd class?
(e.g., in [0, 2, 4, 6, 8] or in [1, 3, 5, 7, 9])

Class-IL

With task unknown, which digit is it?
(i.e., choice from 0 to 9)



Current Approaches

- **Replay/Rehearsal-based methods**
- **Regularization-based methods**
- **Architectural methods**



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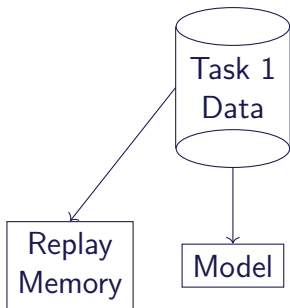
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Current Approaches

- **Replay/Rehearsal-based methods**
 - Replay samples from previous tasks while learning a new task.
- **Regularization-based methods**
 - Update to model parameters is regularized according to a parameter's importance for previous tasks.
- **Architectural methods**
 - Expand network architecture to learn new tasks.

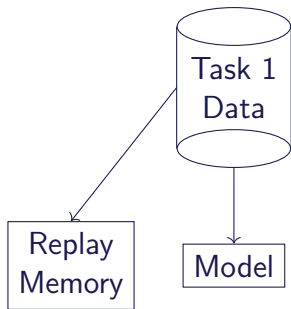
Replay Methods



Task 1 Training

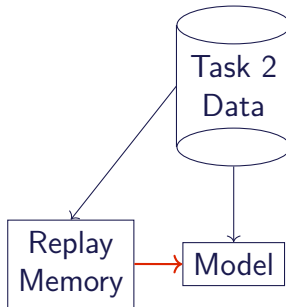
- Save subset of samples in replay memory.

Replay Methods



Task 1 Training

- Save subset of samples in replay memory.



Task 2 Training

- Replay stored samples from previous tasks.
- Save subset of samples in replay memory.



Replay Methods

Why replay works?

- For training, mix data from new task and replay samples.
 - **Replay samples:** Won't allow changes to weights important for previous tasks.
 - **New task samples:** Learn the new task.
- The quality of stored samples is very important!



Replay Methods

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Is there another way to obtain replay samples?



Replay Methods

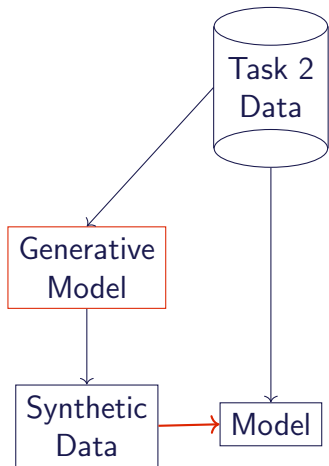
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Is there another way to obtain replay samples?

- Train a generative model in-parallel to your classifier.
- Get replay samples from the generative model [Shin, 2017].

Replay Methods



- Exact replay
 - Actual samples from the original dataset are used for replay.
- Generative replay
 - Samples for replay are obtained from generative models.
 - L2 problem is shifted to generative models.



Replay Methods

- Learning in deep neural networks and brains with similarity-weighted interleaved learning, 2022 - Only previous memories with high similarity to the new data.

Coresets

- Gradient based sample selection for online continual learning, 2019 - Select samples that exhibit maximum variance in gradient.
- Online Continual Learning with Maximally Interfered Retrieval, 2019. - Samples most affected by a given gradient update.



Regularization Methods



Regularization Methods

- Use an additional penalty term during learning.
- Without regularization

$$\mathcal{L}_N = \sum_{x \in \mathcal{D}_N} \mathcal{E}(y_{output}, y_{desired}) \quad (1)$$

- \mathcal{E} could be MSE, cross entropy, etc.



