The Frequency Domain

And How It Can Be Used To Aid Artificial Intelligence

John Edwards
jedwards@numerix-dsp.com

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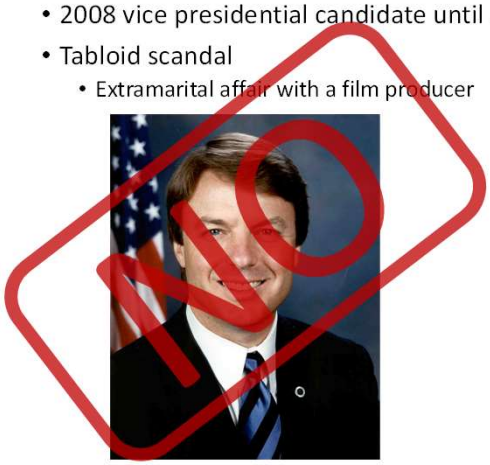
John Edwards

- US Attorney
- Former US Senator
- 2008 vice presidential candidate until …
- Tabloid scandal
  - Extramarital affair with a film producer



- DSP, AI and Embedded Systems Consultant
  - > 30 years experience
  - Lucky enough to be at the start of the DSP revolution
  - Digital Communications
    - V Series Modems, VOIP, WiMAX, 3G (WCDMA) and 4G(LTE) – basestations and mobiles
  - Audio
    - Pro-audio and Voice User Interface products
  - AI for vibration analysis
- Member of the IET and IEEE
- Regular contributor of papers at international DSP conferences
- Presents bespoke DSP training courses to companies
- Visiting lecturer at the University of Oxford
  - Post Graduate DSP course on the Summer Engineering Program for Industry

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Poll

Quiz - What level of Digital Signal Processing knowledge do you have ?

I have programmed DSP algorithms in C/Assembly
I have developed DSP algorithms in Python, Matlab or other high level language
I have done some data analysis in Excel or other similar application
I have no DSP knowledge

The Advance of Machine Learning

- What's the difference between Artificial Intelligence and Machine Learning ?
  - AI is slideware (and detecting cats vs dogs on Facebook)
  - ML is software
    - MIT Technology Review *
  - ;-)
- Machine Learning is …
  - Sometimes referred to as Artificial Intelligence of Things (AIoT)
  - Learning in the cloud
    - Tensorflow, Colab and TPUs are great
  - Deployment at the edge – end-point or edge controller
    - Tensorflow Lite / TinyML
  - The applications are vast and diverse
- These techniques can be used in many other AI and Data Science scenarios

* https://www.technologyreview.com/2020/08/18/1007196/ai-research-machine-learning-applications-problems-opinion/

Applications Of Machine Learning

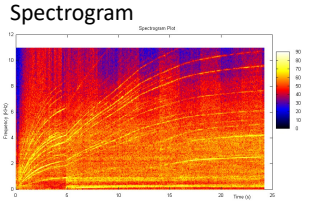
- Image recognition (E.G. human/vehicle/cyclist recognition) at the edge is super important
- But there are potentially even more applications for applying ML to 1D, streaming, data
  - Machine Vibration Analysis
    - Predictive maintenance of industrial machines
  - Speech Recognition
  - Medical health care and automated patient monitoring
  - Environmental monitoring and protection
  - Health, Safety and Security
  - Logistics and Distribution
  - These applications do not require the same level of MIPS, memory and power consumption as image recognition style applications

