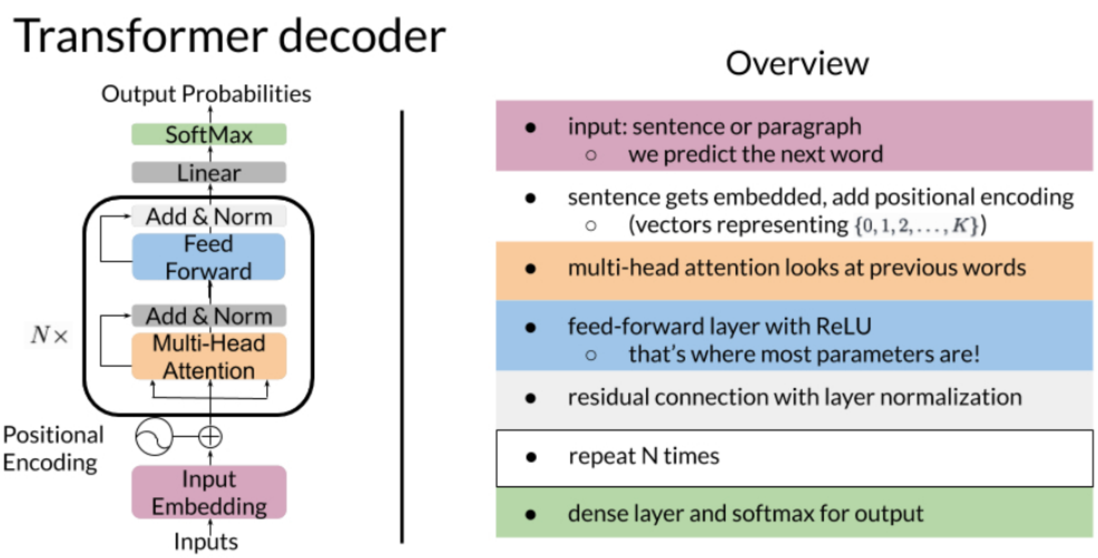
The Transformer Decoder: Ungraded Lab Notebook

In this notebook, you'll explore the transformer decoder and how to implement it with Trax.

Background

In the last lecture notebook, you saw how to translate the mathematics of attention into NumPy code. Here, you'll see how multi-head causal attention fits into a GPT-2 transformer decoder, and how to build one with Trax layers. In the assignment notebook, you'll implement causal attention from scratch, but here, you'll exploit the handy-dandy `tl.CausalAttention()` layer.

The schematic below illustrates the components and flow of a transformer decoder. Note that while the algorithm diagram flows from the bottom to the top, the overview and subsequent Trax layer codes are top-down.



Imports

In [1]:

```
import sys
import os

import time
import numpy as np
import gin

import textwrap
wrapper = textwrap.TextWrapper(width=70)

import trax
from trax import layers as tl
from trax.fastmath import numpy as jnp

# to print the entire np array
np.set_printoptions(threshold=sys.maxsize)
```

```
INFO:tensorflow:tokens_length=568 inputs_length=512 targets_length=114 noise_density=0.15 mean_noise_span_length=3.0
```

Sentence gets embedded, add positional encoding

Embed the words, then create vectors representing each word's position in each sentence $\in \{ 0, 1, 2, \ldots , K\}$ = `range(max_len)`, where `max_len` = $K+1$)

