CONDITION BASED MONITORING AND PROGRNOSTICS APPROACH FOR AN AGING AIRCRAFT MAINTENANCE SYSTEM USING DEEP NEURAL NETS

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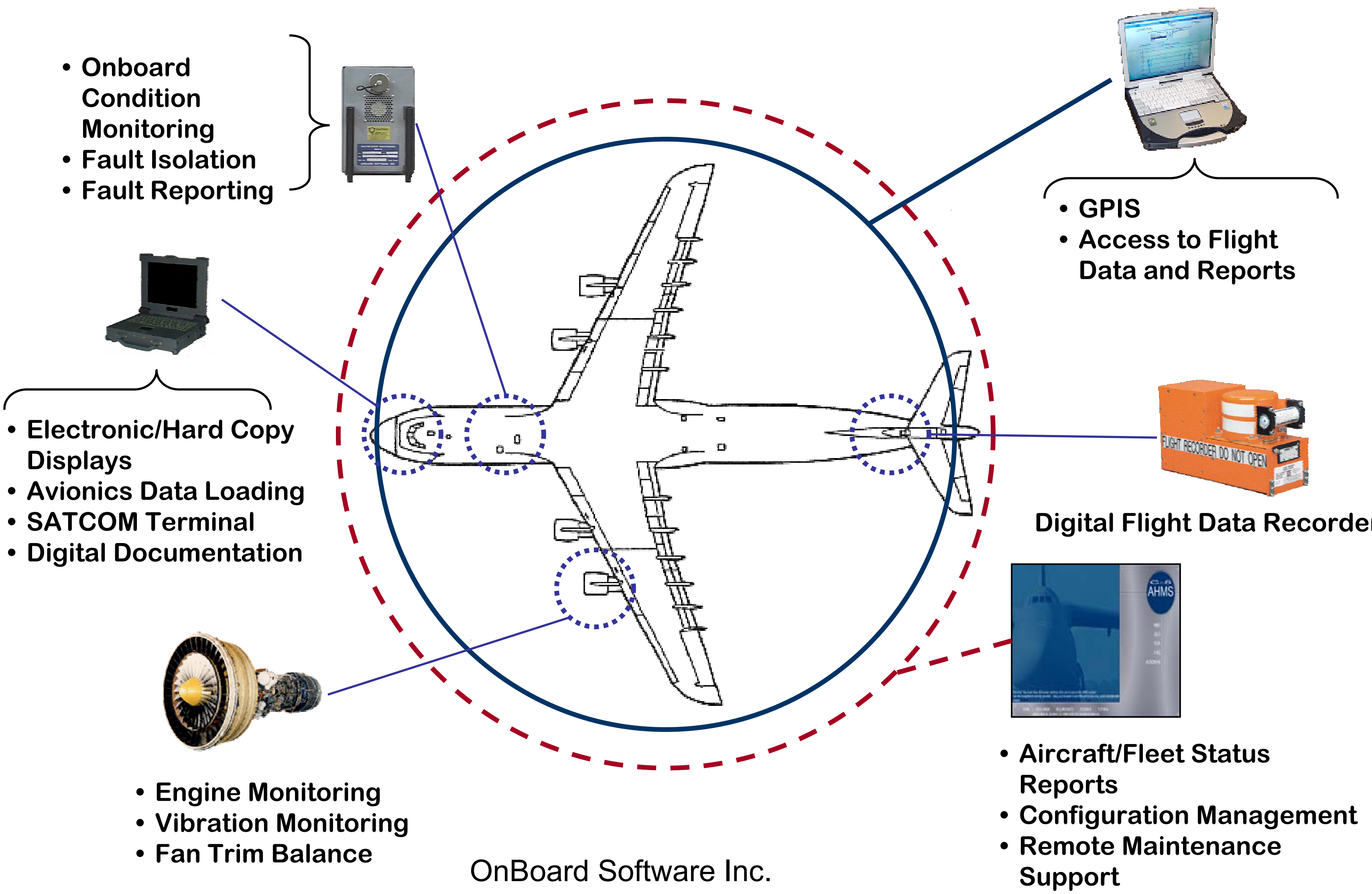
CBM & Prognostic Outline

- Background: the plant, current practice
- Converting University research into engineering
- Neural Net background
- Deep NN & Long Short Term Memory NN