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- With regularization,

$$\mathcal{L}_N = \sum_{x \in \mathcal{D}_N} \mathcal{E} + \text{parameter-wise penalty} \quad (2)$$



Regularization Methods

Regularization: Old wine in new bottles!

$$\mathcal{L}_N = \sum_{x \in \mathcal{D}_N} \mathcal{E} + \lambda \sum_i \theta_i^2 \quad (3)$$

- **L2 Regularization**
- θ_i denotes parameters of your network.
- λ determines how strongly regularization is applied.
- *Almost* a standard technique to prevent overfitting.



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- **L2 Regularization**
- θ_i denotes parameters of your network.
- λ determines how strongly regularization is applied.
- *Almost* a standard technique to prevent overfitting.
- Keep θ_i close to zero.

$$\mathcal{L}_N = \sum_{x \in \mathcal{D}_N} \mathcal{E} + \lambda \sum_i (\theta_i - 0)^2 \quad (4)$$



Regularization Methods

$$\mathcal{L}_B = \sum_{x \in B} \mathcal{E} + \lambda \sum_i \theta_i^2 \quad (5)$$

- λ is same for all θ_i .
- All parameters might not be equally important!



Regularization Methods

$$\mathcal{L}_B = \sum_{x \in B} \mathcal{E} + \lambda \sum_i \theta_i^2 \quad (5)$$

- λ is same for all θ_i .
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$$\mathcal{L}_B = \sum_{x \in B} \mathcal{E} + \lambda_i \sum_i \theta_i^2 \quad (6)$$

- High λ_i for less important θ_i .
- Low λ_i for highly important θ_i .



Regularization Methods

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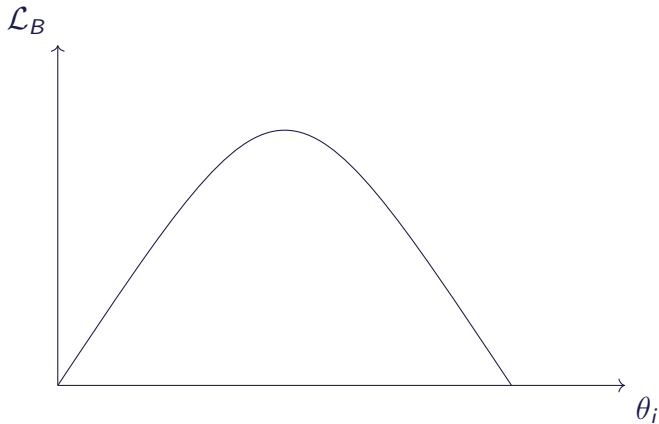
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- High λ_i for less important θ_i .
- Low λ_i for highly important θ_i .
- **How do we set λ_i ?**

