

Deep Learning

Lecture 3: Automatic differentiation

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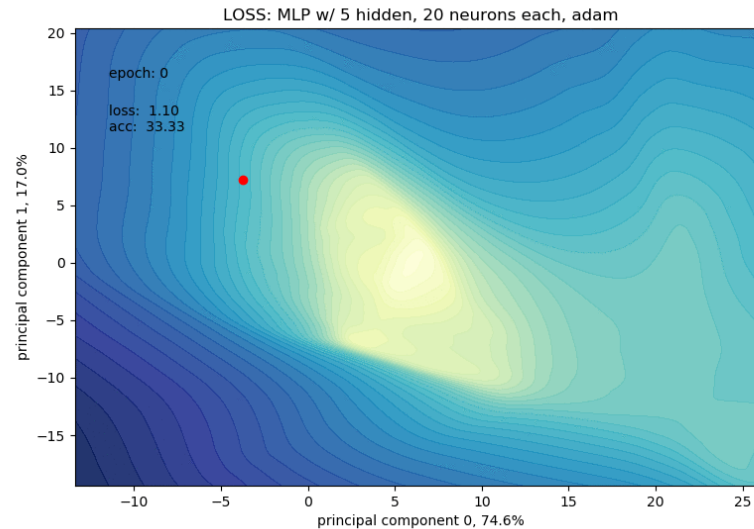
Today

- Calculus
- Automatic differentiation
- Implementation
- Beyond neural networks



Implementing backpropagation by hand is like programming in assembly language. You will probably never do it, but it is important for having a mental model of how everything works.

Roger Grosse



Motivation

- Gradient-based training algorithms are the workhorse of deep learning.
- Deriving gradients by hand is tedious and error prone. This becomes quickly impractical for complex models.
- Changes to the model require rederiving the gradient.

Programs as differentiable functions

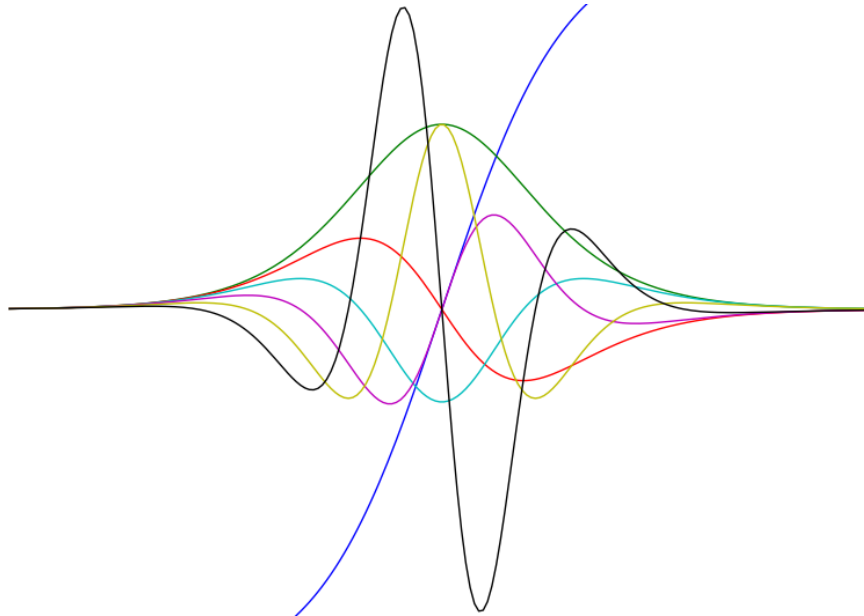
A program is defined as a composition of primitive operations that we know how to differentiate individually.

```
import jax.numpy as jnp
from jax import grad

def predict(params, inputs):
    for W, b in params:
        outputs = jnp.dot(inputs, W) + b
        inputs = jnp.tanh(outputs)
    return outputs

def loss_fun(params, inputs, targets):
    preds = predict(params, inputs)
    return jnp.mean((preds - targets)**2)

grad_fun = grad(loss_fun)
```



Modern frameworks support higher-order derivatives.

```
def tanh(x):  
    y = jnp.exp(-2.0 * x)  
    return (1.0 - y) / (1.0 + y)  
  
fp = grad(tanh)  
fpp = grad(grad(tanh)) # what sorcery is this?!  
...
```

Automatic differentiation

Automatic differentiation (AD) provides a family of techniques for evaluating the **derivatives** of a function specified **by a computer program**.

