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Exercise 4 Report

The results show that **Batch Normalization (BN)** made a **small improvement early and at the end**, but overall both models performed very similarly on MNIST.

- **Faster start with BN:** In the first epochs, BN had lower test error (e.g., **Epoch 1: 1.16% with BN vs 1.55% without BN**, Epoch 2: **1.11% vs 1.26%**).
- **Final performance:** By the last epoch, BN achieved a slightly better test error (**0.76% with BN vs 0.85% without BN**).
- **Stability:** Test error fluctuates in both cases; BN is not consistently better for every epoch (e.g., Epoch 6–9 BN was sometimes worse).
- **Conclusion:** For this CNN on MNIST, **adding BN helps a bit (better early learning and slightly better final test error)**, but the improvement is **not huge** because MNIST is an easy dataset and even the non-BN CNN trains well.
- The training result are shown in the pictures below

1 → Without BN

Epoch 01	Train error:	1.40%	Test error:	1.55%
Epoch 02	Train error:	0.98%	Test error:	1.26%
Epoch 03	Train error:	0.50%	Test error:	0.89%
Epoch 04	Train error:	0.54%	Test error:	1.10%
Epoch 05	Train error:	0.30%	Test error:	1.00%
Epoch 06	Train error:	0.26%	Test error:	0.94%
Epoch 07	Train error:	0.14%	Test error:	0.87%
Epoch 08	Train error:	0.14%	Test error:	0.76%
Epoch 09	Train error:	0.18%	Test error:	0.92%
Epoch 10	Train error:	0.10%	Test error:	0.85%

2 →

==== Training WITH BatchNorm ===				
Epoch 01	Train error:	0.80%	Test error:	1.16%
Epoch 02	Train error:	0.57%	Test error:	1.11%
Epoch 03	Train error:	0.31%	Test error:	0.87%
Epoch 04	Train error:	0.27%	Test error:	1.04%
Epoch 05	Train error:	0.31%	Test error:	0.93%
Epoch 06	Train error:	0.26%	Test error:	1.15%
Epoch 07	Train error:	0.16%	Test error:	0.99%
Epoch 08	Train error:	0.10%	Test error:	0.81%
Epoch 09	Train error:	0.15%	Test error:	1.02%
Epoch 10	Train error:	0.10%	Test error:	0.76%

==== Classification error (%) by epoch (TEST) ===

Epoch | No BN | With BN

1		1.55%		1.16%
2		1.26%		1.11%
3		0.89%		0.87%
4		1.10%		1.04%
5		1.00%		0.93%
6		0.94%		1.15%
7		0.87%		0.99%
8		0.76%		0.81%
9		0.92%		1.02%
10		0.85%		0.76%

MNIST: CNN with vs without Batch Normalization

