Analyzing Software using Deep Learning

Introduction

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Prof. Dr. Michael Pradel

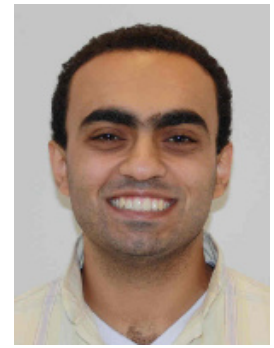
Software Lab, TU Darmstadt

About Me

- **Michael Pradel**
- **At TU Darmstadt since 2014**

- **Before joining TUDA**
  - Master-level studies in Dresden and Paris
  - Master thesis at EPFL, Switzerland
  - PhD at ETH Zurich, Switzerland
  - Postdoctoral researcher at UC Berkeley, USA

About the Software Lab



- **My research group since 2014**
- **Focus: Tools and techniques for building reliable, efficient, and secure software**
  - Program analysis
  - Test generation
- **Thesis and job opportunities**

Plan for Today

- **Introduction**
  - What the course is about
  - Why it is interesting
  - How it can help you
- **Organization**
  - Lectures and final exam
  - Course project
- **Basics**
  - Program analysis
  - Deep learning

What is Program Analysis?

- **Automated analysis of program behavior, e.g., to**
  - find programming errors
  - optimize performance
  - find security vulnerabilities

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Why Do We Need It?

Basis for various tools that make developers productive

- Compilers
- Bug finding tools
- Performance profilers
- Code completion
- Automated testing
- Code summarization/documentation

Traditional Approaches

- **Analysis has built-in knowledge about the problem to solve**
- **Significant human effort to create a program analysis**
  - Conceptual challenges
  - Implementation effort
- **Analyze a single program at a time**

Learning from Existing Data

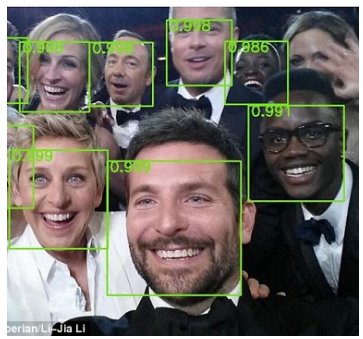
- **Huge amount of existing code ("big code")**
- **Programs are regular and repetitive**
- **Machine learning: Extract knowledge and apply in new contexts**
- **Learn how to ..**
  - .. complete partial code
  - .. use an API
  - .. fix programming errors
  - .. create inputs for testing

Deep Learning

Class of machine learning algorithms

- Neural network architectures
- ”Deep” = multiple layers
- Features and representation of inputs are extracted automatically

Revolutionizes entire areas



AlphaGo

This Course

Intersection of program analysis and deep learning

- Some of the basics:
  E.g., program representations, neural network architectures
- State of the art research results:
  Based on recent research papers
- Hands-on experience:
  Coding project

Not This Course

What this course is not about

- Detailed coverage of program analysis
- Detailed coverage of machine learning
- Programming tutorial for TensorFlow

Check out related courses

- E.g., ”Program Testing and Analysis” (winter semester)

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Organization

- **Weekly meetings**
  - 6 lectures
  - 6 Q&A sessions for course project
- **Reading material**
- **2nd half of semester (from May 14):**
  - Course project
- **July 9: Submission of project**
- **Exam period: Written exam**

Grading

50% written exam

- Content of lectures and reading material
- Open book, one hour
- Will test your understanding, not your memory

50% course project

- Effectiveness of your implementation
- Documentation and code quality

Piazza

Platform for discussions, in-class quizzes, and sharing additional material

- Please register and enroll for the class
- Use it for all questions related to the course
- Messages sent to all students go via Piazza (not TUCaN!)

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Learning Material

There is no script or single book that covers everything

- Slides and hand-written nodes:
  Available after lecture
- Pointers to papers, book chapters, and web resources

Course Project

- **Individual project**
- **Same task for everybody**
- **Implement and evaluate a neural network that predicts/generates code**
- **Based on existing tools**
  - TensorFlow library for machine learning
  - Python
- **More details on May 14**

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Program Analysis

Many ways to represent (parts of) a program

- Sequence of characters
- Sequence of tokens
- Abstract syntax tree
- Control flow graph
- Call graph
- etc.