- \neq symbolic differentiation, which aims at identifying some human-readable expression of the derivative.
- \neq numerical differentiation (finite differences), which may introduce round-off errors.

Calculus

Derivative

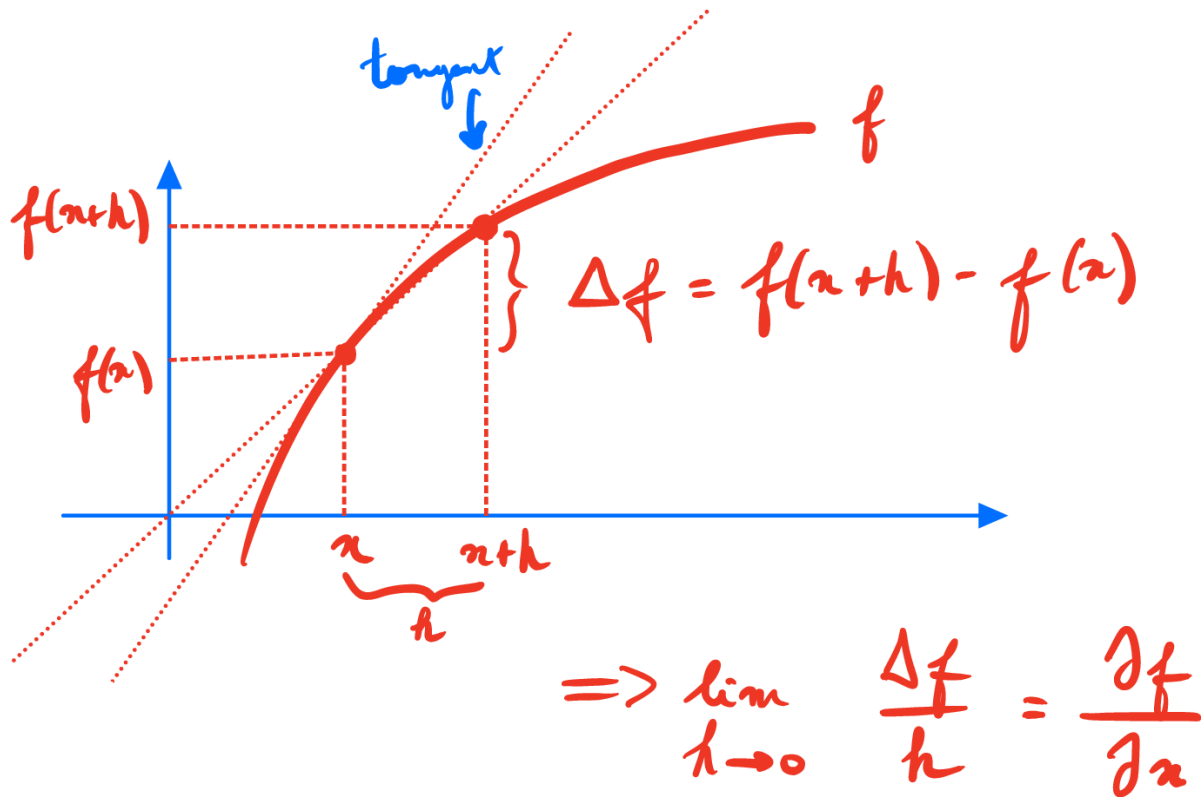
Let $f : \mathbb{R} \rightarrow \mathbb{R}$.

The derivative of f is

$$f'(x) = \frac{\partial f}{\partial x}(x) \triangleq \lim_{h \rightarrow 0} \frac{f(x+h) - f(x)}{h},$$

where

- $f'(x)$ is the Lagrange notation,
- $\frac{\partial f}{\partial x}(x)$ is the Leibniz notation.



The derivative $\frac{\partial f(x)}{\partial x}$ of f represents its instantaneous rate of change at x .

Gradient

The gradient of $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is

$$\nabla f(\mathbf{x}) \triangleq \begin{bmatrix} \frac{\partial f}{\partial x_1}(\mathbf{x}) \\ \vdots \\ \frac{\partial f}{\partial x_n}(\mathbf{x}) \end{bmatrix} \in \mathbb{R}^n,$$

i.e., a vector that gathers the partial derivatives of f .