OBSI C-5 Modernization



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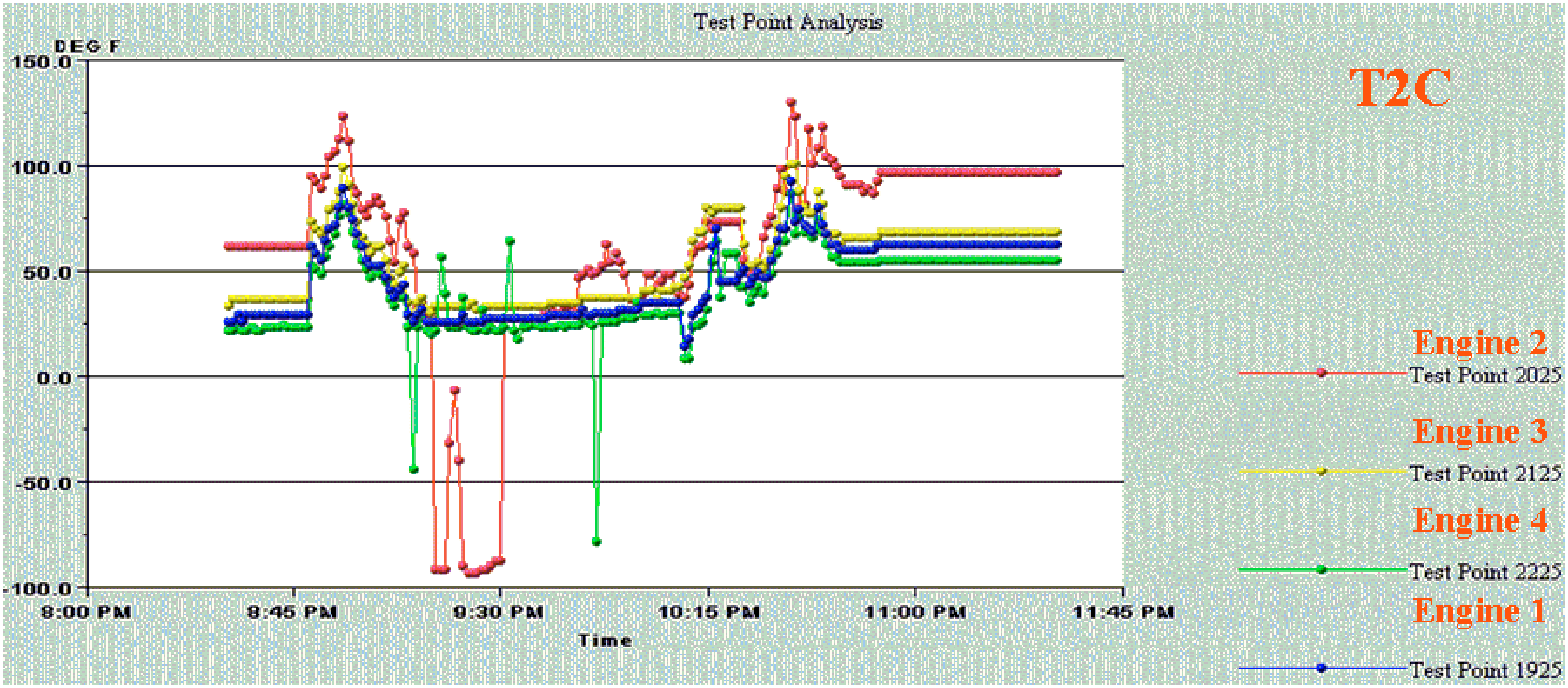
C-5 Modernization

- Replaced 1750 with PowerPC
- Replaced Jovial with C++
- Replaced Flight Engineer console with military laptop
- Replaced Tape Deck with PC-card
- Replaced printer
- Replaced Ground station with laptop
- Implemented SQL database
- Implemented interactive flight data viewer

C-5 Instrumentation Background

- C-5 Flight data recording
  - 800+ sensors
    - Most are discrete (digital)
  - Fault codes:
    - Implemented via scripting language using state & time
  - Variable recording rates
    - Typically use linear interpolation of analog signals
    - Use straight line interpolation of discrete signals

C-5 Turbine Inlet Temperature



Flight data file showing sensor problems: spikes, drop-out, offset error
From OBSI QLD briefing 2003

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CBM Algorithm Background

- Statistical Techniques
  - Extensive literature & numerous methods
  - Hot areas:
    - Bayesian Networks
    - Support Vector Machines
    - Independent Component Analysis
- Artificial Neural Net Techniques
  - Often used as a general purpose adaptive fit
  - AKA “non-linear modeling”
  - Advanced capabilities: Deep NN, LSTM

Other Applicable Technology

- Frequency Domain analysis
  - Bacharowski (2006)
  - Electronic signature analysis (ORNL)
- Accurate Modeling
  - Turso & Litt (2004)
- 3-layer Neural Net examples
  - Turso & Litt (2004)
  - Brotherton & Johnson (2001)

Implementation Perspective

- 2D map of data & computation dimensions
  - Effect of Moore's Law
- 2D map of complexity & maturity dimensions
  - Practicality
- Wetware versus software
  - The biological models give reassurance

Perspective: Data & Computation Dimensions

- Moore's law =>
  - With time, can approach problems using more memory & greater processing
- Computer Science has evolved along with hardware
  - Small Data & Efficient Computation =>
    - Exact reasoning using small data sets
    - Emphasis on efficient algorithms
  - Large Data =>
    - Statistical & Inexact Reasoning on large data sets
  - Big Computation =>
    - Genetic algorithms & gradient based learning
  - Both =>
    - Hybrids of Genetic Algorithms & Neural Nets

Perspective: Practicality

- Additional dimensions:
  - Algorithm Complexity
    - Occam's razor: Bias or prejudice against complexity
    - The world is getting more complex anyway
    - Automation (adaptive systems) is the solution
  - Algorithm Maturity
    - Engineering requires "well behaved" algorithms
    - Having a choice of algorithms so as to avoid over constraining the implementation