Program Analysis

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Tokens

Tokenizer (or lexer)

- Part of compiler
- Splits sequence of characters into subsequences called tokens

E.g., for Java, six kinds of tokens:

- Identifiers, e.g., `MyClass`
- Keywords, e.g., `if`
- Separators, e.g., `.` or {
- Operators, e.g., `*` or `++`
- Literals, e.g., `23` or `"hi"`
- Comments, e.g., `/* bla */`

Tokens : Example

```
if ( flag == true ) {
    name = "Joe" ;
}
```

Identifier
Keywords
Separators
Operators
Literal

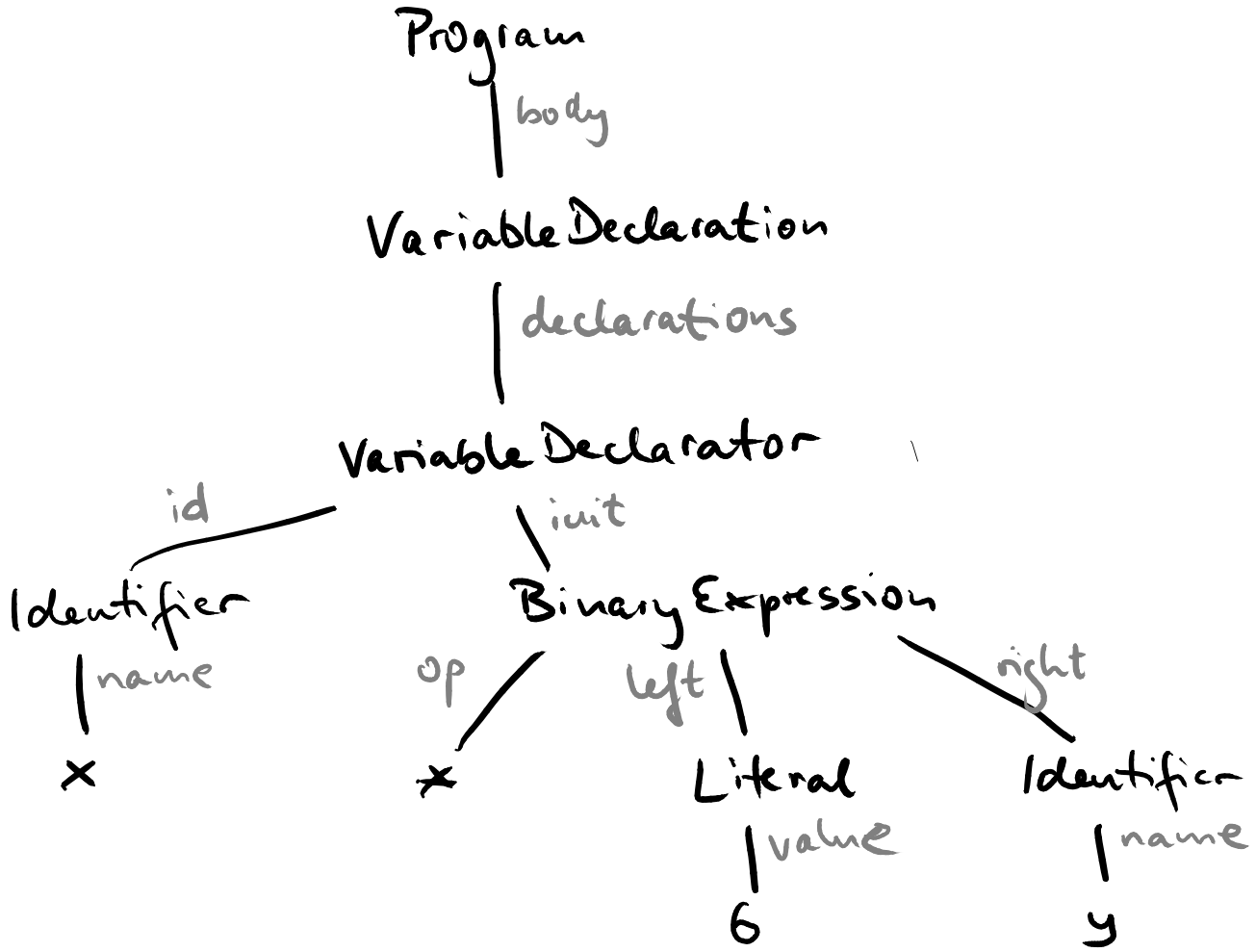
Abstract Syntax Tree

- **Tree representation of source code**