Applying the definition of the derivative coordinate-wise, we have

$$[\nabla f(\mathbf{x})]_j = \frac{\partial f}{\partial x_j}(\mathbf{x}) = \lim_{h \rightarrow 0} \frac{f(\mathbf{x} + h\mathbf{e}_j) - f(\mathbf{x})}{h},$$

where \mathbf{e}_j is the j -th basis vector.

Jacobian

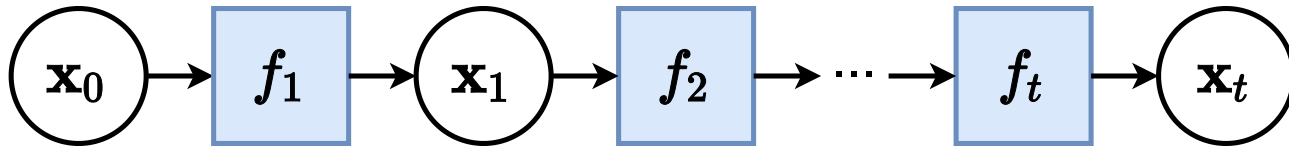
The Jacobian of $\mathbf{f} : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is

$$\begin{aligned} J_{\mathbf{f}}(\mathbf{x}) &= \frac{\partial \mathbf{f}}{\partial \mathbf{x}}(\mathbf{x}) \triangleq \begin{bmatrix} \frac{\partial f_1}{\partial x_1}(\mathbf{x}) & \cdots & \frac{\partial f_1}{\partial x_n}(\mathbf{x}) \\ \vdots & & \vdots \\ \frac{\partial f_m}{\partial x_1}(\mathbf{x}) & \cdots & \frac{\partial f_m}{\partial x_n}(\mathbf{x}) \end{bmatrix} \in \mathbb{R}^{m \times n} \\ &= \begin{bmatrix} \frac{\partial \mathbf{f}}{\partial x_1}(\mathbf{x}) & \cdots & \frac{\partial \mathbf{f}}{\partial x_n}(\mathbf{x}) \end{bmatrix} \\ &= \begin{bmatrix} \nabla f_1(\mathbf{x})^T \\ \vdots \\ \nabla f_m(\mathbf{x})^T \end{bmatrix} \end{aligned}$$

The gradient's transpose is thus a wide Jacobian ($m = 1$).

Automatic differentiation

Chain composition



Let us assume a function $\mathbf{f} : \mathbb{R}^n \rightarrow \mathbb{R}^m$ that decomposes as a chain composition

$$\mathbf{f} = \mathbf{f}_t \circ \mathbf{f}_{t-1} \circ \dots \circ \mathbf{f}_1,$$

for functions $\mathbf{f}_k : \mathbb{R}^{n_{k-1}} \rightarrow \mathbb{R}^{n_k}$, for $k = 1, \dots, t$.

By the chain rule,

$$\begin{aligned}\frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_0} &= \frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_{t-1}} \underbrace{\frac{\partial \mathbf{x}_{t-1}}{\partial \mathbf{x}_0}}_{\text{recursive case}} \\ &= \frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_{t-1}} \frac{\partial \mathbf{x}_{t-1}}{\partial \mathbf{x}_{t-2}} \cdots \frac{\partial \mathbf{x}_2}{\partial \mathbf{x}_1} \frac{\partial \mathbf{x}_1}{\partial \mathbf{x}_0}\end{aligned}$$

Forward accumulation

$$\frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_0} = \frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_{t-1}} \left(\frac{\partial \mathbf{x}_{t-1}}{\partial \mathbf{x}_{t-2}} \left(\cdots \left(\frac{\partial \mathbf{x}_2}{\partial \mathbf{x}_1} \frac{\partial \mathbf{x}_1}{\partial \mathbf{x}_0} \right) \cdots \right) \right)$$

Reverse accumulation

$$\frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_0} = \left(\left(\cdots \left(\frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_{t-1}} \frac{\partial \mathbf{x}_{t-1}}{\partial \mathbf{x}_{t-2}} \right) \cdots \right) \frac{\partial \mathbf{x}_2}{\partial \mathbf{x}_1} \right) \frac{\partial \mathbf{x}_1}{\partial \mathbf{x}_0}$$

Complexity

The time complexity of the forward and reverse accumulations are

$$\mathcal{O}\left(n_0 \sum_{k=1}^{t-1} n_k n_{k+1}\right) \quad \text{and} \quad \mathcal{O}\left(n_t \sum_{k=0}^{t-2} n_k n_{k+1}\right).$$

(Prove it!)

