```
! pip install setuptools==66
```

```
Looking in indexes: https://pypi.org/simple, https://us-python.pkg.dev/colab-wheels/public/simple/
Requirement already satisfied: setuptools==66 in /usr/local/lib/python3.10/dist-packages (66.0.0)
```

```
! pip install d2l==1.0.0b0
```

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Requirement already satisfied: pycparser in /usr/local/lib/python3.10/dist-packages (from cffi>=1.0.1->argon2-cffi-bindings->
```

```
! pip install ptflops
```

```
Looking in indexes: https://pypi.org/simple, https://us-python.pkg.dev/colab-wheels/public/simple/
Collecting ptflops
  Downloading ptflops-0.7.tar.gz (13 kB)
  Preparing metadata (setup.py) ... done
Requirement already satisfied: torch in /usr/local/lib/python3.10/dist-packages (from ptflops) (2.0.0+cu118)
Requirement already satisfied: typing-extensions in /usr/local/lib/python3.10/dist-packages (from torch->ptflops) (4.5.0)
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```

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Requirement already satisfied: MarkupSafe>=2.0 in /usr/local/lib/python3.10/dist-packages (from jinja2->torch->ptflops) (2.1.
Requirement already satisfied: mpmath>=0.19 in /usr/local/lib/python3.10/dist-packages (from sympy->torch->ptflops) (1.3.0)
Building wheels for collected packages: ptflops
  Building wheel for ptflops (setup.py) ... done
  Created wheel for ptflops: filename=ptflops-0.7-py3-none-any.whl size=11093 sha256=b0a98c8e71b48002531a50fff040e5217d568151
  Stored in directory: /root/.cache/pip/wheels/b9/54/3b/f84523431ce82e08462644d279c0e13a51a00236e237e6bc7e
Successfully built ptflops
Installing collected packages: ptflops
Successfully installed ptflops-0.7
```

```
import time
import os
import math
import pandas as pd
import torch
import torchvision
from torch import nn
from torchvision import transforms
from d2l import torch as d2l
#from ptflops import get_model_complexity_info
```

D2L Stuff

```
class HyperParameters:
    def save_hyperparameters(self, ignore=[]):
        raise NotImplemented


def add_to_class(Class):
    def wrapper(obj):
        setattr(Class, obj.__name__, obj)
    return wrapper


class ProgressBoard(d2l.HyperParameters):
    def __init__(self, xlabel=None, ylabel=None, xlim=None,
                 ylim=None, xscale='linear', yscale='linear',
                 ls=['-', '--', '-.', ':'], colors=['C0', 'C1', 'C2', 'C3'],
                 fig=None, axes=None, figsize=(3.5, 2.5), display=True):
        self.save_hyperparameters()

    def draw(self, x, y, label, every_n=1):
        raise NotImplemented


class Module(nn.Module, d2l.HyperParameters):
    def __init__(self, plot_train_per_epoch=2, plot_valid_per_epoch=1):
        super().__init__()
        self.save_hyperparameters()
        self.board = ProgressBoard()
    def loss(self, y_hat, y):
        raise NotImplementedError

    def forward(self, X):
        assert hasattr(self, 'net'), 'Neural network is defined'
        return self.net(X)

    def plot(self, key, value, train):
        """Plot a point in animation."""
        assert hasattr(self, 'trainer'), 'Trainer is not inited'
        self.board.xlabel = 'epoch'
        if train:
            x = self.trainer.train_batch_idx / \
                self.trainer.num_train_batches
            n = self.trainer.num_train_batches / \
                self.plot_train_per_epoch
        else:
            x = self.trainer.epoch + 1
            n = self.trainer.num_val_batches / \
                self.plot_valid_per_epoch
        self.board.draw(x, value.to(d2l.cpu()).detach().numpy(),
                        ('train_' if train else 'val_') + key,
                        every_n=int(n))
    def training_step(self, batch):
        l = self.loss(self(*batch[:-1]), batch[-1])
```

```
        self.plot('loss', l, train=True)
        return l

    def validation_step(self, batch):
        l = self.loss(self(*batch[:-1]), batch[-1])
        self.plot('loss', l, train=False)
        return l

    def configure_optimizers(self):
        raise NotImplementedError


class Trainer(d2l.HyperParameters):
    def __init__(self, max_epochs, num_gpus=0, gradient_clip_val=0):
        self.save_hyperparameters()
        assert num_gpus == 0, 'No GPU support yet'

    def prepare_data(self, data):
        self.train_dataloader = data.train_dataloader()
        self.val_dataloader = data.val_dataloader()
        self.num_train_batches = len(self.train_dataloader)
        self.num_val_batches = (len(self.val_dataloader)
                                if self.val_dataloader is not None else 0)

    def prepare_model(self, model):
        model.trainer = self
        model.board.xlim = [0, self.max_epochs]
        self.model = model

    def fit(self, model, data):
        self.prepare_data(data)
        self.prepare_model(model)
        self.optim = model.configure_optimizers()
        self.epoch = 0
        self.train_batch_idx = 0
        self.val_batch_idx = 0
        for self.epoch in range(self.max_epochs):
            self.fit_epoch()

    def fit_epoch(self):
        raise NotImplementedError


@d2l.add_to_class(d2l.Trainer)
def prepare_batch(self, batch):
    return batch

@d2l.add_to_class(d2l.Trainer)
def fit_epoch(self):
    self.model.train()

