



# 10-423/10-623 Generative AI

Machine Learning Department  
School of Computer Science  
Carnegie Mellon University


## Audio Understanding and Synthesis

Matt Gormley & Pat Virtue

Lecture 24

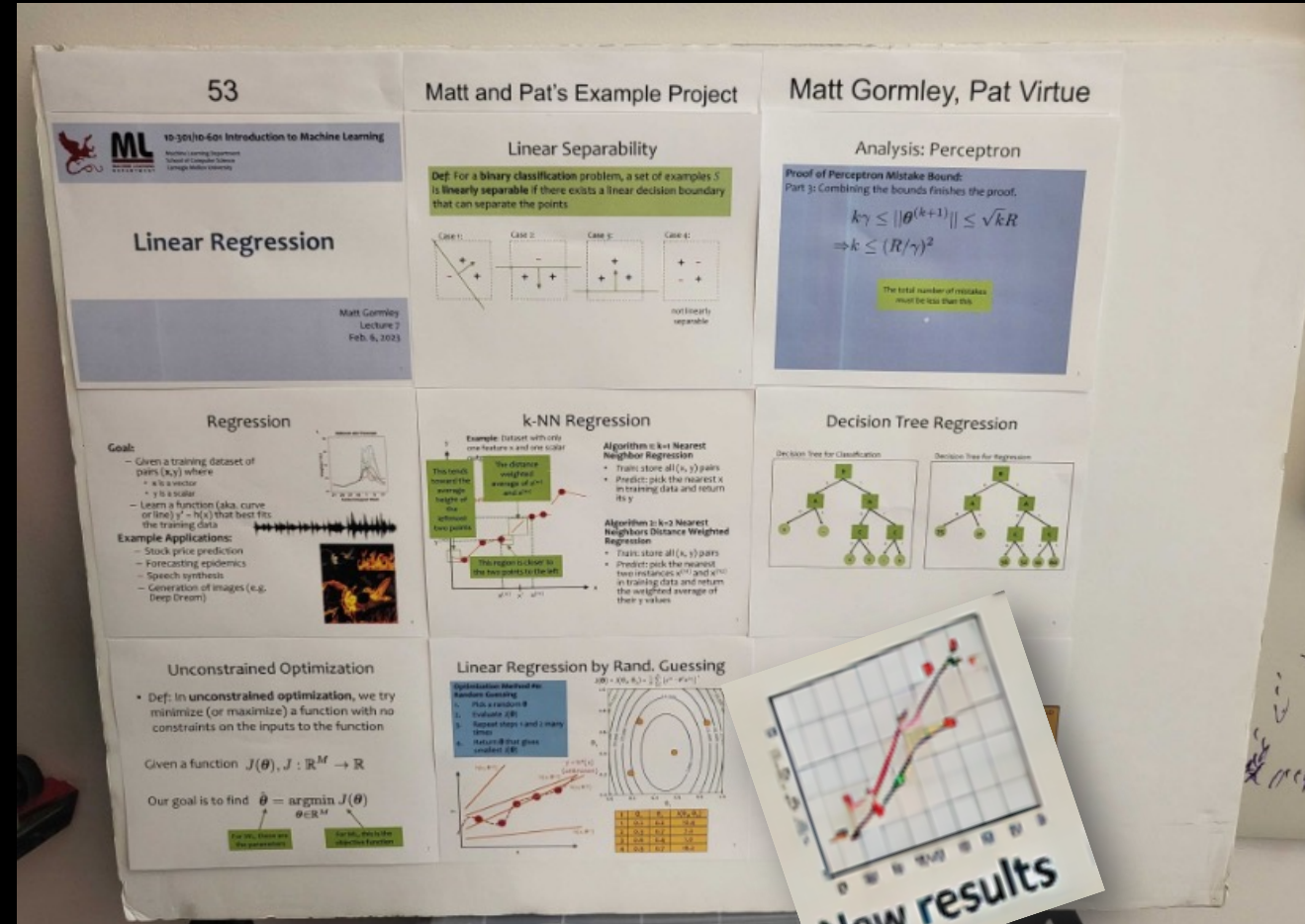
Apr. 16, 2025

# Reminders

- **Project Midway Report**
  - Due: Thu, Apr-17 at 11:59pm
- **HW623**
  - Only for students registered in 10-623
  - Due: Mon, Apr-21 at 11:59pm
- **Project “Poster”**
  - Upload Due: Sun, Apr-27 at 11:59pm 
  - Presentations: Tue, Apr-29 at 8:30am-11:30am
- **Project Final Report**
  - Due: Thu, May 1 at 11:59pm
- **Project Code Upload**
  - Due: Thu, May 1 at 11:59pm

# “Poster” Printing

- the new “poster” format enables us to delay the submission deadline from Friday to Sunday
- if you need to modify your poster to include a small update, feel free to print a modified version



# Audio Understanding and Synthesis

- Outline
  - working with audio data
    - Mel spectrogram
  - speech transcription (speech-to-text)
    - Whisper
  - speech generation (audio continuation)
    - autoregressive audio codec models (AudioLM)
  - music generation
    - MIDI generation (MusicTransformer)
    - audio tokenization (EnCodec)
    - Text-to-music generation (e.g. MusicGen)
  - combining speech and text models
    - speech+text-to-text (SpeechVerse)

# **AUDIO UNDERSTANDING & SYNTHESIS**

# Working with Audio Data

- Pulse-code modulation (PCM) representation
  - an audio recording device takes many samples of pressure (amplitude)
  - a raw audio file has several parameters:
    - # of channels (e.g. stereo has two)
    - bit depth (# of bits used to represent each amplitude)
    - sampling rate (how many samples are taken per second)
  - **example:** a 44.1 kHz 16-bit stereo recording has 44,100 samples per second, each sample consists of two 16-bit integers, one for each channel



Figure 1: A second of generated speech.

# Working with Audio Data

Figure from <https://kinder-chen.medium.com/denoising-data-with-fast-fourier-transform-a81d9f38cc4c>

- Sound wave representation
  - if we were recording audio of a **single** unchanging sound, we could run a **single** Fast Fourier Transform (FFT) to extract the sinusoidal waves that gave rise to the samples we observe
- Mel-spectrogram representation
  - in practice sound changes over time and so we need to run **many FFTs of overlapping windows** to extract a usable representation of real audio
  - the output of this process is a **spectrogram**, and can be easily visualized as an image
  - to obtain a **mel-spectrogram**, we pass the frequencies through a frequency-to-mel map

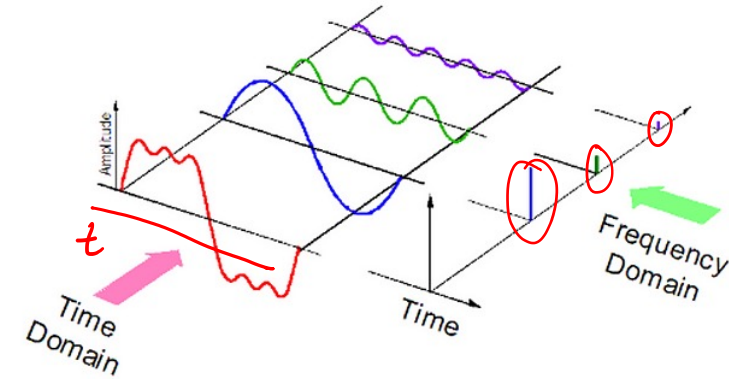


Figure from <https://towardsdatascience.com/audio-deep-learning-made-simple-part-2-why-mel-spectrograms-perform-better-aad889a93505>