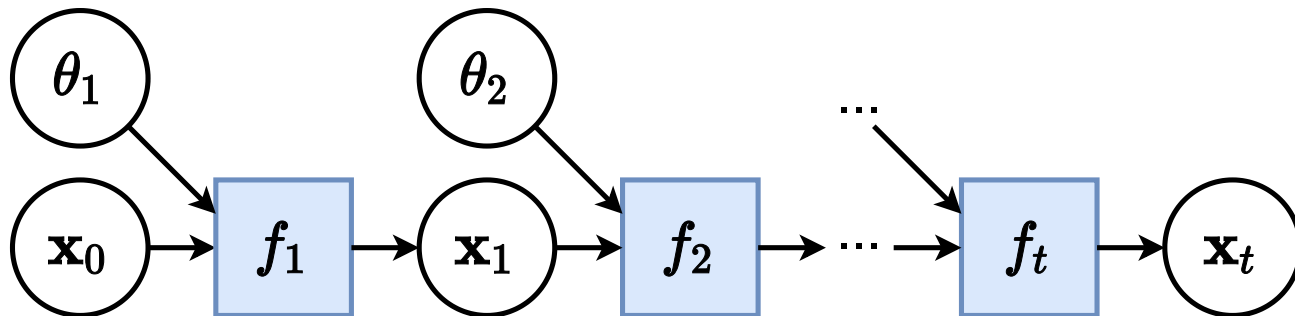
If $n_t \ll n_0$ (which is typical in deep learning), then **backward accumulation is cheaper**. And vice-versa.

Multi-layer perceptron

Chain compositions can be generalized to feedforward neural networks of the form

$$\mathbf{x}_k = \mathbf{f}_k(\mathbf{x}_{k-1}, \theta_k)$$

for $k = 1, \dots, t$, and where θ_k are vectors of parameters and $\mathbf{x}_0 \in \mathbb{R}^{n_0}$ is given. In supervised learning, \mathbf{f}_t usually corresponds to a scalar loss ℓ , hence $n_t = 1$.



(whiteboard example)

AD on computer programs

Let $\mathbf{f}(\mathbf{x}_1, \dots, \mathbf{x}_s)$ denote a generic function where

- $\mathbf{x}_1, \dots, \mathbf{x}_s$ are the input variables,
- $f(\mathbf{x}_1, \dots, \mathbf{x}_s)$ is implemented by a computer program producing intermediate variables $(\mathbf{x}_{s+1}, \dots, \mathbf{x}_t)$,
- t is the total number of variables, with \mathbf{x}_t denoting the output variable,
- $\mathbf{x}_k \in \mathbb{R}^{n_k}$, for $k = 1, \dots, t$.

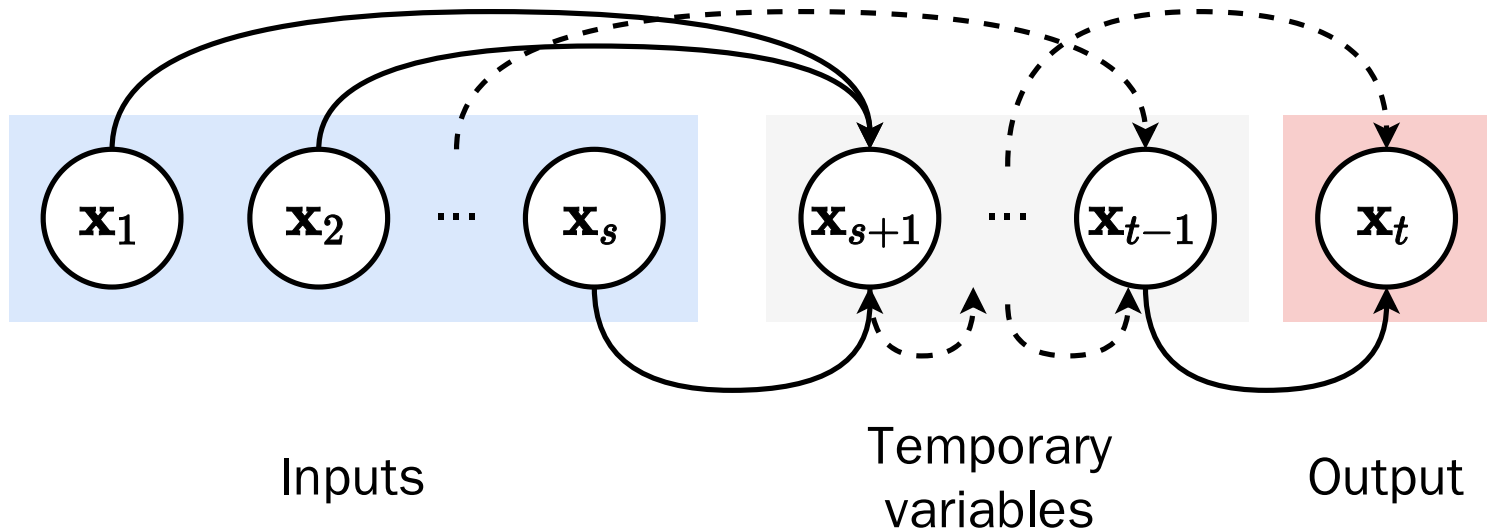
The goal is to compute the Jacobians $\frac{\partial \mathbf{f}}{\partial \mathbf{x}_k} \in \mathbb{R}^{n_t \times n_k}$, for $k = 1, \dots, s$.