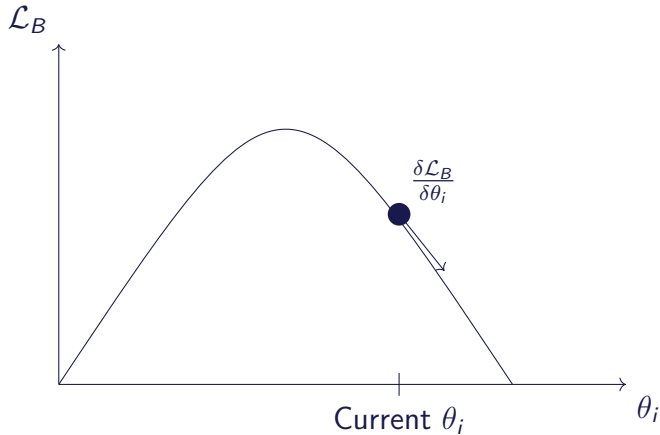


Regularization Methods



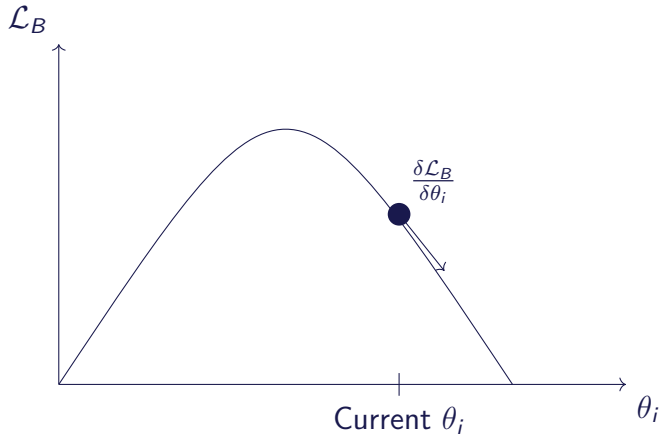


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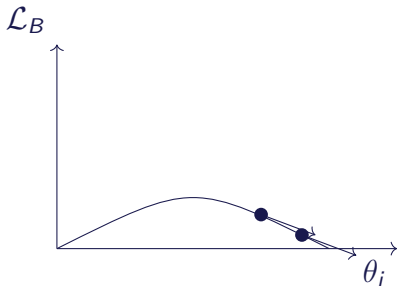


Regularization Methods



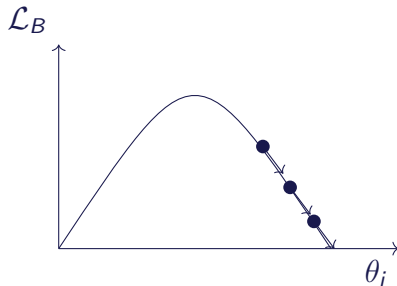
The usual gradient descent!

Regularization Methods



Low gradient

- Little change in loss.
- Less importance.



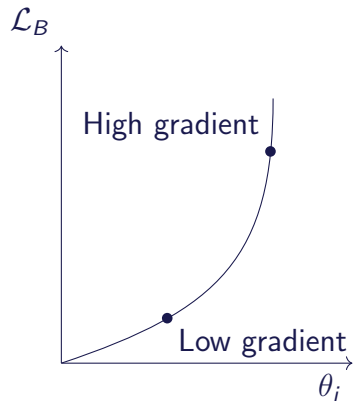
High gradient

- Large change in loss.
- High importance.

Regularization Methods

Continual learning

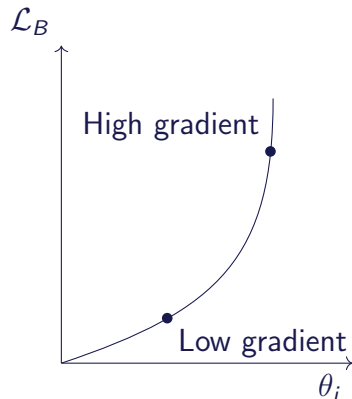
- Use parameters less important for previous tasks to learn new task.
 - Low gradient for previous tasks.
 - High gradient for current task.



Regularization Methods

Continual learning

- Use parameters less important for previous tasks to learn new task.
 - Low gradient for previous tasks.
 - High gradient for current task.
- Double derivative (gradient of the gradient) represents speed of change in the gradient.





Regularization Methods

$$\mathcal{L}_{new} = \sum_{x \in new} \mathcal{E} + c \lambda_i \sum_i (\theta_i - \theta_{i,prev})^2 \quad (7)$$

- θ_{prev} represents network parameters after learning previous tasks.
- λ_i would be estimated using double derivative [Kirkpatrick, 2016].

$$\lambda_i \propto \frac{\delta^2 \mathcal{L}}{\delta \theta_i^2}$$

- $(\theta_i - \theta_{prev})$ has the effect of keeping θ_i close to θ_{prev} when λ_i is high.
- c controls strength of regularization.