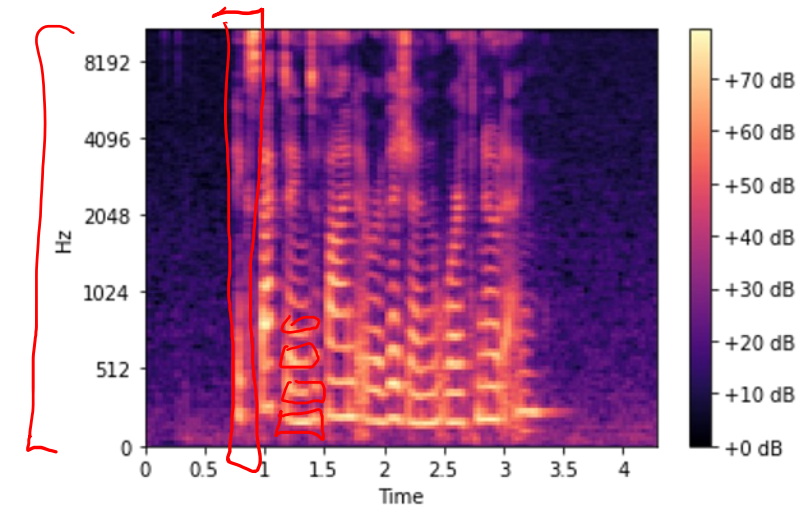
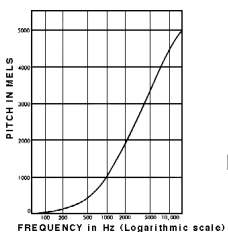
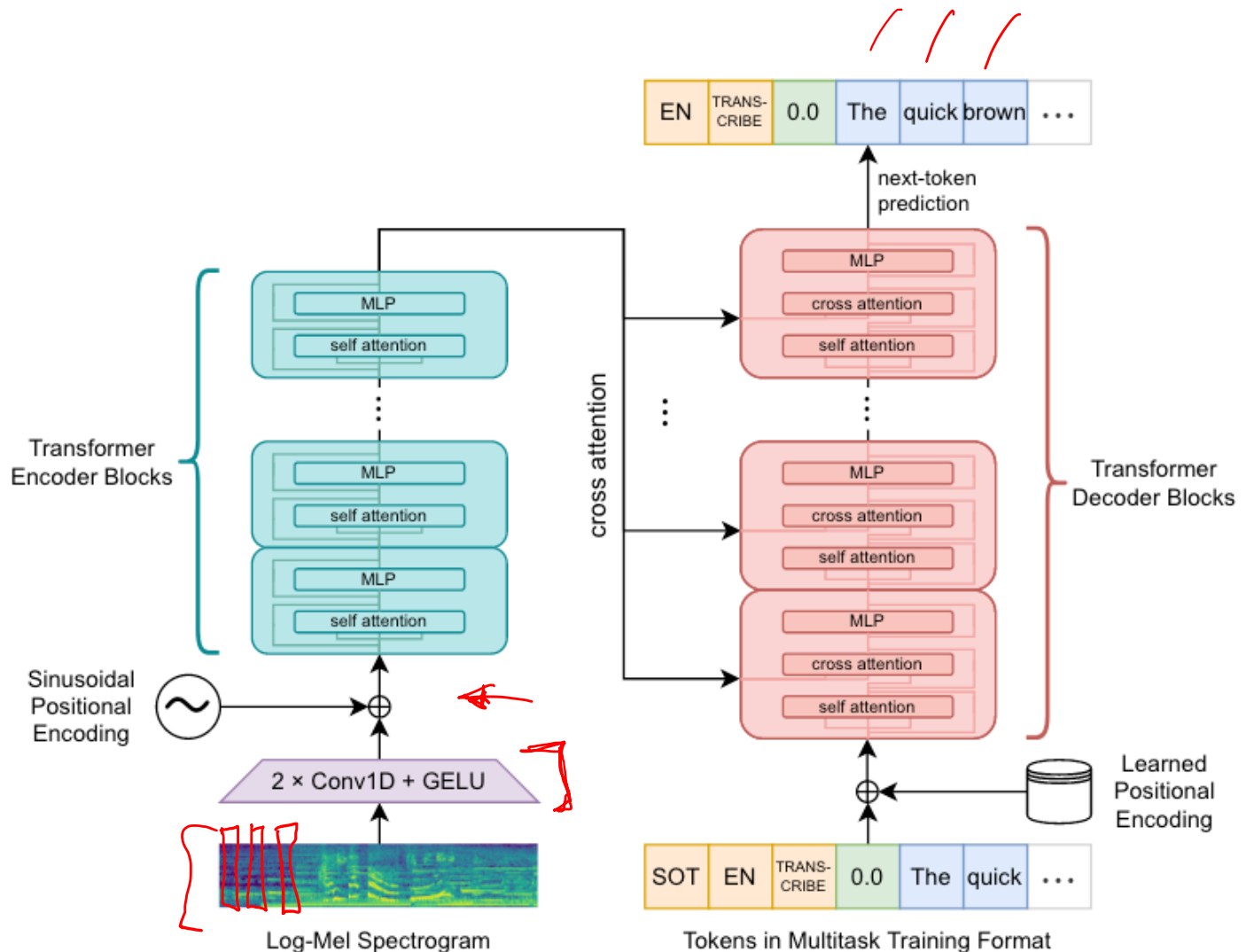


Figure from <https://www.sfu.ca/sonic-studio-webdav/handbook/Mel.html>



# Speech Transcription: Whisper

- **Speech transcription** is the task of taking in the audio of speech and generating the text transcript
- **Whisper** is an encoder-decoder Transformer model for speech transcription
- The **input** is the log-mel-spectrogram of the audio (30 second chunk) [16kHz, 80 channels, 25 ms window, 10 ms stride]

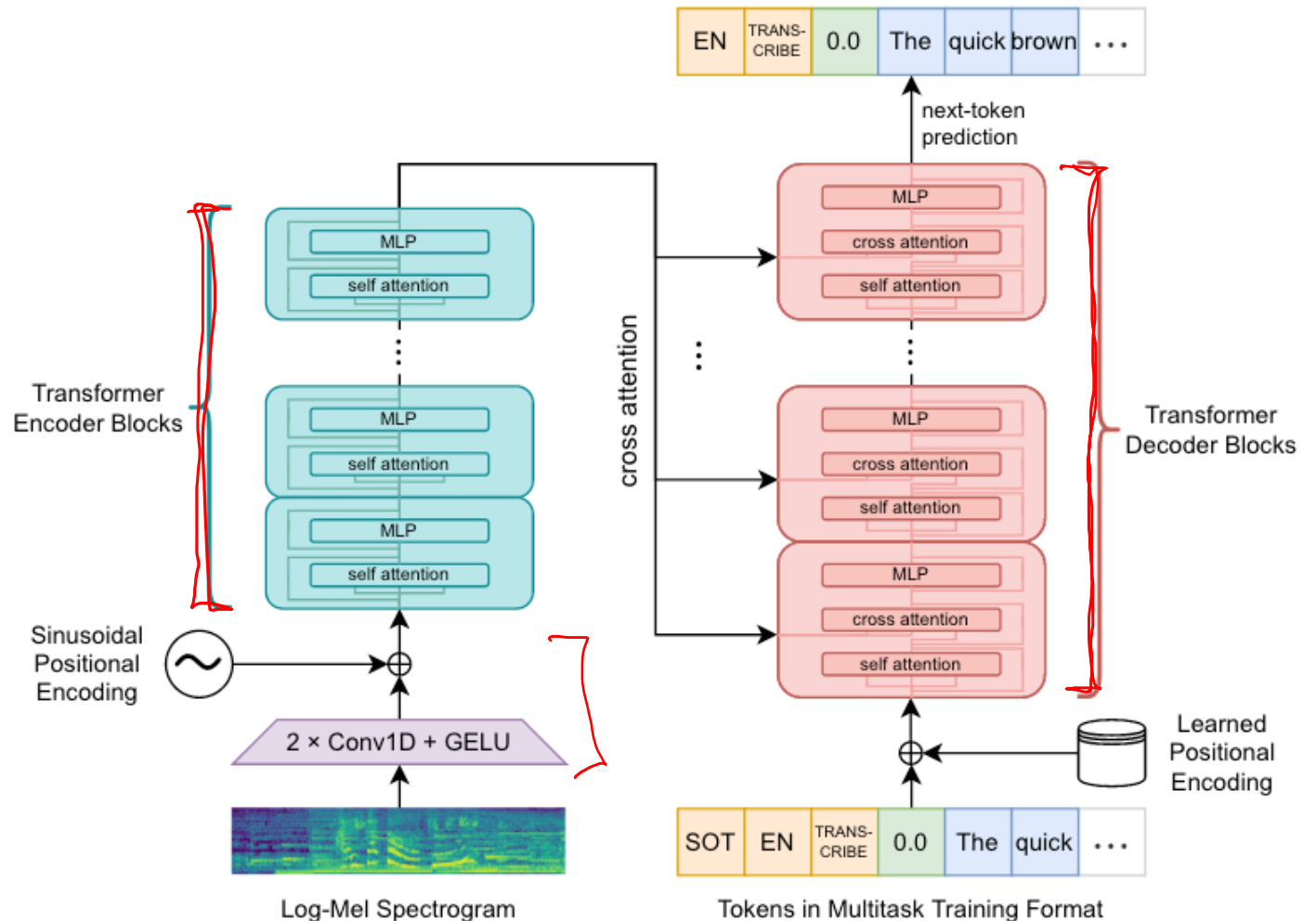




# Speech Transcription: Whisper

## Whisper

- model is *almost* identical to Vaswani et al. (2017)
- encoder: output of two convolution layers (filter={3,3}, stride={1,2}) + sinusoidal positional embeddings
- decoder: learned positional embeddings
- same # of transformer blocks in encoder / decoder (32)



# Speech Transcription: Whisper

- many tasks are used to train a single model
- special tokens are used to indicate the type of task, the language, etc.
- timestamp tokens allow the generation of time-aligned transcripts