Computer programs as computational graphs

A numerical algorithm is a succession of instructions of the form

$$\forall k = s + 1, \dots, t, \quad \mathbf{x}_k = \mathbf{f}_k(\mathbf{x}_1, \dots, \mathbf{x}_{k-1})$$

where \mathbf{f}_k is a function which only depends on the previous variables.



This computation can be represented by a **directed acyclic graph** where

- the nodes are the variables \mathbf{x}_k ,
- an edge connects \mathbf{x}_i to \mathbf{x}_k if \mathbf{x}_i is an argument of \mathbf{f}_k .

The evaluation of $\mathbf{x}_t = \mathbf{f}(\mathbf{x}_1, \dots, \mathbf{x}_s)$ thus corresponds to a forward traversal of this graph.

Forward mode

The **forward mode** of automatic differentiation consists in computing

$$\frac{\partial \mathbf{x}_k}{\partial \mathbf{x}_1} \in \mathbb{R}^{n_k \times n_1}$$

for all variables \mathbf{x}_k , iteratively from $k = s + 1$ to $k = t$.

Initialization

Set the Jacobians of the input nodes with

$$\begin{aligned} \frac{\partial \mathbf{x}_1}{\partial \mathbf{x}_1} &= \mathbf{1}_{n_1 \times n_1} \\ \frac{\partial \mathbf{x}_2}{\partial \mathbf{x}_1} &= \mathbf{0}_{n_2 \times n_1} \\ &\dots \\ \frac{\partial \mathbf{x}_s}{\partial \mathbf{x}_1} &= \mathbf{0}_{n_s \times n_1} \end{aligned}$$

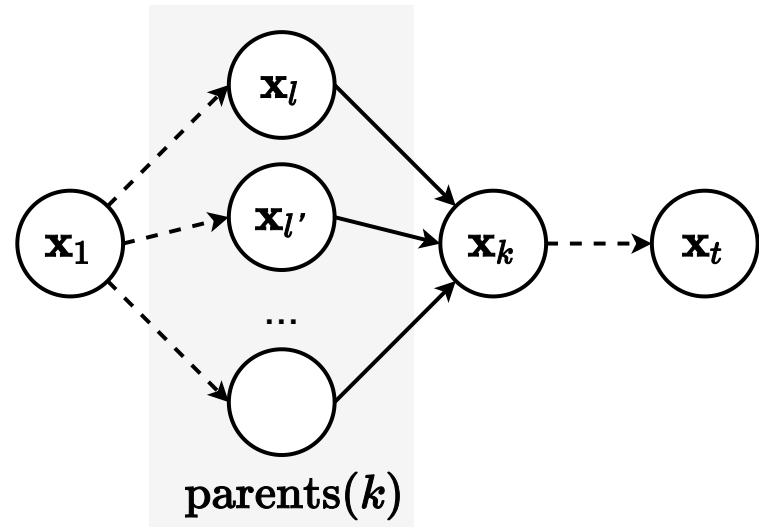
Forward recursive update

For all $k = s + 1, \dots, t$,

$$\frac{\partial \mathbf{x}_k}{\partial \mathbf{x}_1} = \sum_{l \in \text{parents}(k)} \left[\frac{\partial \mathbf{x}_k}{\partial \mathbf{x}_l} \right] \times \frac{\partial \mathbf{x}_l}{\partial \mathbf{x}_1},$$

where

- $\left[\frac{\partial \mathbf{x}_k}{\partial \mathbf{x}_l} \right]$ denotes the on-the-fly computation of the Jacobian locally associated to the primitive \mathbf{f}_k ,
- $\frac{\partial \mathbf{x}_l}{\partial \mathbf{x}_1}$ is obtained from the previous iterations (in topological order).



