

Automatic Differentiation

Seminar

Optimization for ML. Faculty of Computer Science. HSE University

Forward mode



Figure 1: Illustration of forward chain rule to calculate the derivative of the function v_i with respect to w_k .

- Uses the forward chain rule
- Has complexity $d \times \mathcal{O}(T)$ operations

Reverse mode



Figure 2: Illustration of reverse chain rule to calculate the derivative of the function L with respect to the node v_i .

- Uses the backward chain rule
- Stores the information from the forward pass
- Has complexity $\mathcal{O}(T)$ operations

Toy example

Example

$$f(x_1, x_2) = x_1 * x_2 + \sin x_1$$

Let's calculate the derivatives $\frac{\partial f}{\partial x_i}$ using forward and reverse modes.

Toy example

Example

$$f(x_1, x_2) = x_1 * x_2 + \sin x_1$$

Let's calculate the derivatives $\frac{\partial f}{\partial x_i}$ using forward and reverse modes.



Figure 3: Illustration of computation graph of $f(x_1, x_2)$.

Automatic Differentiation with JAX

Example №1

$$f(X) = \text{tr}(AX^{-1}B)$$

$$\nabla f = -X^{-T}A^TB^TX^{-T}$$

Automatic Differentiation with JAX

Example №1

$$f(X) = \text{tr}(AX^{-1}B)$$

$$\nabla f = -X^{-T}A^TB^TX^{-T}$$

Example №2

$$g(x) = 1/3 \cdot \|x\|_2^3$$

$$\nabla^2 g = \|x\|_2^{-1}xx^T + \|x\|_2I_n$$

Automatic Differentiation with JAX

Example №1

$$f(X) = \text{tr}(AX^{-1}B)$$

$$\nabla f = -X^{-T}A^TB^TX^{-T}$$

Example №2

$$g(x) = 1/3 \cdot \|x\|_2^3$$

$$\nabla^2 g = \|x\|_2^{-1}xx^T + \|x\|_2I_n$$

Let's calculate the gradients and Hessians of f and g in python 🐍

Problem 1

Question

Which of the AD modes would you choose (forward/ reverse) for the following computational graph of primitive arithmetic operations?



Figure 4: Which mode would you choose for calculating gradients there?

Problem 2

Suppose, we have an invertible matrix A and a vector b , the vector x is the solution of the linear system $Ax = b$, namely one can write down an analytical solution $x = A^{-1}b$.

Question

Find the derivatives $\frac{\partial L}{\partial A}$, $\frac{\partial L}{\partial b}$.



Figure 5: x could be found as a solution of linear system

Problem 3

Suppose, we have the rectangular matrix $W \in \mathbb{R}^{m \times n}$, which has a singular value decomposition:

$$W = U\Sigma V^T, \quad U^T U = I, \quad V^T V = I, \\ \Sigma = \text{diag}(\sigma_1, \dots, \sigma_{\min(m,n)})$$

The regularizer $R(W) = \text{tr}(\Sigma)$ in any loss function encourages low rank solutions.

Question

Find the derivative $\frac{\partial R}{\partial W}$.



Figure 6: Computation graph for singular regularizer

Computation experiment with JAX

Let's make sure numerically that we have correctly calculated the derivatives in problems 2-3 🧠

Feedforward Architecture



Figure 7: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The activations marked with an f . The gradient of the loss with respect to the activations and parameters marked with b .

Feedforward Architecture



Figure 7: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The activations marked with an f . The gradient of the loss with respect to the activations and parameters marked with b .

! Important

The results obtained for the f nodes are needed to compute the b nodes.

Vanilla backpropagation



Figure 8: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The purple color indicates nodes that are stored in memory.

Vanilla backpropagation



Figure 8: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The purple color indicates nodes that are stored in memory.

- All activations f are kept in memory after the forward pass.

Vanilla backpropagation



Figure 8: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The purple color indicates nodes that are stored in memory.

- All activations f are kept in memory after the forward pass.
- Optimal in terms of computation: it only computes each node once.

Vanilla backpropagation



Figure 8: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The purple color indicates nodes that are stored in memory.

- All activations f are kept in memory after the forward pass.
- Optimal in terms of computation: it only computes each node once.
- High memory usage. The memory usage grows linearly with the number of layers in the neural network.

Memory poor backpropagation



Figure 9: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The purple color indicates nodes that are stored in memory.

Memory poor backpropagation



Figure 9: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The purple color indicates nodes that are stored in memory.

- Each activation f is recalculated as needed.

Memory poor backpropagation



Figure 9: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The purple color indicates nodes that are stored in memory.

- Each activation f is recalculated as needed.
- Optimal in terms of memory: there is no need to store all activations in memory.

Memory poor backpropagation



Figure 9: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The purple color indicates nodes that are stored in memory.

- Each activation f is recalculated as needed.
- Optimal in terms of memory: there is no need to store all activations in memory.
- Computationally inefficient. The number of node evaluations scales with n^2 , whereas it vanilla backprop scaled as n : each of the n nodes is recomputed on the order of n times.

Checkpointed backpropagation



Figure 10: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The purple color indicates nodes that are stored in memory.

Checkpointed backpropagation

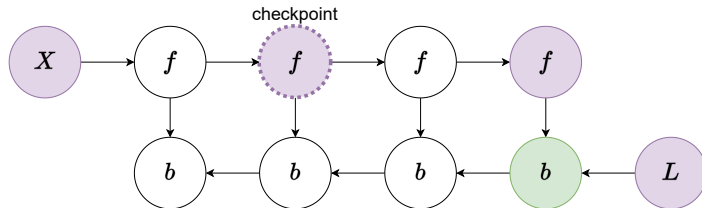


Figure 10: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The purple color indicates nodes that are stored in memory.

- Trade-off between the **vanilla** and **memory poor** approaches. The strategy is to mark a subset of the neural net activations as checkpoint nodes, that will be stored in memory.

Checkpointed backpropagation



Figure 10: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The purple color indicates nodes that are stored in memory.

- Trade-off between the **vanilla** and **memory poor** approaches. The strategy is to mark a subset of the neural net activations as checkpoint nodes, that will be stored in memory.
- Faster recalculation of activations f . We only need to recompute the nodes between a b node and the last checkpoint preceding it when computing that b node during backprop.

Checkpointed backpropagation



Figure 10: Computation graph for obtaining gradients for a simple feed-forward neural network with n layers. The purple color indicates nodes that are stored in memory.

- Trade-off between the **vanilla** and **memory poor** approaches. The strategy is to mark a subset of the neural net activations as checkpoint nodes, that will be stored in memory.
- Faster recalculation of activations f . We only need to recompute the nodes between a b node and the last checkpoint preceding it when computing that b node during backprop.
- Memory consumption depends on the number of checkpoints. More effective than **vanilla** approach.

Gradient checkpointing visualization

The animated visualization of the above approaches 

An example of using a gradient checkpointing 