- **”Abstract” because some details of syntax omitted**
  - E.g., { in Java
- **Nodes: Construct in source code**
- **Edges: Parent-child relationship**
- **Check out Esprima for obtaining ASTs of Javascript: http://esprima.org/demo**

Abstract Syntax Trees: Example

Example: JavaScript

```
var x = 6 * y;
```



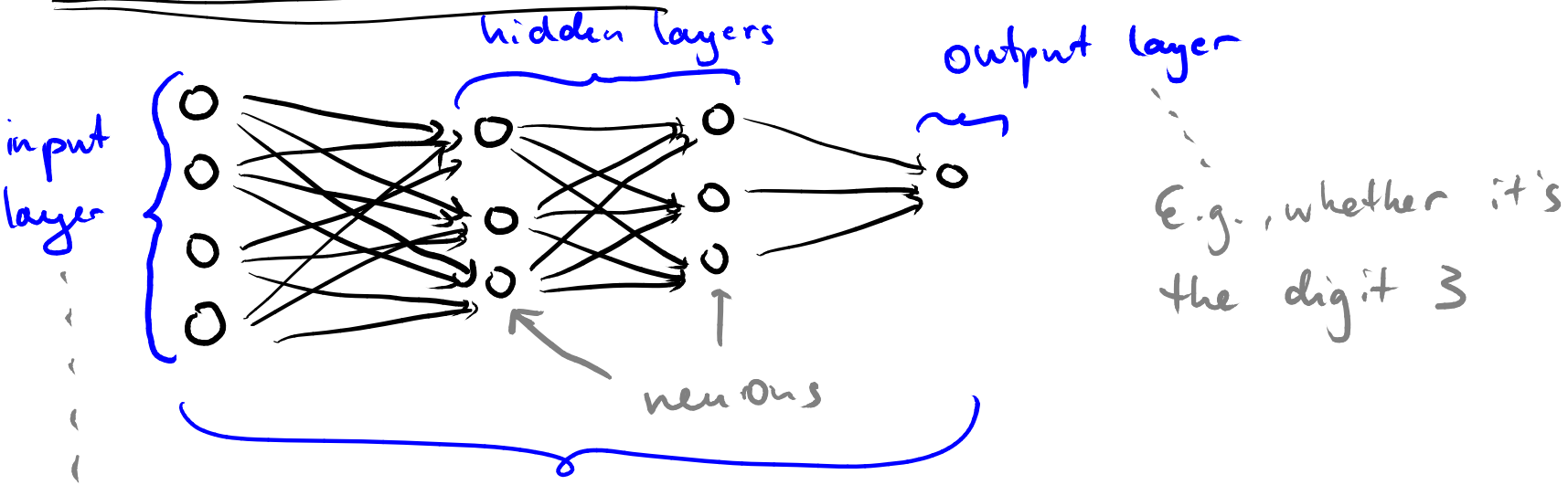
Deep Learning: Example

Example: Handwriting recognition

- Goal: Recognize digits 0..9
- Easy for a human but challenging for a computer
- Idea: Learn from a large number of training examples
- Deep learning: $> 99\%$ accuracy

