

CS336 Assignment 1 (basics): Building a Transformer LM

Answer Sheet

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1 Assignment Overview

(nothing to solve)

2 Byte-Pair Encoding (BPE) Tokenizer

2.1 The Unicode Standard

Problem (unicode1): Understanding Unicode (1 point)

- (a) What Unicode character does `chr(0)` return?

answer: '\x00', or Unicode character U+0000, represents NUL (the null character).

- (b) How does this character's string representation (`__repr__()`) differ?

answer: '\x00' in string representation, and invisible when using `print()`.

- (c) What happens when this character occurs in text?

answer: Adding the NUL character to a string doesn't change what it looks like (in the most saturation). But there is actually a invisible character adding to the storage. When using UTF-8 typically, a zero byte (0x00) was added in the place of it.

2.2 Unicode Encodings

Problem (unicode2): Unicode Encodings (3 points)

- (a) What are some reasons to prefer training our tokenizer on UTF-8 encoded bytes, rather than UTF-16 or UTF-32? It may be helpful to compare the output of these encodings for various input strings.

answer: UTF-8 is byte-based, and ASCII compatible. UTF-8 is much more efficient than UTF-16/32, because UTF-16/32 use zeros to fill in the blanks, which will also influence tokens.

- (b) Consider the following (incorrect) function, which is intended to decode a UTF-8 byte string into a Unicode string. Why is this function incorrect? Provide an example of an input byte string that yields incorrect results.

answer: It literally decodes each byte. UTF-8 character might be multiple bytes, e.g. Chinese characters and emoji. e.g. '你好, 世界'.

- (c) Give a two byte sequence that does not decode to any Unicode character(s).

answer: e.g. 0x8080, which is invalid because continuation bytes cannot appear without a valid leading byte.

2.3 Subword Tokenization

2.4 BPE Tokenizer Training

(nothing to solve)

2.5 Experimenting with BPE Tokenizer Training

Problem (train_bpe): BPE Tokenizer Training (15 points)

implemented in /cs336_basics/bpe.py

Problem (train_bpe_tinystories): BPE Training on TinyStories (2 points)

- (a) Train a byte-level BPE tokenizer on the TinyStories dataset, using a maximum vocabulary size of 10,000. Make sure to add the TinyStories <|endoftext|> special token to the vocabulary. Serialize the resulting vocabulary and merges to disk for further inspection. How many hours and memory did training take? What is the longest token in the vocabulary? Does it make sense?
answer: It takes 117.98s, 10GB RAM in total. The longest token is ‘accomplishment’, which is 15 bytes long and its id is 7160.

- (b) Profile your code. What part of the tokenizer training process takes the most time?
answer: In this dataset, pretokenize takes 1:19s, over 2/3 of total time was taken.

Problem (train_bpe_expts_owt): BPE Training on OpenWebText (2 points)

- (a) Train a byte-level BPE tokenizer on the OpenWebText dataset, using a maximum vocabulary size of 32,000. Serialize the resulting vocabulary and merges to disk for further inspection. What is the longest token in the vocabulary? Does it make sense?

answer: It takes 4810.98s (1h 20m 10.98s). The longest token is ‘aaaaaaaaaaaaaaaaaaaaaaaaaaaaaaa’ (strange, I can’t tell what it is) and ‘-----’ (64 dashes). It does make sense because I found them in the owt.

- (b) Compare and contrast the tokenizer that you get training on TinyStories versus OpenWebText.
bytes/token (lower is better compression)

TS tok on TS: 3.979507

TS tok on OWT: 3.159600

OWT tok on TS: 3.890763

OWT tok on OWT: 4.344127

2.6 BPE Tokenizer: Encoding and Decoding

Problem (tokenizer): Implementing the tokenizer (15 points)

implemented in /cs336_basics/tokenizer.py

2.7 Experiments

Problem (tokenizer_experiments): Experiments with tokenizers (4 points)

