# Accelerating a CNN on Vortex

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***Abstract*—We accelerate a CNN using the Vortex GPGPU.**

**Keywords—CNN, Vortex GPGPU, FashionMNIST, GPU, Tensor Core Unit**

## I. Introduction & Motivation

Convolutional Neural Networks (CNNs) consist mostly of convolution operations, which comprise 90% of overall runtime in typical inference workloads. Per-kernel analysis via standalone regression tests shows that convolution is the dominant bottleneck.

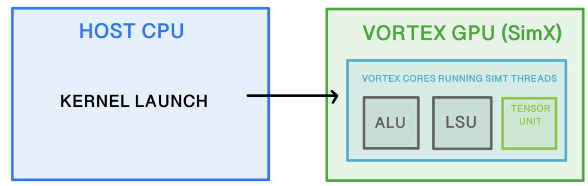
- Convolution IPC ≈ 2.8
- Pooling IPC ≈ 1.26
- ReLU IPC ≈ 0.81

(These IPC values are measured from isolated regression kernels and represent peak per-kernel behavior rather than end-to-end pipeline IPC.)

The regression tests alongside the data-parallel nature of convolutional operations demonstrated to us that CNNs were optimal for parallelization on GPU architectures. Our motivation was to explore how a CNN inference pipeline can be mapped onto the Vortex GPGPU architecture, and to evaluate the potential performance benefits of accelerating convolution using Vortex's Tensor Core Unit (TCU). We trained a CNN on the FashionMNIST dataset using TensorFlow, implemented an end-to-end CNN inference pipeline on Vortex as a baseline using conventional floating-point operations. The tensor-core–accelerated path is evaluated at the convolution kernel level using im2col + GEMM and is not fully integrated into the end-to-end multi-image CNN pipeline. We trained a simplified CNN architecture on the FashionMNIST dataset using TensorFlow, and ported the resulting weights to the Vortex execution environment. Our primary goal was to leverage the Vortex Tensor Core Unit (TCU) to accelerate the convolution.

## II. Implementation

### *A. High Level Architecture*




We use a Host CPU (running C++) to launch kernels on the Vortex GPU (SimX). The Vortex GPU contains Vortex cores that run SIMT (Single Instruction, Multiple Thread) threads, which can leverage the dedicated Tensor Unit for accelerated operations. The CNN consists of the following layers:

- Conv2D: 3 × 3 kernel, 8 output channels
- MaxPool2D: 2 × 2 pooling
- ReLU activation
- Flatten
- Fully Connected layer: 1352 → 10

The model was trained in Python using Keras on the Fashion-MNIST dataset and achieves approximately 90% validation accuracy. The trained weights were exported and reused without modification in the Vortex inference pipeline.

### *B. Software stack & execution paths*

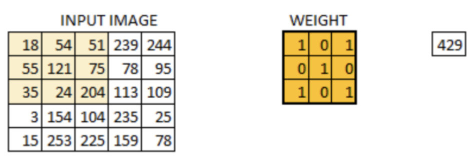
On the software side, CNN layers were implemented in C++ targeting the Vortex ISA. The full inference pipeline—including convolution, ReLU activation, and pooling—was executed on the GPU. Two distinct convolution paths were developed: a baseline implementation using standard floating-point operations, and an accelerated implementation that transforms the convolution into a matrix multiplication using im2col, enabling execution on the tensor core.

We used the FashionMNIST dataset, consisting of 60,000 grayscale 28×28 images labeled into 10 clothing categories. A simple CNN architecture (convolution, activation, pooling, followed by a fully connected layer) was trained in TensorFlow. The trained weights were exported and ported into the Vortex environment. While convolution, ReLU, and pooling were implemented on the GPU, the fully connected layer remained on the host CPU due to time and stability constraints.

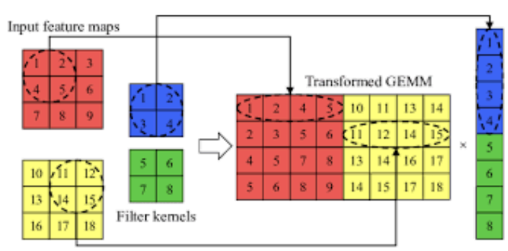
To ensure functional correctness, the pipeline was validated layer by layer against a Python reference implementation. Intermediate tensors from the Vortex execution (convolution output, pooling output, ReLU output, and logits) were printed and numerically compared against Python outputs for identical inputs and weights. All layers matched the Python reference within floating-point tolerance. Final predictions and probability distributions were also consistent with the reference model.