Biological neuron

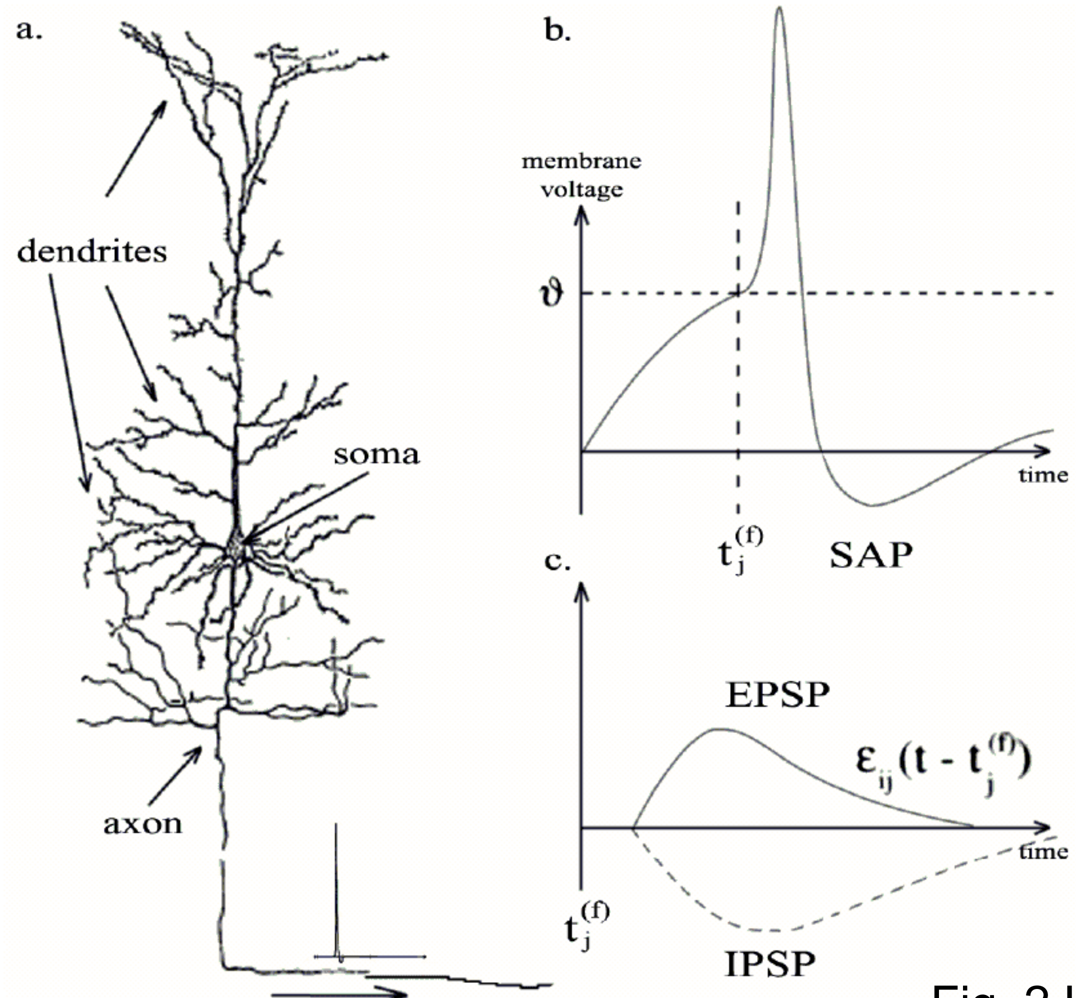


Fig. 2 Koopman (2003)

Wetware Modeling

- O'Reilly & Frank (2006)
  - LSTM versus biology
  - Training efficiency match
- Koopman etal (2003)
  - LSTM versus spiking models
  - Performance match
- Izhikevich (2004)
  - Can generate many spiking behaviors via parameter adjustment

