

# Continual Lifelong Learning



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## Problem Description

- Machine vs. Human learning

- Catastrophic Forgetting

- Overcoming Catastrophic Forgetting

## Elastic Weight Consolidation

## Continual Learning Through Synaptic Intelligence

## Comparison and Outlook

- Experiments

## Problem Description

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- ▶ State-of-the art ANNs rival human performance in a variety of domain-specific tasks

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How do we enable learning in an online fashion for ANNs?

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Problem: Minimise total loss function without access to loss function of previous tasks

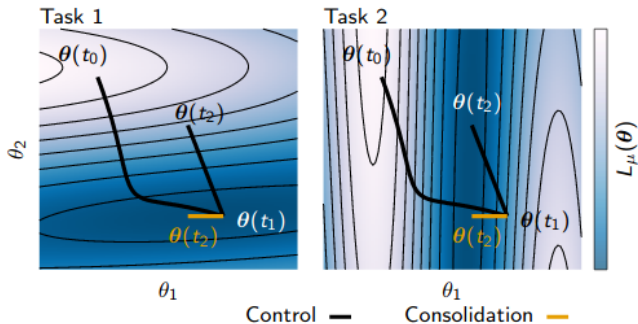


Figure: Illustration of Catastrophic Forgetting [ZPG17]

## 1. Architectural approach

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## 2. Functional approach

- ▶ Add regularisation term that penalises changes in input-output function, i.e. predictions are similar across tasks
- ▶ Computationally expensive: For every new data point, compute forward pass through old task's network

## 3. Structural approach

- ▶ Penalties on the parameters s.t. they remain close to values for old task
- ▶ Mimic complexity of biological synapses
- ▶ Retain task relevant information and measure of importance

# Elastic Weight Consolidation

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Let  $\mathcal{D}_A, \mathcal{D}_B$  be two independent tasks  $\mathcal{D}_A \cup \mathcal{D}_B = \mathcal{D}$  with learned parameters  $\theta_A, \theta_B$ :

$$\log p(\theta|\mathcal{D}) = \log p(\mathcal{D}|\theta) + \log p(\theta) - \log p(\mathcal{D}) \quad (1)$$

Independence of  $\mathcal{D}_A, \mathcal{D}_B$  gives

$$\log p(\theta|\mathcal{D}) = \underbrace{\log p(\mathcal{D}_B|\theta)}_{=-\mathcal{L}_B} + \log p(\theta|\mathcal{D}_A) - \log p(\mathcal{D}_B) \quad (2)$$

All information (including which parameters are important) about task  $A$  absorbed in posterior  $p(\theta|\mathcal{D}_A)$ .

$$\mathcal{L}(\theta) = \mathcal{L}_B(\theta) + \sum_i \frac{\lambda}{2} F_i (\theta_i - \theta_{A,i}^*)^2 \quad (3)$$

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- ▶ Posterior  $p(\theta|\mathcal{D}_A)$  approximated by  $F$
- ▶ Iteratively applicable to more than 2 tasks

# Continual Learning Through Synaptic Intelligence

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How does learning task  $k$  change the total loss? Let  $\mathbf{g} = \partial_{\boldsymbol{\theta}} \mathcal{L}$ :

$$\int_C \mathbf{g}(\boldsymbol{\theta}(t)) d\boldsymbol{\theta} = \int_{t_0}^{t_1} \mathbf{g}(\boldsymbol{\theta}(t)) \cdot \boldsymbol{\theta}'(t) dt \quad (4)$$

$$= \sum_{\mu} \sum_k \int_{t^{\mu-1}}^{t^{\mu}} g_k(\boldsymbol{\theta}(t)) \theta'_k(t) dt \quad (5)$$

$$= - \sum_{\mu} \omega_k^{\mu} \quad (6)$$

$\omega_k^{\mu}$  contribution of  $\mu$ th task and  $k$ th parameter to change in total loss

- Update  $\omega_k^\mu$  online as running sum

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  1. contribution of  $\theta_k$  to drop in Loss  $\omega_k^\nu$
  2. How much it changed  $\theta_k(t^\nu) - \theta_k(t^{\nu-1}) = \Delta_k^\nu$

(7)



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For current task  $\mu$ :

$$\Omega_k^\mu = \sum_{\nu < \mu} \frac{\omega_k^\nu}{(\Delta_k^\nu)^2 + \xi} \quad (7)$$

$$\tilde{\mathcal{L}}_{\mu}(\theta) = \mathcal{L}_{\mu}(\theta) + c \underbrace{\sum_k \Omega_k^{\mu} (\theta_k(t^{\mu-1}) - \theta_k)^2}_{\text{surrogate loss}} \quad (8)$$

$c$  strength parameter trading off old vs. new memories

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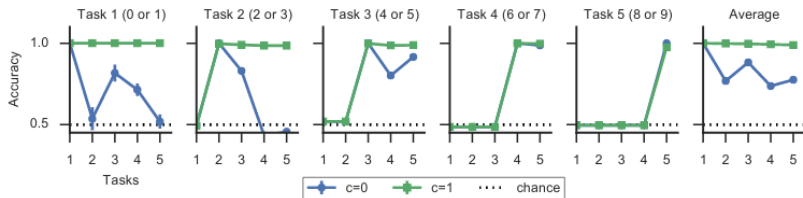
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- ▶ Surrogate loss approximates summed loss functions of previous tasks
  - ▶ Same minimum as previous parameter configuration
  - ▶ Same  $\omega_k^{\nu}$  over  $\Delta_k$
- ▶ Derivation only valid for two task; but empirically works for more

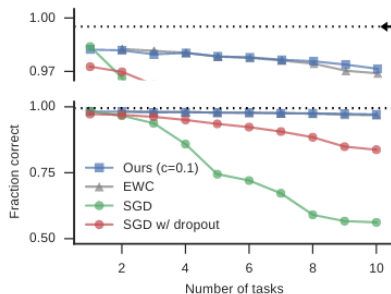
## Comparison and Outlook

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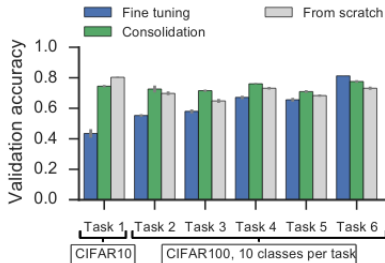
- Divide MNIST into 5 subsets of consecutive digits; learn to distinguish between two consecutive digits



- ▶ Randomly permute all MNIST pixels for a task
- ▶ Performance measured by correctness across all tasks
- ▶ Correlations of  $\omega_k^\mu$  decrease across different tasks  $\mu$ :  
”Using different weights to learn new tasks”



- First image classification on CIFAR-10, then 5 additional tasks corresponding to 10 consecutive classes from CIFAR-100
- Better validation accuracy than networks trained on single task only: Less prone to overfitting





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- ▶ Synaptic Intelligence
  - ▶ Online estimate over entire learning trajectory
  - ▶ Doesn't scale naturally to multiple tasks

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- ▶ Can we cluster important weights and use other sparsity regularisation strategies such as group Lasso?

*In addition to adding depth to our networks, we may need to add intelligence to our synapses.*



Friedemann Zenke, Ben Poole, and Surya Ganguli.  
Continual learning through synaptic intelligence, 2017.