

Basics of Deep Learning

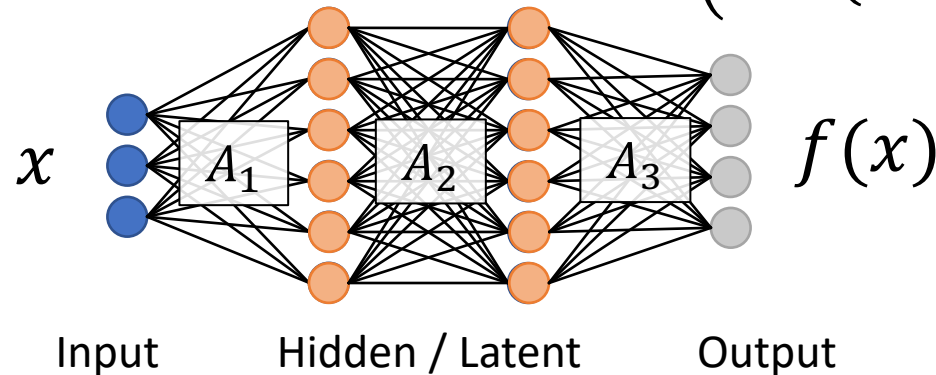
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What is deep learning?

Sequential transformations learned from data

- ▶ Classical deep neural networks $f(x) = \sigma(A_3\sigma(A_2\sigma(A_1x)))$



- ▶ More generally, [deep models](#) are sequential transformations:

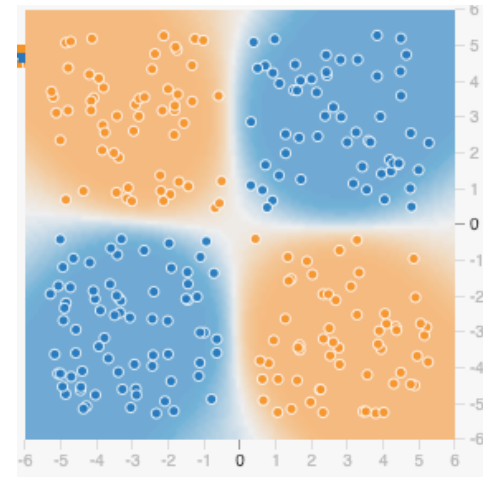
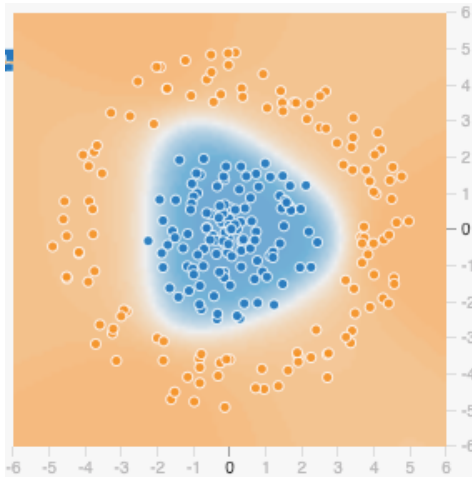
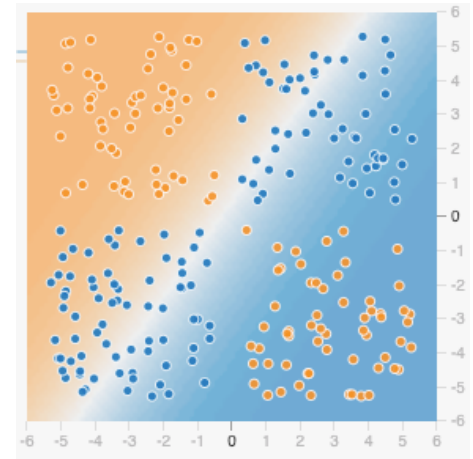
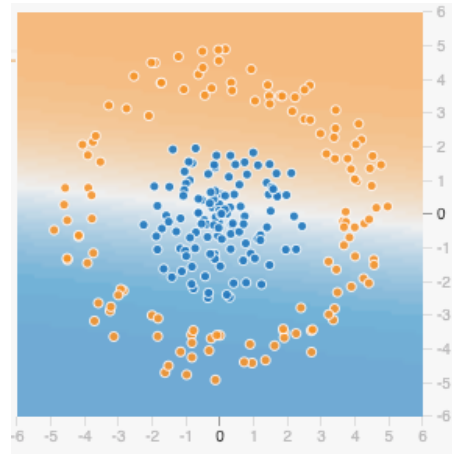
$$f(x) = f_3(f_2(f_1(x)))$$