    for batch in self.train_dataloader:
        loss = self.model.training_step(self.prepare_batch(batch))
        self.optim.zero_grad()
        with torch.no_grad():
            loss.backward()
            if self.gradient_clip_val > 0:  # To be discussed later
                self.clip_gradients(self.gradient_clip_val, self.model)
            self.optim.step()
        self.train_batch_idx += 1


    if self.val_dataloader is None:
        return
    self.model.eval()
    for batch in self.val_dataloader:
        with torch.no_grad():
            self.model.validation_step(self.prepare_batch(batch))
        self.val_batch_idx += 1


class DataModule(d2l.HyperParameters):
    def __init__(self, root='../data', num_workers=4):
        self.save_hyperparameters()

    def get_dataloader(self, train):
        raise NotImplementedError
```

```
    def train_dataloader(self):
        return self.get_dataloader(train=True)

    def val_dataloader(self):
        return self.get_dataloader(train=False)
```

French Dataset

```
class MTFraEng(d2l.DataModule):
    """The English-French dataset."""
    def _download(self):
        d2l.extract(d2l.download(
            d2l.DATA_URL+'fra-eng.zip', self.root,
            '94646ad1522d915e7b0f9296181140edcf86a4f5'))
        with open(self.root + '/fra-eng/fra.txt', encoding='utf-8') as f:
            return f.read()

data = MTFraEng()
raw_text = data._download()
print(raw_text[:75])
```

```
Downloading ../data/fra-eng.zip from http://d2l-data.s3-accelerate.amazonaws.com/fra-eng.zip...
Go.	Va !
Hi.	Salut !
Run!	Cours !
Run!	Courez !
Who?	Qui ?
Wow!	Ça alors !
```

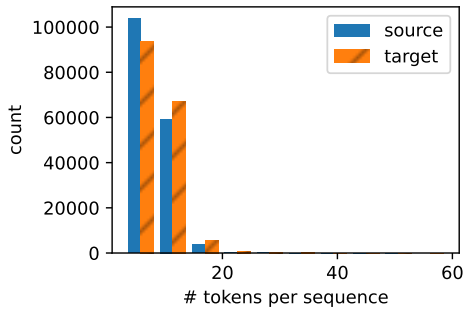
```
@d2l.add_to_class(MTFraEng)
def _preprocess(self, text):
    # Replace non-breaking space with space
    text = text.replace('\u202f', ' ').replace('\xa0', ' ')
    # Insert space between words and punctuation marks
    no_space = lambda char, prev_char: char in ',.!?' and prev_char != ' '
    out = [' ' + char if i > 0 and no_space(char, text[i - 1]) else char
           for i, char in enumerate(text.lower())]
    return ''.join(out)

text = data._preprocess(raw_text)
print(text[:80])
```

```
go .	va !
hi .	salut !
run !	cours !
run !	courez !
who ?	qui ?
wow !	ça alors !
```

```
@d2l.add_to_class(MTFraEng)
def _tokenize(self, text, max_examples=None):
    src, tgt = [], []
    for i, line in enumerate(text.split('\n')):
        if max_examples and i > max_examples: break
        parts = line.split('\t')
        if len(parts) == 2:
            # Skip empty tokens
            src.append([t for t in f'{parts[0]} <eos>'.split(' ') if t])
            tgt.append([t for t in f'{parts[1]} <eos>'.split(' ') if t])
    return src, tgt

src, tgt = data._tokenize(text)
src[:6], tgt[:6]
```

```
([['go', '.', '<eos>'],
  ['hi', '.', '<eos>'],
  ['run', '!', '<eos>'],
  ['run', '!', '<eos>'],
  ['who', '?', '<eos>'],
  ['wow', '!', '<eos>']],
 [['va', '!', '<eos>'],
  ['salut', '!', '<eos>'],
  ['cours', '!', '<eos>'],
  ['courez', '!', '<eos>'],
```

```
       ['qui', '?', '<eos>'],
       ['ça', 'alors', '!', '<eos>']])


def show_list_len_pair_hist(legend, xlabel, ylabel, xlist, ylist):
    """Plot the histogram for list length pairs."""
    d2l.set_figsize()
    _, _, patches = d2l.plt.hist(
        [[len(l) for l in xlist], [len(l) for l in ylist]])
    d2l.plt.xlabel(xlabel)
    d2l.plt.ylabel(ylabel)
    for patch in patches[1].patches:
        patch.set_hatch('/')
    d2l.plt.legend(legend)

show_list_len_pair_hist(['source', 'target'], '# tokens per sequence',
                        'count', src, tgt);
```




```
@d2l.add_to_class(MTFraEng)
def __init__(self, batch_size, num_steps=9, num_train=512, num_val=128):
    super(MTFraEng, self).__init__()
    self.save_hyperparameters()
    self.arrays, self.src_vocab, self.tgt_vocab = self._build_arrays(
        self._download())

@d2l.add_to_class(MTFraEng)
def _build_arrays(self, raw_text, src_vocab=None, tgt_vocab=None):
    def _build_array(sentences, vocab, is_tgt=False):
        pad_or_trim = lambda seq, t: (
            seq[:t] if len(seq) > t else seq + ['<pad>'] * (t - len(seq)))
        sentences = [pad_or_trim(s, self.num_steps) for s in sentences]
        if is_tgt:
            sentences = [['<bos>'] + s for s in sentences]
        if vocab is None:
            vocab = d2l.Vocab(sentences, min_freq=2)
        array = torch.tensor([vocab[s] for s in sentences])
        valid_len = (array != vocab['<pad>']).type(torch.int32).sum(1)
        return array, vocab, valid_len
    src, tgt = self._tokenize(self._preprocess(raw_text),
                              self.num_train + self.num_val)
    src_array, src_vocab, src_valid_len = _build_array(src, src_vocab)
    tgt_array, tgt_vocab, _ = _build_array(tgt, tgt_vocab, True)
    return ((src_array, tgt_array[:,:-1], src_valid_len, tgt_array[:,1:]),
            src_vocab, tgt_vocab)