Following slides based on Chapter 1 of neuralnetworksanddeeplearning.com

Network of neurons



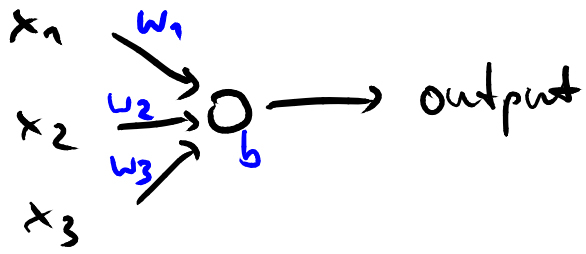
E.g., whether it's the digit 3

E.g. pixels of an image

Perceptrons

Most basic kind of neuron

- ↳ binary inputs
- ↳ binary output

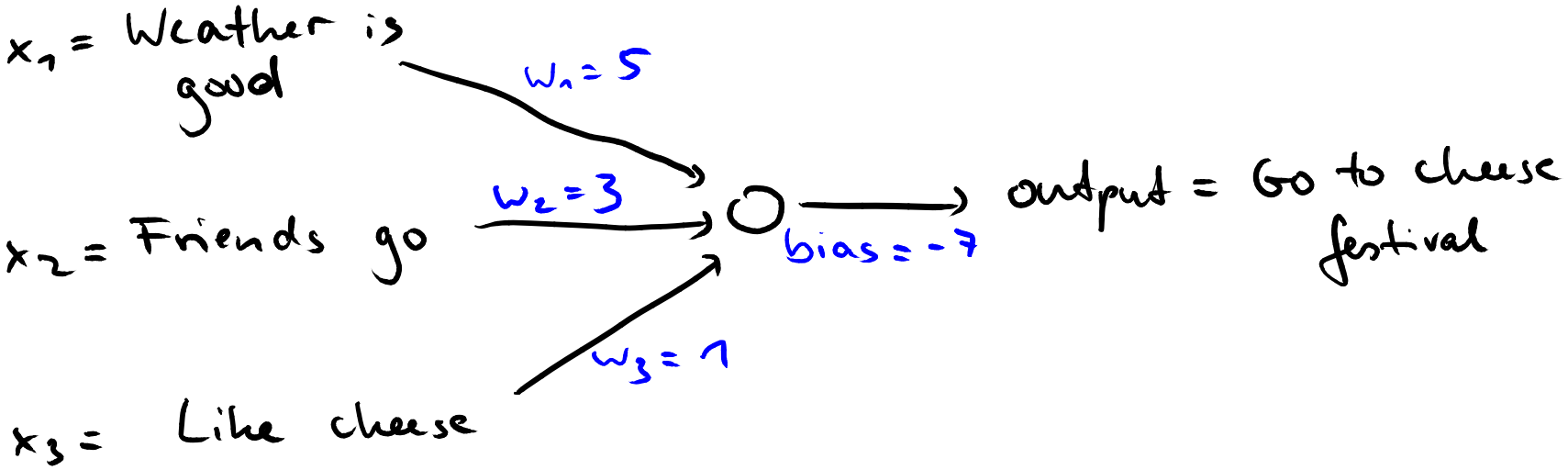


$$\text{output} = \begin{cases} 0 & \text{if } \sum_j w_j x_j \leq \text{threshold} \\ 1 & \text{if } \sum_j w_j x_j > \text{threshold} \end{cases}$$

$$= \begin{cases} 0 & \text{if } w \cdot x + b \leq 0 \\ 1 & \text{if } w \cdot x + b > 0 \end{cases}$$

w ... weights
b ... bias

Example



Assume: $x_1 = 1$, $x_2 = 1$, $x_3 = 0$

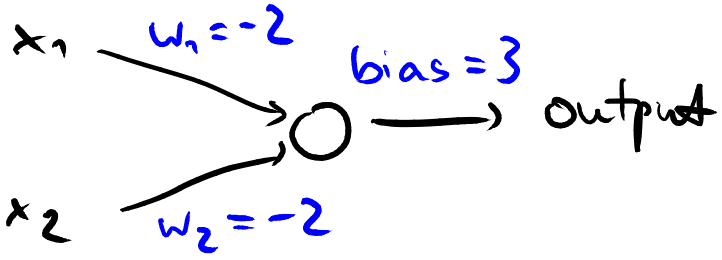
Quiz: Output?