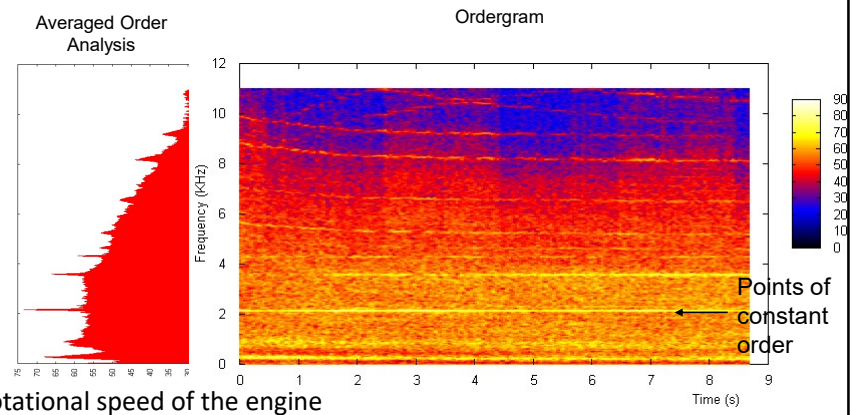
Machine Learning Architectures

- ML at the end-point (as opposed to the edge) has advantages over the cloud
  - Latency
  - Cost
  - Power consumption
  - Always on network
  - Security
- However this moves the “cost” from the service provider to the consumer/customer
  - End-points are deployed in higher quantities.
    - Therefore “cost” is critical
- Question – How can we help optimize the ML recognizer for the above constraints ?
  - Let’s start by looking at an example application

Monitoring A Rolls-Royce 250-C30P Gas Turbine Engine

Spectrogram





- Order analysis adjusts for rotational speed of the engine
- The spectrum has clearly defined peaks that depend on the health of the engine

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The Traditional AI Model

- Chuck lots of data and lots of MIPS at the problem and let the algorithm do the work
- Ok, let's think about frequency analysis, for a moment
- Fortunately Endollith has already done this for us ☺
  - He's developed a Neural Network trained to implement the FFT
  - https://gist.github.com/endolith/98863221204541bf017b6cae71cb0a89
  - Awesome, all I need to do is teach his NN some more DSP algorithms and I can sit on a beach drinking Piña coladas while his algorithm does all my work – woo hoo
  - Unfortunately, it requires a lot of MIPS and memory to infer the frequency domain output ☹
  - Note, this is a great project and if you are interested in maths and AI then clone the repo and have a play
- So if we want to teach a Neural Network how to recognize vibration and failure modes then it makes sense to pre-process the input signal to extract the features that will help the recognizer
  - A process called Feature Extraction or Feature Engineering

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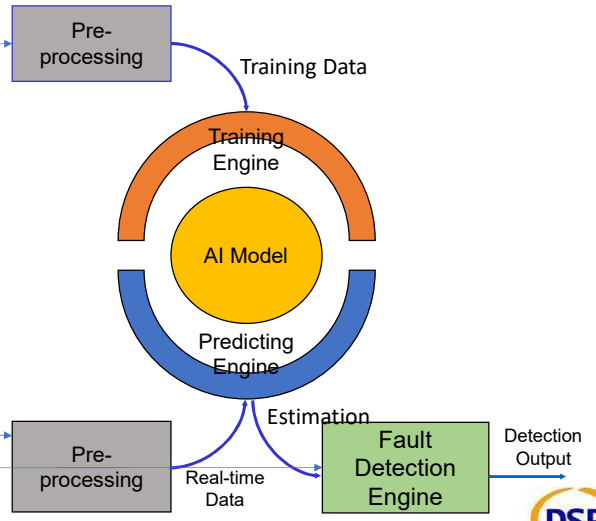
Machine Vibration Monitoring Application

- Multiple stages to both training and inferring
  - Signal preparation
    - Filtering and noise removal
    - Level normalization
  - Feature engineering
    - Spectrum analysis
    - Cepstrum analysis
    - Peak detection
    - Zero crossing detection
  - Feature recognition
    - Event characterization
    - Fault characterization



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Signal Processing Is The Solution

It's All About The Maths

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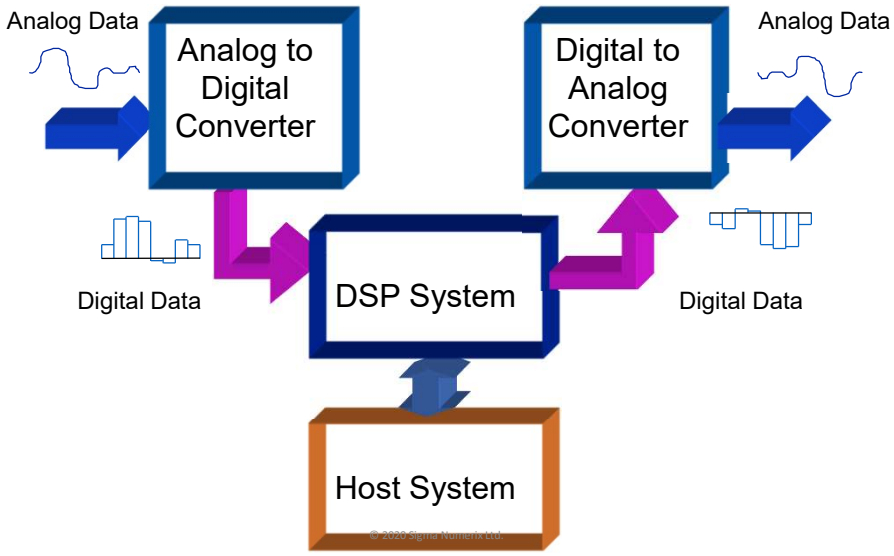
DSP System Fundamentals



