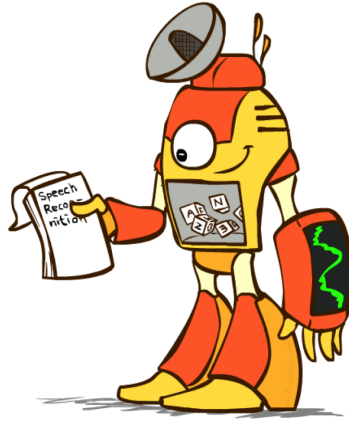


# Introduction to Artificial Intelligence

Lecture: Communication

Prof. Gilles Louppe  
[g.louppe@uliege.be](mailto:g.louppe@uliege.be)

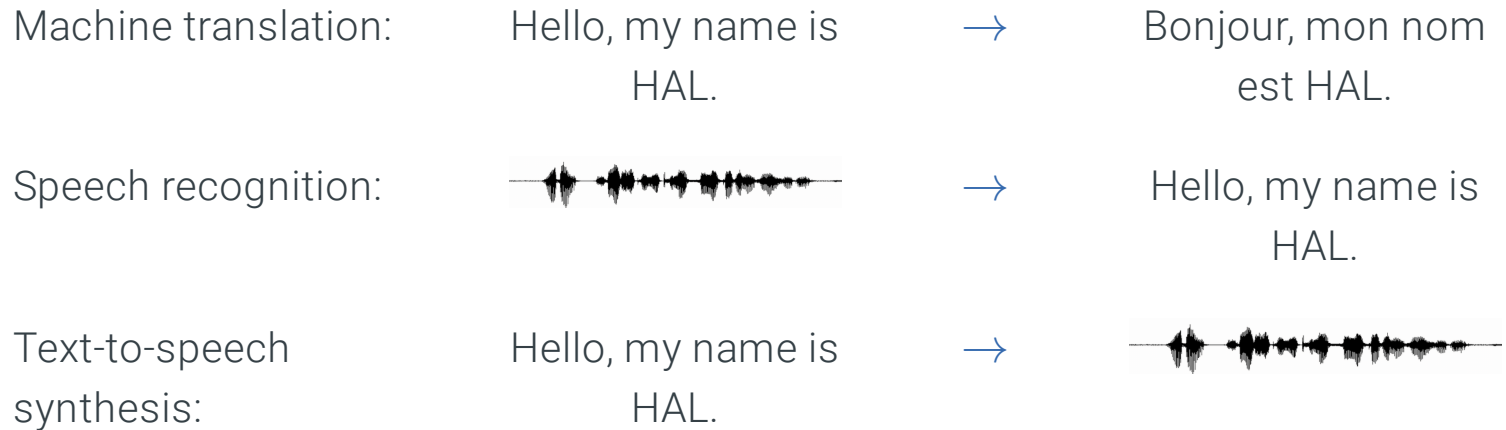
# Today



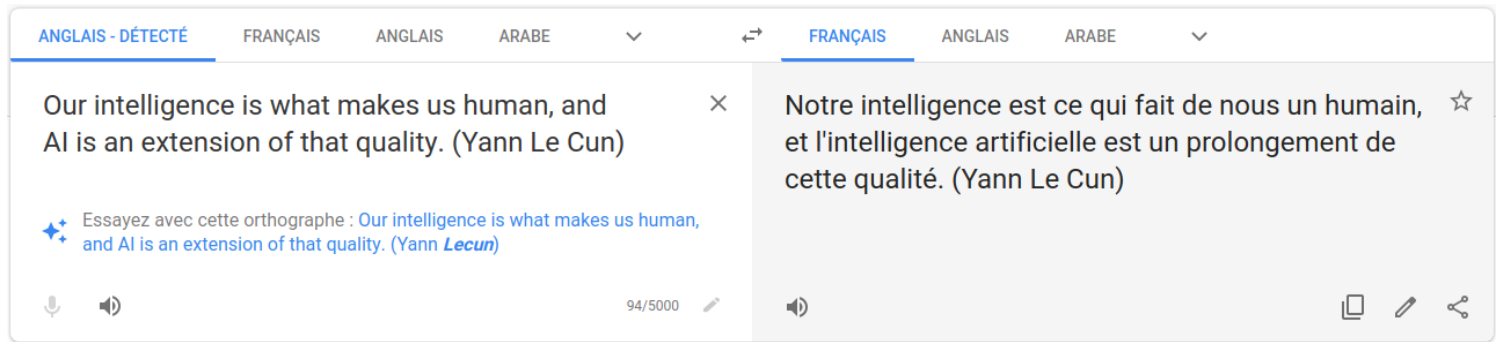
Can you **talk** to an artificial agent? Can it understand what you say?

- Machine translation
- Speech recognition
- Text-to-speech synthesis

## Sequence-to-sequence mapping



# Machine translation



*Envoyer des commentaires*

## Machine translation

Automatic translation of text from one natural language (the source) to another (the target), while preserving the intended meaning.

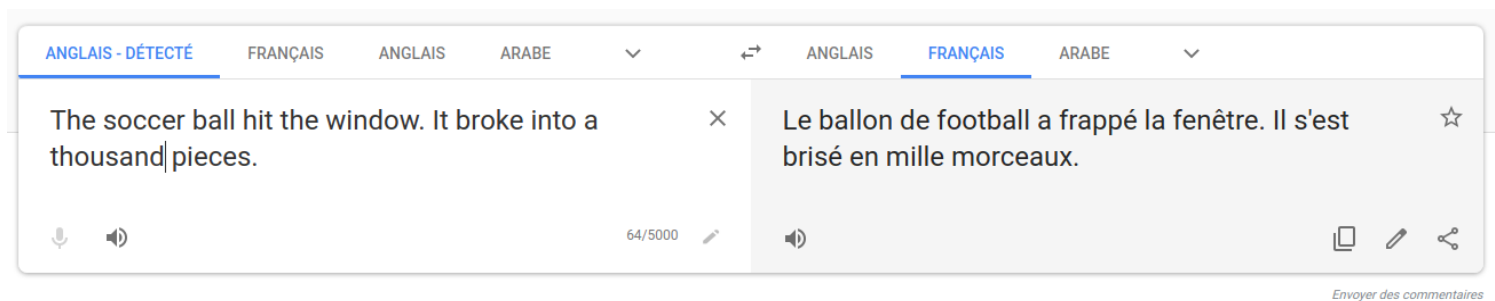
### Exercise

How would you engineer a machine translation system?