The two execution paths used to implement the convolution layer:

1. **Baseline Path (FPU-only execution):** Uses the regular CNN operation, relying on the Floating-Point Unit (FPU) for computation.




2. **Accelerated Path (Tensor core execution):** Uses the **im2col + GEMM** conversion method to map the convolution operation to matrix multiplication, which is then accelerated by the Tensor Core Unit (TCU) in Vortex.




*C. GPU Pipeline Architecture*

The CNN model used consists of convolutional, pooling, and ReLU layers.

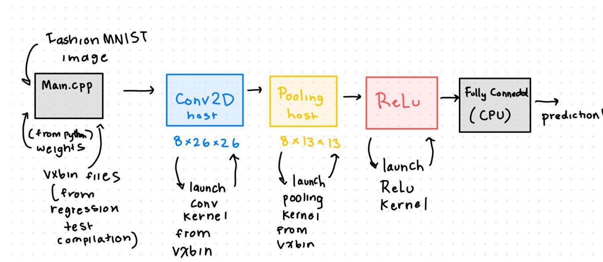



*Figure 1: GPU Pipeline Architecture*

## III. Evaluation and Results

*A. Overall evaluation of results*

The Vortex CNN achieves 89% accuracy on 100 Fashion-MNIST images, closely matching the Python reference model. Misclassifications primarily occur between visually similar classes such as Shirt and Coat, consistent with expected dataset behavior.

Functionally, the baseline CNN pipeline executed end-to-end on Vortex, producing consistent intermediate outputs (convolution, ReLU, pooling) when compared against reference CPU results for single-image inference. The accelerated tensor-core version was also compiled and executed successfully, confirming integration of the im2col + GEMM path. Performance was evaluated using SimX metrics, including instruction count, execution cycles, and instructions per cycle (IPC), across multiple warp and thread configurations. Results showed that the accelerated CNN achieved modest but measurable IPC improvements in certain configurations, particularly at higher warp and thread counts.

For example, with 4 warps and 8 threads, IPC increased from approximately 0.576 (baseline) to 0.614 (accelerated). In other configurations, performance was comparable, highlighting the sensitivity of results to kernel configuration and workload size. While single-image correctness was validated, multi-image accuracy evaluation was not fully completed due to a persistent convolution output mismatch leading to constant predictions. Our evaluation nonetheless shows the feasibility of tensor-core acceleration on Vortex.

### *B. Baseline convolutional layer vs. im2col + TCU accelerated GEMM performance results*

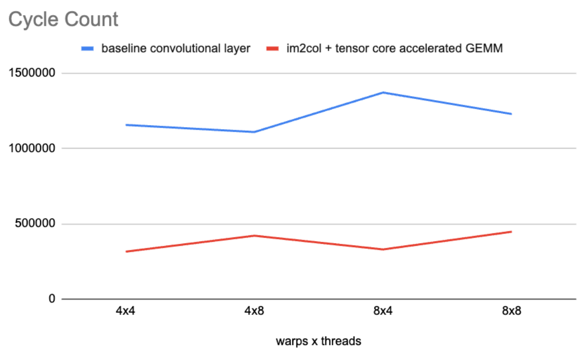



*Figure 2: Cycle count comparison between 2 execution paths*

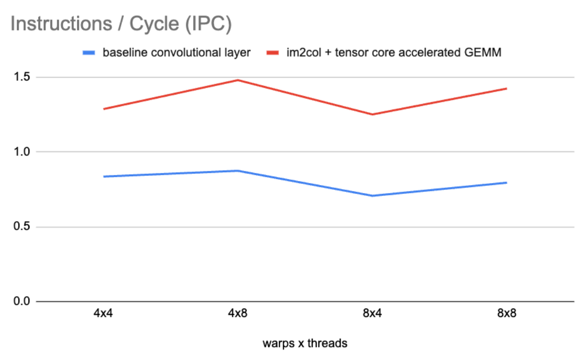



*Figure 3: IPC comparison between 2 execution paths*

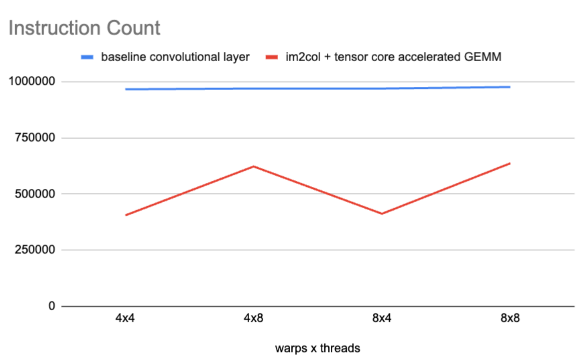



*Figure 4: Instruction count comparison between 2 execution paths*

These results show that the im2col + TCU path reduces cycle count and increases IPC in higher-parallelism configurations, while instruction count remains comparable due to data reorganization overhead.