LSTM performance comparison

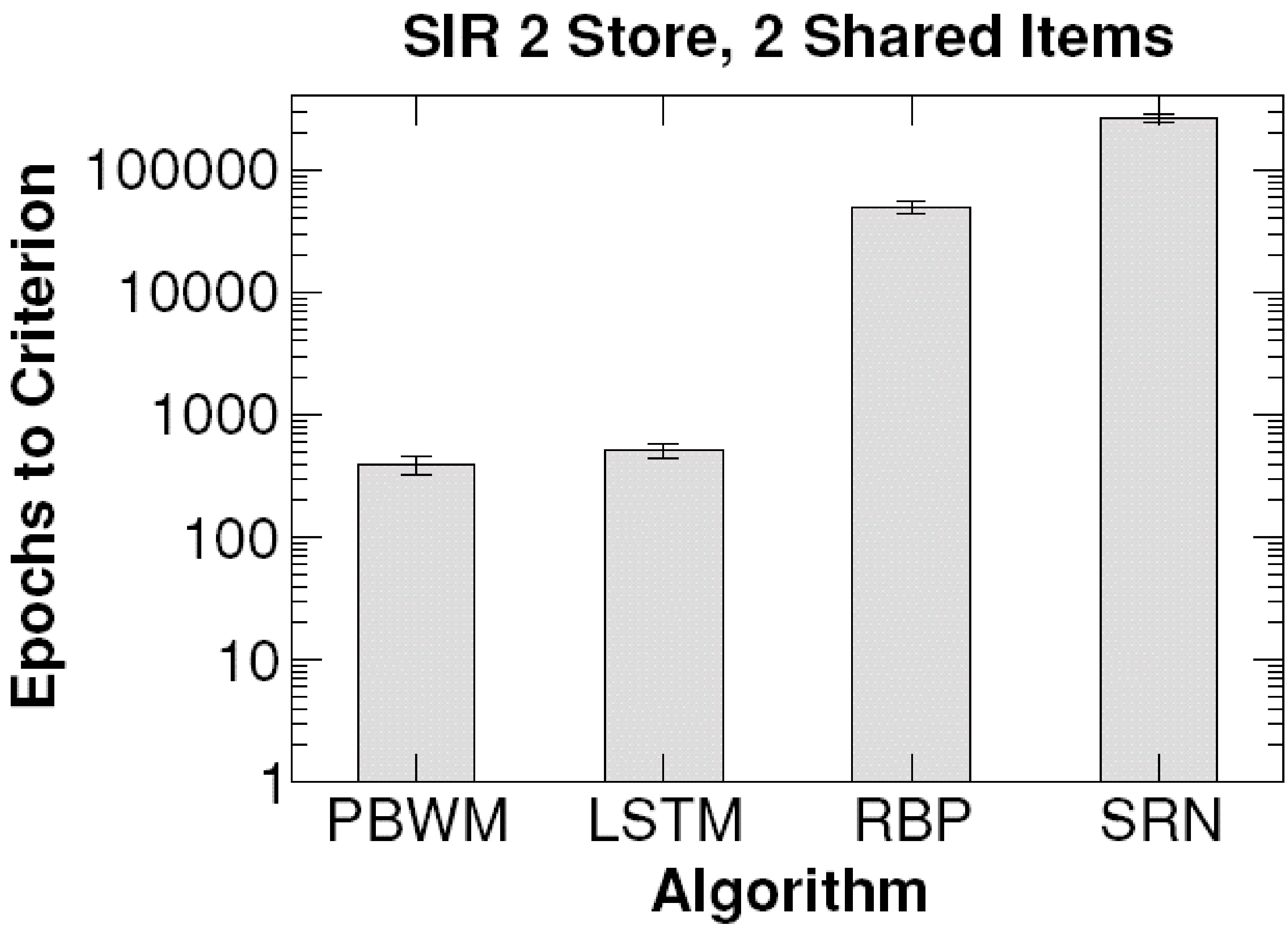


Fig 11b O'Reilly (2006)