## Issue of dictionary lookups

顶部	/ <b>top</b> /roof/
顶端	/summit/peak/ <b>top</b> /apex/
顶头	/coming directly towards one/ <b>top</b> /end/
盖	/lid/ <b>top</b> /cover/canopy/build/Gai/
盖帽	/surpass/ <b>top</b> /
极	/extremely/pole/utmost/ <b>top</b> /collect/receive/
尖峰	/peak/ <b>top</b> /
面	/fade/side/surface/aspect/ <b>top</b> /face/flour/
摘心	/ <b>top</b> /topping/

Natural languages are not 1:1 mappings of each other!



To obtain a correct translation, one must decide whether "it" refers to the soccer ball or to the window.

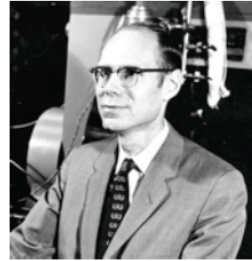
Therefore, one must understand physics as well as language.

# History



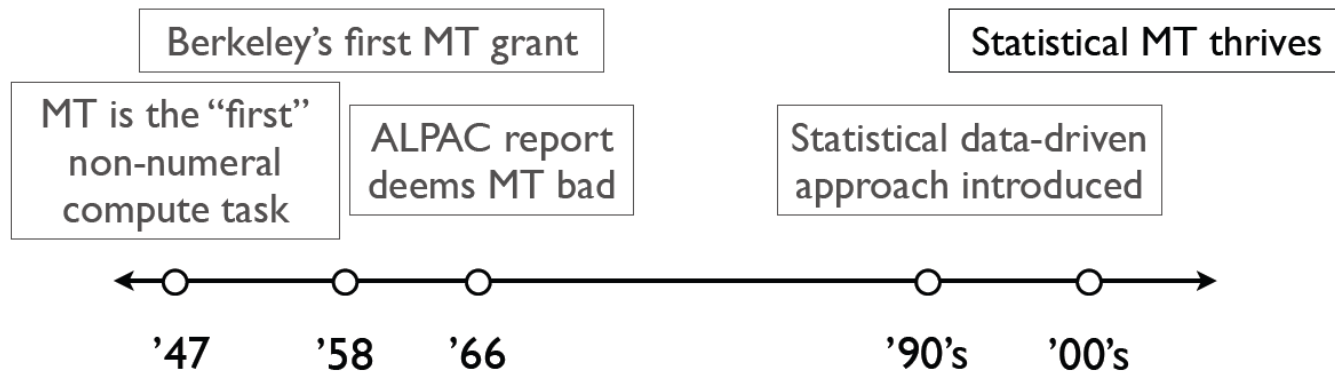
Warren Weaver

When I look at an article in Russian, I say: "This is really written in English, but it has been coded in some strange symbols. I will now proceed to decode."



John Pierce

"Machine Translation" presumably means going by algorithm from machine-readable source text to useful target text... In this context, there has been no machine translation...





# Data-driven machine translation

*Target language corpus:*

I will get to it soon

See you later

He will do it

*Sentence-aligned parallel corpus:*

Yo lo haré mañana  
I will do it tomorrow

Hasta pronto  
See you soon

Hasta pronto  
See you around

*Machine translation system:*

Yo lo haré pronto

NOVEL SENTENCE

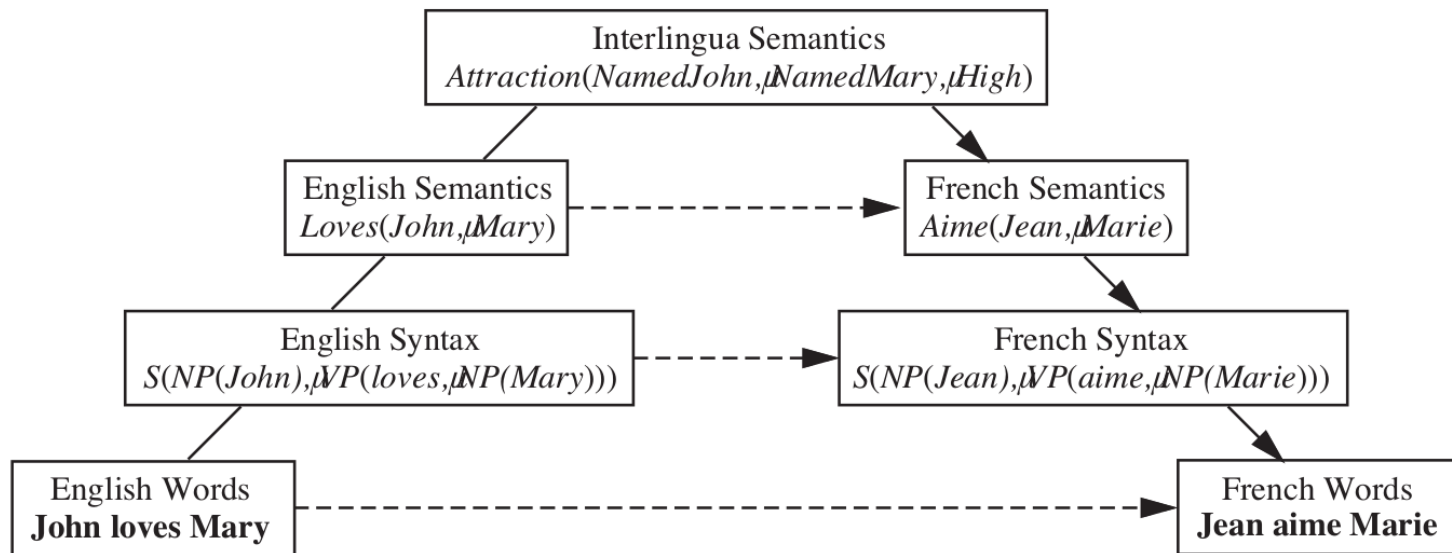
Model of  
translation

I will do it soon

## Machine translation systems

Translation systems must model the source and target languages, but systems vary in the type of models they use.