@d2l.add_to_class(MTFraEng)
def get_dataloader(self, train):
    idx = slice(0, self.num_train) if train else slice(self.num_train, None)
    return self.get_tensorloader(self.arrays, train, idx)


data = MTFraEng(batch_size=3)
src, tgt, src_valid_len, label = next(iter(data.train_dataloader()))
print('source:', src.type(torch.int32))
print('decoder input:', tgt.type(torch.int32))
print('source len excluding pad:', src_valid_len.type(torch.int32))
print('label:', label.type(torch.int32))
```

```
     source: tensor([[ 16,   7, 108,   2,   3,   4,   4,   4,   4],
             [ 25,  72,   2,   3,   4,   4,   4,   4,   4],
             [160, 111,   2,   3,   4,   4,   4,   4,   4]], dtype=torch.int32)
     decoder input: tensor([[  3, 179, 200,  99,   0,   4,   5,   5,   5],
```

```
            [  3,   6,   2,   4,   5,   5,   5,   5,   5],
            [  3,   6,   0,   4,   5,   5,   5,   5,   5]], dtype=torch.int32)
     source len excluding pad: tensor([5, 4, 4], dtype=torch.int32)
     label: tensor([[179, 200,  99,   0,   4,   5,   5,   5,   5],
            [  6,   2,   4,   5,   5,   5,   5,   5,   5],
            [  6,   0,   4,   5,   5,   5,   5,   5,   5]], dtype=torch.int32)
```

```
@d2l.add_to_class(MTFraEng)
def build(self, src_sentences, tgt_sentences):
    raw_text = '\n'.join([src + '\t' + tgt for src, tgt in zip(
        src_sentences, tgt_sentences)])
    arrays, _, _ = self._build_arrays(
        raw_text, self.src_vocab, self.tgt_vocab)
    return arrays

src, tgt, _,  _ = data.build(['hi .'], ['salut .'])
print('source:', data.src_vocab.to_tokens(src[0].type(torch.int32)))
print('target:', data.tgt_vocab.to_tokens(tgt[0].type(torch.int32)))
```

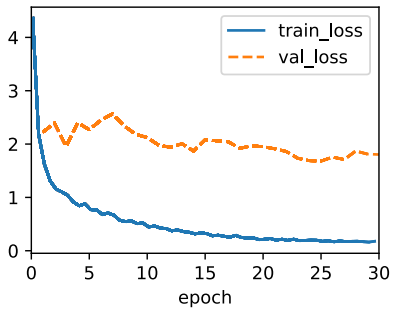
```
     source: ['hi', '.', '<eos>', '<pad>', '<pad>', '<pad>', '<pad>', '<pad>', '<pad>']
     target: ['<bos>', 'salut', '.', '<eos>', '<pad>', '<pad>', '<pad>', '<pad>', '<pad>']
```

1a) Baseline Transformer

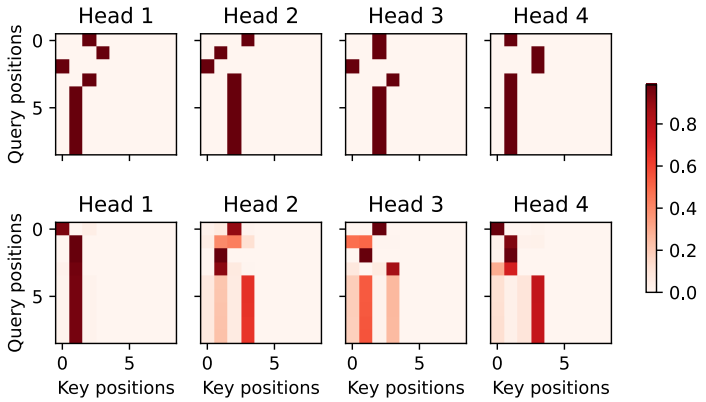
```
class PositionWiseFFN(nn.Module):
    """The positionwise feed-forward network."""
    def __init__(self, ffn_num_hiddens, ffn_num_outputs):
        super().__init__()
        self.dense1 = nn.LazyLinear(ffn_num_hiddens)
        self.relu = nn.ReLU()
        self.dense2 = nn.LazyLinear(ffn_num_outputs)

    def forward(self, X):
        return self.dense2(self.relu(self.dense1(X)))


class AddNorm(nn.Module):
    """The residual connection followed by layer normalization."""
    def __init__(self, norm_shape, dropout):
        super().__init__()
        self.dropout = nn.Dropout(dropout)
        self.ln = nn.LayerNorm(norm_shape)

    def forward(self, X, Y):
        return self.ln(self.dropout(Y) + X)


class TransformerEncoderBlock(nn.Module):
    """The Transformer encoder block."""
    def __init__(self, num_hiddens, ffn_num_hiddens, num_heads, dropout,
                 use_bias=False):
        super().__init__()
        self.attention = d2l.MultiHeadAttention(num_hiddens, num_heads,
                                                dropout, use_bias)
        self.addnorm1 = AddNorm(num_hiddens, dropout)
        self.ffn = PositionWiseFFN(ffn_num_hiddens, num_hiddens)
        self.addnorm2 = AddNorm(num_hiddens, dropout)