| **Instructions** | | |
|---|---|---|
| warps x threads | baseline convolutional layer | im2col + tensor core accelerated GEMM |
| 4x4 | 965937 | 404965 |
| 4x8 | 969329 | 622506 |
| 8x4 | 969345 | 412065 |
| 8x8 | 976113 | 636646 |
| | | |
| **Cycle count** | | |
| warps x threads | baseline convolutional layer | im2col + tensor core accelerated GEMM |
| 4x4 | 1156420 | 314735 |
| 4x8 | 1109267 | 420558 |
| 8x4 | 1371561 | 329484 |
| 8x8 | 1228958 | 447052 |
| | | |
| **IPC** | | |
| warps x threads | baseline convolutional layer | im2col + tensor core accelerated GEMM |
| 4x4 | 0.8352821639 | 1.286685624 |
| 4x8 | 0.8738464229 | 1.480190604 |
| 8x4 | 0.7067458174 | 1.25063736 |
| 8x8 | 0.7942606664 | 1.424098315 |

*Table 1: Data from Figures 2,3,4 demonstrating baseline performance vs accelerated performance.*

Future work includes fully integrating WMMA-based convolution into the multi-image inference pipeline.

## IV. Artifacts Evaluation

To reproduce our results, please follow these steps:

GitHub: **https://github.com/gupann/vortex-accelerating-cnn**

### *A. Build Vortex*

```
mkdir build && cd build
../configure
make
```

### *B. Run CNN Inference*

```
make -C demo/CNN
make -C demo/CNN run-simx
```

### *C. Sweep Performance*

```
./ci/blackbox.sh --driver=simx --app=CNN \

--cores=4 --warps=4 --threads=4 --args="-n64"
```

### *D. Run Regression Kernels*

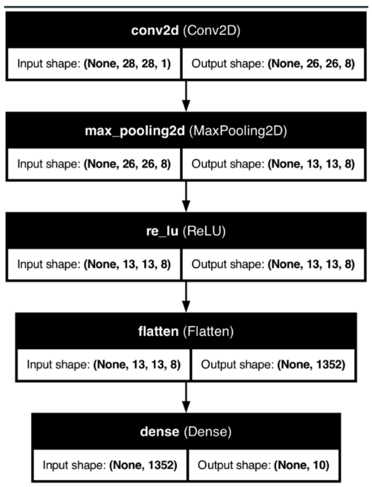
```
./ci/blackbox.sh --driver=simx --app=cnn_conv

./ci/blackbox.sh --driver=simx --app=cnn_pool

./ci/blackbox.sh --driver=simx --app=cnn_relu
```

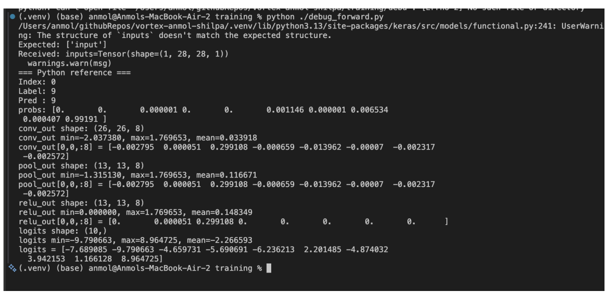
### *E. Python Reference*

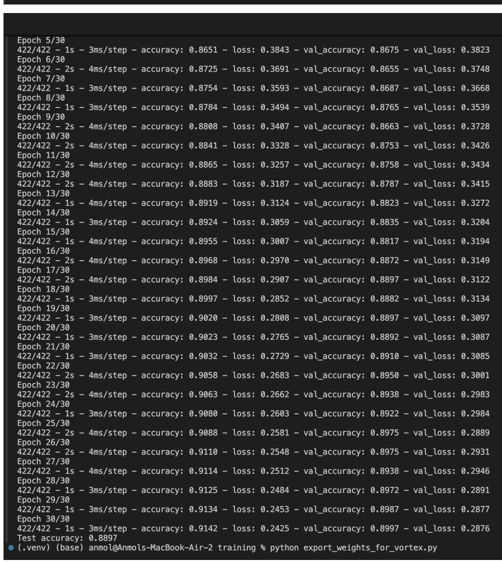
```
cd training

python cnn.py

python debug_forward.py
```