$$w \cdot x = 5 \cdot 1 + 3 \cdot 1 + 0 \cdot 1 = 8$$

$$\text{output} = \begin{cases} 0 & \text{if } 8 - 7 \leq 0 \\ 1 & \text{if } 8 - 7 > 0 \end{cases} \longrightarrow \text{Go to festival}$$

Computing Logical Functions

NAND gate



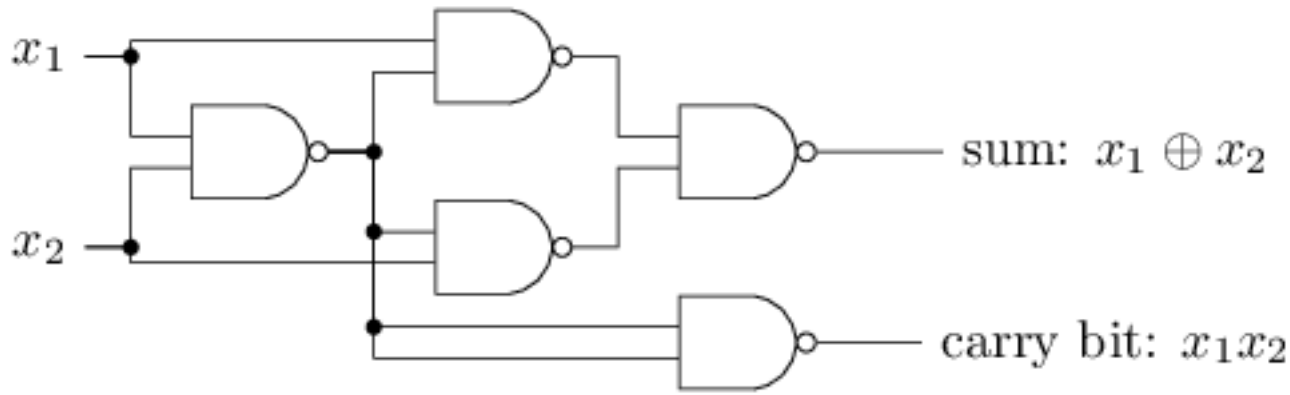
x_1	x_2	output	
0	0	1	because $0+3>0$
0	1	1	" $-2+3>0$
1	0	1	" "
1	1	0	because $-2-2+3 \leq 0$

Universal Computation

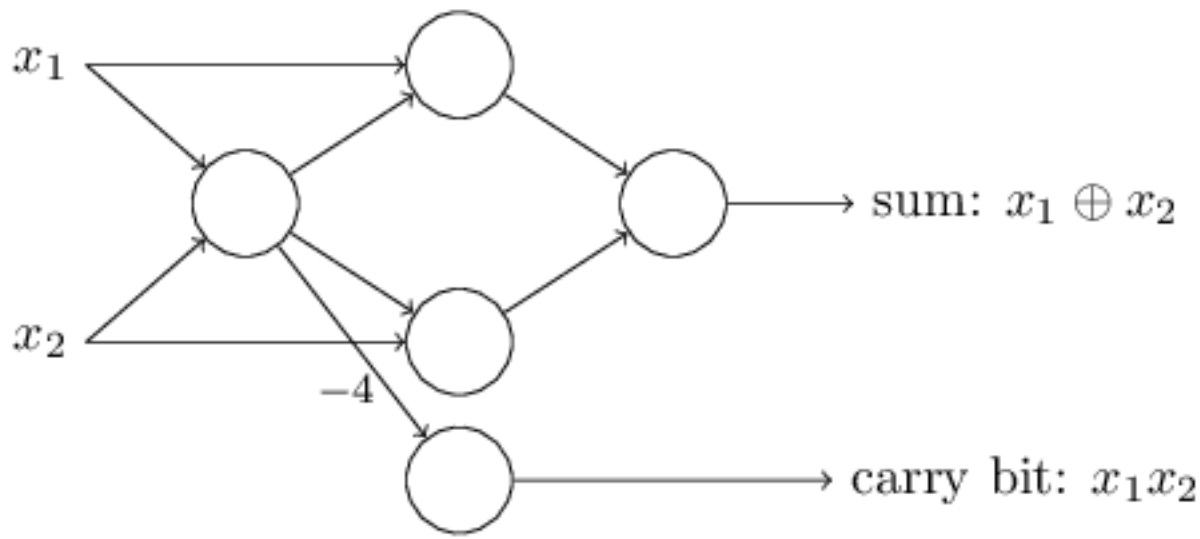
- Networks of NAND perceptrons can simulate every circuit containing only NAND gates
- Can express arbitrary computations!