    def forward(self, X, valid_lens):
        Y = self.addnorm1(X, self.attention(X, X, X, valid_lens))
        return self.addnorm2(Y, self.ffn(Y))


class TransformerEncoder(d2l.Encoder):
    """The Transformer encoder."""
    def __init__(self, vocab_size, num_hiddens, ffn_num_hiddens,
                 num_heads, num_blks, dropout, use_bias=False):
        super().__init__()
        self.num_hiddens = num_hiddens
        self.embedding = nn.Embedding(vocab_size, num_hiddens)
        self.pos_encoding = d2l.PositionalEncoding(num_hiddens, dropout)
        self.blks = nn.Sequential()
        for i in range(num_blks):
            self.blks.add_module("block"+str(i), TransformerEncoderBlock(
                num_hiddens, ffn_num_hiddens, num_heads, dropout, use_bias))
```

```
    def forward(self, X, valid_lens):
        # Since positional encoding values are between -1 and 1, the embedding
        # values are multiplied by the square root of the embedding dimension
        # to rescale before they are summed up
        X = self.pos_encoding(self.embedding(X) * math.sqrt(self.num_hiddens))
        self.attention_weights = [None] * len(self.blks)
        for i, blk in enumerate(self.blks):
            X = blk(X, valid_lens)
            self.attention_weights[
                i] = blk.attention.attention.attention_weights
        return X


class TransformerDecoderBlock(nn.Module):
    # The i-th block in the Transformer decoder
    def __init__(self, num_hiddens, ffn_num_hiddens, num_heads, dropout, i):
        super().__init__()
        self.i = i
        self.attention1 = d2l.MultiHeadAttention(num_hiddens, num_heads,
                                                 dropout)
        self.addnorm1 = AddNorm(num_hiddens, dropout)
        self.attention2 = d2l.MultiHeadAttention(num_hiddens, num_heads,
                                                 dropout)
        self.addnorm2 = AddNorm(num_hiddens, dropout)
        self.ffn = PositionWiseFFN(ffn_num_hiddens, num_hiddens)
        self.addnorm3 = AddNorm(num_hiddens, dropout)

    def forward(self, X, state):
        enc_outputs, enc_valid_lens = state[0], state[1]
        # During training, all the tokens of any output sequence are processed
        # at the same time, so state[2][self.i] is None as initialized. When
        # decoding any output sequence token by token during prediction,
        # state[2][self.i] contains representations of the decoded output at
        # the i-th block up to the current time step
        if state[2][self.i] is None:
            key_values = X
        else:
            key_values = torch.cat((state[2][self.i], X), dim=1)
        state[2][self.i] = key_values
        if self.training:
            batch_size, num_steps, _ = X.shape
            # Shape of dec_valid_lens: (batch_size, num_steps), where every
            # row is [1, 2, ..., num_steps]
            dec_valid_lens = torch.arange(
                1, num_steps + 1, device=X.device).repeat(batch_size, 1)
        else:
            dec_valid_lens = None
        # Self-attention
        X2 = self.attention1(X, key_values, key_values, dec_valid_lens)
        Y = self.addnorm1(X, X2)
        # Encoder-decoder attention. Shape of enc_outputs:
        # (batch_size, num_steps, num_hiddens)
        Y2 = self.attention2(Y, enc_outputs, enc_outputs, enc_valid_lens)
        Z = self.addnorm2(Y, Y2)
        return self.addnorm3(Z, self.ffn(Z)), state


class TransformerDecoder(d2l.AttentionDecoder):
    def __init__(self, vocab_size, num_hiddens, ffn_num_hiddens, num_heads,
                 num_blks, dropout):
        super().__init__()
        self.num_hiddens = num_hiddens
        self.num_blks = num_blks
        self.embedding = nn.Embedding(vocab_size, num_hiddens)
        self.pos_encoding = d2l.PositionalEncoding(num_hiddens, dropout)
        self.blks = nn.Sequential()
        for i in range(num_blks):
            self.blks.add_module("block"+str(i), TransformerDecoderBlock(
                num_hiddens, ffn_num_hiddens, num_heads, dropout, i))
        self.dense = nn.LazyLinear(vocab_size)

    def init_state(self, enc_outputs, enc_valid_lens):
        return [enc_outputs, enc_valid_lens, [None] * self.num_blks]

    def forward(self, X, state):
        X = self.pos_encoding(self.embedding(X) * math.sqrt(self.num_hiddens))
        self._attention_weights = [[None] * len(self.blks) for _ in range (2)]
```

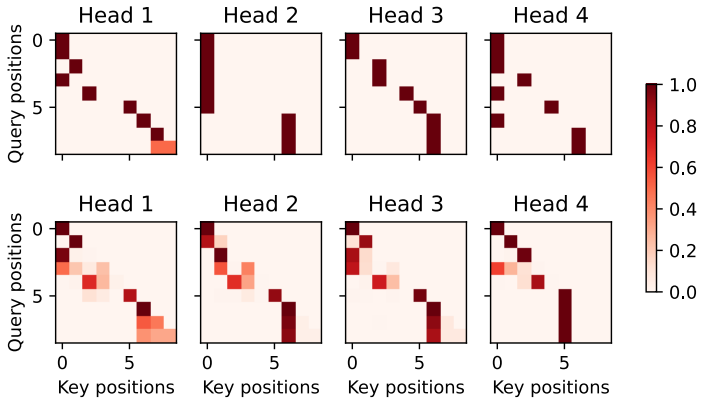
```
        for i, blk in enumerate(self.blks):
            X, state = blk(X, state)
            # Decoder self-attention weights
            self._attention_weights[0][
                i] = blk.attention1.attention.attention_weights
            # Encoder-decoder attention weights
            self._attention_weights[1][
                i] = blk.attention2.attention.attention_weights
        return self.dense(X), state