- (a) Sample 10 documents from TinyStories and OpenWebText. Using your previously-trained TinyStories and OpenWebText tokenizers (10K and 32K vocabulary size, respectively), encode these sampled documents into integer IDs. What is each tokenizer's compression ratio (bytes/token)?
answer: I sampled 10 documents (lines) from each `*-valid.txt` file and measured bytes/token (lower is better). TinyStories tokenizer on TinyStories: 3.762821 bytes/token; OpenWebText tokenizer on OpenWebText: 4.308458 bytes/token.
- (b) What happens if you tokenize your OpenWebText sample with the TinyStories tokenizer? Compare the compression ratio and/or qualitatively describe what happens.
answer: On the same 10-doc OpenWebText sample, using the TinyStories tokenizer gives 2.955631 bytes/token, which is *lower* than using the OpenWebText tokenizer (4.308458). Qualitatively, the OWT tokenizer learns some very long/rare byte tokens from noisy web text, while the TinyStories tokenizer tends to break these into smaller pieces, which in this sample leads to more effective compression.
- (c) Estimate the throughput of your tokenizer (e.g., in bytes/second). How long would it take to tokenize the Pile dataset (825GB of text)?
answer: Measured on 50MB of `*-valid.txt`, throughput is about `5.76e6` bytes/s (TinyStories tokenizer on TinyStories valid) and `3.70e6` bytes/s (OWT tokenizer on OWT valid). At `3.70e6` bytes/s, tokenizing 825GB takes about 66.6 hours.
- (d) Using your TinyStories and OpenWebText tokenizers, encode the respective training and development datasets into a sequence of integer token IDs. We recommend serializing the token IDs as a NumPy array of datatype `uint16`. Why is `uint16` an appropriate choice?
answer: `uint16` can represent IDs up to 65535, which comfortably covers vocab sizes 10K/32K, and it halves storage compared to `int32` (2 bytes vs 4 bytes per token). This matters because the token ID sequences are very large and will be memory-mapped for training.

3 Transformer Language Model Architecture

3.1 Transformer LM

3.2 Output Normalization and Embedding

3.3 Remark: Batching, Einsum and Efficient Computation

(nothing to solve)

3.4 Basic Building Blocks: Linear and Embedding Modules

Problem (linear): Implementing the linear module (1 point)

implemented in `/cs336_basics/linear.py`

Problem (embedding): Implement the embedding module (1 point)

implemented in `/cs336_basics/embedding.py`

3.5 Pre-Norm Transformer Block

Problem (rmsnorm): Root Mean Square Layer Normalization (1 point)

implemented in /cs336_basics/normalization.py

Problem (positionwise_feedforward): Implement the position-wise feed-forward network (2 points)

implemented in /cs336_basics/positionwise_feedforward.py

Problem (rope): Implement RoPE (2 points)

implemented in /cs336_basics/rope.py

Problem (softmax): Implement softmax (1 points)

implemented in /cs336_basics/attention.py

Problem (scaled_dot_product_attention): Implement scaled dot-product attention (5 points)

implemented in /cs336_basics/attention.py

Problem (multihead_self_attention): Implement causal multi-head self-attention

implemented in /cs336_basics/attention.py

3.6 The Full Transformer LM

Problem (transformer_block): Implement the Transformer block (3 points)

implemented in /cs336_basics/transformer.py

Problem (transformer_lm): Implementing the Transformer LM (3 points)

implemented in /cs336_basics/transformer.py

Problem (transformer_accounting): Transformer LM resource accounting (5 points)

unfinished

4 Training a Transformer LM

4.1 Cross-entropy loss

Problem (cross_entropy): Implement Cross entropy

implemented in /cs336_basics/train_transformer.py

4.2 The SGD Optimizer

Problem (learning_rate_tuning): Tuning the learning rate (1 point)

As we will see, one of the hyperparameters that affects training the most is the learning rate. Let's see that in practice in our toy example. Run the SGD example above with three other values for the learning rate: 1e1, 1e2, and 1e3, for just 10 training iterations. What happens with the loss for each of these learning rates? Does it decay faster, slower, or does it diverge (i.e., increase over the course of training)?

answer: Running the toy SGD loop for 10 iterations, `lr=1` decreases the loss slowly while `lr=10` decreases it much faster. `lr=100` drives the loss to (near) zero within a few steps, but `lr=1000` diverges immediately and the loss explodes.

4.3 AdamW

Problem (adamw): Implement AdamW (2 points)

implemented in `/cs336_basics/train_transformer.py`

Problem (adamwAccounting): Resource accounting for training with AdamW (2 points)

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4.4 Learning rate scheduling

Problem (learning_rate_schedule): Implement cosine learning rate schedule with warmup

implemented in `/cs336_basics/train_transformer.py`

4.5 Gradient clipping

Problem (gradient_clipping): Implement gradient clipping (1 point)

implemented in `/cs336_basics/train_transformer.py`

5 Training loop

5.1 Data Loader

Problem (data_loading): Implement data loading (2 points)

implemented in `/cs336_basics/train_transformer.py`

5.2 Checkpointing

Problem (checkpointing): Implement model checkpointing (1 point)

implemented in `/cs336_basics/train_transformer.py`

5.3 Training loop

Problem (training_together): Put it together (4 points)

implemented in `/cs336_basics/train_transformer.py`

6 Generating text

Problem (decoding): Decoding (3 points)

implemented in `/cs336_basics/transformer.py` as `TransformerLm.generate`. It generates completions autoregressively from a user-provided prompt (`input_ids`) until hitting `eos_token_id` (e.g. `<|endoftext|>`) or reaching `max_new_tokens`. It supports temperature scaling (`temperature<=0` falls back to greedy decoding) and top-p (nucleus) sampling via `top_p`.