Example: Adding Two Bits

NAND gate:



Network of perceptrons:



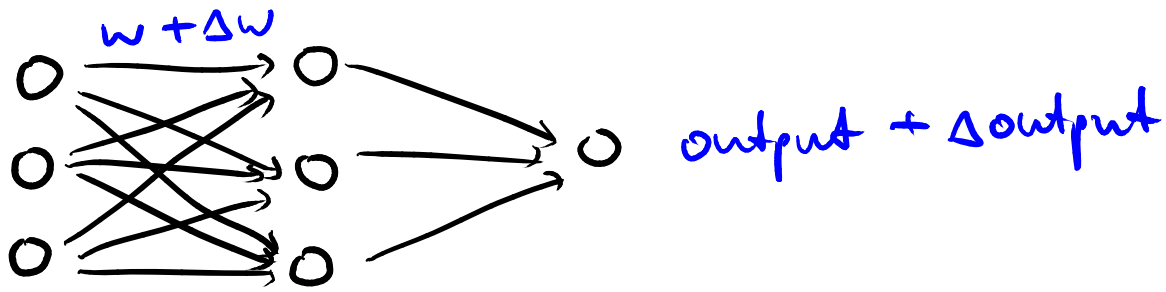
Challenge: Set Weights and Biases

- More complex networks can perform arbitrary computations
- How to decide on the weights and biases?
- Option 1: Hand-tune them

  $\rightarrow$ Infeasible for complex networks
- Option 2: Learn them

  $\rightarrow$ Key idea behind machine learning with neural networks

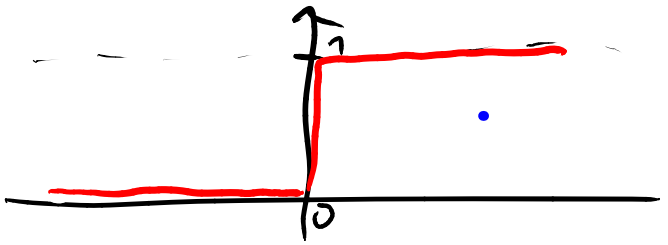
Making Learning Possible



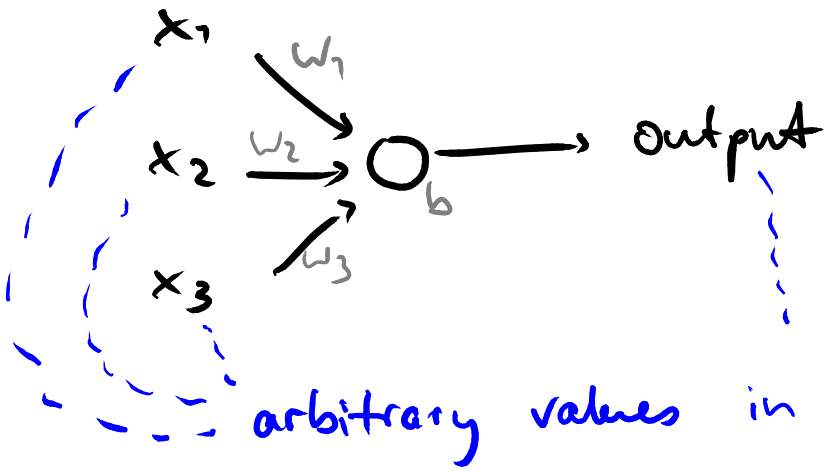
Want: Small change of weights & biases causes small change of output.