Regularization Methods

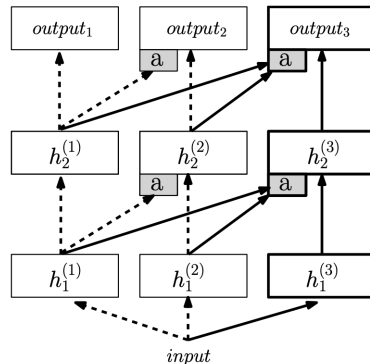
- Continual learning through synaptic intelligence - Computationally less intensive method for estimating λ .
- Memory Aware Synapses: Learning what (not) to forget - Effect of a parameter change on the network output.
- Optimization and Generalization of Regularization-Based Continual Learning: a Loss Approximation Viewpoint - Unifies various parameter-level regularization methods.
- Continual learning with node-importance based adaptive group sparse regularization, 2020 - Regularization at the level of neurons.



Architectural Methods

Architectural Methods

- Expand the network to learn new tasks.
- Brute force approach to L^2 .
- Leads to parameter explosion.



Progressive Neural Networks[Rusu, 2016]



Architectural Methods

- **Progress & compress: A scalable framework for continual learning.** - Introduced a compression step for progressive neural networks.

Prune/Add weights to the network

- **Lifelong learning with dynamically expandable networks.**
- **Compacting, picking and growing for unforgetting continual learning.**
- **Learn to grow: A continual structure learning framework for overcoming catastrophic forgetting.**

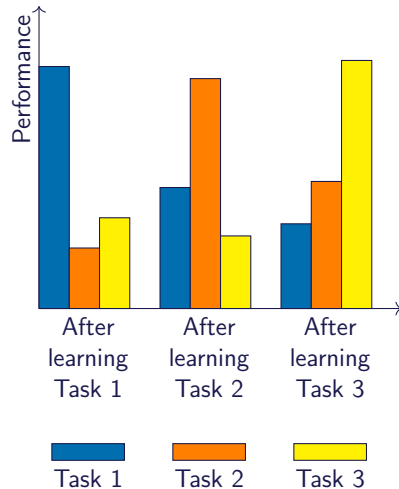


Evaluating and Debugging L^2 Methods



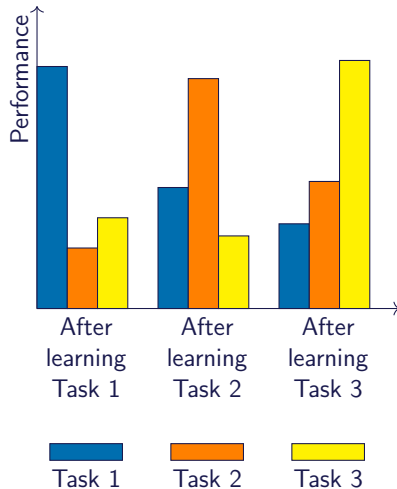
Interpreting L^2 Results

- What do you notice?



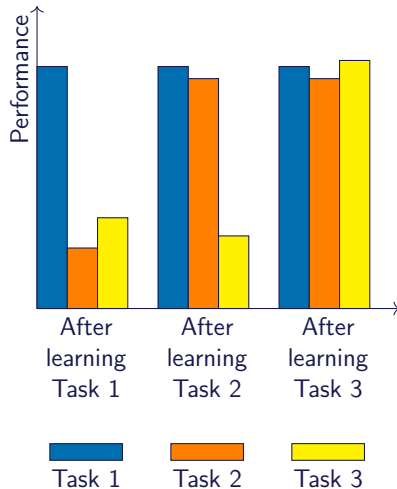
Interpreting L^2 Results

- What do you notice?
- Learned task performance is getting worse after each task is trained.
- This is a sign of catastrophic forgetting!