- Some systems analyze the source language text all the way into an [interlingua knowledge representation](#) and then generate sentences in the target language from that representation.
- Other systems are based on a [transfer model](#). They keep a database of translation rules and whenever the rule matches, they translate directly. Transfer can occur at the lexical, syntactic or semantic level.



**Figure 23.12** The Vauquois triangle: schematic diagram of the choices for a machine translation system (Vauquois, 1968). We start with English text at the top. An interlingua-based system follows the solid lines, parsing English first into a syntactic form, then into a semantic representation and an interlingua representation, and then through generation to a semantic, syntactic, and lexical form in French. A transfer-based system uses the dashed lines as a shortcut. Different systems make the transfer at different points; some make it at multiple points.

# Statistical machine translation

To translate an English sentence  $e$  into a French sentence  $f$ , we seek the strings of words  $f^*$  such that

$$f^* = \arg \max_f P(f|e).$$

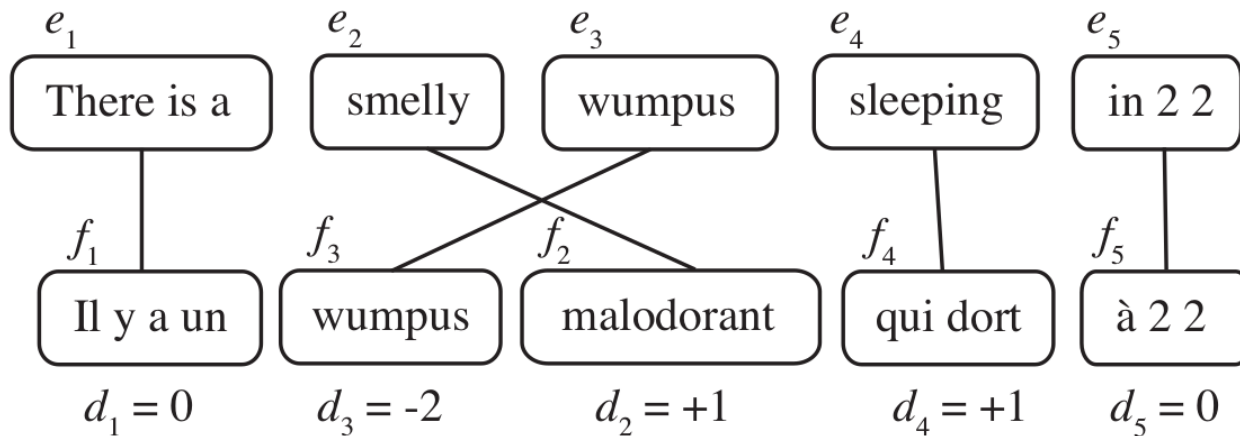
- The language model  $P(f|e)$  is learned from a **bilingual corpus**, i.e. a collection of parallel texts, each an English/French pair.
- Most of the English sentences to be translated will be novel, but will be composed of phrases that have been seen before.
- The corresponding French phrases will be reassembled to form a French sentence that makes sense.

Given an English source sentence  $e$ , finding a French translation  $f$  is a matter of three steps:

- Break  $e$  into phrases  $e_1, \dots, e_n$ .
- For each phrase  $e_i$ , choose a corresponding French phrase  $f_i$ . We use the notation  $P(f_i|e_i)$  for the phrasal probability that  $f_i$  is a translation of  $e_i$ .
- Choose a permutation of the phrases  $f_1, \dots, f_n$ . For each  $f_i$ , we choose a distortion

$$d_i = \text{start}(f_i) - \text{end}(f_{i-1}) - 1,$$

which is the number of words that phrase  $f_i$  has moved with respect to  $f_{i-1}$ ; positive for moving to the right, negative for moving the left.




---

**Figure 23.13** Candidate French phrases for each phrase of an English sentence, with distortion ( $d$ ) values for each French phrase.

We define the probability  $P(f, d|e)$  that the sequence of phrases  $f$  with distortions  $d$  is a translation of the sequence of phrases  $e$ .

Assuming that each phrase translation and each distortion is independent of the others, we have

$$P(f, d|e) = \prod_i P(f_i|e_i)P(d_i).$$

- The best  $f$  and  $d$  cannot be found through enumeration because of the combinatorial explosion.
- Instead, local beam search with a heuristic that estimates probability has proven effective at finding a nearly-most-probable translation.

All that remains is to learn the phrasal and distortion probabilities:

1. Find parallel texts.
2. Segment into sentences.
3. Align sentences.
4. Align phrases.
5. Extract distortions.
6. Improve estimates with expectation-maximization.



# Neural machine translation

Modern machine translation systems are all based on **neural networks** of various types, often architected as compositions of

- recurrent networks for sequence-to-sequence learning,
- convolutional networks for modeling spatial dependencies.
- transformer networks.

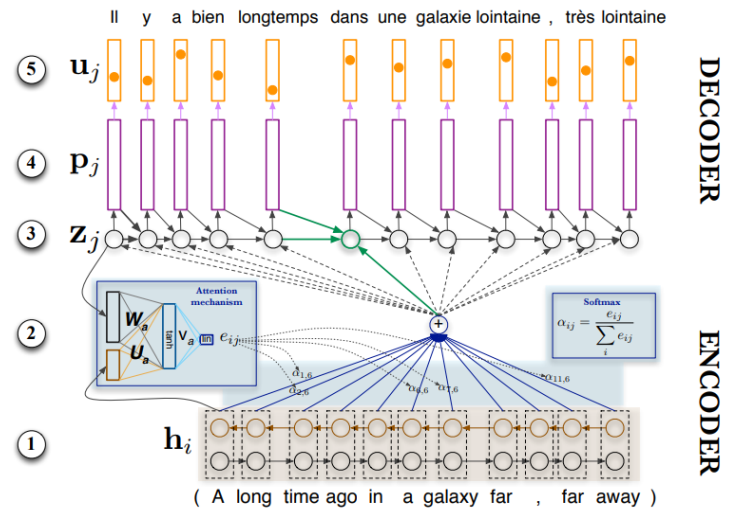


## Google's Neural Machine Translation

...reduced translation errors by an average of 60% when compared to the prior Google Translate technology

# Attention-based recurrent neural network

- Encoder: bidirectional RNN, producing a set of annotation vectors  $h_i$ .
- Decoder: attention-based.
  - Compute attention weights  $\alpha_{ij}$ .
  - Compute the weighted sum of the annotation vectors, as a way to align the input words to the output words.
  - Decode using the context vector, the embedding of the previous output word and the hidden state.



