Deep Learning Training At Scale
Spring Crest Deep Learning Accelerator
(Intel® Nervana™ NNP-T)

Andrew Yang | 8/8/19
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DEEP LEARNING TRAINING

- Real-world performance - time to train and power efficiency
- Compute used for largest models & training sets doubles every 3.5 months**
- GEMM's and Convolutions dominate majority of computation required for Deep Neural Networks.
- Primary factors that drive a DL training accelerator
  - Power
  - Compute
  - Memory & Communication
  - Scale-out

* Based on analysis of ResNet, FaceNet, Open NMT
**https://openai.com/blog/ai-and-compute/
• Train a network as fast as possible within a given power budget, targeting larger models and datasets
• Balance between Compute, Communication, & Memory
• Re-use on-die data as much as possible
• Optimize for batched workloads
• Built-in scale-out support
• Support future workloads
• PCIe Gen 4 x16 EP
• 4x HBM2
• 64 lanes SerDes
• 24 Tensor Processors
• Up to 119 TOPS
• 60 MB on-chip distributed memory
• Management CPU and Interfaces
• 2.5D packaging
**SPRING CREST (NPN-T) IMPLEMENTATION**

- TSMC CLN16FF+
- 680mm$^2$, 1200mm$^2$ interposer
- 27 Billion Transistors
- 60mm x 60mm/6-2-6 3325 pin BGA package
- 4x8GB HBM2-2400 memory
- Up to 1.1Ghz core frequency
- 64 lanes SerDes HSIO up to 3.58Tbps aggregate BW
- PCIe Gen 4 x16, SPI, I2C, GPIOs
- PCIe & OAM form factors
- Air-cooled, 150-250W typical workload power
**NNP-T SOFTWARE STACK**

- Full software stack built with open components
- Direct integration with DL frameworks
- **nGraph:** Hardware agnostic deep learning library and compiler for DL platform developers.
  - Provides common set of optimizations for NNP-T across DL frameworks
- **Argon:** NNP-T DNN compute & communication kernel library
- **Low-level programmability:** NNP-T kernel development toolchain w/tensor compiler

[Image of NNP-T components and integration with open-source frameworks]
NNP-T PROGRAMMING MODEL

- Flexible and programmable Tensor-based ISA
  - Limited instruction set
  - Extensible with uController custom instructions
- Same distributed programming model for both intra and inter-chip
  - Explicit SW memory management and message passing
  - Synchronization primitives
  - Compute has affinity to local data
- DL workloads are dominated by a limited set of operations
TENSOR PROCESSING CLUSTER (TPC)

Convolution Engine
Local Memory Bank
Local Memory Bank
...
**BFLOAT16 NUMERICS**

- Bfloat16 w/ FP32 accumulation
  - No sacrifice in SOTA accuracy, improved power efficiency & training time*
  - Minimal model changes

<table>
<thead>
<tr>
<th>Numeric format</th>
<th>Area/Power efficient</th>
<th>Easy to Converge?</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>FP32</td>
<td>No</td>
<td>Yes</td>
<td>Industry standard</td>
</tr>
<tr>
<td>FP16</td>
<td>Yes</td>
<td>Medium</td>
<td>Good precision for Fprop. Bprop/Update is more challenging.</td>
</tr>
<tr>
<td>16b Integer formats</td>
<td>Yes</td>
<td>No</td>
<td>Better area/power than FP, but hard to use</td>
</tr>
<tr>
<td>Bfloat16</td>
<td>Yes</td>
<td>Yes</td>
<td>Good at Fprop, Bprop, and Update</td>
</tr>
<tr>
<td>8/4/2/1b integer</td>
<td>Extreme</td>
<td>Extremely difficult</td>
<td>Research areas</td>
</tr>
</tbody>
</table>

- Bfloat16 Matrix Multiply Core (32x32)
- FP32 & BF16 support for all other operations
- 2x multiply cores per TPC to amortize SoC resources
- Vector operations for non-GEMM
  - Compound pipeline
  - DL specific optimizations
    - Activation functions, RNG, Reductions & accumulations
    - Programmable FP32 look-up tables
**MEMORY SUBSYSTEM**

- Four stacks of HBM2-2400 8GB devices
  - 1.22TBps raw bandwidth and 32GB total device memory. ECC protected
- 2.5MB/TPC of local scratchpad memory
  - 60 MB total distributed memory, ECC protected
  - Native Tensor Transpose
  - Simultaneous read and write on each MRB
  - 1.4TBps local read/write bandwidth per-TPC
- Support for direct memory to memory transfer for both HBM and MRB
SPRING CREST ON-DIE COMMUNICATION

- Bidirectional 2-D mesh architecture to allow any to any communication
- Prioritized for throughput and congestion avoidance
- Cut-through forwarding and multicast support
- 2.6TBps total cross-sectional BW, 1.3TBps per-direction
- All peripheral devices shared through the mesh (HBM, SerDes)
- Separate meshes for different traffic types
- Support for direct peer to peer communication between TPCs
• Run the largest models across multiple chips and across chassis
• 16 quads of 112Gbps. 3.58Tbps total bi-directional BW per chip
• Fully programmable router w/multi-cast support enables multiple glue-less topologies
  • Reliable transmission
  • Virtual channels and priorities for traffic management
• Direct low-latency local memory transfer
• Support for up to 1024 nodes
• DL workloads require a variety of GEMM sizes

• Minimize HBM memory boundedness with on-die data re-use => higher utilization of compute resources

• Faster training, less idle resources

• ~2x better than published utilization of competitive products

<table>
<thead>
<tr>
<th>GEMM Size</th>
<th>Spring Crest Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1024 x 700 x 512</td>
<td>31.1%</td>
</tr>
<tr>
<td>1760 x 7133 x 1760</td>
<td>44.5%</td>
</tr>
<tr>
<td>2048 x 7133 x 2048</td>
<td>46.7%</td>
</tr>
<tr>
<td>2560 x 7133 x 2560</td>
<td>57.1%</td>
</tr>
<tr>
<td>4096 x 7133 x 4096</td>
<td>57.4%</td>
</tr>
<tr>
<td>5124 x 9124 x 2048</td>
<td>55.5%</td>
</tr>
</tbody>
</table>

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Performance measured on July 10, 2019 on pre-production NNP-T Spring Crest silicon, using 22 TPCs at 900MHz core clock and 2GHz HBM clock. Host is an Intel® Xeon® Gold 6130T CPU @ 2.10GHz with 64 GB of system memory. For more complete information about performance and benchmark results, visit www.intel.com/benchmarks.

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Based on NVIDIA DGX-1, NVIDIA V100 GPU, Linux Kernel 4.4.0-124-generic, CUDA 10.0.130, CuDNN 7.3.1.20, NVIDIA Driver 410.48, Intel® Xeon® CPU E5-2698v4@2.2GHz.
**SPRING CREST CONVOLUTIONS**

- Various convolution hyperparameters are required by DL workloads
- Support multiple tensor layouts for maximum on-die data reuse resulting higher compute efficiency

**Convolution Performance**

<table>
<thead>
<tr>
<th>Description</th>
<th>Spring Crest Utilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>c64xh56xw56_k64xr3xs3_st1_n128</td>
<td>86%</td>
</tr>
<tr>
<td>c128xh28xw28_k128xr3xs3_st1_n128</td>
<td>71%</td>
</tr>
<tr>
<td>c512xh28xw28_k128xr1xs1_st1_n128</td>
<td>65%</td>
</tr>
<tr>
<td>c128xh28xw28_k512xr1xs1_st1_n128</td>
<td>59%</td>
</tr>
<tr>
<td>c256xh14xw14_k1024xr1xs1_st1_n128</td>
<td>62%</td>
</tr>
<tr>
<td>c256xh28xw28_k512xr1xs1_st2_n128</td>
<td>71%</td>
</tr>
<tr>
<td>c32xh120xw120_k64xr5xs5_st1_n128</td>
<td>87%</td>
</tr>
</tbody>
</table>

C=# input dimensions, H=height, W=width, K=# filters, R=filter X, S=filter Y, ST=stride N=minibatch size

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**SPRING CREST COMMUNICATION PERFORMANCE**

- Benchmarked on ring topology (intra and inter-chassis)
- Support for different All-reduce algorithms with different communication patterns

<table>
<thead>
<tr>
<th>Communication Kernels</th>
<th>Within-chassis (8 cards)</th>
<th>Cross-chassis (16, 32 cards)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth (BW)</td>
<td>Spring Crest 16x ICL</td>
<td>Spring Crest 16x ICL</td>
</tr>
<tr>
<td>2-card Send/Recv BW (GB/s)</td>
<td>161</td>
<td>161</td>
</tr>
<tr>
<td>Allreduce BW (GB/s)</td>
<td>151</td>
<td>151</td>
</tr>
<tr>
<td>Broadcast BW (GB/s)</td>
<td>147</td>
<td>147</td>
</tr>
</tbody>
</table>

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COMMUNICATION PERFORMANCE

- Low overhead and direct memory transfer result in low latency
- High efficiency even at moderate transfer sizes
- Cross-chassis scale-out with the same network/connectivity

<table>
<thead>
<tr>
<th>Allreduce Latency, 2KB (µs)</th>
<th>Spring Crest 16x ICL</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 cards (in-chassis)</td>
<td>3</td>
</tr>
<tr>
<td>4 cards (in-chassis)</td>
<td>8</td>
</tr>
<tr>
<td>8 cards (in-chassis)</td>
<td>9</td>
</tr>
<tr>
<td>16 cards (cross-chassis)</td>
<td>30</td>
</tr>
<tr>
<td>32 cards (cross-chassis)</td>
<td>36</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Allreduce Data Rate (GB/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Message Size</td>
</tr>
<tr>
<td>1 MB</td>
</tr>
<tr>
<td>8 MB</td>
</tr>
<tr>
<td>32 MB</td>
</tr>
<tr>
<td>128 MB</td>
</tr>
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CONCLUDING REMARKS

• Domain specific acceleration has a place in DL training
  • Training time and model size continue to be bottlenecks
• Numerics and compute tailored for DL
• No legacy workloads to support
• Architect from ground up to reduce data movement and keep compute units fed
• Higher utilization and efficiency on micro-benchmarks translate into better overall WL performance => Faster, more power efficient training