LSTM generalization error

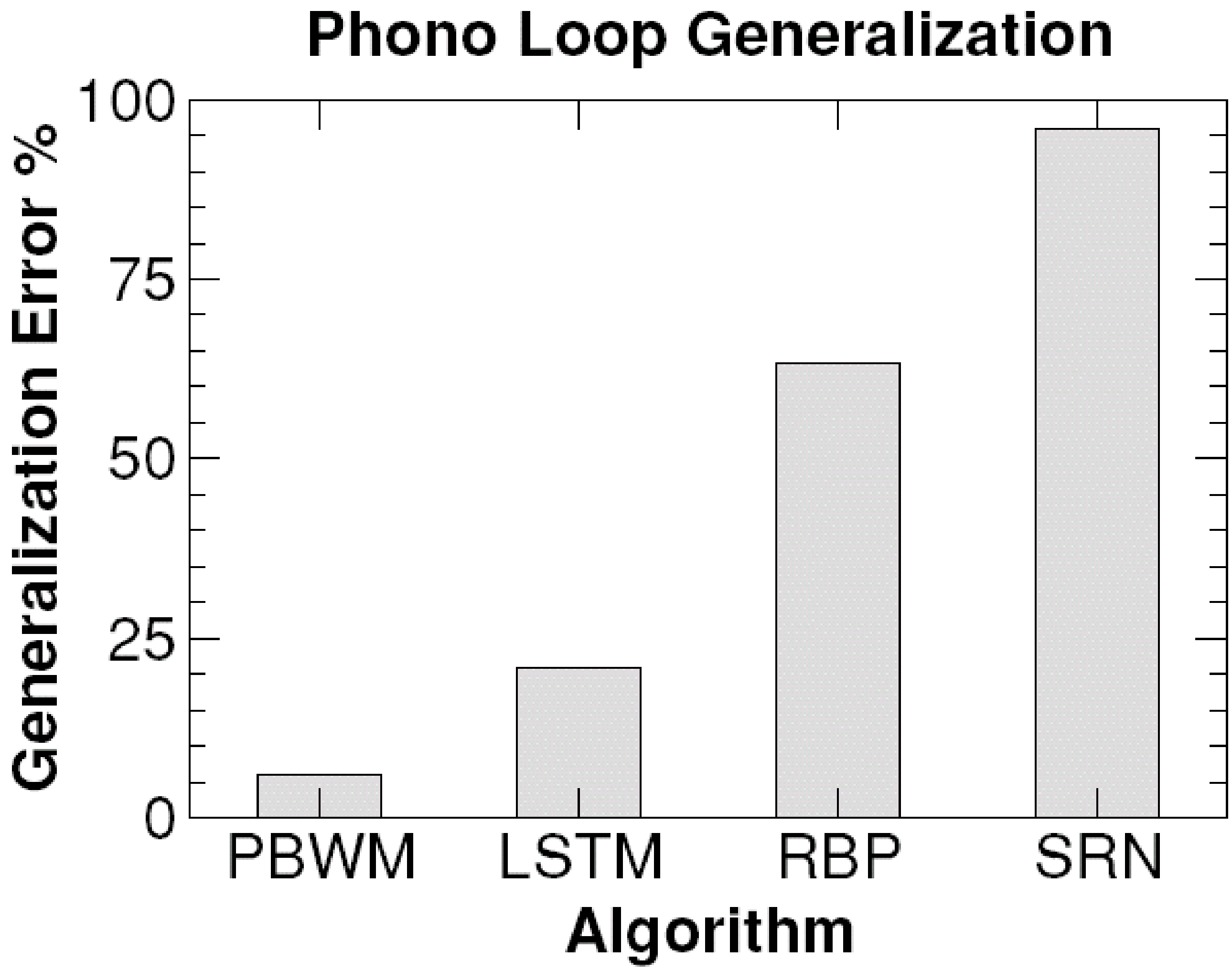
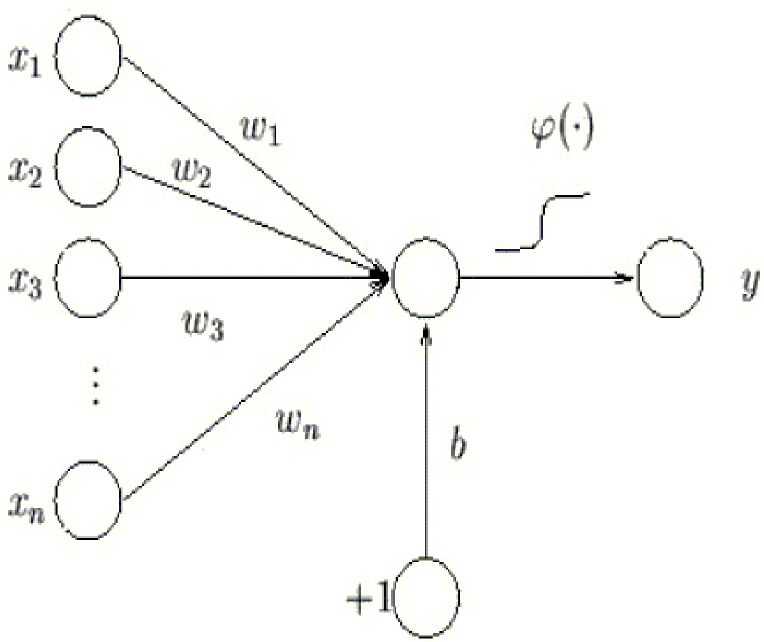


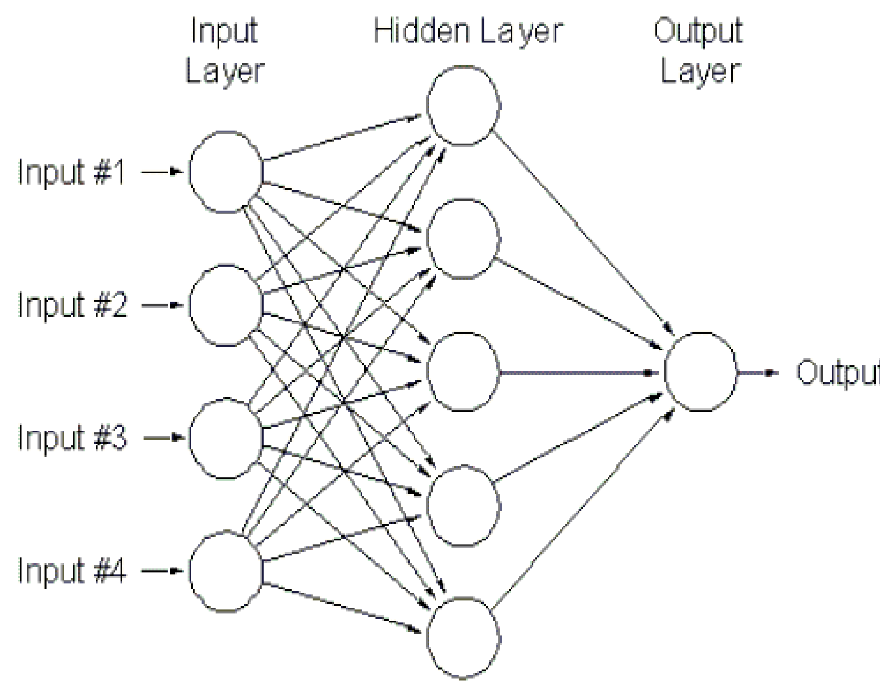
Fig. 14b O'Reilly (2006)

3-layer Neural Net

Single Neuron



Neural Network



From pg. 3 Kushal (2006)

Neural Net Technology

- Kohonen Self-Organizing Map
  – Unsupervised classification
- 3-Layer
  – Assumes feature detectors are known
  – Many variations
- Multi-Layer
  – Learns feature detectors
  – Success with Convolutional Nets
  – Not suited for time domain (IMHO)
- Recursive
  – Full generality
  – Success with LSTM
  – Can handle long & variable time patterns

Convolutional NN

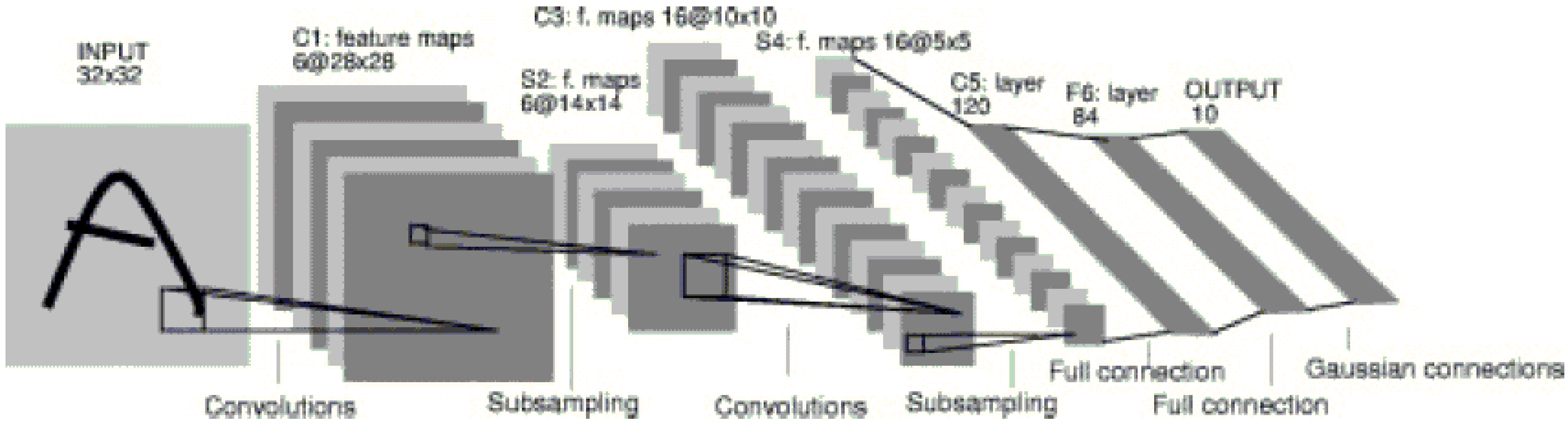
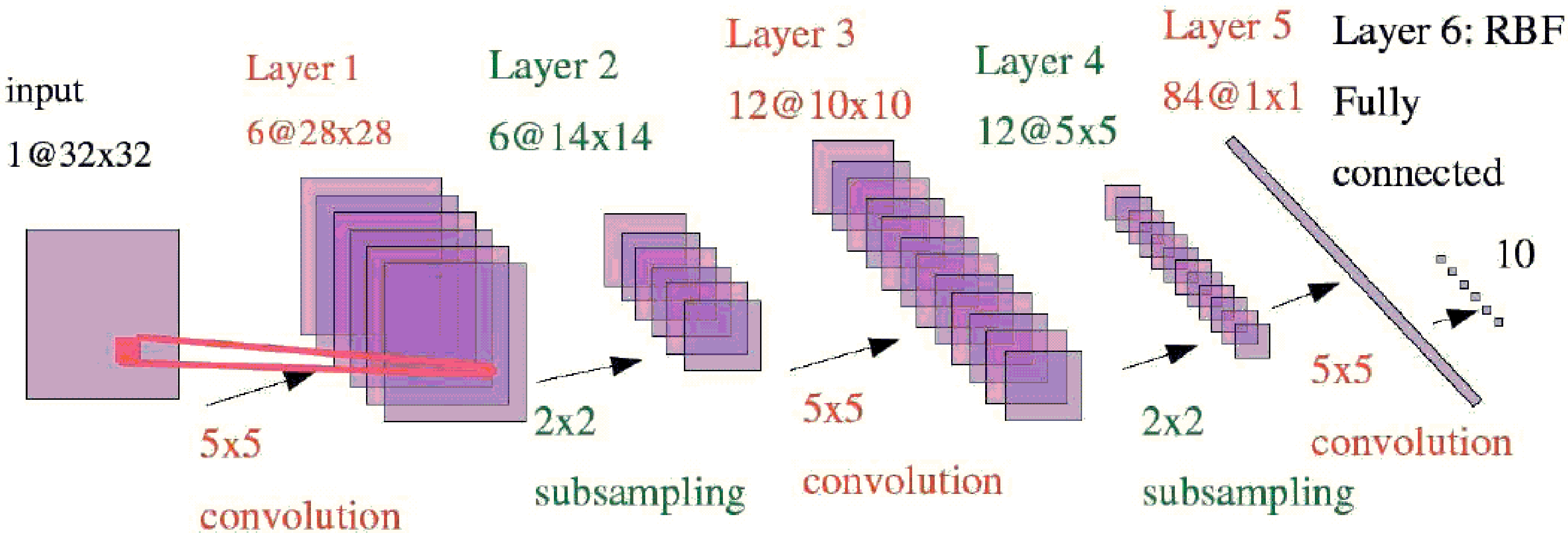


Fig. 2 LeCun 1998



Pg. 6 Kushal 2006

LSTM "neuron"

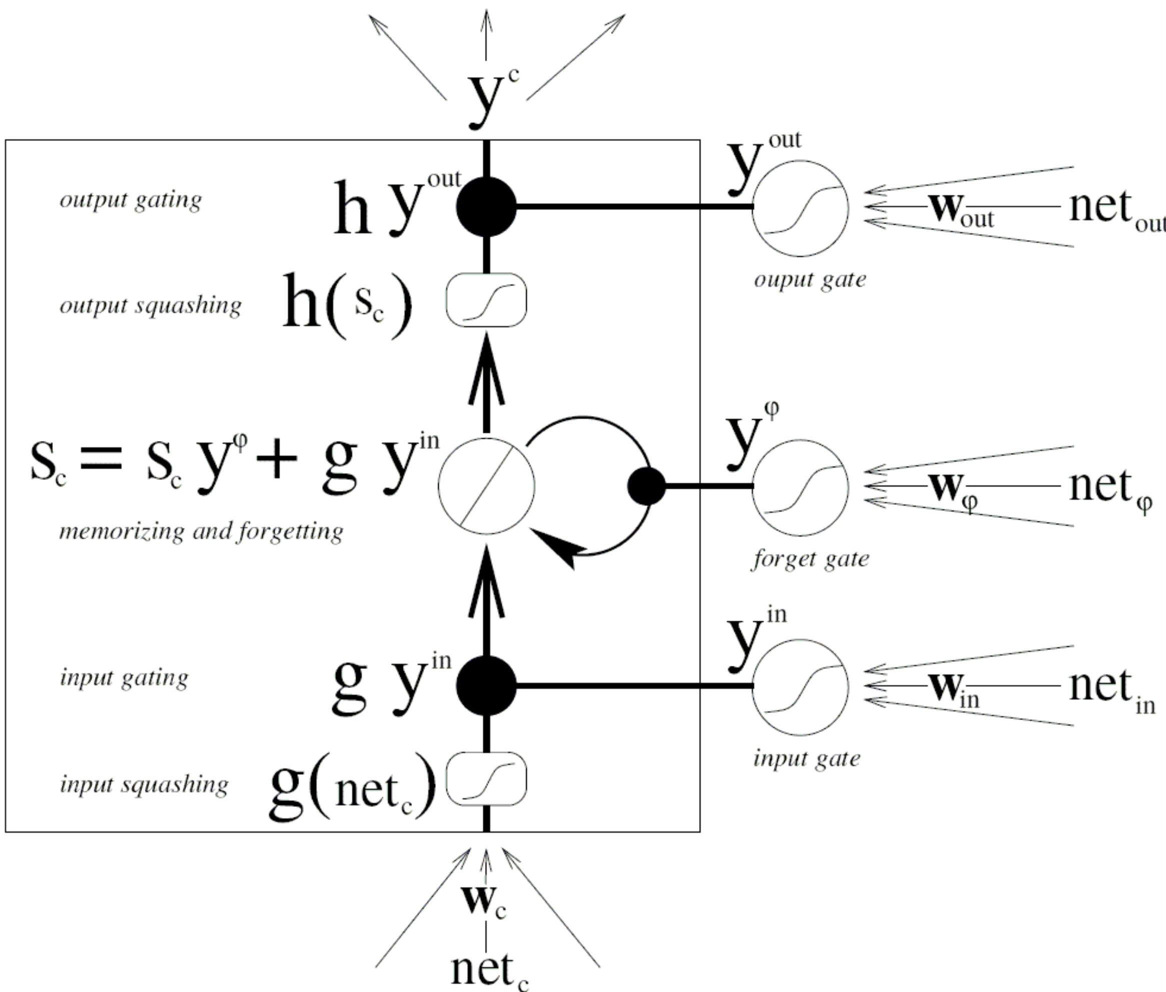


Fig. 3.1 Gers (2001)