# Speech recognition



# Recognition as inference



Speech recognition can be viewed as an instance of the problem of **finding the most likely sequence** of state variables  $\mathbf{w}_{1:L}$ , given a sequence of observations  $\mathbf{y}_{1:T}$ .

- In this case, (hidden) state variables are the words and the observations are sounds.
- The input audio waveform from a microphone is converted into a sequence of fixed size acoustic vectors  $\mathbf{y}_{1:T}$  in a process called **feature extraction**.
- The decoder attempts to find the sequence of words  $\mathbf{w}_{1:L} = w_1, \dots, w_L$  which is the most likely given the sequence  $\mathbf{y}_{1:T}$ :

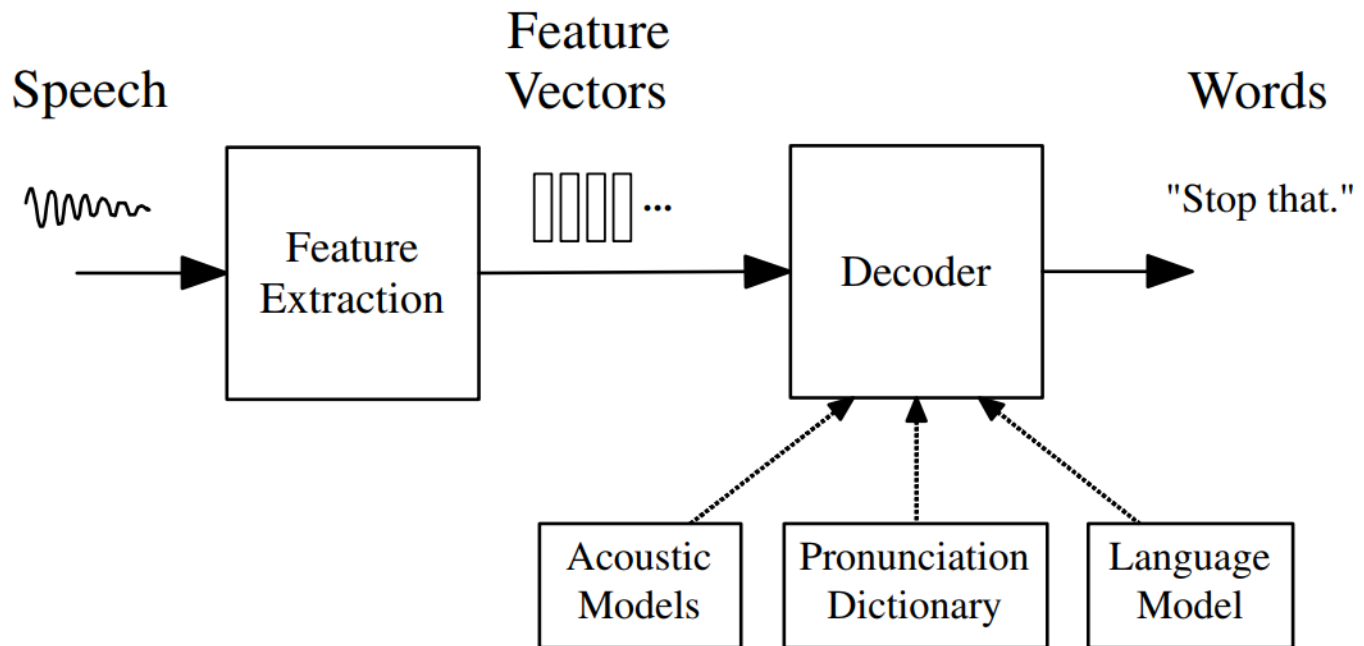
$$\hat{\mathbf{w}}_{1:L} = \arg \max_{\mathbf{w}_{1:L}} P(\mathbf{w}_{1:L} | \mathbf{y}_{1:T})$$

Since  $P(\mathbf{w}_{1:L}|\mathbf{y}_{1:T})$  is difficult to model directly, Bayes' rule is the used to solve the equivalent problem

$$\hat{\mathbf{w}}_{1:L} = \arg \max_{\mathbf{w}_{1:L}} p(\mathbf{y}_{1:T}|\mathbf{w}_{1:L})P(\mathbf{w}_{1:L}),$$