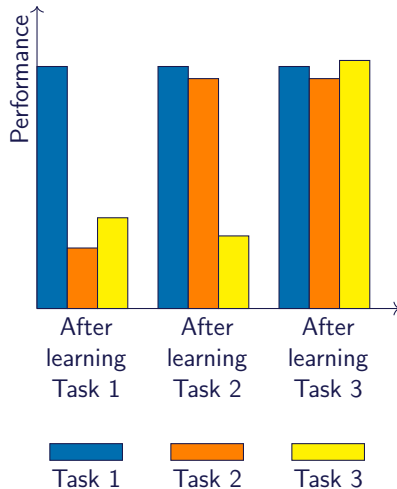
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Interpreting L^2 Results

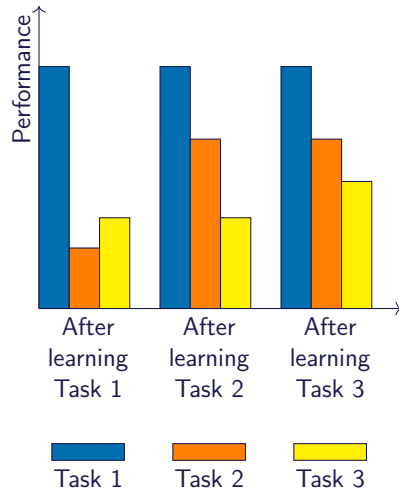
- What do you notice?
- Learned task performance is maintained after learning a new task.
- This indicates no forgetting!





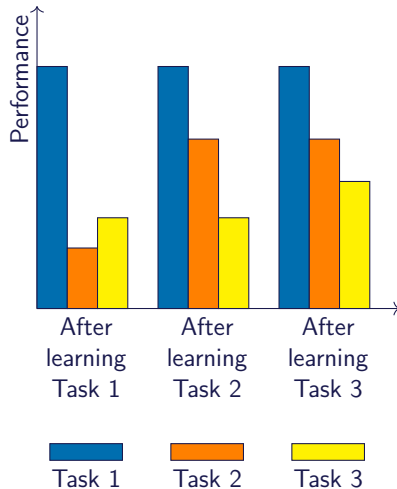
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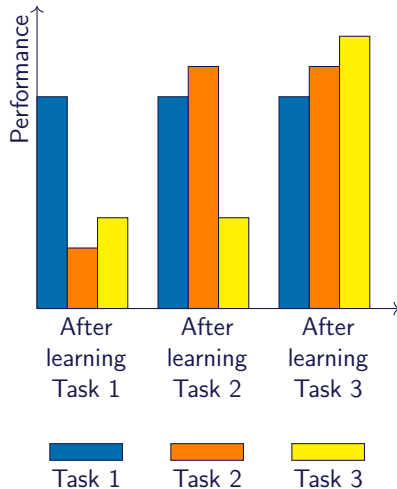
Interpreting L^2 Results

- What do you notice?
- Learned task performance is maintained but new tasks are not learned well enough.
- Problematic learning
 - Over regularization.
 - Limited network capacity.



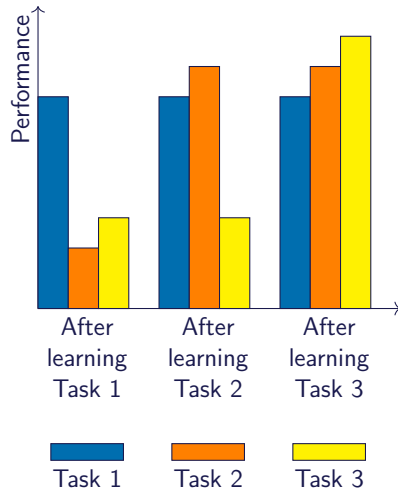
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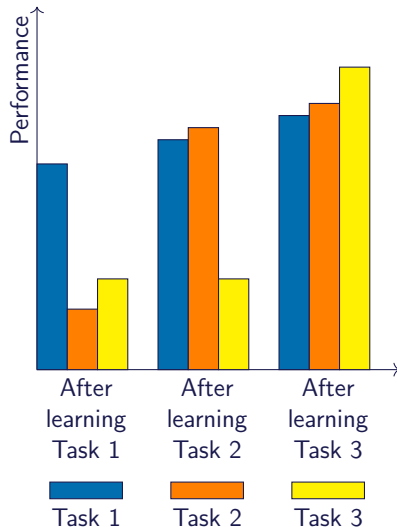
Interpreting L^2 Results

- What do you notice?
- Learned task performance is maintained
- New task performance is higher than previous task.
- **Forward transfer**
 - Future tasks utilize knowledge from previous tasks.