(whiteboard example)

Forward mode automatic differentiation needs to be repeated for $k = 1, \dots, s$. For a large s , this is prohibitive.

However, the cost in terms of memory is limited since temporary variables can be freed as soon as their child nodes have all been computed.

Backward mode

Instead of evaluating the Jacobians $\frac{\partial \mathbf{x}_k}{\partial \mathbf{x}_1} \in \mathbb{R}^{n_k \times n_1}$ for $k = s + 1, \dots, t$, the **reverse mode** of automatic differentiation consists in computing

$$\frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_k} \in \mathbb{R}^{n_t \times n_k}$$

recursively from $k = t$ down to $k = 1$.

Initialization

Set the Jacobian of the output node to

$$\frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_t} = \mathbf{1}_{n_t \times n_t}.$$

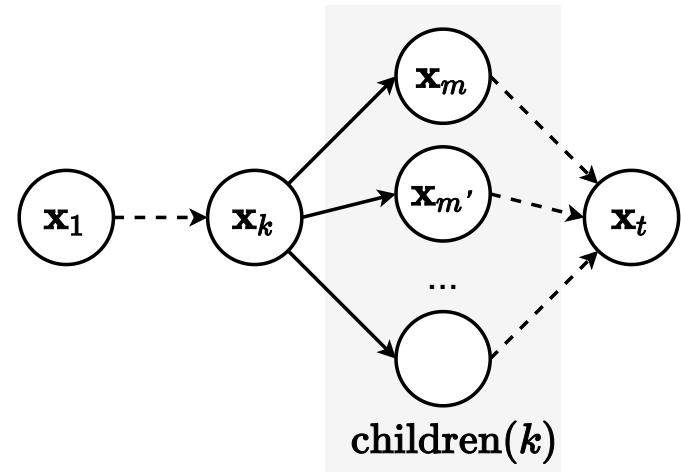
Backward recursive update

For all $k = t - 1, \dots, 1$,

$$\frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_k} = \sum_{m \in \text{children}(k)} \frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_m} \times \begin{bmatrix} \frac{\partial \mathbf{x}_m}{\partial \mathbf{x}_k} \end{bmatrix}$$

where

- $\frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_m}$ is obtained from previous iterations (in reverse topological order) and is known as the adjoint,
- $\begin{bmatrix} \frac{\partial \mathbf{x}_m}{\partial \mathbf{x}_k} \end{bmatrix}$ denotes the on-the-fly computation of the Jacobian locally associated to the primitive \mathbf{f}_m .



(whiteboard example)

The advantage of backward mode automatic differentiation is that a single traversal of the graph allows to compute all $\frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_k}$.

However, the cost in terms of memory is significant since all the temporary variables computed during the forward pass must be kept in memory.

Implementations

 PyTorch

 TensorFlow



Primitives

Most automatically-differentiable frameworks are defined by a collection of composable [primitive](#) operations.



Search docs

TUTORIALS

JAX Quickstart

How to Think in JAX

The Autodiff Cookbook

Autobatching log-densities example

Training a Simple Neural Network, with
Tensorflow Datasets Data Loading

ADVANCED JAX TUTORIALS

JAX - The Sharp Bits

Custom derivative rules for JAX-
transformable Python functions

How JAX primitives work

Writing custom Jaxpr interpreters in
JAX

Training a Simple Neural Network, with
PyTorch Data Loading

XLA in Python

Caution: This is a pedagogical notebook
covering some low level XLA details, the
APIs herein are neither public nor
stable!

Docs » [Public API: jax package](#) » [jax.lax package](#)

[Edit on GitHub](#)

jax.lax package

`jax.lax` is a library of primitives operations that underpins libraries such as `jax.numpy`. Transformation rules, such as JVP and batching rules, are typically defined as transformations on `jax.lax` primitives.