where

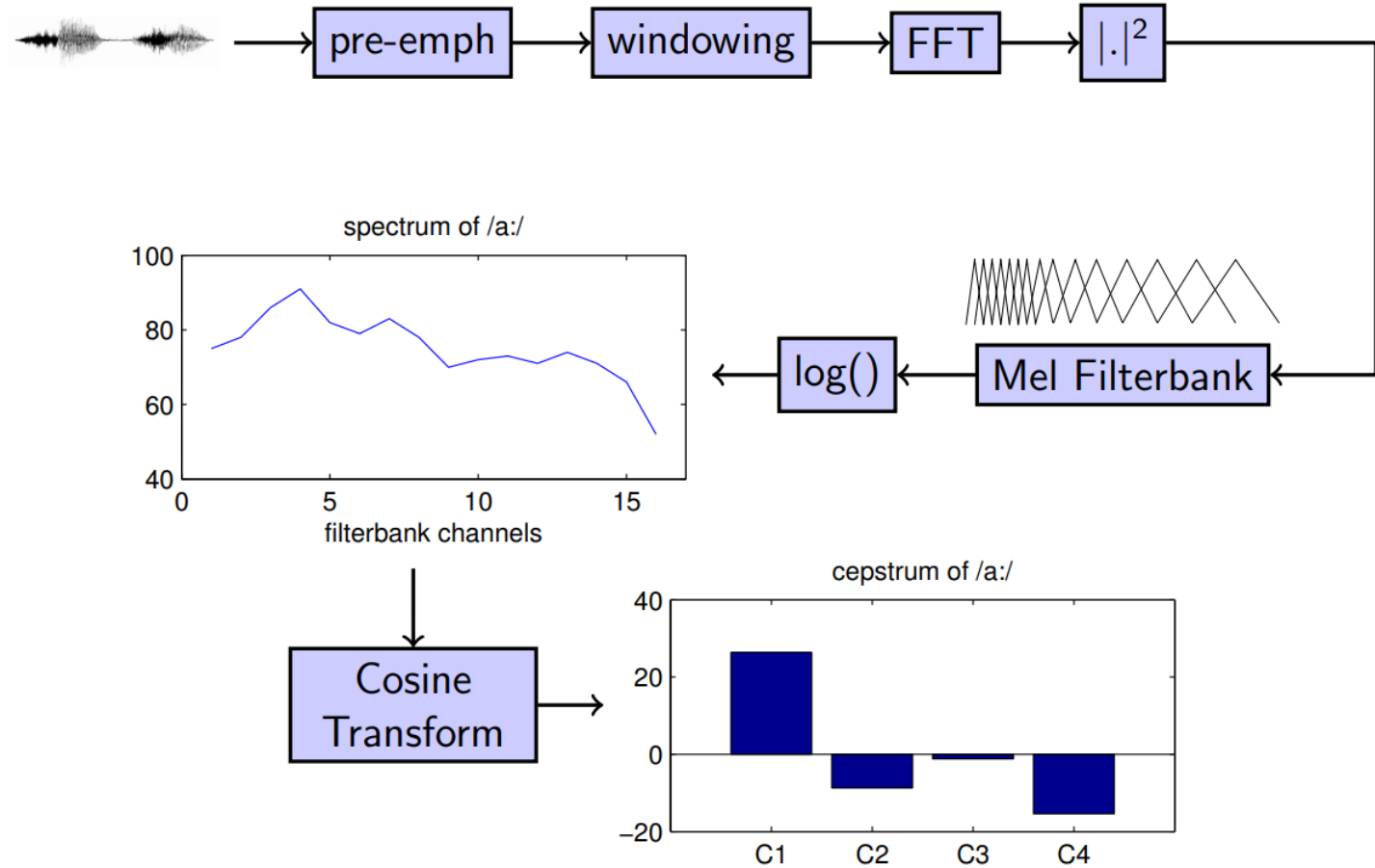
- the likelihood  $p(\mathbf{y}_{1:T}|\mathbf{w}_{1:L})$  is the **acoustic model**;
- the prior  $P(\mathbf{w}_{1:L})$  is the **language model**.



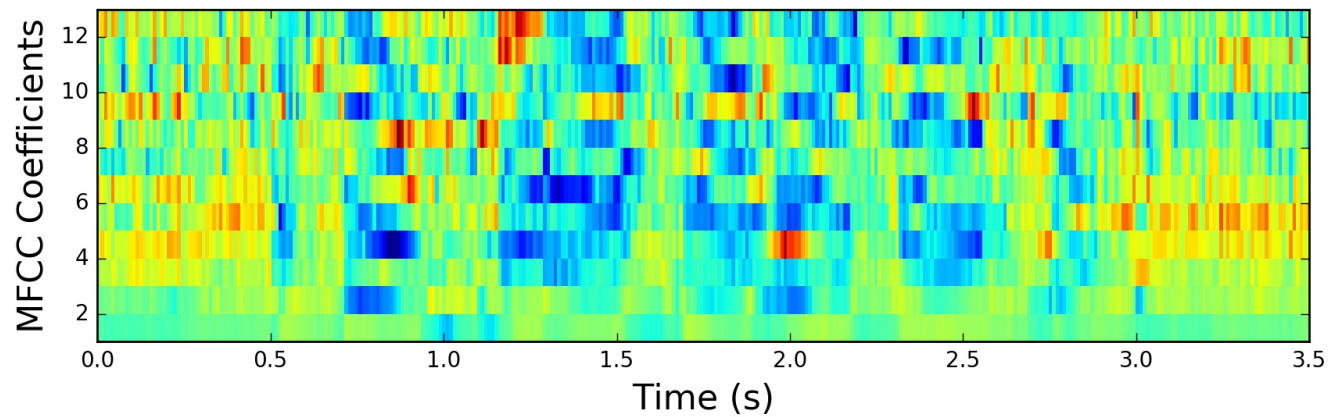
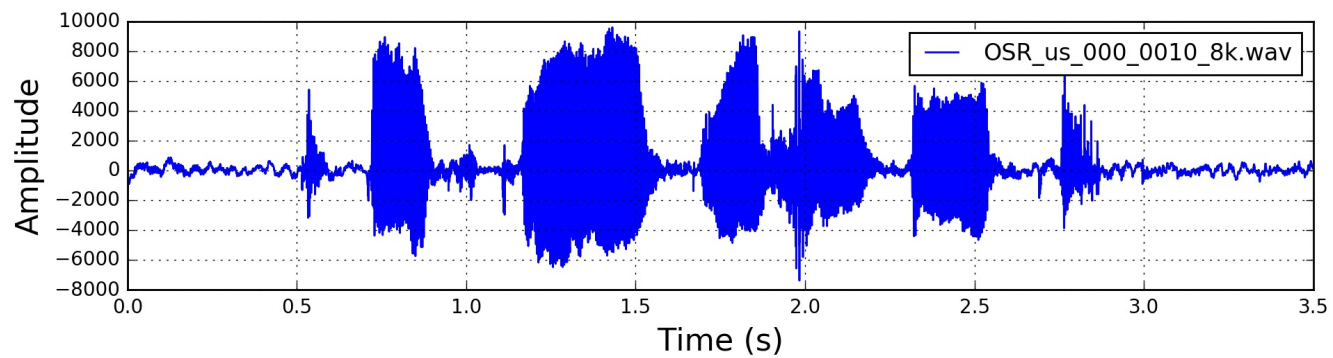
## Feature extraction

- The feature extraction seeks to provide a compact representation  $\mathbf{y}_{1:T}$  of the speech waveform.
- This form should minimize the loss of information that discriminates between words.
- One of the most widely used encoding schemes is based on **mel-frequency cepstral coefficients** (MFCCs).





MFCCs calculation.



Feature extraction from the signal in the time domain to MFCCs.