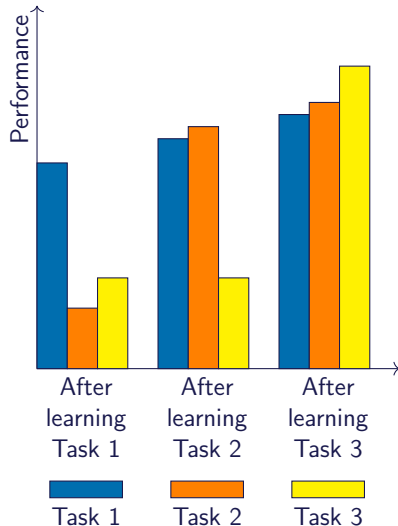
Interpreting L^2 Results

- What do you notice?



Interpreting L^2 Results

- What do you notice?
- Learned task performance is growing.
- New task performance is higher than previous task.
- Forward and **backward transfer**
 - Future tasks utilize knowledge from previous tasks.
 - Previous tasks gain from future tasks.





Metrics

- Metrics allow us to determine which scenario our model results represent.
- All L^2 metrics are computed from the accuracy matrix
Lopez-paz, 2017.

Accuracy Matrix

Testing task

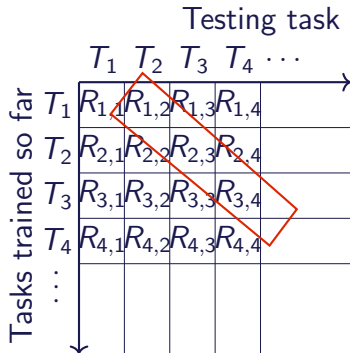
| | T_1 | T_2 | T_3 | T_4 | \dots |
|---------|-----------|-----------|-----------|-----------|---------|
| T_1 | $R_{1,1}$ | $R_{1,2}$ | $R_{1,3}$ | $R_{1,4}$ | |
| T_2 | $R_{2,1}$ | $R_{2,2}$ | $R_{2,3}$ | $R_{2,4}$ | |
| T_3 | $R_{3,1}$ | $R_{3,2}$ | $R_{3,3}$ | $R_{3,4}$ | |
| T_4 | $R_{4,1}$ | $R_{4,2}$ | $R_{4,3}$ | $R_{4,4}$ | |
| \dots | | | | | |

Tasks trained so far

$R_{m,n}$: The performance of the model on task T_n , after continually training till task T_m

Accuracy Matrix

- Increasing \rightarrow Positive Forward transfer

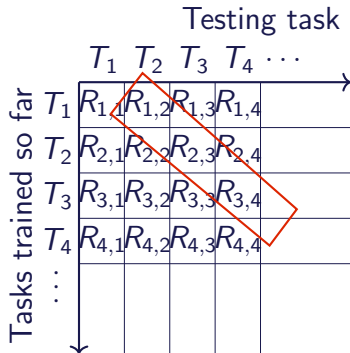


Accuracy Matrix

- Increasing \rightarrow Positive Forward transfer
- Measuring forward transfer (FWT)

$$\frac{1}{T-1} \sum_{i=2}^T (R_{i-1,i} - b_i) \quad (8)$$

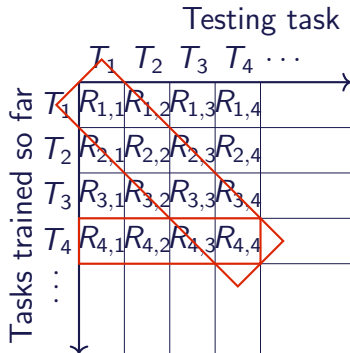
- b_i is accuracy before training.