- ▶ $z^{(1)} = f_1(x)$ (Layer 1)
- ▶ $z^{(2)} = f_2(z^{(1)})$ (Layer 2)
- ▶ $z^{(3)} = f_3(z^{(2)})$ (Layer 3)

- ▶ [Deep learning](#) estimates these transformations from data

Motivation: Linear models cannot model complex classification boundaries

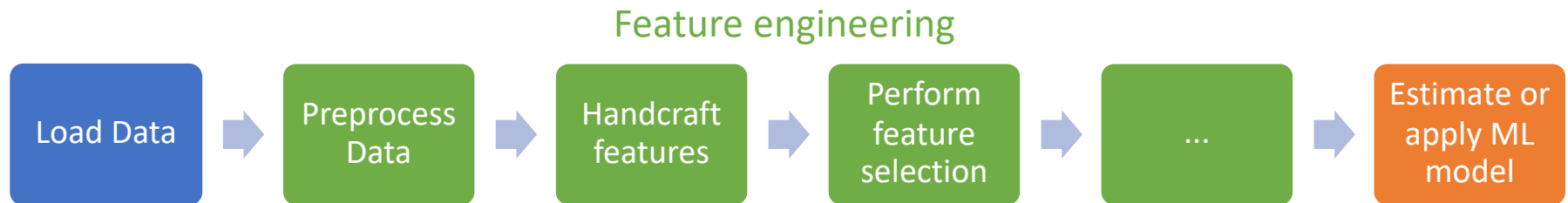
- ▶ Linear models cannot capture complex patterns
- ▶ With deep neural network, we can capture non-linear patterns



