Dynamic Multi-Resolution Data Storage
(Varifocal Storage)

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Approximate Computing is Everywhere

General-Purpose Exact Computing

Approximate Computing
Approximate Computing in General-Purpose Computers

Retrieve Raw Data

Adjust Data Resolutions

Low-Resolution Data

DRAM

GPU

FPGA

Raw Data

SSD

System Interconnect (e.g., PCIe)

CPU

Compute

TPU

Quality Control (e.g., PCIe)
Limited Interconnect Bandwidth

The PCIe Root Complex on a processor has only limited (e.g., 48) PCIe 3.0 lanes.

Bandwidth LIMIT 4

System Interconnect (e.g., PCIe)

Processing time

System Interconnect (e.g., PCIe)

Limited Bandwidth
Bottleneck in Approximate Computing Pipeline

Storage Medium Access

SSD

PCIe

CPU

Accelerator

Data XCHG SSD/Main Memory

Adjust Data Resolutions

Data XCHG Main Memory/Accelerator

Compute Kernel

Data XCHG SSD/Main Memory

Adjust Data Resolutions

Data XCHG Main Memory/Accelerator

Compute Kernel

Data XCHG SSD/Main Memory

Adjust Data Resolutions

Data XCHG Main Memory/Accelerator

Compute Kernel
Data Adjustment Can be 100x More Than Compute Kernels

"Data adjustment" is more expensive than compute!

* Approximate compute kernels running on NVIDIA's Tesla T4 with data from an NVMe SSD
The Missing Opportunity

The internal bandwidth of an SSD is rich

Application can’t use the rich bandwidth because we only see this part!

System Interconnect (e.g., PCIe)

System Interconnect (e.g., PCIe)

Each ~500MB/sec x 16 channels == 8GB/sec
Varifocal Storage: A Holistic System Architecture

Retrieve Raw Data

Adjust Data Resolutions

Varifocal Storage (VS)

System Interconnect (e.g., PCIe)

Quality Control (e.g., PCIe)

Compute

DRAM

CPU

GPU

FPGA

TPU
Outline

- Approximate computing and its shifting bottleneck
- **Overview of Varifocal Storage (VS)**
- Evaluation of Varifocal Storage (VS)
- Conclusion
Dynamic Multi-Resolution Data Storage (Varifocal Storage)

Provide operators to adjust data resolutions
Support various resolutions and exact data
Quality control mechanisms
Drop-in upgrade to existing SSD hardware
System Architecture of Varifocal Storage

Data, operator, desired resolution & quality knobs

Varifocal Storage

Non-volatile Memory

Applications

Resolution

Quality Knobs

data, operator, desired resolution & quality knobs

adjusted data and feedback

access raw data

perform data adjustment/QC

Adjusted Data
Previously in Approximate Computing

SSD
- Storage Medium Access
- Data XCHG SSD/Main Memory
- Adjust Data Resolutions

PCIe
- Data XCHG SSD/Main Memory
- Adjust Data Resolutions
- Compute Kernel

CPU
- Adjust Data Resolutions
- Data XCHG Main Memory/Accelerator

Accelerator
- Compute Kernel
Data Processing Pipeline in Varifocal Storage

- **Varifocal Storage**
  - Adjust Data Resolutions
  - Produce lower-resolution data

- **PCIe**
  - Data XCHG VS/Main Memory
  - Ship only data with reduced resolutions (smaller data size) — the critical path in conventional approximate computing

- **CPU**
  - Data XCHG Main Memory
  - CPU computation can potentially be skipped

- **PCIe**
  - Data XCHG Main Memory/Accelerator

**Compute Kernel**
- Compute Kernel
- Compute Kernel
- Compute Kernel
- Compute Kernel
- Compute Kernel
Traditional Quality Control

- Raw Data
- Lower-resolution
- 25% Resolution Test
- Compute
- Tiger
- Reject Result
- Better-resolution
- 50% Resolution Test
- Re-compute
- Bear

System Interconnect (e.g., PCIe)
- SSD
- CPU
- DRAM

System Interconnect (e.g., PCIe)
- GPU
- TPU
- FPGA

Lower-resolution

Better-resolution

25% Resolution

50% Resolution

Test

Test
Garbage in, garbage out
Quality Control

Autofocus

iFilter
Autofocus

Varifocal Storage (VS)

Raw Data → Lower-resolution → 25% Resolution → Reject if it becomes garbage → Better-resolution → 50% Resolution → Use this resolution for the same dataset later → Pass! Compute → Bear

CPU → DRAM → TPU → FPGA → System Interconnect (e.g., PCIe)

Test

Use this resolution for the same dataset later
Varifocal Storage (VS)

Autofocus on Operator A
25% Resolution

Autofocus on Operator B
45% Resolution

Autofocus on Operator C
50% Resolution

Pass!
Use this resolution/operator for the same dataset later
Pass!

Send Smaller One & Compute

Test

iFilter

System Interconnect (e.g., PCIe)

System Interconnect (e.g., PCIe)

Bear
Outline

• Approximate computing and its shifting bottleneck
• Overview of Varifocal Storage (VS)
• Evaluation of Varifocal Storage (VS)
• Conclusion
“Ideal” Modern Computing Architecture

Cost  Performance  Flexibility  Quality

QC PASSED

ESCAL

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Cost in Varifocal Storage

Abundant processor cycles are wasted!

$0 Cost!
“Ideal” Modern Computing Architecture

- Cost
- Performance
- Flexibility
- Quality

ESCAL

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Performance of Varifocal Storage (VS)

- Speedup over conventional Approximate Computing

- VS-manual
- VS+Autofocus
- VS+iFilter
- Exact Computing

- BFS, black-scholes, DWT2d, hotspot, Inverse2j, Jmeint, KMeans, kNN, Stream-Cluster, SVM-Train, XGBoost-Train, CNN-Predict, SVM-Predict, XGBoost-Predict, Average, GM
“Ideal” Modern Computing Architecture

- Cost
- Performance
- Flexibility
- Quality

ESCAL

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**Flexibility — Same Datasets, Different Resolutions**

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Benchmark</th>
<th>Operator</th>
<th>Resolution</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>KMeans</td>
<td>Quantization</td>
<td>0.25</td>
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<tr>
<td></td>
<td>kNN</td>
<td>Packing</td>
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<td>Streamcluster</td>
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<td>Packing</td>
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<tr>
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<td>CNN-Predict</td>
<td>Quantization</td>
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<tr>
<td></td>
<td>XGB-Predict</td>
<td>Packing</td>
<td>0.5</td>
</tr>
</tbody>
</table>

— all from single raw data storage
“Ideal” Modern Computing Architecture
Quality Control — Adapt to Different Datasets (Jmeint)

![Bar chart showing speedup vs. range of value within datasets.]

- VS w/ Autofocus
- IRA — host only quality control

Range of value within datasets:
- 0 – 31
- 0 – 65535
- 0 – 4.3B

Speedup
Conclusion

- Thanks to your great research — the bottleneck in Approximate Computing has shifted!
- To further improve the application performance, we need a full-stack/holistic system design for Approximate Computing
- Varifocal Storage presents an architecture that can adjust data resolution, perform quality control in storage and coordinate these tasks with applications.
Thank you!

CNS-1940046
CNS-1940048

NC STATE UNIVERSITY

Faculty Research Award

NVIDIA

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