## Acoustic model

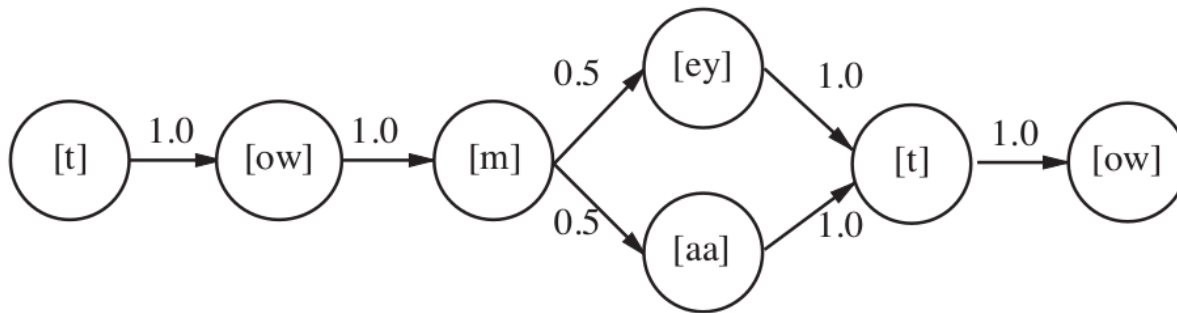
A spoken word  $w$  is decomposed into a sequence of  $K_w$  basic sounds called **base phones** (such as vowels or consonants).

- This sequence is called its pronunciation  $\mathbf{q}_{1:K_w}^w = q_1, \dots, q_{K_w}$ .
- Pronunciations are related to words through **pronunciations models** defined for each word.
- e.g. "Artificial intelligence" is pronounced  $/\alpha:t \text{ɪ} 'f \text{ɪ} \int (\text{ə}) \text{l} \text{ɪ} \text{n}$   
 $'t \text{ɛ} \text{l} \text{ɪ} \text{d} \int (\text{ə}) \text{n} \text{s}/$ .

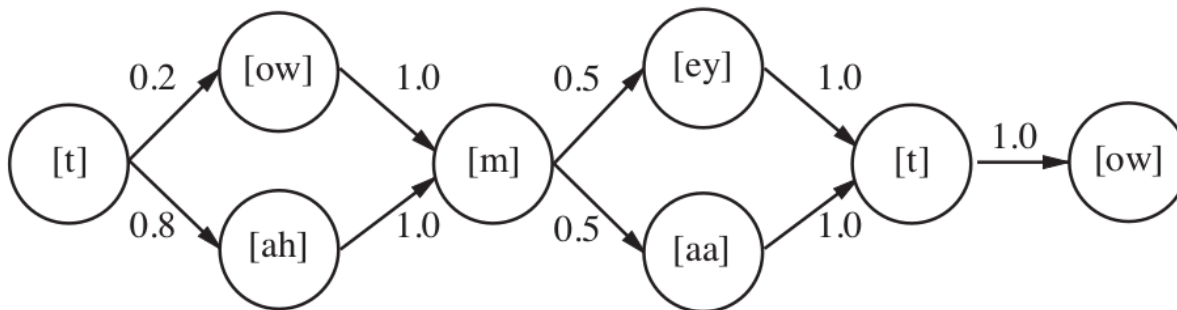
Vowels		Consonants B–N		Consonants P–Z	
Phone	Example	Phone	Example	Phone	Example
[iy]	<b>b<u>e</u>at</b>	[b]	<b><u>b</u>et</b>	[p]	<b><u>p</u>et</b>
[ih]	<b>b<u>i</u>t</b>	[ch]	<b><u>C</u>het</b>	[r]	<b><u>r</u>at</b>
[eh]	<b>b<u>e</u>t</b>	[d]	<b><u>d</u>ebt</b>	[s]	<b><u>s</u>et</b>
[æ]	<b>b<u>a</u>t</b>	[f]	<b><u>f</u>at</b>	[sh]	<b><u>sh</u>oe</b>
[ah]	<b>b<u>u</u>t</b>	[g]	<b><u>g</u>et</b>	[t]	<b><u>t</u>en</b>
[ao]	<b>b<u>o</u>ught</b>	[hh]	<b><u>h</u>at</b>	[th]	<b><u>th</u>ick</b>
[ow]	<b>b<u>o</u>at</b>	[hv]	<b><u>h</u>igh</b>	[dh]	<b><u>th</u>at</b>
[uh]	<b>b<u>o</u>ok</b>	[jh]	<b><u>j</u>et</b>	[dx]	<b>b<u>u</u>tter</b>
[ey]	<b>b<u>a</u>it</b>	[k]	<b><u>k</u>ick</b>	[v]	<b><u>v</u>et</b>
[er]	<b>B<u>e</u>rt</b>	[l]	<b><u>l</u>et</b>	[w]	<b><u>w</u>et</b>
[ay]	<b>b<u>u</u>y</b>	[el]	<b>bott<u>l</u>e</b>	[wh]	<b><u>w</u>hich</b>
[oy]	<b>b<u>o</u>y</b>	[m]	<b><u>m</u>et</b>	[y]	<b><u>y</u>et</b>
[axr]	<b>din<u>e</u>r</b>	[em]	<b>bottom</b>	[z]	<b><u>z</u>oo</b>
[aw]	<b>d<u>o</u>wn</b>	[n]	<b><u>n</u>et</b>	[zh]	<b>meas<u>u</u>re</b>
[ax]	<b><u>a</u>bout</b>	[en]	<b>butt<u>o</u>n</b>		
[ix]	ros <u>e</u> s	[ng]	<b>sing</b>		
[aa]	c <u>o</u> t	[eng]	<b>wash<u>u</u>ng</b>	[-]	<i>silence</i>

**Figure 23.14** The ARPA phonetic alphabet, or **ARPAbet**, listing all the phones used in American English. There are several alternative notations, including an International Phonetic Alphabet (IPA), which contains the phones in all known languages.