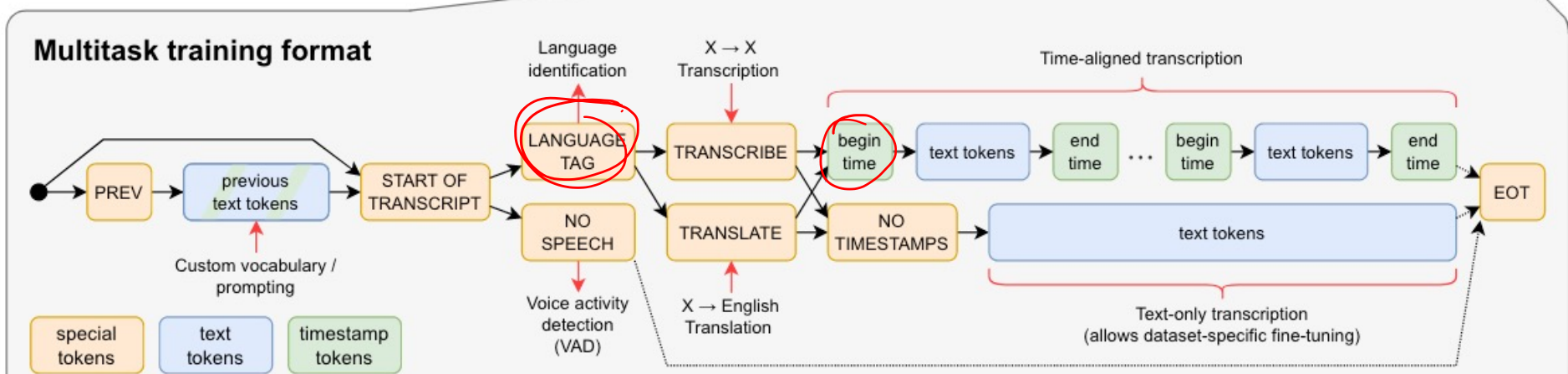
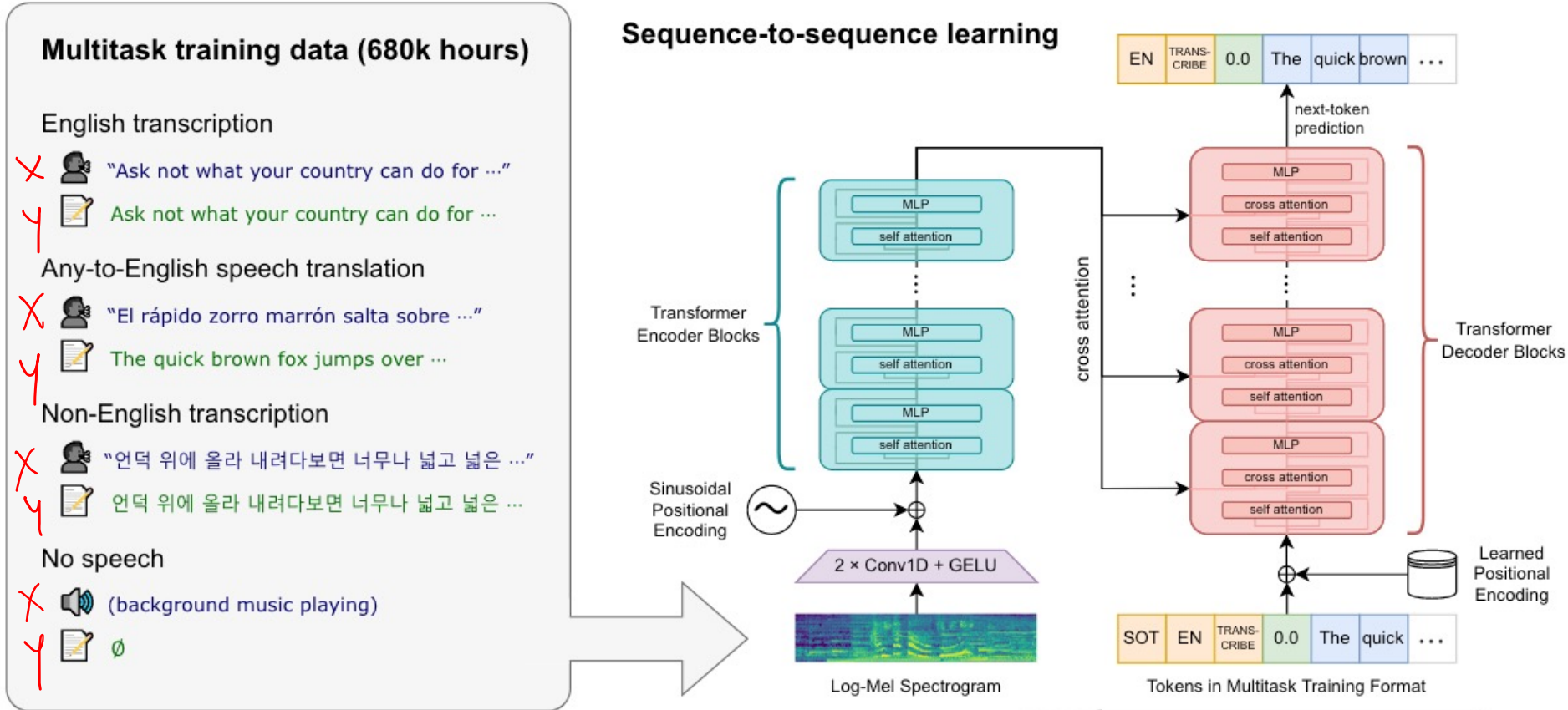
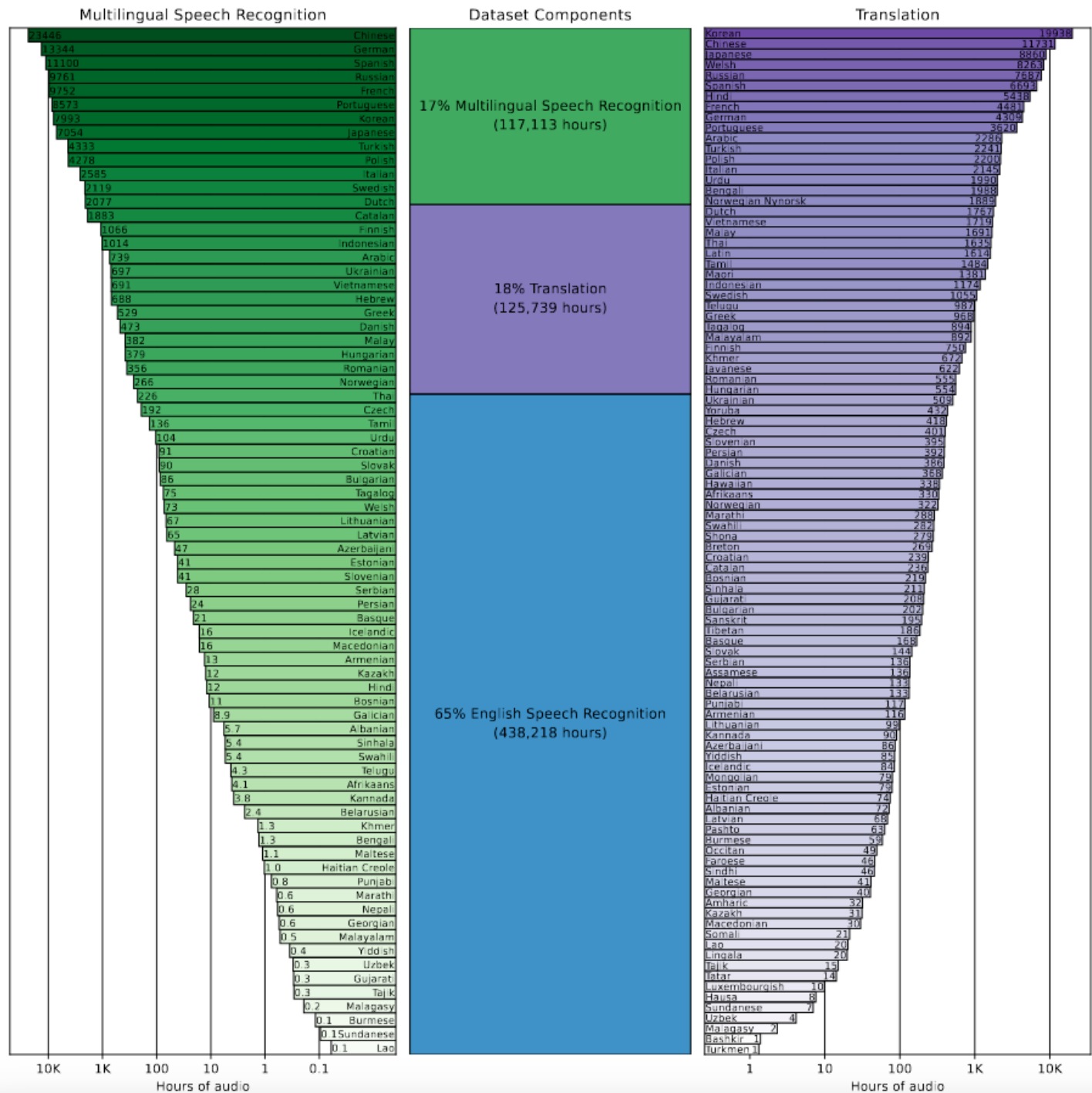