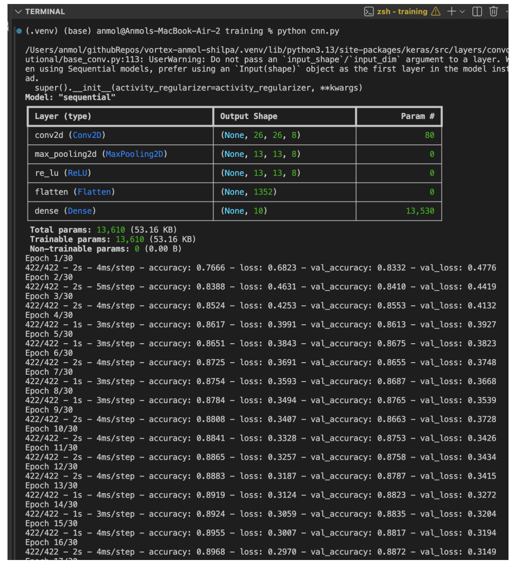
# V. Appendix

## A. Training model with Python & Keras



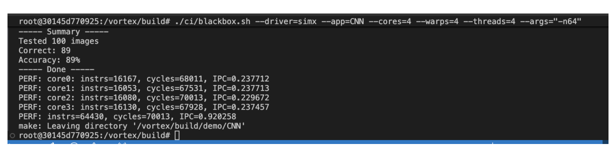



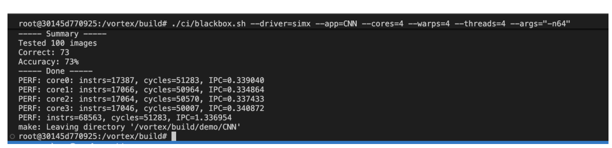




## B. Vortex regression performance


## C. Relu IPC performance improvement



### D. Vortex accuracy: terminal output

```
make: Leaving directory '/vortex/build/demo/CNN'
root@30145d770925:/vortex/build# make -C demo/CNN run-simx
make: Entering directory '/vortex/build/demo/CNN'
LD_LIBRARY_PATH=/vortex/build/runtime: VORTEX_DRIVER=simx ./CNN -n64
------ Vortex Fashion-MNIST CNN ------
Opened Vortex device.
Loading weights...
img 0 | gt=9 (Ankle boot) | pred=9 (Ankle boot) | CORRECT

--- DEBUG (img 0) ---
Conv output: 8x26x26
conv_out shape: 8x26x26
conv_out min=-2.03738, max=1.76965, mean=0.0339184
conv_out[y=0,x=0,c=0..7] = -0.00279455 5.09787e-05 0.299108 -0.000659352 -0.0139618 -6.963e-05 -0.00231739 -0.00257161
Pool output: 8x13x13
pool_out shape: 8x13x13
pool_out min=-1.31513, max=1.76965, mean=0.116671
pool_out[y=0,x=0,c=0..7] = -0.00279455 5.09787e-05 0.299108 -0.000659352 -0.0139618 -6.963e-05 -0.00231739 -0.00257161
relu_out shape: 8x13x13
relu_out min=0, max=1.76965, mean=0.148349
relu_out[y=0,x=0,c=0..7] = 0 5.09787e-05 0.299108 0 0 0 0 0
logits = -7.68908 -9.79067 -4.65973 -5.69069 -6.23622 2.20149 -4.87403 3.94215 1.16613 8.96472
Ground truth: 9 (Ankle boot)
Prediction : 9 (Ankle boot)
Result: CORRECT
Prediction: 9
Probabilities: 5.80518e-08 7.09754e-09 1.20073e-06 4.2826e-07 2.48193e-07 0.00114614 9.6912e-07 0.00653429 0.000406993 0.99191
--- END DEBUG ---

img 1 | gt=2 (Pullover) | pred=2 (Pullover) | CORRECT
img 2 | gt=1 (Trouser) | pred=1 (Trouser) | CORRECT
img 3 | gt=1 (Trouser) | pred=1 (Trouser) | CORRECT
img 4 | gt=6 (Shirt) | pred=6 (Shirt) | CORRECT
img 5 | gt=1 (Trouser) | pred=1 (Trouser) | CORRECT
img 6 | gt=4 (Coat) | pred=4 (Coat) | CORRECT
img 7 | gt=6 (Shirt) | pred=6 (Shirt) | CORRECT
img 8 | gt=5 (Sandal) | pred=5 (Sandal) | CORRECT
img 9 | gt=7 (Sneaker) | pred=7 (Sneaker) | CORRECT
img 10 | gt=4 (Coat) | pred=4 (Coat) | CORRECT
img 11 | gt=5 (Sandal) | pred=5 (Sandal) | CORRECT
img 12 | gt=7 (Sneaker) | pred=8 (Bag) | WRONG
img 13 | gt=3 (Dress) | pred=3 (Dress) | CORRECT
img 14 | gt=4 (Coat) | pred=4 (Coat) | CORRECT
img 15 | gt=1 (Trouser) | pred=1 (Trouser) | CORRECT