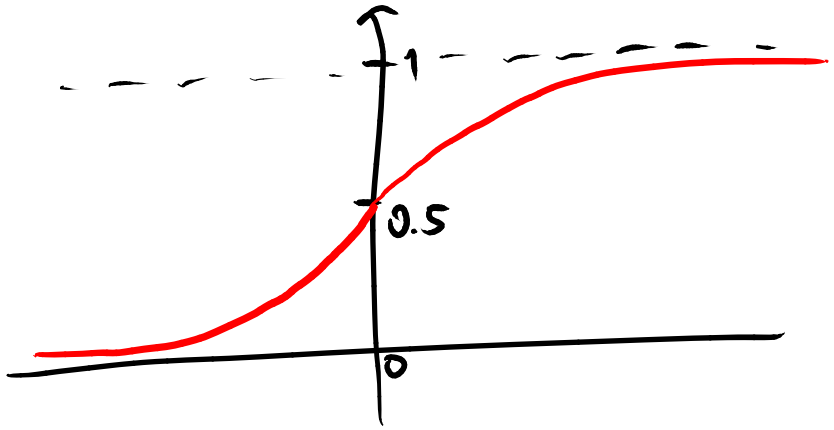
Problem: Perceptron doesn't have this property

output = step $(w \cdot x + b)$



Sigmoid Neuron





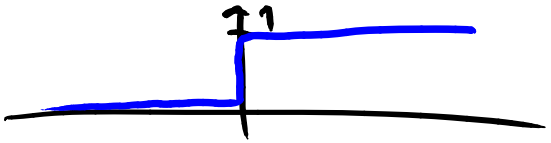
$$\text{output} = \sigma(w \cdot x + b)$$

σ: sigmoid fct.: $\sigma(z) = \frac{1}{1+e^{-z}} = \frac{1}{1+\exp(-\sum_j w_j x_j + b)}$

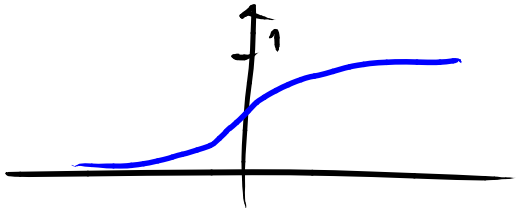
→ Enables learning:
Small change causes small change

Activation Functions

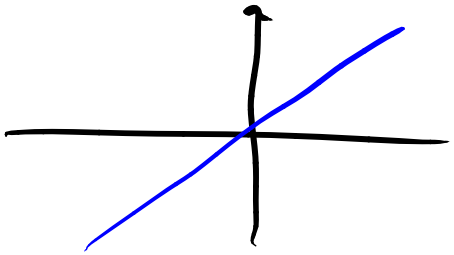
step function



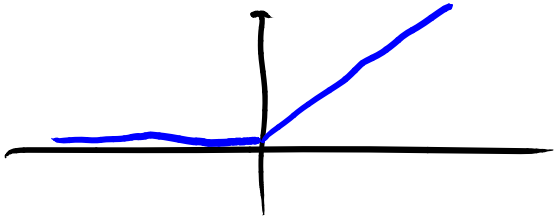
sigmoid / logistic function



identity function

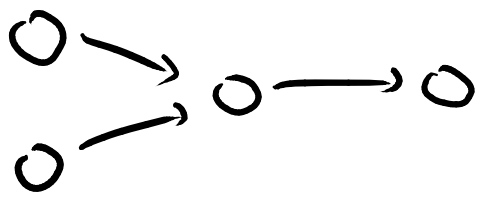


rectified linear unit



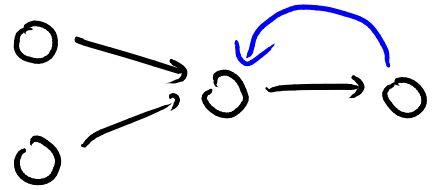
Different activation fcts. are useful in different kinds of networks

Feedforward Network



- Output of layer $n-1$ is input to layer n
- No loops, information is never feed back
- Useful if input/output pairs are independent of each other
  - ↳ E.g., recognize digit