Figure from <https://arxiv.org/abs/2212.04356>

# Speech Transcription: Whisper

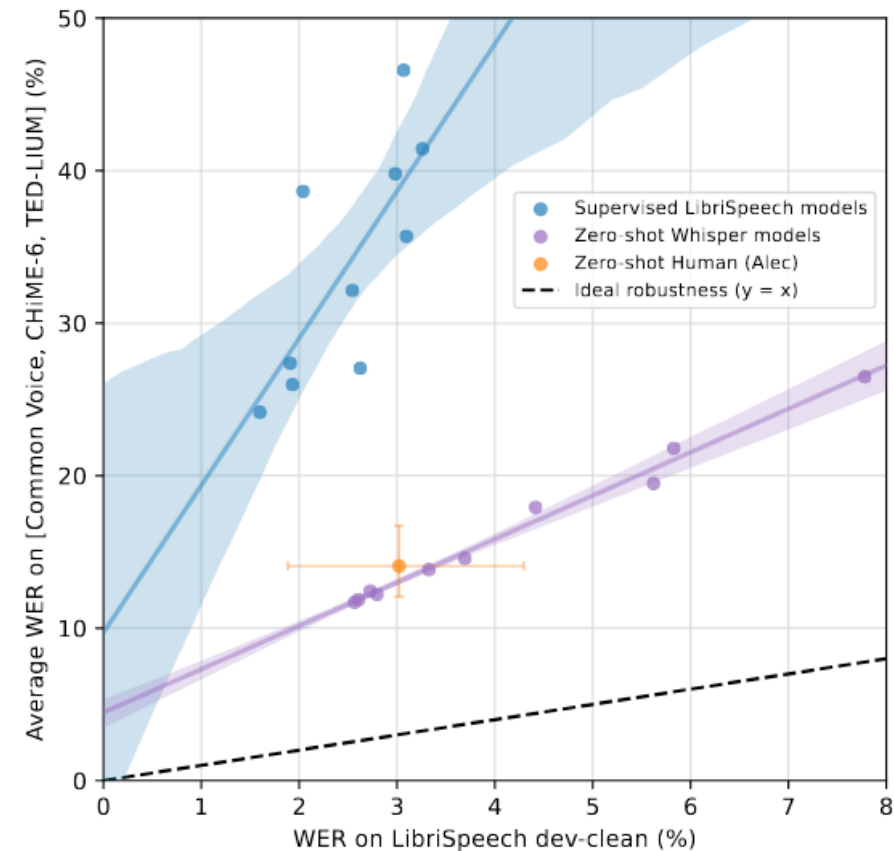
- Large model has 1.5B parameters
- Training dataset is so large that only 2-3 epochs are used



# Speech Transcription: Whisper

## Results:

- Whisper closes the gap to human level performance on LibriSpeech English WER

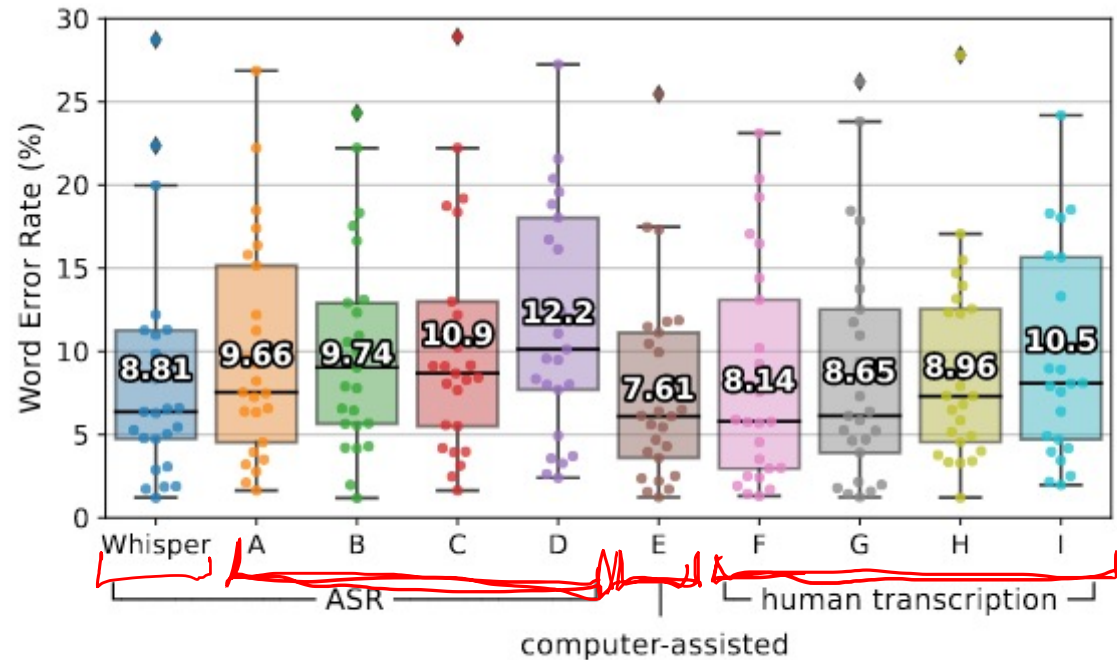


**Figure 2. Zero-shot Whisper models close the gap to human robustness.** Despite matching or outperforming a human on LibriSpeech dev-clean, supervised LibriSpeech models make roughly twice as many errors as a human on other datasets demonstrating their brittleness and lack of robustness. The estimated robustness frontier of zero-shot Whisper models, however, includes the 95% confidence interval for this particular human.

# Speech Transcription: Whisper

## Results:

- Whisper closes the gap to human level performance on LibriSpeech English WER



*Figure 7. Whisper's performance is close to that of professional human transcribers.* This plot shows the WER distributions of 25 recordings from the Kincaid46 dataset transcribed by Whisper, the same 4 commercial ASR systems from Figure 6 (A-D), one computer-assisted human transcription service (E) and 4 human transcription services (F-I). The box plot is superimposed with dots indicating the WERs on individual recordings, and the aggregate WER over the 25 recordings are annotated on each box.

# Whisper Demo

- **Transcript:** This is the Micro Machine Man presenting the most midget miniature motorcade of Micro Machines. Each one has dramatic details, terrific trim, precision paint jobs, plus incredible Micro Machine Pocket Play Sets. There's a police station, fire station, restaurant, service station, and more. Perfect pocket portables to take any place. And there are many miniature play sets to play with, and each one comes with its own special edition Micro Machine vehicle and fun, fantastic features that miraculously move. Raise the boatlift at the airport marina. Man the gun turret at the army base. Clean your car at the car wash. Raise the toll bridge. And these play sets fit together to form a Micro Machine world. Micro Machine Pocket Play Sets, so tremendously tiny, so perfectly precise, so dazzlingly detailed, you'll want to pocket them all. Micro Machines are Micro Machine Pocket Play Sets sold separately from Galoob. The smaller they are, the better they are.



<https://www.youtube.com/watch?v=zLP6oT3uqV8>

# Speech Transcription: Whisper

## Results:

- strong performance on high resource languages
- not-so-strong performance on low resource languages

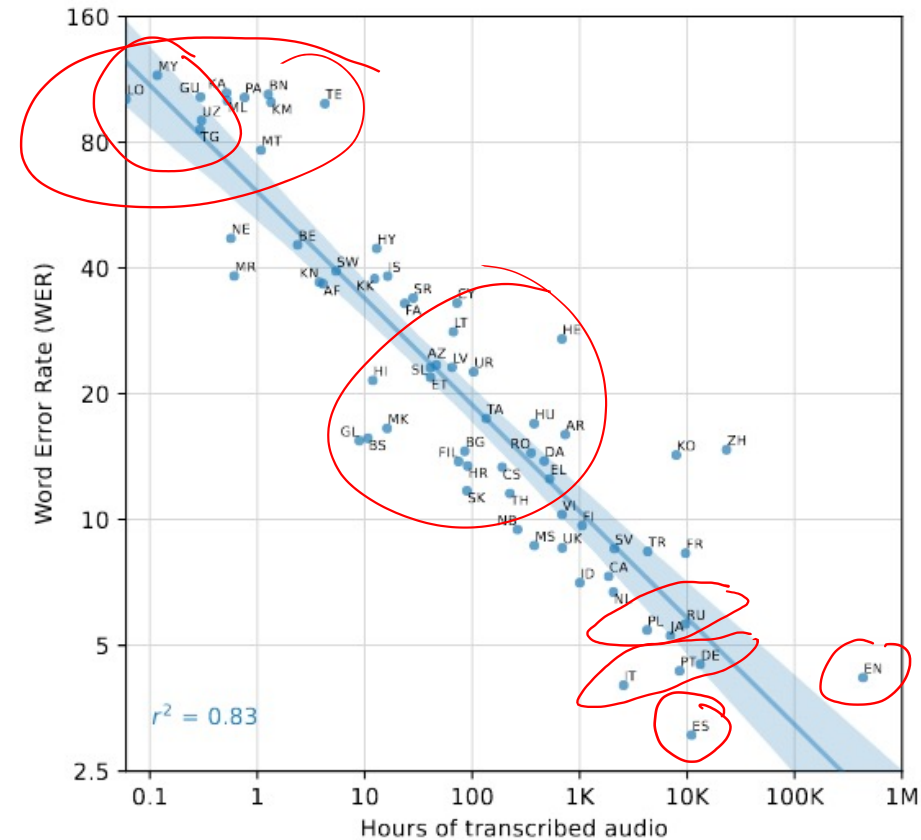


Figure 3. Correlation of pre-training supervision amount with downstream speech recognition performance. The amount of pre-training speech recognition data for a given language is very predictive of zero-shot performance on that language in Fleurs.