img 16 | gt=2 (Pullover) | pred=2 (Pullover) | CORRECT
img 17 | gt=4 (Coat) | pred=4 (Coat) | CORRECT
img 18 | gt=8 (Bag) | pred=8 (Bag) | CORRECT
img 19 | gt=0 (T-shirt/top) | pred=0 (T-shirt/top) | CORRECT
img 20 | gt=2 (Pullover) | pred=2 (Pullover) | CORRECT
img 21 | gt=5 (Sandal) | pred=5 (Sandal) | CORRECT
img 22 | gt=7 (Sneaker) | pred=7 (Sneaker) | CORRECT
img 23 | gt=9 (Ankle boot) | pred=5 (Sandal) | WRONG
img 24 | gt=1 (Trouser) | pred=1 (Trouser) | CORRECT
img 25 | gt=4 (Coat) | pred=6 (Shirt) | WRONG
img 26 | gt=6 (Shirt) | pred=6 (Shirt) | CORRECT
img 27 | gt=0 (T-shirt/top) | pred=0 (T-shirt/top) | CORRECT
img 28 | gt=9 (Ankle boot) | pred=9 (Ankle boot) | CORRECT
img 29 | gt=3 (Dress) | pred=3 (Dress) | CORRECT
img 30 | gt=8 (Bag) | pred=8 (Bag) | CORRECT
img 31 | gt=8 (Bag) | pred=8 (Bag) | CORRECT
img 32 | gt=3 (Dress) | pred=3 (Dress) | CORRECT
img 33 | gt=3 (Dress) | pred=3 (Dress) | CORRECT
img 34 | gt=8 (Bag) | pred=8 (Bag) | CORRECT
img 35 | gt=0 (T-shirt/top) | pred=0 (T-shirt/top) | CORRECT
img 36 | gt=7 (Sneaker) | pred=7 (Sneaker) | CORRECT
img 37 | gt=5 (Sandal) | pred=5 (Sandal) | CORRECT
img 38 | gt=7 (Sneaker) | pred=7 (Sneaker) | CORRECT
img 39 | gt=9 (Ankle boot) | pred=9 (Ankle boot) | CORRECT
img 40 | gt=6 (Shirt) | pred=0 (T-shirt/top) | WRONG
img 41 | gt=1 (Trouser) | pred=1 (Trouser) | CORRECT
img 42 | gt=3 (Dress) | pred=6 (Shirt) | WRONG
img 43 | gt=7 (Sneaker) | pred=7 (Sneaker) | CORRECT
img 44 | gt=6 (Shirt) | pred=6 (Shirt) | CORRECT
img 45 | gt=7 (Sneaker) | pred=7 (Sneaker) | CORRECT
img 46 | gt=2 (Pullover) | pred=2 (Pullover) | CORRECT
```

```
img 45 | gt=7 (Sneaker) | pred=7 (Sneaker) | CORRECT
img 46 | gt=2 (Pullover) | pred=2 (Pullover) | CORRECT
img 47 | gt=1 (Trouser) | pred=1 (Trouser) | CORRECT
img 48 | gt=2 (Pullover) | pred=2 (Pullover) | CORRECT
img 49 | gt=2 (Pullover) | pred=6 (Shirt) | WRONG
img 50 | gt=4 (Coat) | pred=4 (Coat) | CORRECT
img 51 | gt=4 (Coat) | pred=6 (Shirt) | WRONG
img 52 | gt=5 (Sandal) | pred=5 (Sandal) | CORRECT
img 53 | gt=8 (Bag) | pred=8 (Bag) | CORRECT
img 54 | gt=2 (Pullover) | pred=2 (Pullover) | CORRECT
img 55 | gt=2 (Pullover) | pred=2 (Pullover) | CORRECT
img 56 | gt=8 (Bag) | pred=8 (Bag) | CORRECT
img 57 | gt=4 (Coat) | pred=4 (Coat) | CORRECT
img 58 | gt=8 (Bag) | pred=8 (Bag) | CORRECT