Many of the primitives are thin wrappers around equivalent XLA operations, described by the [XLA operation semantics](#) documentation. In a few cases JAX diverges from XLA, usually to ensure that the set of operations is closed under the operation of JVP and transpose rules.

Where possible, prefer to use libraries such as `jax.numpy` instead of using `jax.lax` directly. The `jax.numpy` API follows NumPy, and is therefore more stable and less likely to change than the `jax.lax` API.

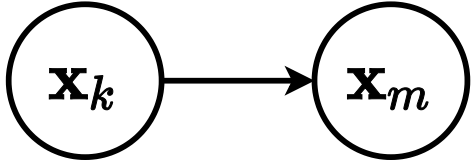
Operators

<code>abs(x)</code>	Elementwise absolute value: $ x $.
<code>add(x, y)</code>	Elementwise addition: $x + y$.
<code>acos(x)</code>	Elementwise arc cosine: $\text{acos}(x)$.
<code>argmax(operand, axis, index_dtype)</code>	Computes the index of the maximum element.
<code>argmin(operand, axis, index_dtype)</code>	Computes the index of the minimum element.
<code>asin(x)</code>	Elementwise arc sine: $\text{asin}(x)$.
<code>atan(x)</code>	Elementwise arc tangent: $\text{atan}(x)$.
<code>atan2(x, y)</code>	Elementwise arc tangent of two variables:
<code>batch_matmul(lhs, rhs[, precision])</code>	Batch matrix multiplication.

Composing primitives

Primitive functions are composed together into a graph that describes the computation. The computational graph is either built

- **ahead of time**, from the abstract syntax tree of the program or using a dedicated API (e.g., Tensorflow 1), or
- **just in time**, by tracing the program execution (e.g., Tensorflow Eager, JAX, PyTorch).

$$\frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_k} = ? \quad \frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_m}$$


A diagram showing two circular nodes. The left node is labeled \mathbf{x}_k and the right node is labeled \mathbf{x}_m . A horizontal arrow points from the left node to the right node, indicating a dependency of \mathbf{x}_m on \mathbf{x}_k .

VJPs

In the backward recursive update, in the situation above, we have when $\mathbf{x}_t \in \mathbb{R}$

$$\frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_k} = \underbrace{\frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_m}}_{1 \times n_m} \underbrace{\begin{bmatrix} \frac{\partial \mathbf{x}_m}{\partial \mathbf{x}_k} \end{bmatrix}}_{n_m \times n_k}$$

- Therefore, each primitive only needs to define its **vector-Jacobian product** (VJP). The Jacobian $\begin{bmatrix} \frac{\partial \mathbf{x}_m}{\partial \mathbf{x}_k} \end{bmatrix}$ is never explicitly built. It is usually simpler, faster, and more memory efficient to compute the VJP directly.
- Most reverse mode AD systems compose VJPs backward to compute $\frac{\partial \mathbf{x}_t}{\partial \mathbf{x}_1}$.

JVPs

Similarly, when $n_1 = 1$, the forward recursive update

$$\frac{\partial \mathbf{x}_k}{\partial \mathbf{x}_1} = \underbrace{\begin{bmatrix} \frac{\partial \mathbf{x}_k}{\partial \mathbf{x}_l} \\ \frac{\partial \mathbf{x}_k}{\partial \mathbf{x}_1} \end{bmatrix}}_{n_k \times n_l} \underbrace{\frac{\partial \mathbf{x}_l}{\partial \mathbf{x}_1}}_{n_l \times 1}$$

is usually implemented in terms of **Jacobian-vector products** (JVP) locally defined at each primitive.

Checkpointing

Checkpointing consists in marking intermediate variables for which the forward values are not stored in memory. These are recomputed during the backward pass, which can save memory at the cost of recomputation.

```
class MLP(nn.Module):
    def __init__(self):
        super().__init__()
        self.layer1 = nn.Linear(100, 200)
        self.relu = nn.ReLU()
        self.layer2 = nn.Linear(200, 10)

    def forward(self, x):
        x = checkpoint(self.layer1, x) # x is not stored
                                       # it will be recomputed
                                       # during the backward pass

        x = self.relu(x)
        x = self.layer2(x)
        return x
```

Higher-order derivatives

```
def tanh(x):  
    y = jnp.exp(-2.0 * x)  
    return (1.0 - y) / (1.0 + y)  
  
fp = grad(tanh)  
fpp = grad(grad(tanh))    # what sorcery is this?!  
...
```

The backward pass is itself a composition of primitives. Its execution can be traced, and reverse mode AD can run on its computational graph!