# Speech Transcription: Whisper

## Results:

- capable of good speech translation performance on a wide variety of languages

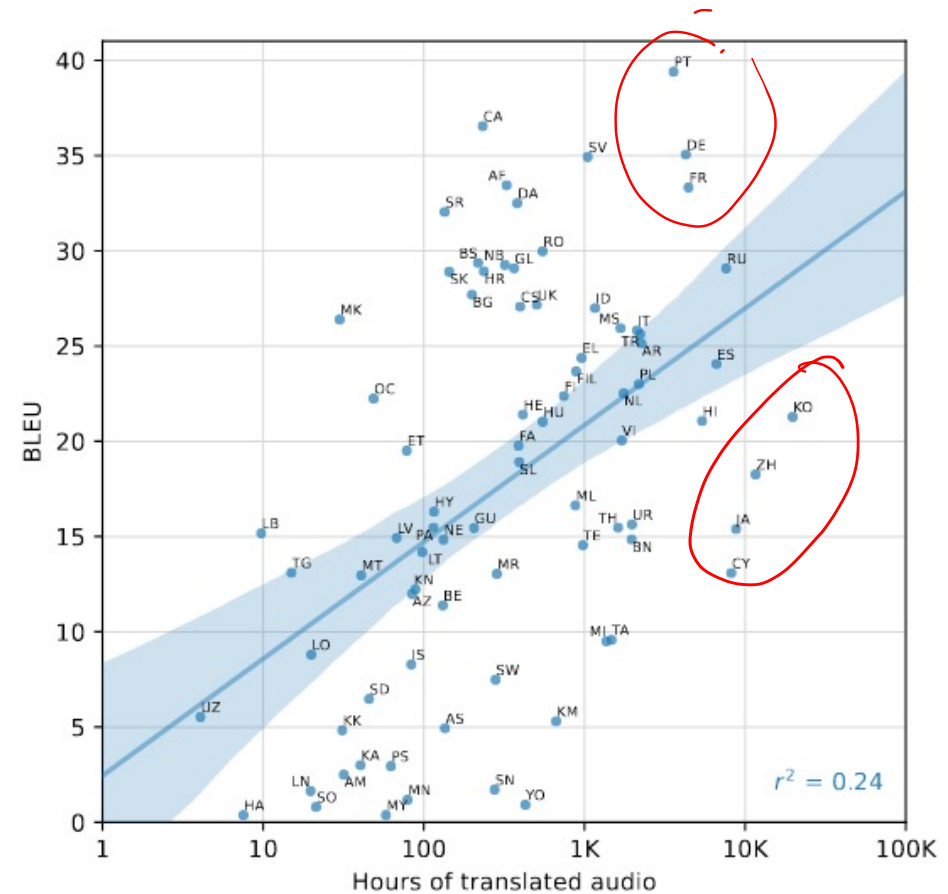
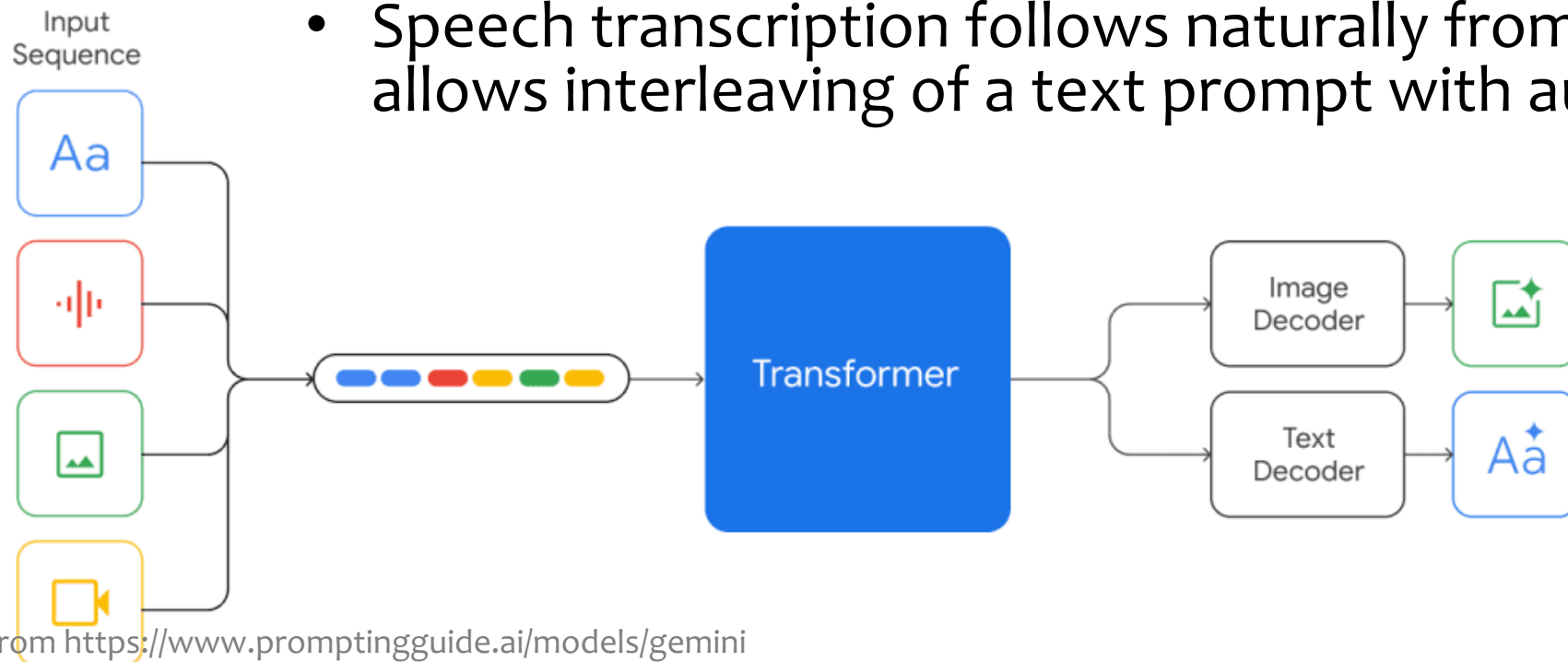


Figure 4. Correlation of pre-training supervision amount with downstream translation performance. The amount of pre-training translation data for a given language is only moderately predictive of Whisper’s zero-shot performance on that language in Fleurs.



# Speech Transcription: Gemini

- Multimodal large language models (e.g. Gemini) are trained with many different modalities as input
- Unlike Whisper, Gemini is a *decoder-only* Transformer
- Gemini converts each audio input to 16kHz, then each second of audio is converted to 25 tokens
- Speech transcription follows naturally from this setup and allows interleaving of a text prompt with audio tokens



# Audio Continuation: AudioLM

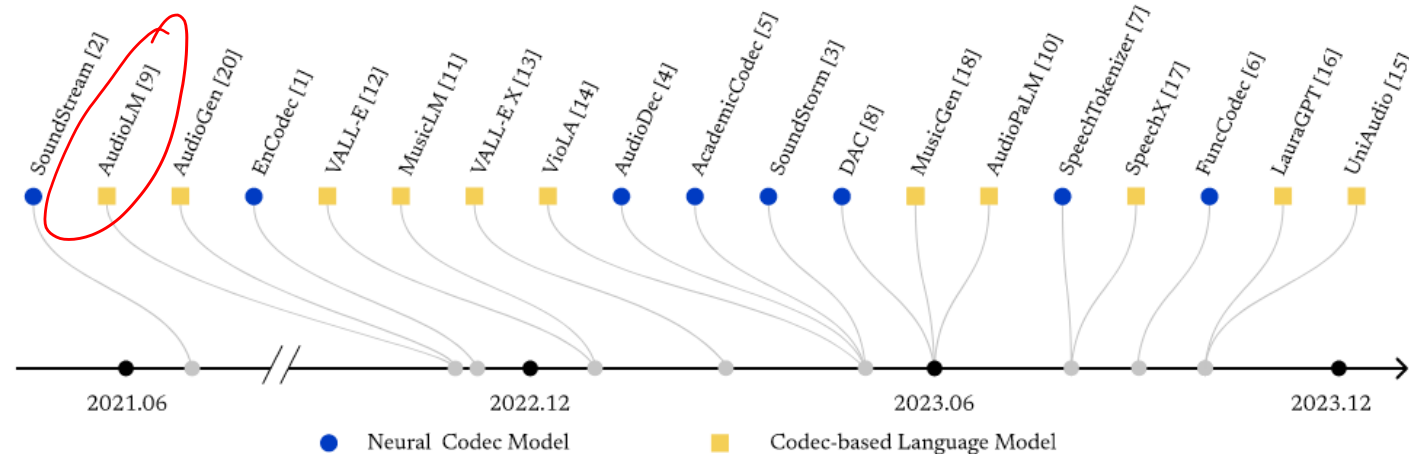


Fig. 1. Timeline of current neural codec models and codec-based language models.

- a variety of models use an audio code to convert the audio signal to a sequence of discrete audio tokens
- we can then train a deep neural LM on these audio tokens and use it to generate speech, music, nature sounds, etc.