Recurrent Neural Networks

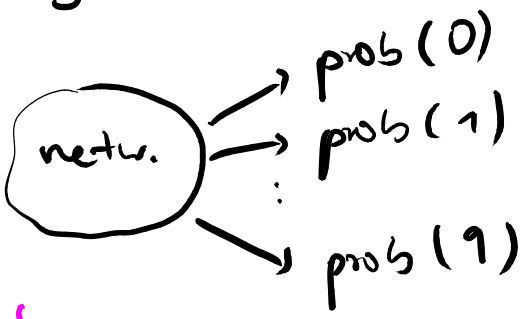


- Output of layer n may be fed back to layers $n, n-1, \ldots$
- Back edges serve as "memory"
- Useful for sequential information
  - ↳ Input/output pair depend on each other

Learning: Cost Function

- Cost function = feedback on how good the output is for a given input

- Example:



If digit is known to be 6, want output:

$$y(x) = (0,0,0,0,0,0,1,0,0,0)^T$$

Actual output may be:

$$a = (0,0,0,0.2,0.0,0.7,0.1,0,0)^T$$

Length of vector:

$$\|(x,y,z)\| = \sqrt{x^2+y^2+z^2}$$

$$C(w,b) = \frac{1}{2 \cdot n} \cdot \sum_x \| y(x) - a \|^2$$ ... quadratic cost function (or: mean squared error)

- nb. of training inputs
- desired
- output of network

Quiz: Cost Function

- **Recognition of hand-written digits**
- **Only digits 0, 1, and 2**
- **Training examples:**

Example	Actual	Desired
1	$(0, 1, 0)^T$	$(0.5, 0.5, 0)^T$
2	$(1, 0, 0)^T$	$(1, 0, 0)^T$

- **What is the value of the cost function?**

Quiz: Cost Function

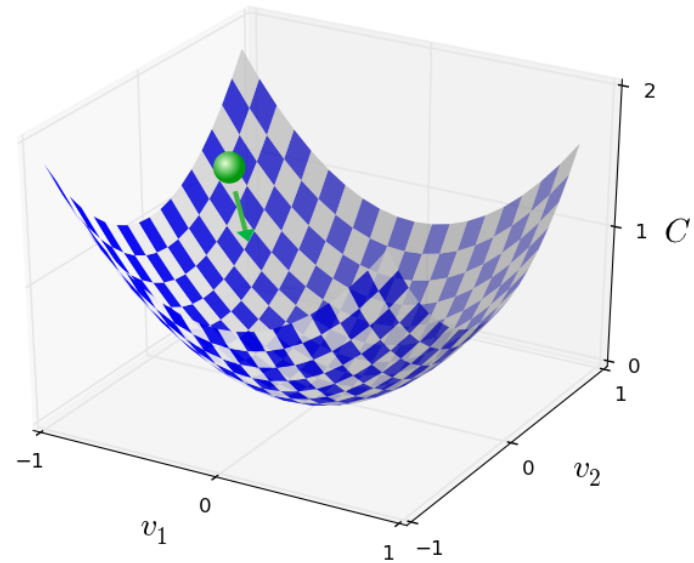
$$C(w,b) = \frac{1}{2 \cdot n} \cdot \sum_x \| y(x) - a \|^2$$

$$= \frac{1}{2 \cdot 2} \cdot \left(\| (-0.5, 0.5, 0)^T \|^2 + \| (0,0,0)^T \|^2 \right)$$

$$= \frac{1}{4} \cdot (0.5 + 0) = 0.125$$

Goal: Minimize Cost Function

- **Goal of learning: Find weights and biases that minimize the cost function**
- **Approach: Gradient descent**
  - Compute gradient of C: Vector of partial derivatives
  - ”Move” closer toward minimum step-by-step
  - Learning rate determines step size



Training Examples

- **Effort of computing gradient depends on number of examples**
- **Stochastic gradient descent**
  - Use small sample of all examples
  - Compute estimate of true gradient
- **Epochs and mini-batches**
  - Split training examples into k mini-batches
  - Train network with each mini-batch
  - Epoch: Each mini-batch used exactly once

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