    @property
    def attention_weights(self):
        return self._attention_weights


data = d2l.MTFraEng(batch_size=128)
num_hiddens, num_blks, dropout = 256, 2, 0.2
ffn_num_hiddens, num_heads = 64, 4
encoder = TransformerEncoder(
    len(data.src_vocab), num_hiddens, ffn_num_hiddens, num_heads,
    num_blks, dropout)
decoder = TransformerDecoder(
    len(data.tgt_vocab), num_hiddens, ffn_num_hiddens, num_heads,
    num_blks, dropout)
model = d2l.Seq2Seq(encoder, decoder, tgt_pad=data.tgt_vocab['<pad>'],
                    lr=0.0015)
trainer = d2l.Trainer(max_epochs=30, gradient_clip_val=1, num_gpus=1)
trainer.fit(model, data)

# Train time: 1min 32sec
```




```
engs = ['go .', 'i lost .', 'he\'s calm .', 'i\'m home .']
fras = ['va !', 'j\'ai perdu .', 'il est calme .', 'je suis chez moi .']
preds, _ = model.predict_step(
    data.build(engs, fras), d2l.try_gpu(), data.num_steps)
for en, fr, p in zip(engs, fras, preds):
    translation = []
    for token in data.tgt_vocab.to_tokens(p):
        if token == '<eos>':
            break
        translation.append(token)
    print(f'{en} => {translation}, bleu,'
          f'{d2l.bleu(" ".join(translation), fr, k=2):.3f}')

 go . => ['va', '!'], bleu,1.000
 i lost . => ["j'ai", 'perdu', '.'], bleu,1.000
 he's calm . => ['il', 'est', '<unk>', '.'], bleu,0.658
 i'm home . => ['je', 'suis', 'chez', 'moi', '.'], bleu,1.000


_, dec_attention_weights = model.predict_step(
    data.build([engs[-1]], [fras[-1]]), d2l.try_gpu(), data.num_steps, True)
enc_attention_weights = torch.cat(model.encoder.attention_weights, 0)
shape = (num_blks, num_heads, -1, data.num_steps)
enc_attention_weights = enc_attention_weights.reshape(shape)
d2l.check_shape(enc_attention_weights,
                (num_blks, num_heads, data.num_steps, data.num_steps))


d2l.show_heatmaps(
    enc_attention_weights.cpu(), xlabel='Key positions',
    ylabel='Query positions', titles=['Head %d' % i for i in range(1, 5)],
    figsize=(7, 3.5))
```




```
dec_attention_weights_2d = [head[0].tolist()
                            for step in dec_attention_weights
                            for attn in step for blk in attn for head in blk]
dec_attention_weights_filled = torch.tensor(
    pd.DataFrame(dec_attention_weights_2d).fillna(0.0).values)
shape = (-1, 2, num_blks, num_heads, data.num_steps)
dec_attention_weights = dec_attention_weights_filled.reshape(shape)
dec_self_attention_weights, dec_inter_attention_weights = \
    dec_attention_weights.permute(1, 2, 3, 0, 4)

d2l.check_shape(dec_self_attention_weights,
                (num_blks, num_heads, data.num_steps, data.num_steps))
d2l.check_shape(dec_inter_attention_weights,
                (num_blks, num_heads, data.num_steps, data.num_steps))


d2l.show_heatmaps(
    dec_self_attention_weights[:, :, :, :],
    xlabel='Key positions', ylabel='Query positions',
    titles=['Head %d' % i for i in range(1, 5)], figsize=(7, 3.5))
```



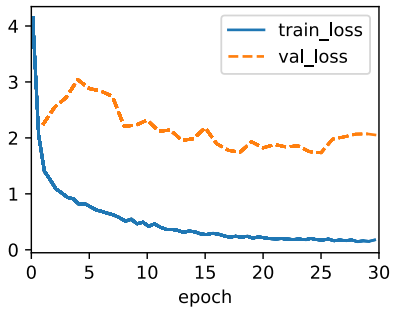

```
len(data.src_vocab)
```

```
194
```

Deepening Baseline Transformer

```
### 3 encoder blocks, 3 decoder blocks ###

data = d2l.MTFraEng(batch_size=128)
num_hiddens, num_blks, dropout = 256, 3, 0.2
ffn_num_hiddens, num_heads = 64, 4
encoder = TransformerEncoder(
    len(data.src_vocab), num_hiddens, ffn_num_hiddens, num_heads,
    num_blks, dropout)
decoder = TransformerDecoder(
    len(data.tgt_vocab), num_hiddens, ffn_num_hiddens, num_heads,
    num_blks, dropout)
```

```
model = d2l.Seq2Seq(encoder, decoder, tgt_pad=data.tgt_vocab['<pad>'],
                    lr=0.0015)
trainer = d2l.Trainer(max_epochs=30, gradient_clip_val=1, num_gpus=1)
trainer.fit(model, data)