# Audio Continuation: AudioLM

**AudioLM** consists of

- **input:**  $x$  a single channel audio input of length  $T=16000$

- **tokenizer model(s):**

- ☆ – *acoustic:* **SoundStream** neural audio codec

- vocab size:  $N=1024$

- *semantic:* w2v-BERT, a self-supervised model that returns a sequence of  $T'$  discrete tokens

- vocab size:  $K=1024$

- length  $T' = T/640$

- **decoder-only Transformer model:**

- trained to maximize the sequence of discrete tokens from the tokenizer

- at test time: autoregressively decodes one token at a time

- ☆ • **detokenizer model:** **SoundStream** decoder

# Audio Continuation: AudioLM

**AudioLM** consists of

- **decoder-only Transformer model:**
  - consists of three stages in a hierarchy
  - each stage conditions on the output of the previous stage
  - separate model for each stage to keep the lengths shorter

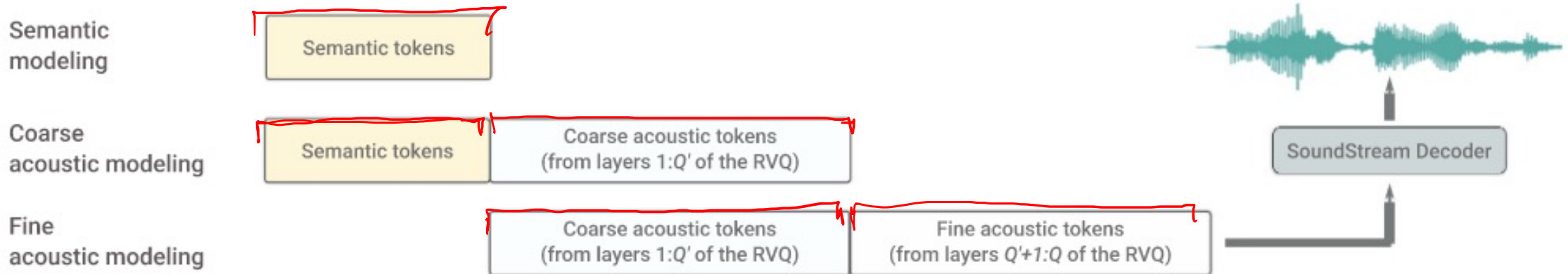


Fig. 2. Three stages of the hierarchical modeling of semantic and acoustic tokens in AudioLM : i) semantic modeling for long-term structural coherence, ii) coarse acoustic modeling conditioned on the semantic tokens and iii) fine acoustic modeling. With the default configuration, for every semantic token there are  $2Q'$  acoustic tokens in the second stage and  $2(Q - Q')$  tokens in the third stage. The factor of 2 comes from the fact that the sampling rate of SoundStream embeddings is twice as that of the w2v-BERT embeddings.

# Audio Continuation: AudioLM

- Demos: <https://google-research.github.io/seanet/audiolm/examples/>

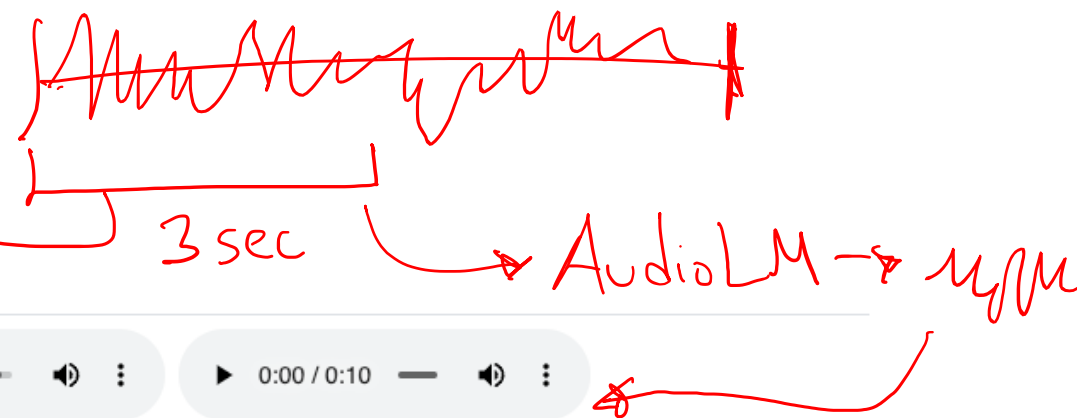
## Speech continuation

Continuations using 3 second prompts from LibriSpeech test-{clean, other}, for speakers and content not seen during training. AudioLM excels at generating continuations that:

- preserve speaker identity, prosody, accent and recording conditions of the prompt,
- have syntactically correct and semantically coherent content.

### Librispeech test-clean

Original	Prompt	Continuations



# Music Generation: Music Transformer

## MUSIC TRANSFORMER: GENERATING MUSIC WITH LONG-TERM STRUCTURE

Cheng-Zhi Anna Huang\* Ashish Vaswani Jakob Uszkoreit Noam Shazeer  
Ian Simon Curtis Hawthorne Andrew M. Dai Matthew D. Hoffman  
Monica Dinulescu Douglas Eck  
Google Brain

### ABSTRACT

Music relies heavily on repetition to build structure and meaning. Self-reference occurs on multiple timescales, from motifs to phrases to reusing of entire sections of music, such as in pieces with ABA structure. The Transformer (Vaswani et al., 2017), a sequence model based on self-attention, has achieved compelling results in many generation tasks that require maintaining long-range coherence. This suggests that self-attention might also be well-suited to modeling music. In musical composition and performance, however, relative timing is critically important. Existing approaches for representing relative positional information in the Transformer modulate attention based on pairwise distance (Shaw et al., 2018). This is impractical for long sequences such as musical compositions since their memory complexity for intermediate relative information is quadratic in the sequence length. We propose an algorithm that reduces their intermediate memory requirement to linear in the sequence length. This enables us to demonstrate that a Transformer with our modified relative attention mechanism can generate minute-long compositions (thousands of steps, four times the length modeled in Oore et al. (2018)) with compelling structure, generate continuations that coherently elaborate on a given motif, and in a seq2seq setup generate accompaniments conditioned on melodies. We evaluate the Transformer with our relative attention mechanism on two datasets, JSB Chorales and Piano-e-Competition, and obtain state-of-the-art results on the latter.

2018  
↓

# Music Generation: Music Transformer

## 3.4 MEMORY EFFICIENT IMPLEMENTATION OF RELATIVE POSITION-BASED ATTENTION

We improve the implementation of relative attention by reducing its intermediate memory requirement from  $O(L^2D)$  to  $O(LD)$ , with example lengths shown in Table 1. We observe that all of the terms we need from  $QR^T$  are already available if we directly multiply  $Q$  with  $E^r$ , the relative position embedding. After we compute  $QE^{rT}$ , its  $(i_q, r)$  entry contains the dot product of the query in position  $i_q$  with the embedding of relative distance  $r$ . However, each relative logit  $(i_q, j_k)$  in the matrix  $S^{rel}$  from Equation 2 should be the dot product of the query in position  $i_q$  and the embedding of the relative distance  $j_k - i_q$ , to match up with the indexing in  $QK^T$ . We therefore need to “skew”  $QE^{rT}$  so as to move the relative logits to their correct positions, as illustrated in Figure 1 and detailed in the next section. The time complexity for both methods are  $O(L^2D)$ , while in practice our method is 6x faster at length 650.

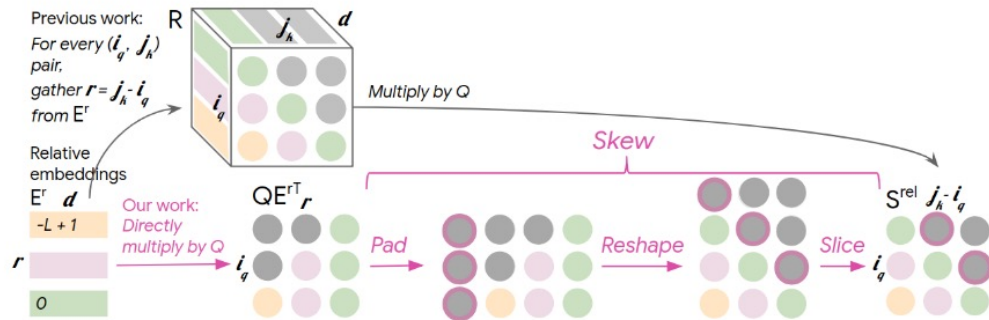


Figure 1: Relative global attention: the bottom row describes our memory-efficient “skewing” algorithm, which does not require instantiating  $R$  (top row, which is  $O(L^2D)$ ). Gray indicates masked or padded positions. Each color corresponds to a different relative distance.

## 3.5 RELATIVE LOCAL ATTENTION

For very long sequences, the quadratic memory requirement of even baseline Transformer is impractical. Local attention has been used for example in Wikipedia and image generation (Liu et al., 2018; Parmar et al., 2018) by chunking the input sequence into non-overlapping blocks. Each block then attends to itself and the one before, as shown by the smaller thumbnail on the top right corner of Figure 2.

To extend relative attention to the local case, we first note that the right block has the same configuration as in the global case (see Figure 1) but much smaller:  $(\frac{L}{M})^2$  (where  $M$  is the number of blocks, and  $N$  be the resulting block length) as opposed to  $L^2$ . The left block is unmasked with relative indices running from  $-1$  (top right) to  $-2N + 1$  (bottom left). Hence, the learned  $E^r$  for the local case has shape  $(2N - 1, N)$ .

Similar to the global case, we first compute  $QE^{rT}$  and then use the following procedure to skew it to have the same indexing as  $QK^T$ , as illustrated in Figure 2.

1. Pad a dummy column vector of length  $N$  after the rightmost column.
2. Flatten the matrix and then pad with a dummy row of length  $N - 1$ .
3. Reshape the matrix to have shape  $(N + 1, 2N - 1)$ .
4. Slice that matrix to retain only the first  $N$  rows and last  $N$  columns, resulting in a  $(N, N)$  matrix.

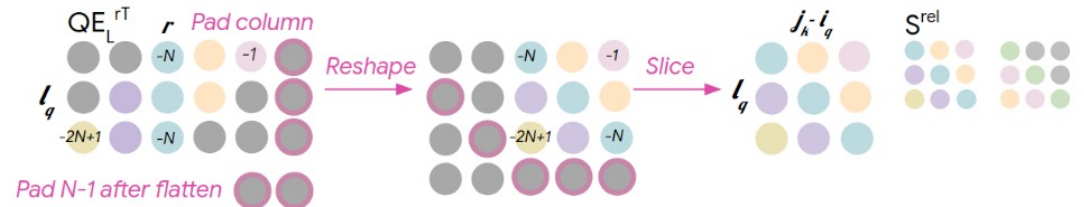


Figure 2: Relative local attention: the thumbnail on the right shows the desired configuration for  $S^{rel}$ . The “skewing” procedure is shown from left to right.

# Music Generation: Music Transformer

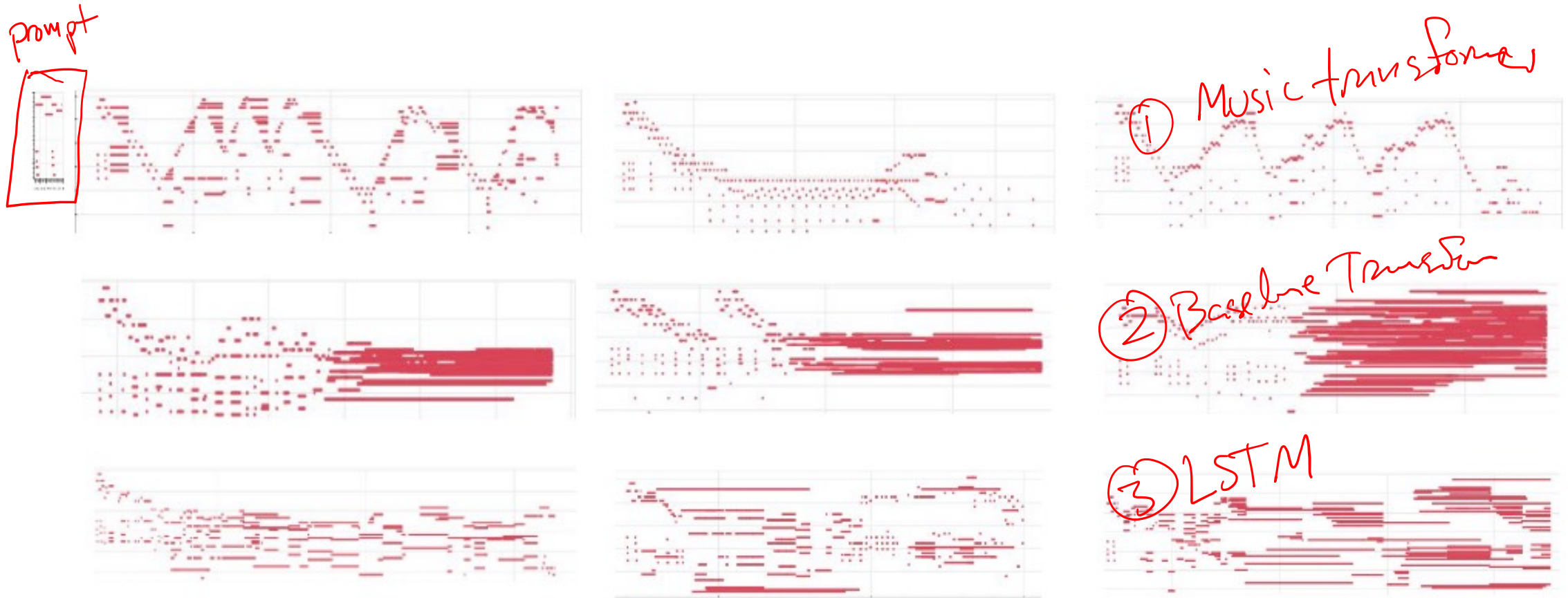


Figure 4: Comparing how models continue a prime (top left). Repeated motives and structure are seen in samples from Transformer with relative attention (top row), but less so from baseline Transformer (middle row) and PerformanceRNN (LSTM) (bottom row).

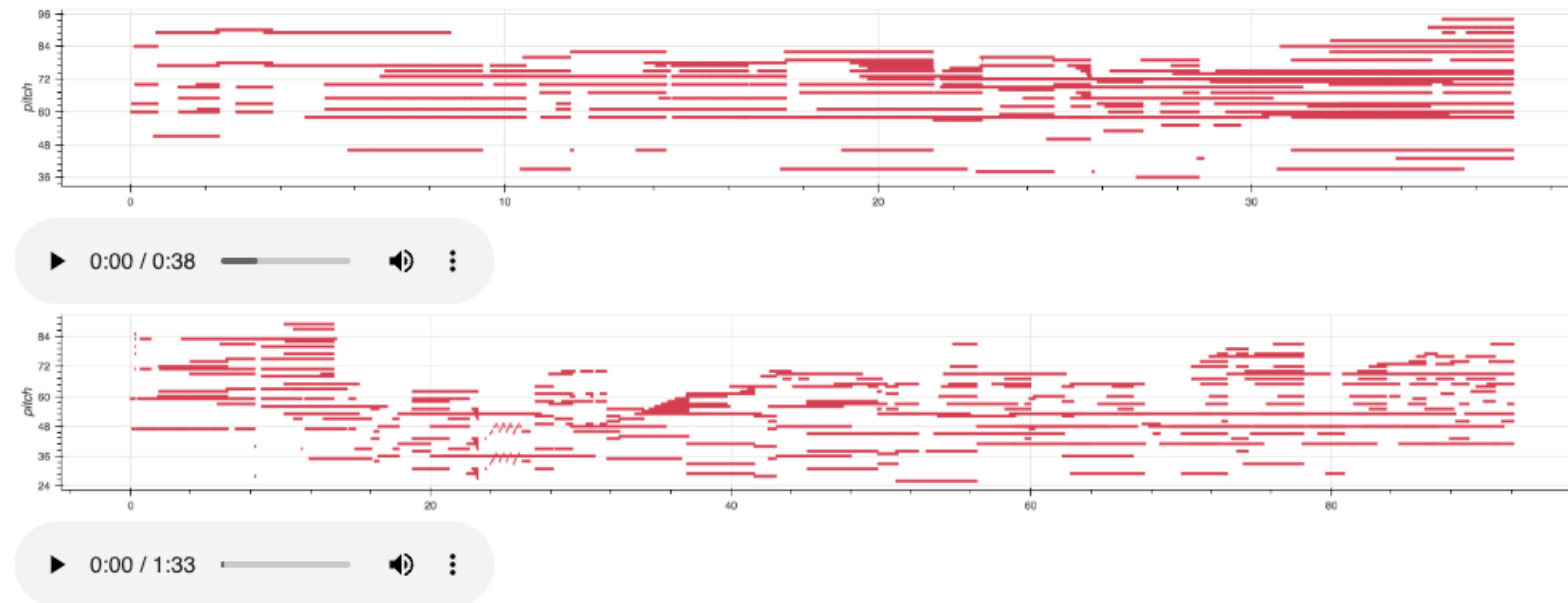


# Music Generation: Music Transformer


- Demos: <https://storage.googleapis.com/music-transformer/index.html>

## Piano-e-Competition Unconditioned Samples

Relative Transformer



# Text-to-Music Generation: MusicGen

- MusicGen Model
  - **audio tokenizer:** EnCodec [Défossez et al., 2022], which is a convolutional auto-encoder
  - **codebook interleaving:** multiple token sequences are predicted in parallel
  - **text prompt model:** T5, Flan-T5, or CLAP
  - **melody prompt model:** information bottleneck 
  - **decoder model:** transformer LM up to 3.3B parameters

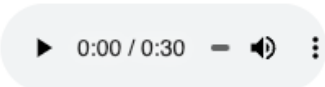
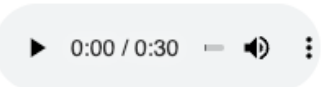
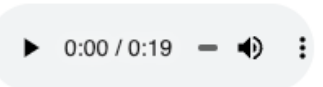
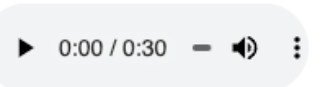
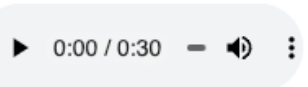
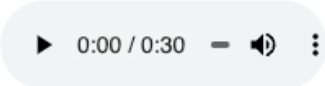
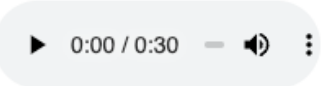
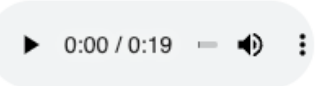
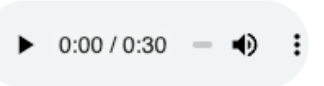
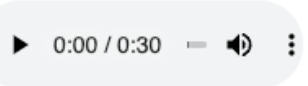
# Text-to-Music Generation: MusicGen

- Demo: <https://ai.honu.io/papers/musicgen/>

## Samples: comparison to prior work

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In the following, we compare MusicGen (including stereo generation) 3.3B to a number of prior work detailed in the paper: [MusicLM](#), using the public [AI Test Kitchen demo](#), [Riffusion](#) using the provided pre-trained modes, and [Mousai](#), which we retrained on the same dataset as our proposed MusicGen model.

desc	MusicGen	MusicGen Stereo	MusicLM	Riffusion	Musai
Pop dance track with catchy melodies, tropical percussion, and upbeat rhythms, perfect for the beach					
A grand orchestral arrangement with thunderous percussion, epic brass fanfares, and soaring strings, creating a cinematic atmosphere fit for a heroic battle.					

# Speech+Text to Text: SpeechVerse

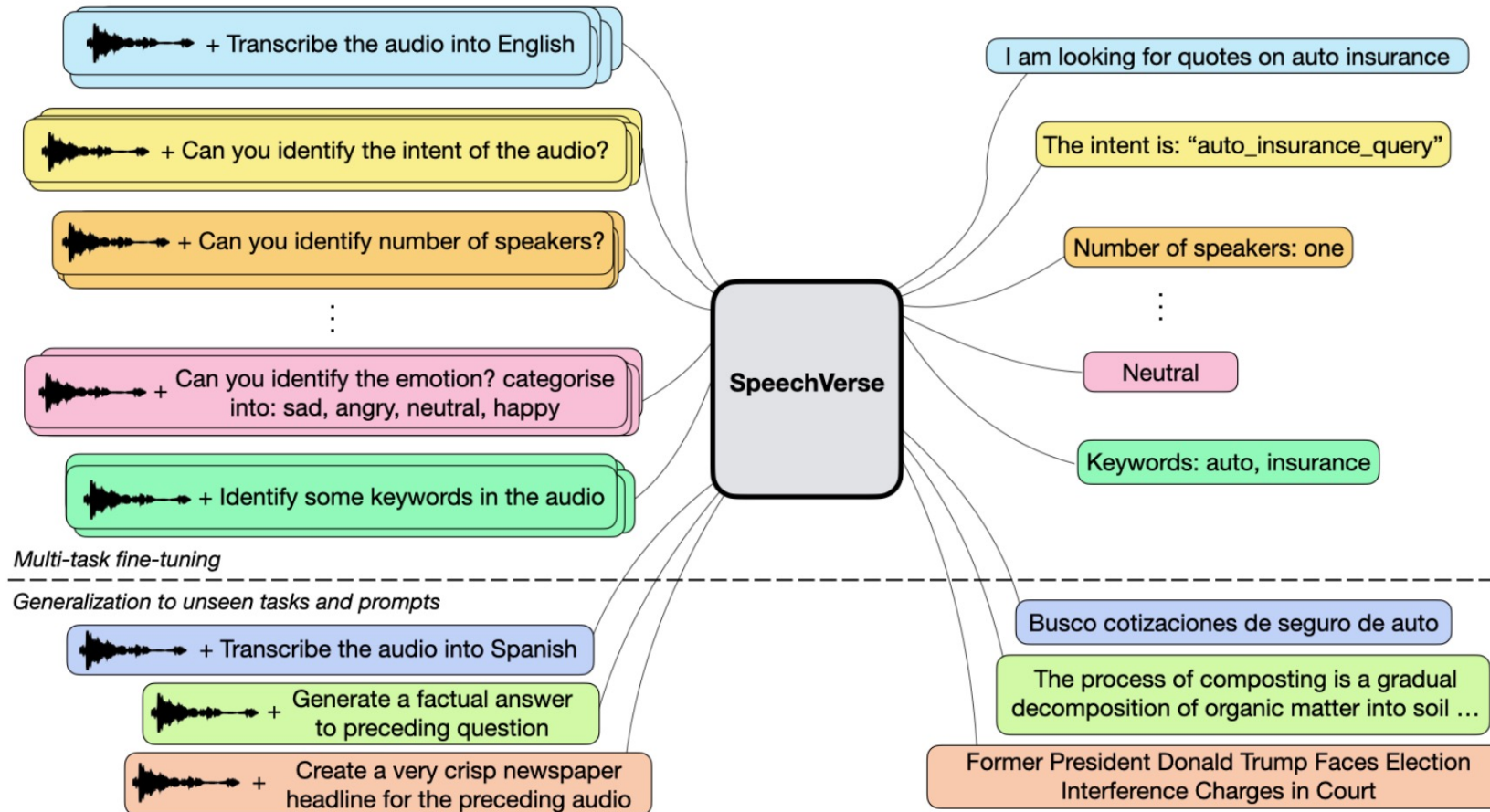


Figure 1: Schematic diagram of the SpeechVerse framework.

# Speech+Text to Text: SpeechVerse

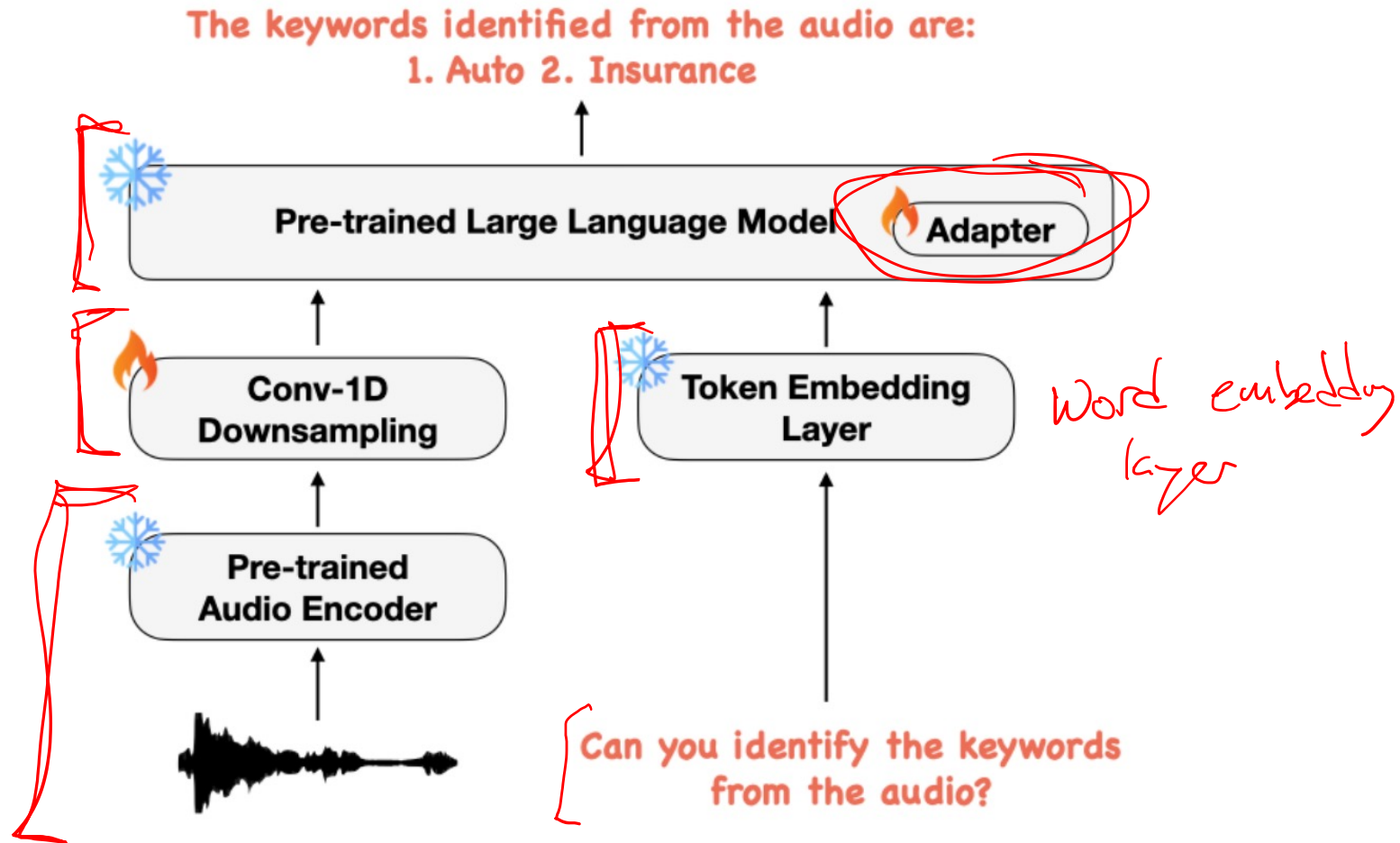


Figure 2: Block diagram of the SpeechVerse architecture.