(demo)

AD beyond neural networks



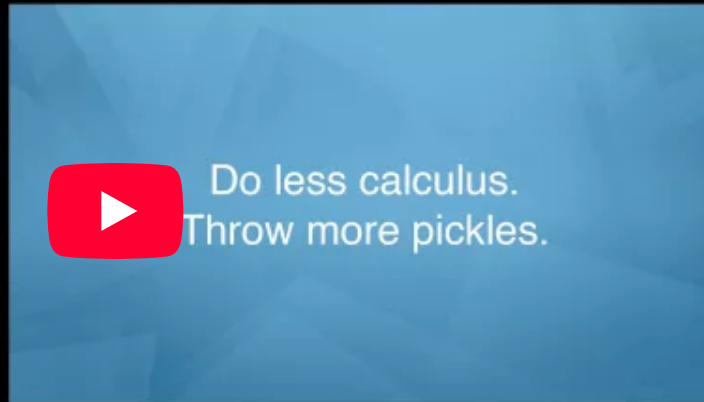
You Should Be Using Automatic Differentiat...



Later bekij...



Delen



hakka labs

You should be using automatic differentiation (Ryan Adams, 2016)



gradsim - under review

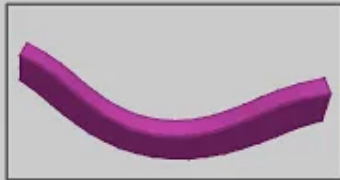


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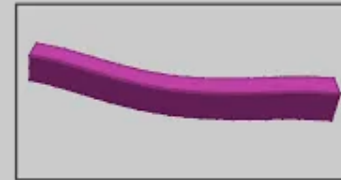
Physical parameter estimation: deformable solids



Initial guess



After optimization

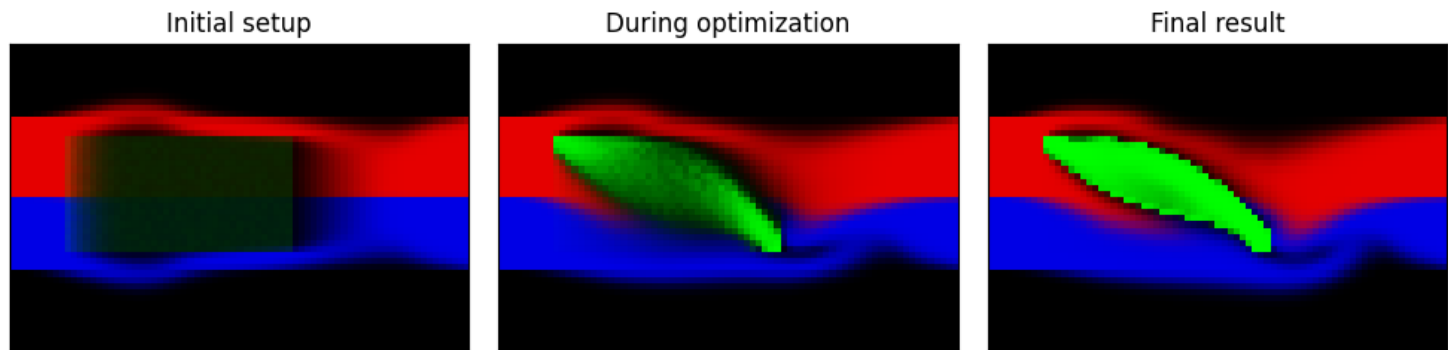


Ground-truth



* Best watched with audio enabled

Differentiable simulation for system identification and visuomotor control
(Murthy Jatavallabhula et al, 2021)



Optimizing a wing (Sam Greydanus, 2020)

[Run in browser]

Summary

- Automatic differentiation is one of the keys that enabled the deep learning revolution.
- Backward mode automatic differentiation is more efficient when the function has more inputs than outputs.
- Applications of AD go beyond deep learning.

References

Slides from this lecture have been largely adapted from:

- Mathieu Blondel, [Automatic differentiation](#), 2020.
- Gabriel Peyré, [Course notes on Optimization for Machine Learning](#), 2020.