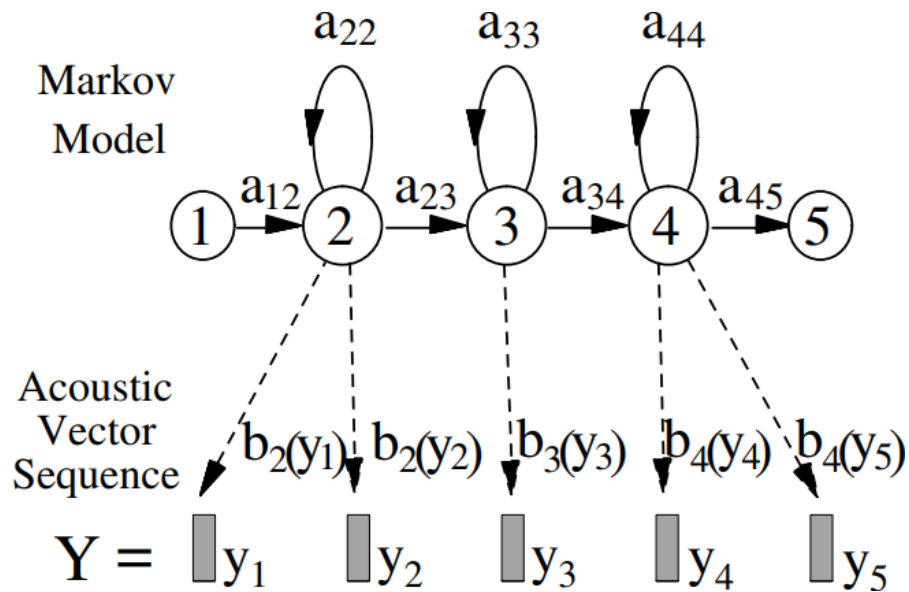
(a) Word model with dialect variation:



(b) Word model with coarticulation and dialect variations



**Figure 23.17** Two pronunciation models of the word “tomato.” Each model is shown as a transition diagram with states as circles and arrows showing allowed transitions with their associated probabilities. (a) A model allowing for dialect differences. The 0.5 numbers are estimates based on the two authors’ preferred pronunciations. (b) A model with a coarticulation effect on the first vowel, allowing either the [ow] or the [ah] phone.



Each base phone  $q$  is represented by **phone model** defined as a three-state continuous density HMM, where

- the transition probability parameter  $a_{ij}$  corresponds to the probability of making the particular transition from state  $s_i$  to  $s_j$ ;
- the output sensor models are Gaussians  $b_j(\mathbf{y}) = \mathcal{N}(\mathbf{y}; \mu^{(j)}, \Sigma^{(j)})$  and relate state variables  $s_j$  to MFCCs  $\mathbf{y}$ .

The full acoustic model can now be defined as a composition of pronunciation models with individual phone models:

$$p(\mathbf{y}_{1:T}|\mathbf{w}_{1:L}) = \sum_{\mathbf{Q}} P(\mathbf{y}_{1:T}|\mathbf{Q})P(\mathbf{Q}|\mathbf{w}_{1:L})$$

where the summation is over all valid pronunciation sequences for  $\mathbf{w}_{1:L}$ ,  $\mathbf{Q}$  is a particular sequence  $\mathbf{q}^{w_1}, \dots, \mathbf{q}^{w_L}$  of pronunciations,

$$P(\mathbf{Q}|\mathbf{w}_{1:L}) = \prod_{l=1}^L P(\mathbf{q}^{w_l}|w_l)$$

as given by the pronunciation model, and where  $\mathbf{q}^{w_l}$  is a valid pronunciation for word  $w_l$ .

Given the composite HMM formed by concatenating all the constituent pronunciations  $\mathbf{q}^{w_1}, \dots, \mathbf{q}^{w_L}$  and their corresponding base phones, the acoustic likelihood is given by

$$p(\mathbf{y}_{1:T}|\mathbf{Q}) = \sum_{\mathbf{s}} p(\mathbf{s}, \mathbf{y}_{1:T}|\mathbf{Q})$$

where  $\mathbf{s} = s_0, \dots, s_{T+1}$  is a state sequence through the composite model and

$$p(\mathbf{s}, \mathbf{y}_{1:T}|\mathbf{Q}) = a_{s_0, s_1} \prod_{t=1}^T b_{s_t}(\mathbf{y}_t) a_{s_t, s_{t+1}}.$$

From this formulation, all model parameters can be efficiently estimated from a corpus of training utterances with expectation-maximization.



## N-gram language model

The prior probability of a word sequence  $\mathbf{w} = w_1, \dots, w_L$  is given by

$$P(\mathbf{w}) = \prod_{l=1}^L P(w_l | w_{l-1}, \dots, w_{l-N+1}).$$

The N-gram probabilities are estimated from training texts by counting N-gram occurrences to form maximum likelihood estimates.

## Decoding

The composite model corresponds to a HMM, from which the most-likely state sequence **s** can be inferred using (a variant of) **Viterbi**.

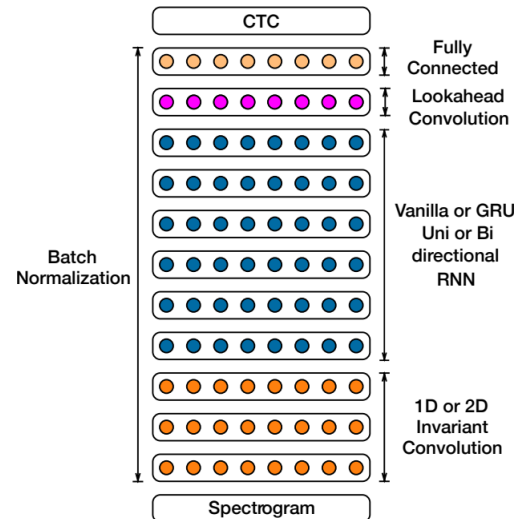
By construction, states **s** relate to phones, phones to pronunciations, and pronunciations to words.

# Neural speech recognition

Modern speech recognition systems are now based on **end-to-end** deep neural network architectures trained on large corpus of data.

## Deep Speech 2

- Recurrent neural network with
  - one or more convolutional input layers,
  - followed by multiple recurrent layers,
  - and one fully connected layer before a softmax layer.
- Total of 35M parameters.
- Same architecture for both English and Mandarin.





SVAIL Tech Notes: Deep Speech: Recognizing B...



Later bekij...