Accuracy Matrix

- Measuring backward transfer (BWT)

$$\frac{1}{T-1} \sum_{i=1}^{T-1} (R_{T,i} - R_{i,i}) \quad (9)$$

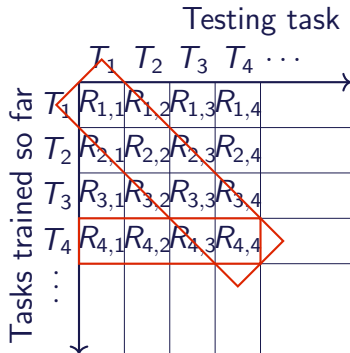


Accuracy Matrix

- Measuring backward transfer (BWT)

$$\frac{1}{T-1} \sum_{i=1}^{T-1} (R_{T,i} - R_{i,i}) \quad (9)$$

- $R_{i,i}$: accuracy after training a task.
- $R_{T,i}$: accuracy after training last task.

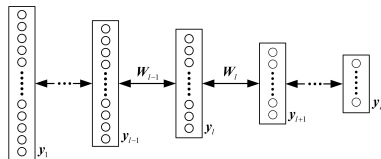




My Research Interests

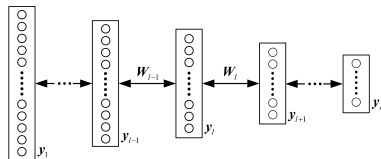
Efficient Generative L^2

- Deep Bidirectional Predictive Coding (DBPC) [Senhui 2023].
- Propagation can occur in both directions in DBPC.



Efficient Generative L^2

- Deep Bidirectional Predictive Coding (DBPC) [Senhui 2023].
- Propagation can occur in both directions in DBPC.
- Single network can do classification and generation.
 - Replay without additional memory!



Efficient Generative L^2



Task 1: 0 and 1



Task 2: 2 and 3



Task 3: 4 and 5



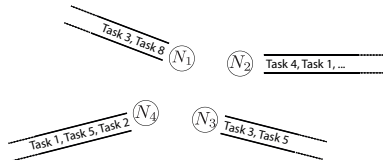
Task 4: 6 and 7



Task 5: 8 and 9

Distributed L^2

- Group of nodes perform L^2 collaboratively.
- Nodes encounter tasks in different sequence.

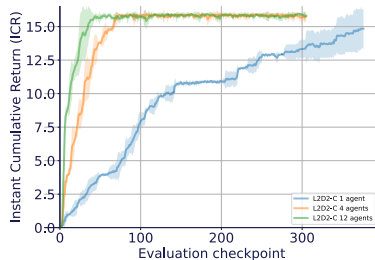
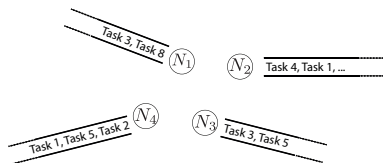


Distributed L^2

- Group of nodes perform L^2 collaboratively.
- Nodes encounter tasks in different sequence.
- Sharing knowledge improves speed of learning

[Nath 2023].

- 12 agents learned 16 tasks faster than a smaller group.
- Agents exchanged knowledge through task-specific masks.

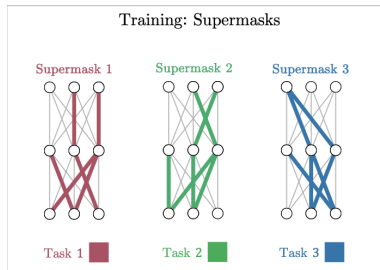


Distributed L^2

- Mask represents a subnetwork in a randomly initialized network

[Wortsman 2020].

- Training involves estimating a mask for a given task.
- Testing involves processing a sample using the estimated mask.





Thank you!

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