<https://playground.tensorflow.org/>

Motivation: Hand crafting features can increase performance but is expensive

Classical Machine Learning



Deep Learning

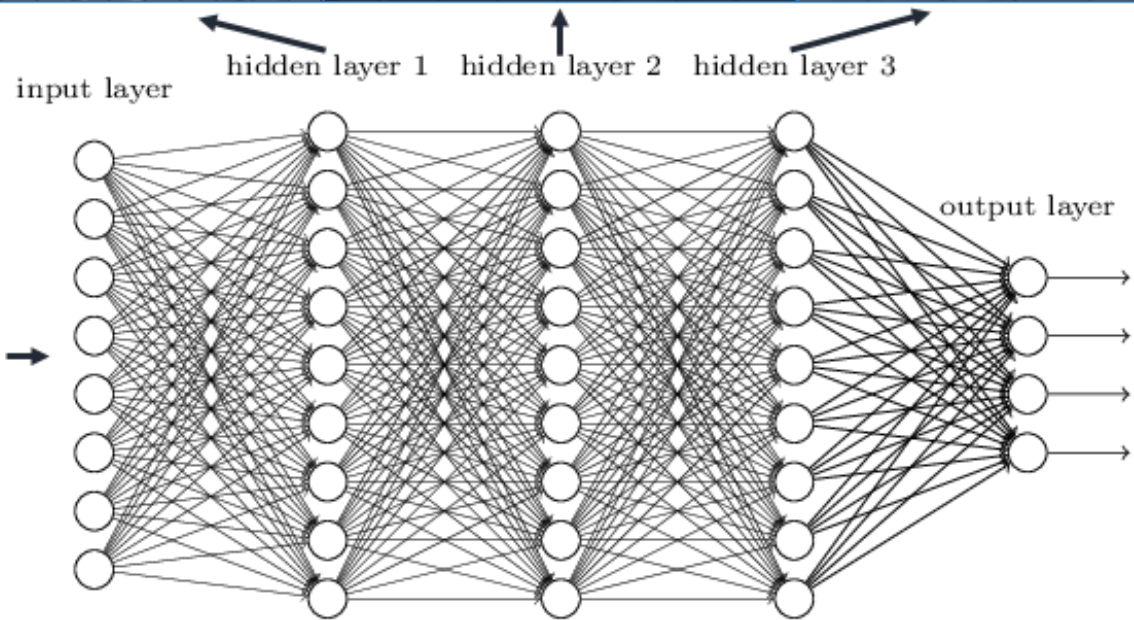
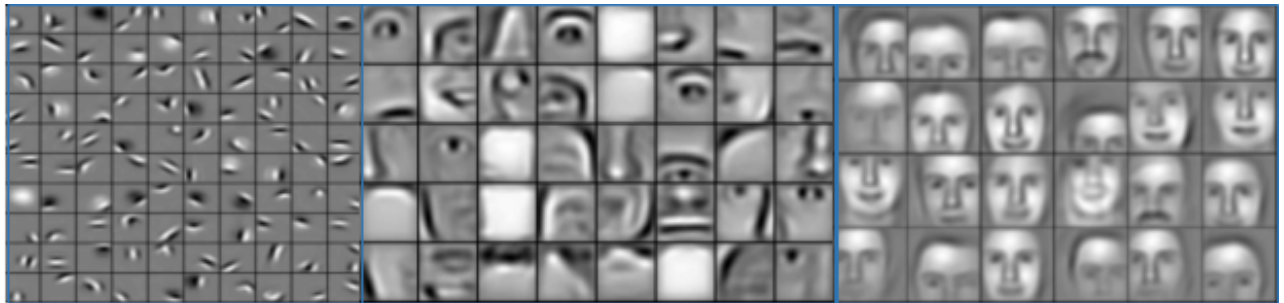
Let the deep model do all the feature engineering automatically! :-)



Caveat: But now you have to select the model architecture (a little like feature engineering).

Motivation: Deep learning can automatically learn a hierarchy of representations

Deep neural networks learn hierarchical feature representations



<https://towardsdatascience.com/a-road-map-for-deep-learning-b9aee0b2919f>

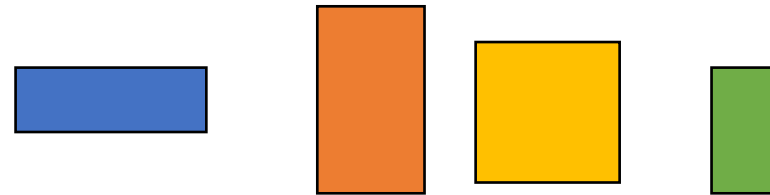
The key design choices of deep learning are architecture, objective function, and algorithm

1. Deep model **architecture**
2. Deep learning optimization **algorithm**
3. Deep learning **objective function** design
 - ▶ (Application specific so we will discuss later with GANs, VAEs, etc.)

The model architecture defines the structure of the model (though not parameter values)

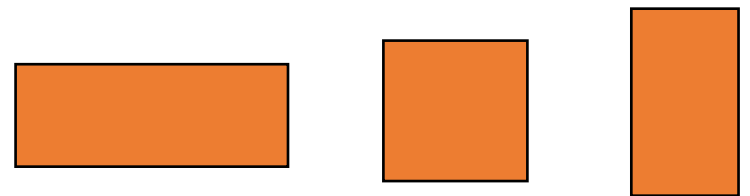
▶ Which layers or modules?