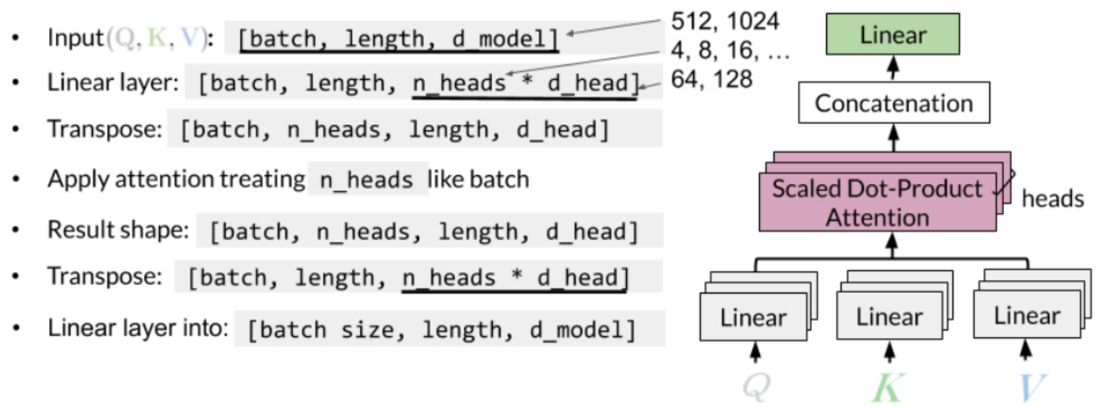
In [2]:

```
def PositionalEncoder(vocab_size, d_model, dropout, max_len, mode):
    """Returns a list of layers that:
    1. takes a block of text as input,
    2. embeds the words in that text, and
    3. adds positional encoding,
       i.e. associates a number in range(max_len) with
       each word in each sentence of embedded input text

    The input is a list of tokenized blocks of text

    Args:
        vocab_size (int): vocab size.
        d_model (int):  depth of embedding.
        dropout (float): dropout rate (how much to drop out).
        max_len (int): maximum symbol length for positional encoding.
        mode (str): 'train' or 'eval'.
    """
    # Embedding inputs and positional encoder
```

```
    # Embedding inputs and positional encoder
    return [
        # Add embedding layer of dimension (vocab_size, d_model)
        tl.Embedding(vocab_size, d_model),
        # Use dropout with rate and mode specified
        tl.Dropout(rate=dropout, mode=mode),
        # Add positional encoding layer with maximum input length and mode specified
        tl.PositionalEncoding(max_len=max_len, mode=mode)]
```

Multi-head causal attention

The layers and array dimensions involved in multi-head causal attention (which looks at previous words in the input text) are summarized in the figure below:



`tl.CausalAttention()` does all of this for you! You might be wondering, though, whether you need to pass in your input text 3 times, since for causal attention, the queries Q, keys K, and values V all come from the same source. Fortunately, `tl.CausalAttention()` handles this as well by making use of the `tl.Branch()` combinator layer. In general, each branch within a `tl.Branch()` layer performs parallel operations on copies of the layer's inputs. For causal attention, each branch (representing Q, K, and V) applies a linear transformation (i.e. a dense layer without a subsequent activation) to its copy of the input, then splits that result into heads. You can see the syntax for this in the screenshot from the `trax.layers.attention.py` source code below:

```
cb.Branch(
    [core.Dense(d_feature), _split_into_heads()],
    [core.Dense(d_feature), _split_into_heads()],
    [core.Dense(d_feature), _split_into_heads()],
),
```

Feed-forward layer

- Typically ends with a ReLU activation, but we'll leave open the possibility of a different activation
- Most of the parameters are here

In [3]:
```
def FeedForward(d_model, d_ff, dropout, mode, ff_activation):
    """Returns a list of layers that implements a feed-forward block.

    The input is an activation tensor.

    Args:
        d_model (int):  depth of embedding.
        d_ff (int): depth of feed-forward layer.
        dropout (float): dropout rate (how much to drop out).
        mode (str): 'train' or 'eval'.
        ff_activation (function): the non-linearity in feed-forward layer.

    Returns:
        list: list of trax.layers.combinators.Serial that maps an activation tensor to an activation tensor.
    """

    # Create feed-forward block (list) with two dense layers with dropout and input normalized
    return [
        # Normalize layer inputs
        tl.LayerNorm(),
        # Add first feed forward (dense) layer (don't forget to set the correct value for n_units)
        tl.Dense(d_ff),
        # Add activation function passed in as a parameter (you need to call it!)
        ff_activation(),  # Generally ReLU
        # Add dropout with rate and mode specified (i.e., don't use dropout during evaluation)
        tl.Dropout(rate=dropout, mode=mode),
        # Add second feed forward layer (don't forget to set the correct value for n_units)
        tl.Dense(d_model),
        # Add dropout with rate and mode specified (i.e., don't use dropout during evaluation)
        tl.Dropout(rate=dropout, mode=mode)
    ]
```

Decoder block

Here, we return a list containing two residual blocks. The first wraps around the causal attention layer, whose inputs are normalized and to which we apply dropout regulation. The second wraps around the feed-forward layer. You may notice that the second call to `tl.Residual()` doesn't call a normalization layer before calling the feed-forward layer. This is because the normalization layer is included in the feed-forward layer.