LSTM Neural Net

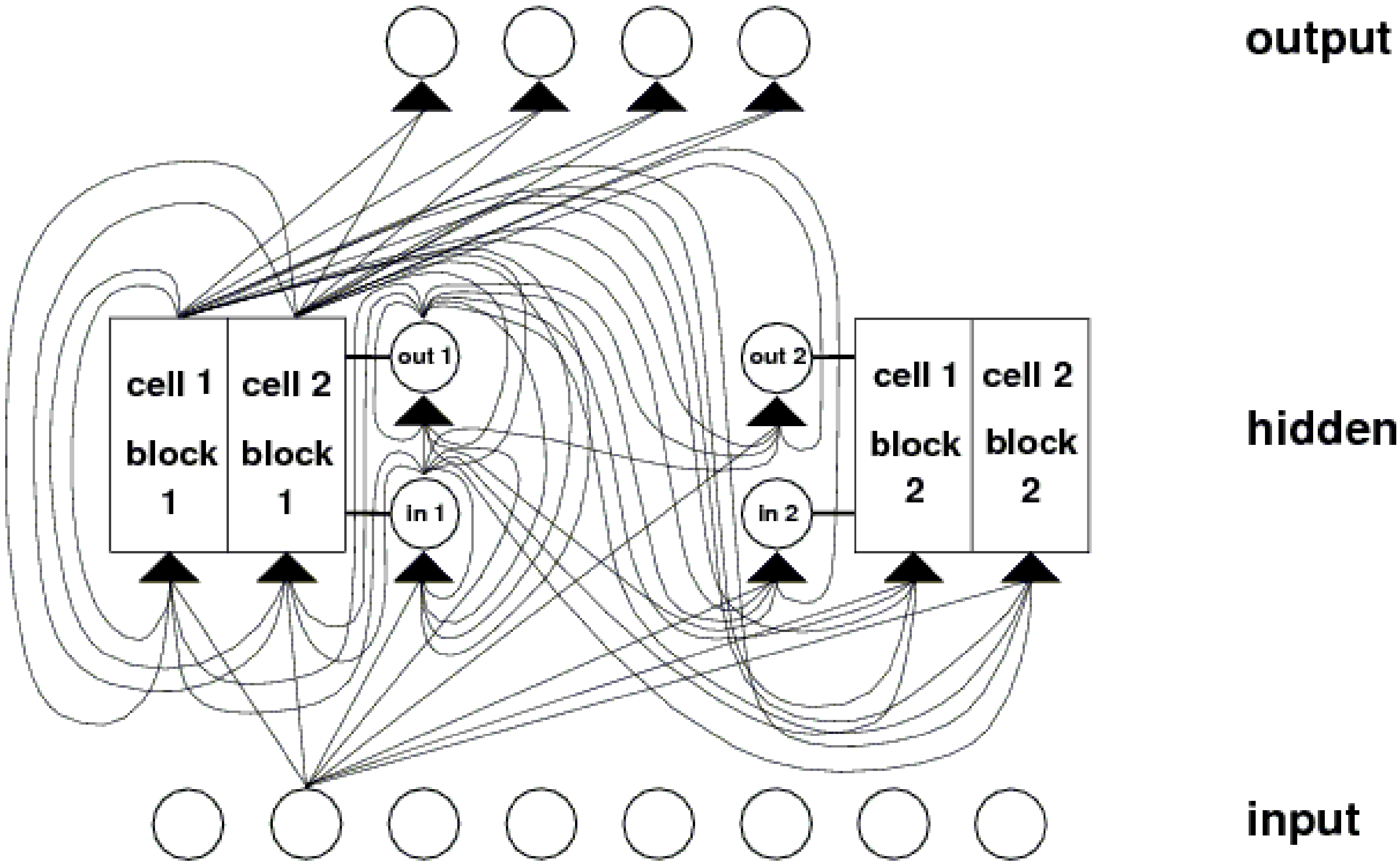


Fig. 2 Hochreiter (1997)

LSTM Applications

- Signal integrity
  - Noise spikes
  - Offset errors (drop outs, calibration error)
  - Gain errors (e.g. transducer malfunction)
- Condition codes
  - Match existing
  - Refine existing
- Anomaly detection
  - Requires trainer

Summary

- Convolutional Nets can learn feature detectors
- LSTM Nets can handle variable time delays
- LSTM Nets comparable in performance to biological models
- LSTM can learn fault conditions

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LSTM References

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Deep Neural Net References

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A. Kushal: ***Gradient Based Learning***, courses.ece.uiuc.edu/ece598/ ffl/paper_presentations/AkashKushal_NN.pdf

Current Best Practice References

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J. Turso & J. Litt 2004: ***Intelligent, Robust Control of Deteriorated Turbofan Engines via Linear Parameter Varying Quadratic Lyapunov Function Design***, First Intelligent Systems Technical Conference.

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Neurological Modeling References

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E. Izhikevich 2004: ***Which Model to Use for Cortical Spiking Neurons***, IEEE Trans. Neural Networks 15:1063-1070. http://vesicle.nsi.edu/users/izhikevich/publications/whichmod.htm

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C. Villarreal & I. Cicek 2004: ***Automated Troubleshooting Tools for Minimizing Downtime and Reducing the Labor and Material Costs of C-5 Aircraft***, Autotestcon-2004 pp 504-510.

Researcher’s Web Sites

Jurgen Schmidhuber: [www.idsia.ch/~juergen/rnn.html]
Extensive LSTM references

Sepp Hochreiter: ni.cs.tu-berlin.de/~hochreit
Simplest LSTM software

Felix Gers: www.felixgers.de
Ph.D. thesis on LSTM

Faustin Gomez: http://www.idsia.ch/~tino/
Genetic Evolution of LSTM

Randall C. O’Reilly: psych.colorado.edu/~oreilly
PDP++

Yann LeCun: yann.lecun.com
Convolutional NN, tutorials & video examples

Geoffrey E. Hinton: www.cs.toronto.edu/~hinton
Convolutional NN, ibid.

LSTM Software

- **Hochreiter:** ni.cs.tu-berlin.de/~hochreit/soft.shtml
  - Simplest LSTM code
- **LSTM Toolbox:** idelnx81.hh.se/bioinf/index.html
  - In Matlab
- **SigmaPi:** sigmapi.sourceforge.net
  - Complete package based on LSTM
- **O'Reilly:** www.cnbc.cmu.edu/Resources/PDP++
  - Extensive neural simulation package, includes LSTM
- **Gers:** C++ www.felixgers.de/SourceCode_Data.html
  - As part of his thesis