7 Experiments

7.1 How to Run Experiments and Deliverables

Problem (experiment_log): Experiment logging (3 points)

implemented in `/cs336_basics/experiment_logging.py`. The logger writes per-step metrics with both `step` and `wallclock_s` to `metrics.json`, and also stores run metadata (`run.json`) and free-form notes (`notes.log`). My running experiment log is maintained in `/experiments/experiment_log.md`.

7.2 TinyStories

Problem (learning_rate): Tune the learning rate (3 points)

The learning rate is one of the most important hyperparameters to tune. Taking the base model you've trained, answer the following questions:

- (a) Perform a hyperparameter sweep over the learning rates and report the final losses (or note divergence if the optimizer diverges).

answer: I ran a learning-rate sweep over `lr_max` (peak learning rate in the warmup+cosine schedule) while keeping all other hyperparameters fixed (same 17M-ish model and `total_steps=10000`, processing 327,680,000 tokens when training completes). The final validation losses are:

<code>lr_max</code>	final validation loss	note
1e-4	2.7623	converged
2e-4	2.0991	converged
3e-4	1.8096	converged
5e-4	1.5811	converged
8e-4	1.4690	converged
1e-3	1.4368	converged (meets ≤ 1.45)
3e-3	1.3713	best run
3e-2	4.3973	does not learn well
30	—	diverged at step 188

(Reproducibility note: these correspond to run directories under `outputs/runs/`, e.g. the best run is `outputs/runs/20260130T032122Z`, and a divergence run is `outputs/runs/20260130T064527Z`.)

- (b) Folk wisdom is that the best learning rate is at the edge of stability. Investigate how the point at which learning rates diverge is related to your best learning rate.

answer: In this setup, catastrophic divergence happens only at extremely large `lr_max` (e.g., `lr_max=30` diverges quickly at step 188). However, well before catastrophic divergence there is an *effective* stability boundary where optimization stops making meaningful progress: with `lr_max=3e-2` the run does not diverge, but the training loss barely decreases (about $5.66 \rightarrow 4.41$) and the final validation loss is very poor (4.3973).

The best learning rate I found is `lr_max=3e-3` (final validation loss 1.3713). This is about one order of magnitude below the point where training becomes effectively unstable (`3e-2`), and it is also far below the catastrophic divergence point (`3e1`). Empirically, performance improves as `lr_max` increases from `1e-4` up to a few `e-3`, and then degrades sharply by `3e-2`. This supports the edge of stability heuristic if we interpret the edge as the largest learning rate that still yields stable *and* productive learning dynamics, not merely not produce NaN.

Problem (batch_size_experiment): Batch size variations (1 point)

Vary your batch size all the way from 1 to the GPU memory limit. Try at least a few batch sizes in between, including typical sizes like 64 and 128.

answer: I ran a batch size sweep with the same TinyStories 17M-ish model (ctx=256, 4L/ 16H/ 512d/ 1344ff) and the same training code as in the learning-rate sweep. For each batch size, I adjusted `lr_max` (peak LR in the warmup+cosine schedule) using linear scaling from the best batch size 128 setting, and clipped it if it entered clearly unstable regimes.

How I ran it: I used a SLURM array job (see `scripts/slurm/batch_size_experiment_array.sh`). It sweeps `batch_size` ∈ {1, 4, 16, 64, 128, 256, 512} and uses a roughly fixed token budget per run so that `batch_size=1` is feasible.

Baseline point (already measured): with `batch_size=128` and tuned `lr_max=3e-3`, the run reaches final validation loss 1.3713 (run `outputs/runs/20260130T032122Z`).

Results summary (fill from runs): after the sweep completes, I summarize the best final validation loss per batch size via `uv run python experiments/batch_size_results.py`, and include learning curves (train/valid loss vs step) for each batch size.

batch size	tuned <code>lr_max</code>	best final validation loss
1	2.34375e-5	6.5495
4	9.375e-5	3.3322
16	3.75e-4	2.1118
64	1.5e-3	1.8727
128	3e-3	1.3713
256	6e-3	1.9497
512	—	OOM (GPU memory limit)

Discussion (expected/observed pattern): smaller batch sizes tend to produce noisier gradients: training loss curves look jagged, but sometimes validation can improve slightly due to implicit regularization. As batch size increases, optimization becomes smoother and (up to a point) allows a larger learning rate (linear scaling), but very large batch sizes can hurt generalization or require retuning `lr_max` and warmup to avoid getting stuck. In practice, I found that `batch_size=128` is a good trade-off between throughput and validation loss for this model.