# Train time: 2mins
```

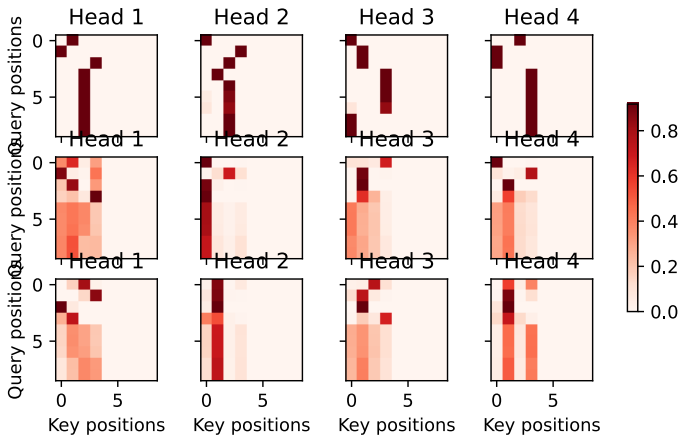



```
engs = ['go .', 'i lost .', 'he\'s calm .', 'i\'m home .']
fras = ['va !', 'j\'ai perdu .', 'il est calme .', 'je suis chez moi .']
preds, _ = model.predict_step(
    data.build(engs, fras), d2l.try_gpu(), data.num_steps)
for en, fr, p in zip(engs, fras, preds):
    translation = []
    for token in data.tgt_vocab.to_tokens(p):
        if token == '<eos>':
            break
        translation.append(token)
    print(f'{en} => {translation}, bleu,'
          f'{d2l.bleu(" ".join(translation), fr, k=2):.3f}')
```

```
go . => ['va', '!'], bleu,1.000
i lost . => ["j'ai", 'perdu', '.'], bleu,1.000
he's calm . => ['il', 'est', 'mouillé', '.'], bleu,0.658
i'm home . => ['je', 'suis', 'chez', 'moi', '.'], bleu,1.000
```

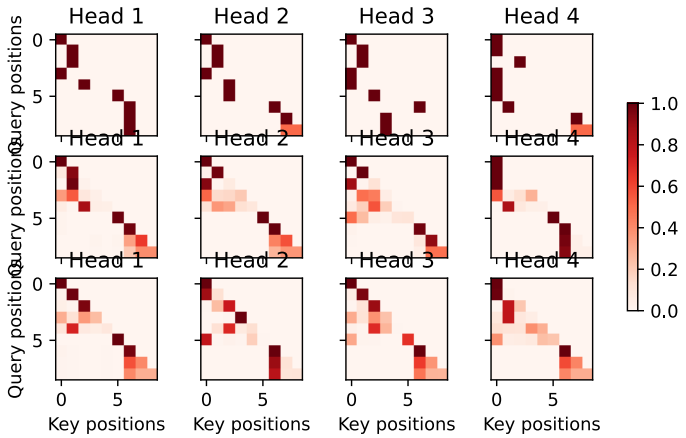
```
_, dec_attention_weights = model.predict_step(
    data.build([engs[-1]], [fras[-1]]), d2l.try_gpu(), data.num_steps, True)
enc_attention_weights = torch.cat(model.encoder.attention_weights, 0)
shape = (num_blks, num_heads, -1, data.num_steps)
enc_attention_weights = enc_attention_weights.reshape(shape)
d2l.check_shape(enc_attention_weights,
                (num_blks, num_heads, data.num_steps, data.num_steps))
```

```
d2l.show_heatmaps(
    enc_attention_weights.cpu(), xlabel='Key positions',
    ylabel='Query positions', titles=['Head %d' % i for i in range(1, 5)],
    figsize=(7, 3.5))
```

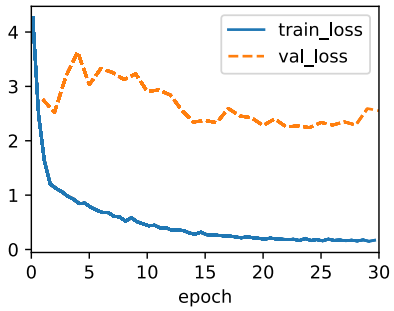



```
dec_attention_weights_2d = [head[0].tolist()
                            for step in dec_attention_weights
                            for attn in step for blk in attn for head in blk]
dec_attention_weights_filled = torch.tensor(
```

```
    pd.DataFrame(dec_attention_weights_2d).fillna(0.0).values)
shape = (-1, 2, num_blks, num_heads, data.num_steps)
dec_attention_weights = dec_attention_weights_filled.reshape(shape)
dec_self_attention_weights, dec_inter_attention_weights = \
    dec_attention_weights.permute(1, 2, 3, 0, 4)

d2l.check_shape(dec_self_attention_weights,
                (num_blks, num_heads, data.num_steps, data.num_steps))
d2l.check_shape(dec_inter_attention_weights,
                (num_blks, num_heads, data.num_steps, data.num_steps))


d2l.show_heatmaps(
    dec_self_attention_weights[:, :, :, :],
    xlabel='Key positions', ylabel='Query positions',
    titles=['Head %d' % i for i in range(1, 5)], figsize=(7, 3.5))
```