img 59 | gt=0 (T-shirt/top) | pred=0 (T-shirt/top) | CORRECT
img 60 | gt=7 (Sneaker) | pred=7 (Sneaker) | CORRECT
img 61 | gt=7 (Sneaker) | pred=7 (Sneaker) | CORRECT
img 62 | gt=8 (Bag) | pred=8 (Bag) | CORRECT
img 63 | gt=5 (Sandal) | pred=5 (Sandal) | CORRECT
img 64 | gt=1 (Trouser) | pred=1 (Trouser) | CORRECT
img 65 | gt=1 (Trouser) | pred=1 (Trouser) | CORRECT
img 66 | gt=2 (Pullover) | pred=3 (Dress) | WRONG
img 67 | gt=3 (Dress) | pred=4 (Coat) | WRONG
img 68 | gt=9 (Ankle boot) | pred=7 (Sneaker) | WRONG
img 69 | gt=8 (Bag) | pred=8 (Bag) | CORRECT
img 70 | gt=7 (Sneaker) | pred=7 (Sneaker) | CORRECT
img 71 | gt=0 (T-shirt/top) | pred=0 (T-shirt/top) | CORRECT
img 72 | gt=2 (Pullover) | pred=2 (Pullover) | CORRECT
img 73 | gt=6 (Shirt) | pred=6 (Shirt) | CORRECT
img 74 | gt=2 (Pullover) | pred=4 (Coat) | WRONG
img 75 | gt=3 (Dress) | pred=3 (Dress) | CORRECT
img 76 | gt=1 (Trouser) | pred=1 (Trouser) | CORRECT
img 77 | gt=2 (Pullover) | pred=2 (Pullover) | CORRECT
img 78 | gt=8 (Bag) | pred=8 (Bag) | CORRECT
img 79 | gt=4 (Coat) | pred=4 (Coat) | CORRECT
img 80 | gt=1 (Trouser) | pred=1 (Trouser) | CORRECT
img 81 | gt=8 (Bag) | pred=8 (Bag) | CORRECT
img 82 | gt=5 (Sandal) | pred=5 (Sandal) | CORRECT
img 83 | gt=9 (Ankle boot) | pred=9 (Ankle boot) | CORRECT
img 84 | gt=5 (Sandal) | pred=5 (Sandal) | CORRECT
img 85 | gt=0 (T-shirt/top) | pred=0 (T-shirt/top) | CORRECT
img 86 | gt=3 (Dress) | pred=3 (Dress) | CORRECT
img 87 | gt=2 (Pullover) | pred=2 (Pullover) | CORRECT
img 88 | gt=0 (T-shirt/top) | pred=0 (T-shirt/top) | CORRECT
img 89 | gt=6 (Shirt) | pred=6 (Shirt) | CORRECT
img 90 | gt=5 (Sandal) | pred=5 (Sandal) | CORRECT
img 91 | gt=3 (Dress) | pred=3 (Dress) | CORRECT
img 92 | gt=6 (Shirt) | pred=6 (Shirt) | CORRECT
img 93 | gt=7 (Sneaker) | pred=7 (Sneaker) | CORRECT
img 94 | gt=1 (Trouser) | pred=1 (Trouser) | CORRECT
img 95 | gt=8 (Bag) | pred=8 (Bag) | CORRECT
img 96 | gt=0 (T-shirt/top) | pred=0 (T-shirt/top) | CORRECT
img 97 | gt=1 (Trouser) | pred=1 (Trouser) | CORRECT
img 98 | gt=4 (Coat) | pred=4 (Coat) | CORRECT
img 99 | gt=2 (Pullover) | pred=2 (Pullover) | CORRECT

------ Summary ------
Tested 100 images
Correct: 89
Accuracy: 89%
------ Done ------
PERF: instrs=53308, cycles=50814, IPC=1.049081
make: Leaving directory '/vortex/build/demo/CNN'
root@30145d770925:/vortex/build#
```