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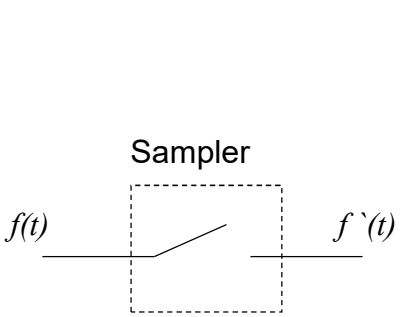
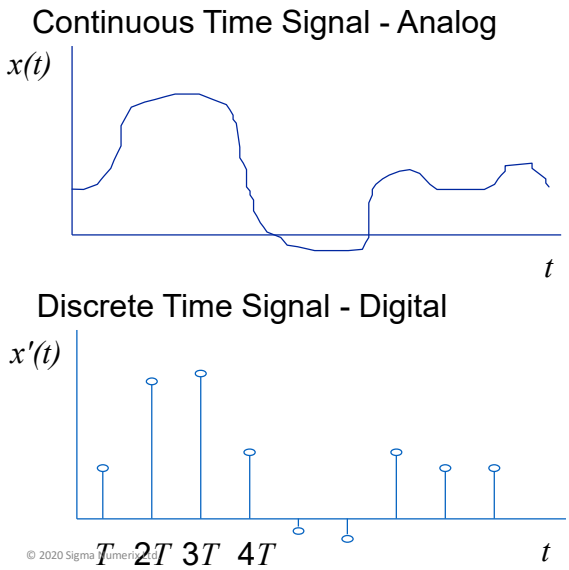
Discrete Time Signals





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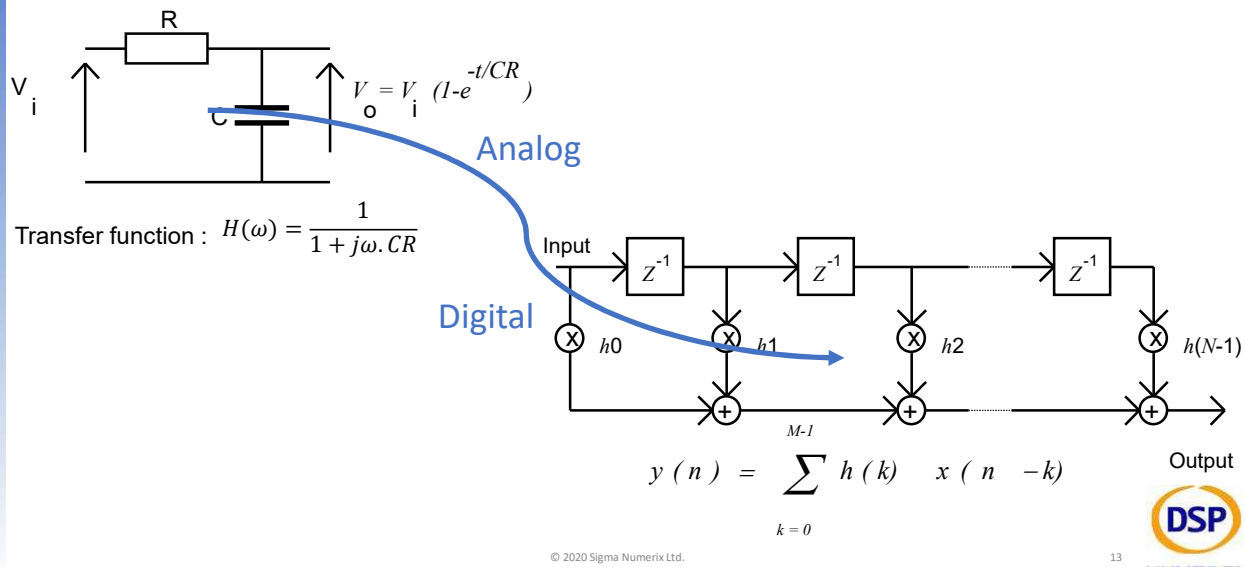
Time Domain Processing – Filtering aka Convolution