- ▶ Fully connected
- ▶ Convolutional
- ▶ Residual blocks
- ▶ ...

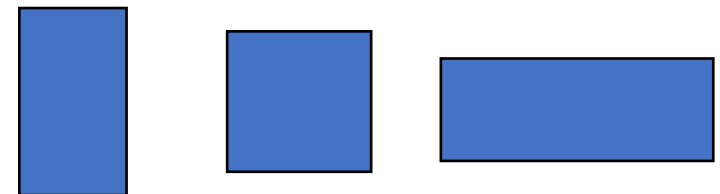


▶ How big?

- ▶ What is the dimensions of the input and output?

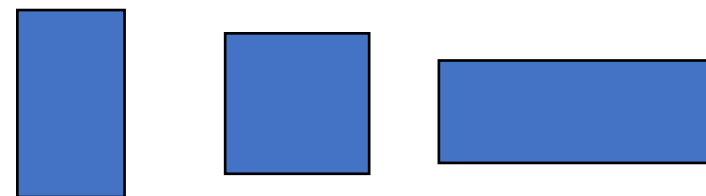
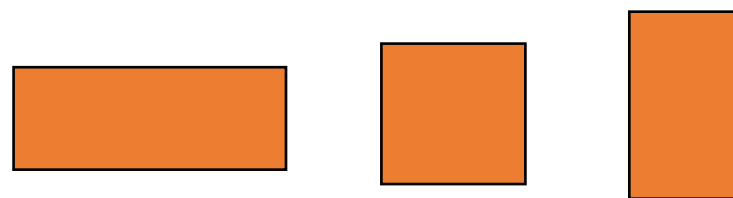
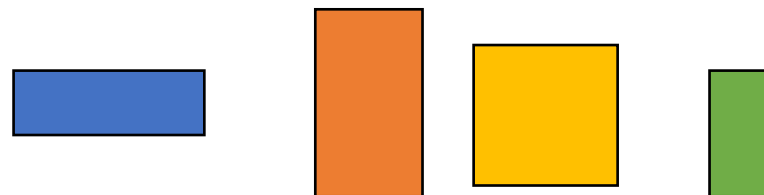


▶ How many and in what order?



The architecture defines the inductive bias of the model

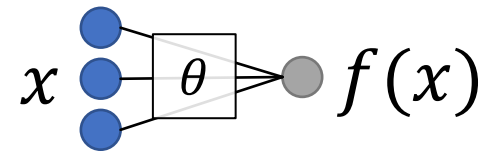
- ▶ **Inductive bias** is the bias of the model to perform better on certain problems
- ▶ A modern view of the “No Free Lunch Theorem”
- ▶ Example: Convolutional networks perform very well on image data
- ▶ Example: Attention-based “Transformer” networks have proven particularly successful for sequence data



Fully connected layers are linear functions followed by elementwise non-linear activation functions

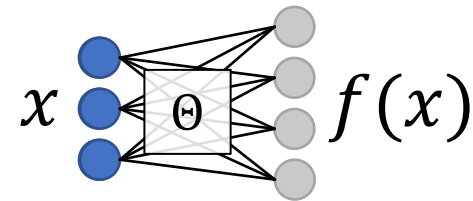
- ▶ Remember logistic regression:

$$f(x) = \sigma(\theta^T x)$$



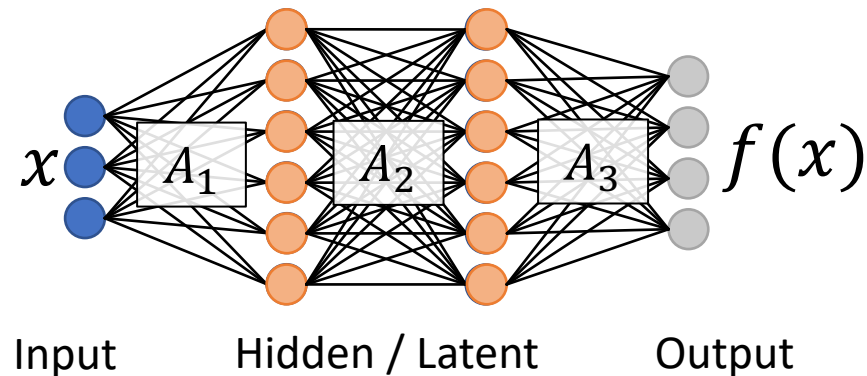
- ▶ A fully connected layer can be seen as multiple logistic regressions:

$$f_{FC}(x) = [\sigma(\theta_1^T x), \dots, \sigma(\theta_k^T x)]$$



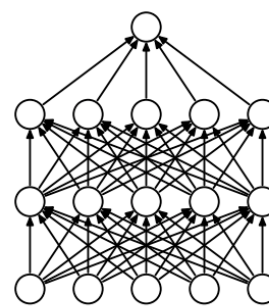
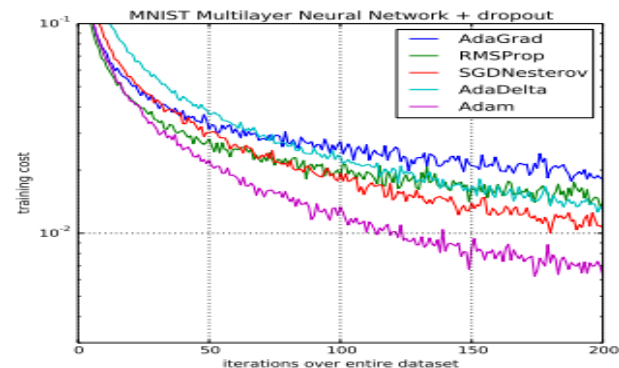
- ▶ A deep fully connected network is multiple fully connected layers:

$$f(x) = \sigma \left(A_3 \sigma \left(A_2 \sigma \left(A_1 x \right) \right) \right)$$

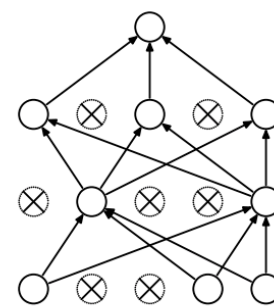


The optimization algorithm defines how the parameters will be updated

- ▶ **Optimizer**
 - ▶ SGD, ADAM, etc.
 - ▶ Step size
- ▶ **Special “optimization” layers**
 - ▶ BatchNorm
 - ▶ Dropout
- ▶ **Order of optimization updates**
 - ▶ Example: Multiple inner optimization problems (e.g., adversarial optimization, GAN)



(a) Standard Neural Net



(b) After applying dropout.

Automatic differentiation enables decoupling between architecture design and algorithm

- ▶ All computation can be broken into simple components
 - ▶ Examples: sum, multiply, exponential, convolution
- ▶ Derivatives can be derived mathematically
- ▶ Derivatives for **any composition** can be derived via chain rule! 😊
- ▶ (Prof. Jeffrey Siskind was a pioneer in automatic differentiation, see <https://www.jmlr.org/papers/volume18/17-468/17-468.pdf>)

Reverse-mode automatic differentiation can be computed in almost the same time as the original computation itself!

- ▶ Forward pass: Original objective computation
$$\mathcal{L}(X, y; \theta) = \frac{1}{n} \sum_i \ell \left(y_i, f_k \left(\cdots f_2(f_1(x_i)) \right) \right)$$

- ▶ Backward pass: Compute gradient by stepping backwards through computation

$$\nabla_{\theta} \mathcal{L}(X, y; \theta)$$

- ▶ Also called “backpropagation” algorithm since it backpropagates the derivative
- ▶ Amazingly, the cost of the forward and backward passes are **equal up to a constant**

PyTorch and TensorFlow implement automatic differentiation directly

- ▶ Demo doing automatic differentiation