```
### 4 encoder blocks, 4 decoder blocks ###

data = d2l.MTFraEng(batch_size=128)
num_hiddens, num_blks, dropout = 256, 4, 0.2
ffn_num_hiddens, num_heads = 64, 4
encoder = TransformerEncoder(
    len(data.src_vocab), num_hiddens, ffn_num_hiddens, num_heads,
    num_blks, dropout)
decoder = TransformerDecoder(
    len(data.tgt_vocab), num_hiddens, ffn_num_hiddens, num_heads,
    num_blks, dropout)
model = d2l.Seq2Seq(encoder, decoder, tgt_pad=data.tgt_vocab['<pad>'],
                    lr=0.0015)
trainer = d2l.Trainer(max_epochs=30, gradient_clip_val=1, num_gpus=1)
trainer.fit(model, data)

# Train time: 2min 13sec
```



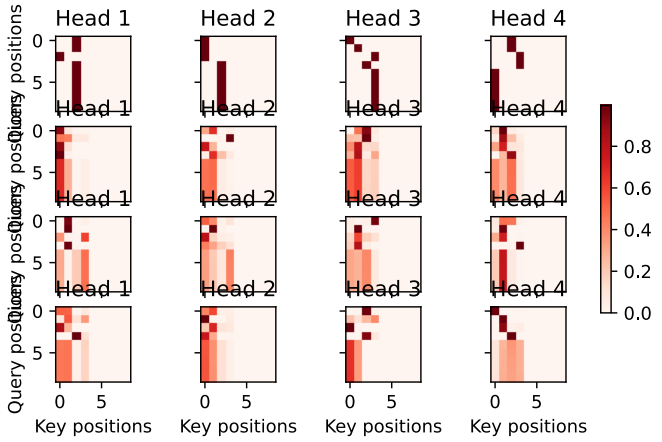

```
engs = ['go .', 'i lost .', 'he\'s calm .', 'i\'m home .']
fras = ['va !', 'j\'ai perdu .', 'il est calme .', 'je suis chez moi .']
preds, _ = model.predict_step(
    data.build(engs, fras), d2l.try_gpu(), data.num_steps)
for en, fr, p in zip(engs, fras, preds):
    translation = []
    for token in data.tgt_vocab.to_tokens(p):
        if token == '<eos>':
```

```
            break
        translation.append(token)
    print(f'{en} => {translation}, bleu,'
          f'{d2l.bleu(" ".join(translation), fr, k=2):.3f}')
```

```
go . => ['va', ',', '!'], bleu,0.000
i lost . => ["j'ai", 'perdu', '.'], bleu,1.000
he's calm . => ['il', 'est', 'mouillé', '.'], bleu,0.658
i'm home . => ['je', 'suis', 'chez', 'moi', '.'], bleu,1.000
```

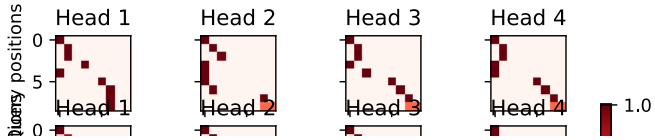
```
_, dec_attention_weights = model.predict_step(
    data.build([engs[-1]], [fras[-1]]), d2l.try_gpu(), data.num_steps, True)
enc_attention_weights = torch.cat(model.encoder.attention_weights, 0)
shape = (num_blks, num_heads, -1, data.num_steps)
enc_attention_weights = enc_attention_weights.reshape(shape)
d2l.check_shape(enc_attention_weights,
                (num_blks, num_heads, data.num_steps, data.num_steps))
```

```
d2l.show_heatmaps(
    enc_attention_weights.cpu(), xlabel='Key positions',
    ylabel='Query positions', titles=['Head %d' % i for i in range(1, 5)],
    figsize=(7, 3.5))
```




```
dec_attention_weights_2d = [head[0].tolist()
                            for step in dec_attention_weights
                            for attn in step for blk in attn for head in blk]
dec_attention_weights_filled = torch.tensor(
    pd.DataFrame(dec_attention_weights_2d).fillna(0.0).values)
shape = (-1, 2, num_blks, num_heads, data.num_steps)
dec_attention_weights = dec_attention_weights_filled.reshape(shape)
dec_self_attention_weights, dec_inter_attention_weights = \
    dec_attention_weights.permute(1, 2, 3, 0, 4)

d2l.check_shape(dec_self_attention_weights,
                (num_blks, num_heads, data.num_steps, data.num_steps))
d2l.check_shape(dec_inter_attention_weights,
                (num_blks, num_heads, data.num_steps, data.num_steps))
```

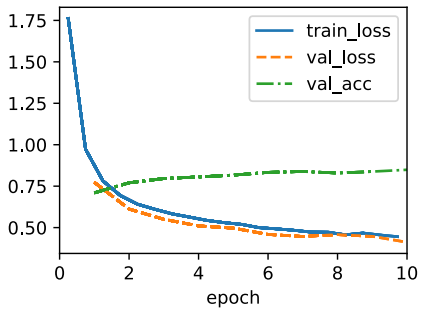
```
d2l.show_heatmaps(
    dec_self_attention_weights[:, :, :, :],
    xlabel='Key positions', ylabel='Query positions',
    titles=['Head %d' % i for i in range(1, 5)], figsize=(7, 3.5))
```



2) Baseline Vision Transformer

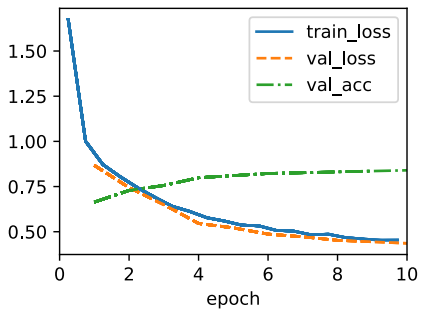
```
class PatchEmbedding(nn.Module):
    def __init__(self, img_size=96, patch_size=16, num_hiddens=512):
        super().__init__()
        def _make_tuple(x):
            if not isinstance(x, (list, tuple)):
                return (x, x)
            return x
        img_size, patch_size = _make_tuple(img_size), _make_tuple(patch_size)
        self.num_patches = (img_size[0] // patch_size[0]) * (
            img_size[1] // patch_size[1])
        self.conv = nn.LazyConv2d(num_hiddens, kernel_size=patch_size,
                                  stride=patch_size)