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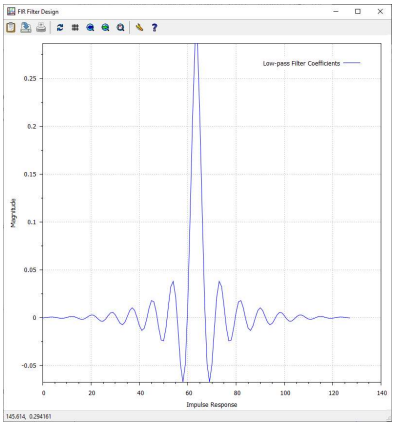
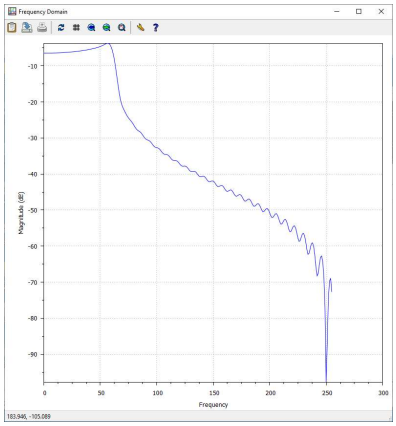
We Can Analyze And Process Signals And Systems In The Time Or Frequency Domains

Time Domain



Frequency Domain



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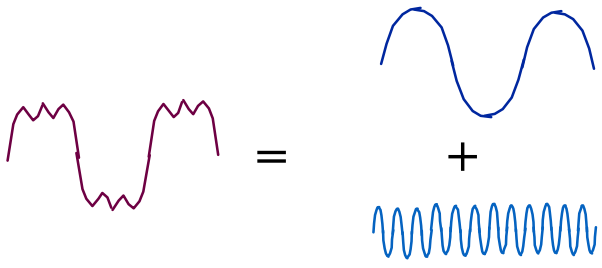
Frequency Domain Processing

Discrete Fourier Transforms

The Fourier Theory

- In 1822, Baron Jean Baptiste Fourier detailed the theory that any real world waveform can be generated by the addition of sinusoidal waves.



(This was arguably developed first by Gauss in 1805)

The Discrete Fourier Transform

$$X(k) = \sum_{n=0}^{N-1} x(n) e^{-j\frac{2\pi nk}{N}} \quad for\ 0 \le k \le N-1$$

- For every frequency, the Fourier Transform $X(k)$ determines the contribution of a complex sinusoid of that frequency in the composition of the signal $x(n)$.
- The Inverse DFT is "the same" except for the phase
- The Fast Fourier Transform (FFT) is just an optimization of this equation

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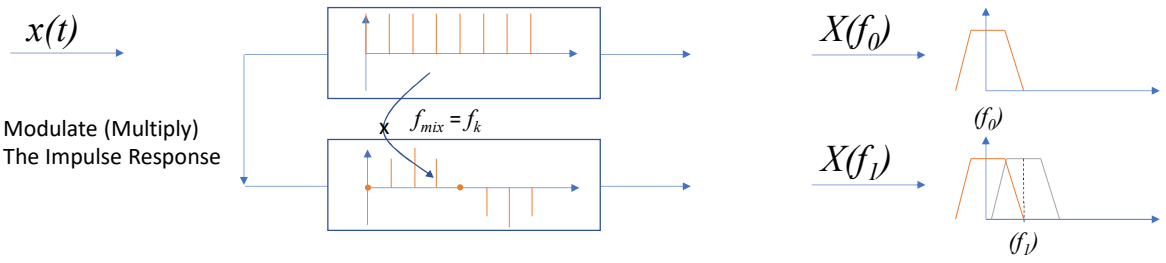
How Does The Discrete Fourier Transform Work



- That's a lot of detail ?
- Yes, but …
  - The DFT is just a bank of filters
  - Each filter has a given centre frequency separated by F_s/N
    - F_s is the sample rate
    - N is the length of the DFT