Delen



Deep Speech 2

# Text-to-speech synthesis

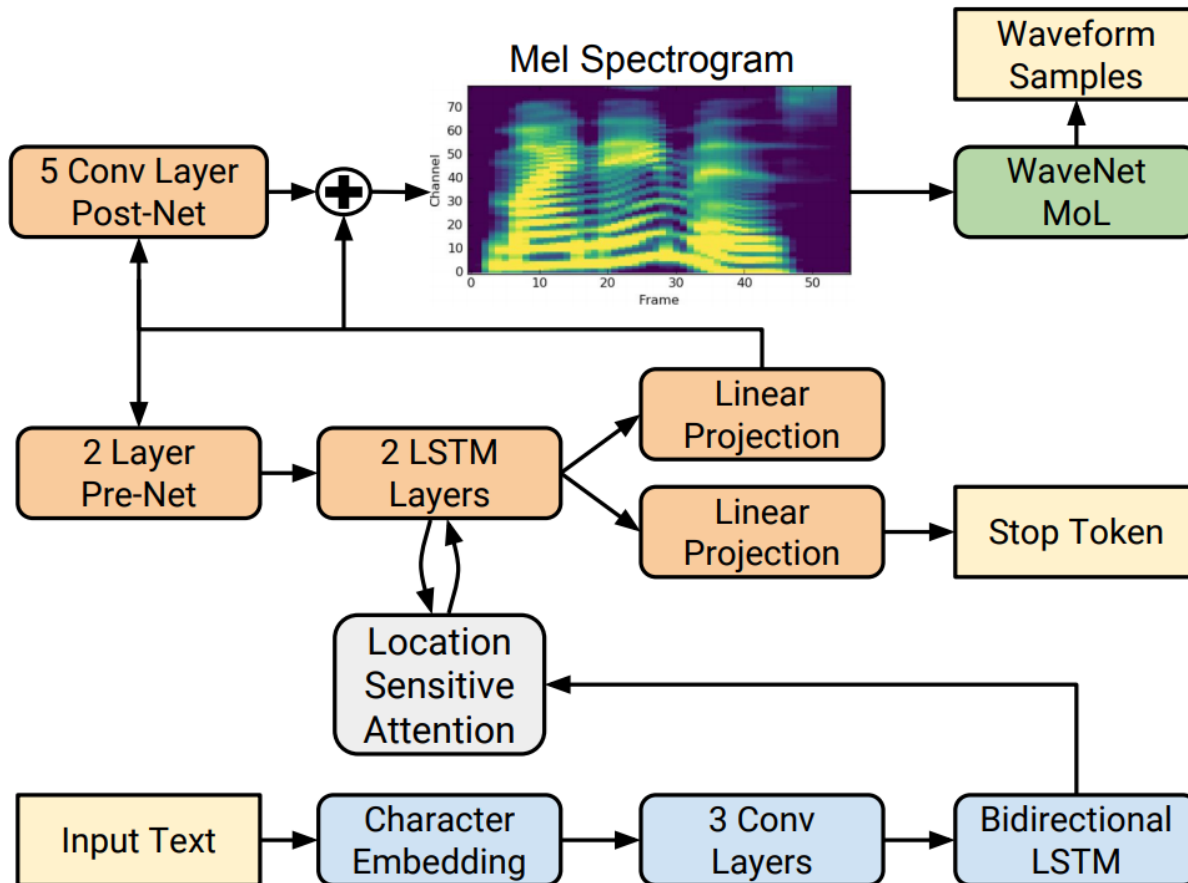
$\mathbf{w}_{1:L}$   
My name is HAL.



# Tacotron 2

The Tacotron 2 system is a **sequence-to-sequence neural network** architecture for text-to-speech. It consists of two components:

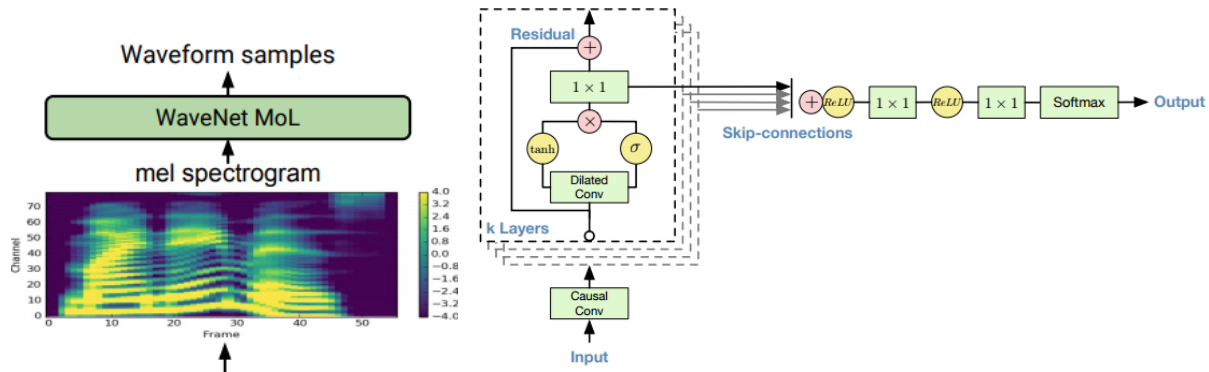
- a recurrent sequence-to-sequence feature prediction network with attention which predicts a sequence of mel spectrogram frames from an input character sequence;
- a **Wavenet vocoder** which generates time-domain waveform samples conditioned on the predicted mel spectrogram frames.





# Wavenet

- The Tacotron 2 architecture produces mel spectrograms as outputs, which remain to be synthesized as waveforms.
- This last step can be performed through another autoregressive neural model, such as **Wavenet**, to transform mel-scale spectrograms into high-fidelity waveforms.



Audio samples at

- [deepmind.com/blog/wavenet-generative-model-raw-audio](https://deepmind.com/blog/wavenet-generative-model-raw-audio)
- [google.github.io/tacotron](https://google.github.io/tacotron)



Google Assistant: Soon in your smartphone.

# Summary

- Natural language understanding is one of the most important subfields of AI.
- Machine translation, speech recognition and text-to-speech synthesis are instances of sequence-to-sequence problems.
- All problems can be tackled with traditional statistical inference methods but require sophisticated engineering.
- State-of-the-art methods are now based on neural networks.