    def forward(self, X):
        # Output shape: (batch size, no. of patches, no. of channels)
        return self.conv(X).flatten(2).transpose(1, 2)


class ViTMLP(nn.Module):
    def __init__(self, mlp_num_hiddens, mlp_num_outputs, dropout=0.5):
        super().__init__()
        self.dense1 = nn.LazyLinear(mlp_num_hiddens)
        self.gelu = nn.GELU()
        self.dropout1 = nn.Dropout(dropout)
        self.dense2 = nn.LazyLinear(mlp_num_outputs)
        self.dropout2 = nn.Dropout(dropout)

    def forward(self, x):
        return self.dropout2(self.dense2(self.dropout1(self.gelu(
            self.dense1(x)))))


class ViTBlock(nn.Module):
    def __init__(self, num_hiddens, norm_shape, mlp_num_hiddens,
                 num_heads, dropout, use_bias=False):
        super().__init__()
        self.ln1 = nn.LayerNorm(norm_shape)
        self.attention = d2l.MultiHeadAttention(num_hiddens, num_heads,
                                                dropout, use_bias)
        self.ln2 = nn.LayerNorm(norm_shape)
        self.mlp = ViTMLP(mlp_num_hiddens, num_hiddens, dropout)

    def forward(self, X, valid_lens=None):
        X = X + self.attention(*([self.ln1(X)] * 3), valid_lens)
        return X + self.mlp(self.ln2(X))


class ViT(d2l.Classifier):
    """Vision Transformer."""
    def __init__(self, img_size, patch_size, num_hiddens, mlp_num_hiddens,
                 num_heads, num_blks, emb_dropout, blk_dropout, lr=0.1,
                 use_bias=False, num_classes=10):
        super().__init__()
        self.save_hyperparameters()
        self.patch_embedding = PatchEmbedding(
            img_size, patch_size, num_hiddens)
        self.cls_token = nn.Parameter(torch.zeros(1, 1, num_hiddens))
        num_steps = self.patch_embedding.num_patches + 1  # Add the cls token
        # Positional embeddings are learnable
        self.pos_embedding = nn.Parameter(
            torch.randn(1, num_steps, num_hiddens))
        self.dropout = nn.Dropout(emb_dropout)
        self.blks = nn.Sequential()
        for i in range(num_blks):
            self.blks.add_module(f"{i}", ViTBlock(
                num_hiddens, num_hiddens, mlp_num_hiddens,
                num_heads, blk_dropout, use_bias))
```

```
        self.head = nn.Sequential(nn.LayerNorm(num_hiddens),
                                  nn.Linear(num_hiddens, num_classes))

    def forward(self, X):
        X = self.patch_embedding(X)
        X = torch.cat((self.cls_token.expand(X.shape[0], -1, -1), X), 1)
        X = self.dropout(X + self.pos_embedding)
        for blk in self.blks:
            X = blk(X)
        return self.head(X[:, 0])


img_size, patch_size = 96, 16
num_hiddens, mlp_num_hiddens, num_heads, num_blks = 32, 128, 8, 2
emb_dropout, blk_dropout, lr = 0.1, 0.1, 0.1
model = ViT(img_size, patch_size, num_hiddens, mlp_num_hiddens, num_heads,
            num_blks, emb_dropout, blk_dropout, lr)
trainer = d2l.Trainer(max_epochs=10, gradient_clip_val=1, num_gpus=1)
data = d2l.FashionMNIST(batch_size=128, resize=(img_size, img_size))
trainer.fit(model, data)

# Train time: 12min 10sec
```



Deepening Baseline Vision Transformer

```
### 3 Blocks ###

img_size, patch_size = 96, 16
num_hiddens, mlp_num_hiddens, num_heads, num_blks = 32, 128, 8, 3
emb_dropout, blk_dropout, lr = 0.1, 0.1, 0.1
model = ViT(img_size, patch_size, num_hiddens, mlp_num_hiddens, num_heads,
            num_blks, emb_dropout, blk_dropout, lr)
trainer = d2l.Trainer(max_epochs=10, gradient_clip_val=1, num_gpus=1)
data = d2l.FashionMNIST(batch_size=128, resize=(img_size, img_size))
trainer.fit(model, data)

# Train time: 17min 5sec
```




```
### 4 Blocks ###

img_size, patch_size = 96, 16
num_hiddens, mlp_num_hiddens, num_heads, num_blks = 32, 128, 8, 4
emb_dropout, blk_dropout, lr = 0.1, 0.1, 0.1
model = ViT(img_size, patch_size, num_hiddens, mlp_num_hiddens, num_heads,
            num_blks, emb_dropout, blk_dropout, lr)
trainer = d2l.Trainer(max_epochs=10, gradient_clip_val=1, num_gpus=1)
```

```
data = d2l.FashionMNIST(batch_size=128, resize=(img_size, img_size))
trainer.fit(model, data)

# Train time: 21min 14sec
```