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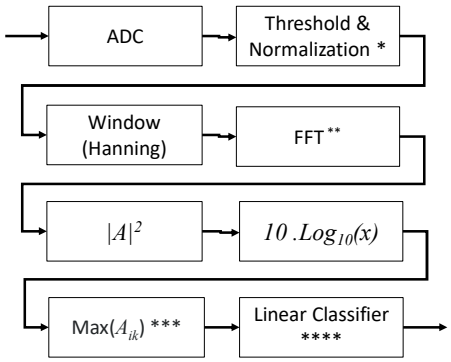
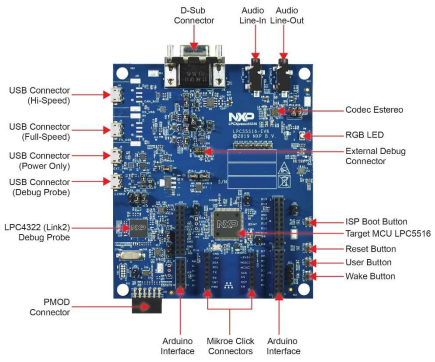
Let's Return To Our Application

The Vibration Monitoring Application

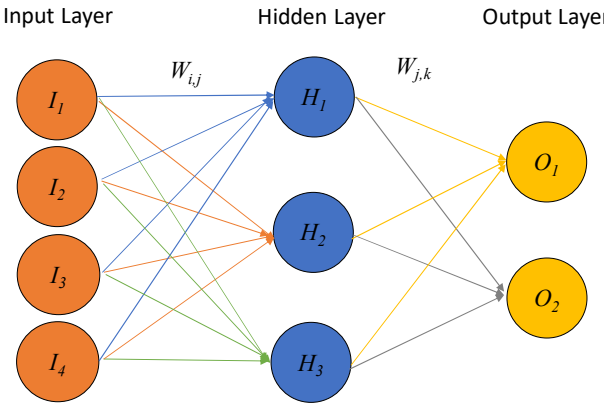


* Do not classify if below threshold
** FFT block options include FFT, Mel Spectrum or MFCC
*** Element wise maximum over 10 frames
**** With convolution kernels on the PowerQuad

- Current real-time implementation uses an NXP LPC55S69
  - Dual Core 32 bit ARM M33 based
  - Coded in C and uses DSP Coprocessor (PowerQuad)
    - DSP (Filtering and Fourier Transform)
    - Machine Learning Inferencing convolutions



Multi-Layer Backpropagation Perceptron Network Solution



- Convolutional Neural Network
  - The convolutions (coloured) are standard DSP convolution operations

- Input Layer Length (FFT Size /2)
  - 64
    - 16 kHz sample rate
- Hidden Layer Length
  - 25
- Model Size
  - Using 16 bit intermediate data
  - 2k bytes + 500 bytes per additional output category
  - Requires about 15 mins of audio, for each category, to train the model
    - Multiple epochs also helps (typically ≈5)
- Model Accuracy
  - >98% *
    - * Depends on the similarity (cross-correlation) between the two signals
- Power consumption
  - < 18 mW continuous

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Conclusions

- There is a lot to be gained from making AI IntelligentAI
- Think about your application
- Think about what Feature Engineering can be applied to the input signal to assist the Neural Network
- Experiment with the Feature Engineering
  - In many industrial applications there is more to be gained by focussing your efforts on this than developing and training a more complex Neural Network

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Access To Additional Information And Resources

- Digital Signal Processing Books
  - The Scientist and Engineer's Guide to Digital Signal Processing; By Steven W. Smith, Ph.D.
    - http://www.dspguide.com
  - Introduction to Signal Processing; by Sophocles J. Orfanidis
    - http://eceweb1.rutgers.edu/~orfanidi/intro2sp/
  - Understanding Digital Signal Processing, Lyons, Prentice Hall
    - https://www.amazon.com/Understanding-Digital-Signal-Processing-3rd/dp/0137027419

- TinyML
  - https://tinyml.org/
  - https://tinymlbook.com/

- Efficient Processing of Deep Neural Networks, Sze et al.
  http://www.morganclaypoolpublishers.com/catalog_Orig/product_info.php?cPath=22&products_id=1530

NUMERIX
http://www.numerix-dsp.com
John Edwards BEng (Hons) CEng MIEEE
Director
jedwards@numerix-dsp.com
https://www.linkedin.com/in/johnedwards/

Thank You Very Much

Questions ?