In [4]:
```
def DecoderBlock(d_model, d_ff, n_heads,
                 dropout, mode, ff_activation):
    """Returns a list of layers that implements a Transformer decoder block.

    The input is an activation tensor.
```

```
    Args:
        d_model (int):  depth of embedding.
        d_ff (int): depth of feed-forward layer.
        n_heads (int): number of attention heads.
        dropout (float): dropout rate (how much to drop out).
        mode (str): 'train' or 'eval'.
        ff_activation (function): the non-linearity in feed-forward layer.

    Returns:
        list: list of trax.layers.combinators.Serial that maps an activation tensor to an activation tensor.
    """

    # Add list of two Residual blocks: the attention with normalization and dropout and feed-forward blocks
    return [
      tl.Residual(
          # Normalize layer input
          tl.LayerNorm(),
          # Add causal attention
          tl.CausalAttention(d_model, n_heads=n_heads, dropout=dropout, mode=mode)
        ),
      tl.Residual(
          # Add feed-forward block
          # We don't need to normalize the layer inputs here. The feed-forward block takes care of that for us.
          FeedForward(d_model, d_ff, dropout, mode, ff_activation)
        ),
      ]
```

The transformer decoder: putting it all together

A.k.a. repeat N times, dense layer and softmax for output

In [5]:

```
def TransformerLM(vocab_size=33300,
                  d_model=512,
                  d_ff=2048,
                  n_layers=6,
                  n_heads=8,
                  dropout=0.1,
                  max_len=4096,
                  mode='train',
                  ff_activation=tl.Relu):
    """Returns a Transformer language model.

    The input to the model is a tensor of tokens. (This model uses only the
    decoder part of the overall Transformer.)

    Args:
        vocab_size (int): vocab size.
        d_model (int):  depth of embedding.
        d_ff (int): depth of feed-forward layer.
        n_layers (int): number of decoder layers.
        n_heads (int): number of attention heads.
        dropout (float): dropout rate (how much to drop out).
        max_len (int): maximum symbol length for positional encoding.
        mode (str): 'train', 'eval' or 'predict', predict mode is for fast inference.
        ff_activation (function): the non-linearity in feed-forward layer.

    Returns:
        trax.layers.combinators.Serial: A Transformer language model as a layer that maps from a tensor of tokens
        to activations over a vocab set.
    """

    # Create stack (list) of decoder blocks with n_layers with necessary parameters
    decoder_blocks = [
        DecoderBlock(d_model, d_ff, n_heads, dropout, mode, ff_activation) for _ in range(n_layers)]

    # Create the complete model as written in the figure
    return tl.Serial(
        # Use teacher forcing (feed output of previous step to current step)
        tl.ShiftRight(mode=mode),
        # Add embedding inputs and positional encoder
        PositionalEncoder(vocab_size, d_model, dropout, max_len, mode),
        # Add decoder blocks
        decoder_blocks,
        # Normalize layer
        tl.LayerNorm(),

        # Add dense layer of vocab_size (since need to select a word to translate to)
        # (a.k.a., logits layer. Note: activation already set by ff_activation)
        tl.Dense(vocab_size),
        # Get probabilities with Logsoftmax
        tl.LogSoftmax()
    )
```

Concluding remarks

In this week's assignment, you'll see how to train a transformer decoder on the cnn_dailymail dataset, available from TensorFlow Datasets (part of TensorFlow Data Services). Because training such a model from scratch is time-intensive, you'll use a pre-trained model to summarize documents later in the assignment. Due to time and storage concerns, we will also not train the decoder on a different summarization dataset in this lab. If you have the time and space, we encourage you to explore the other summarization datasets at TensorFlow Datasets. Which of them might suit your purposes better than the `cnn_dailymail` dataset? Where else can you find datasets for text summarization models?

In [ ]: