Analyzing I/O in Deep Learning Workloads

Hariharan Devarajan (devarajan1@llnl.gov)

DFTracer

Analyzing Parallel I/O
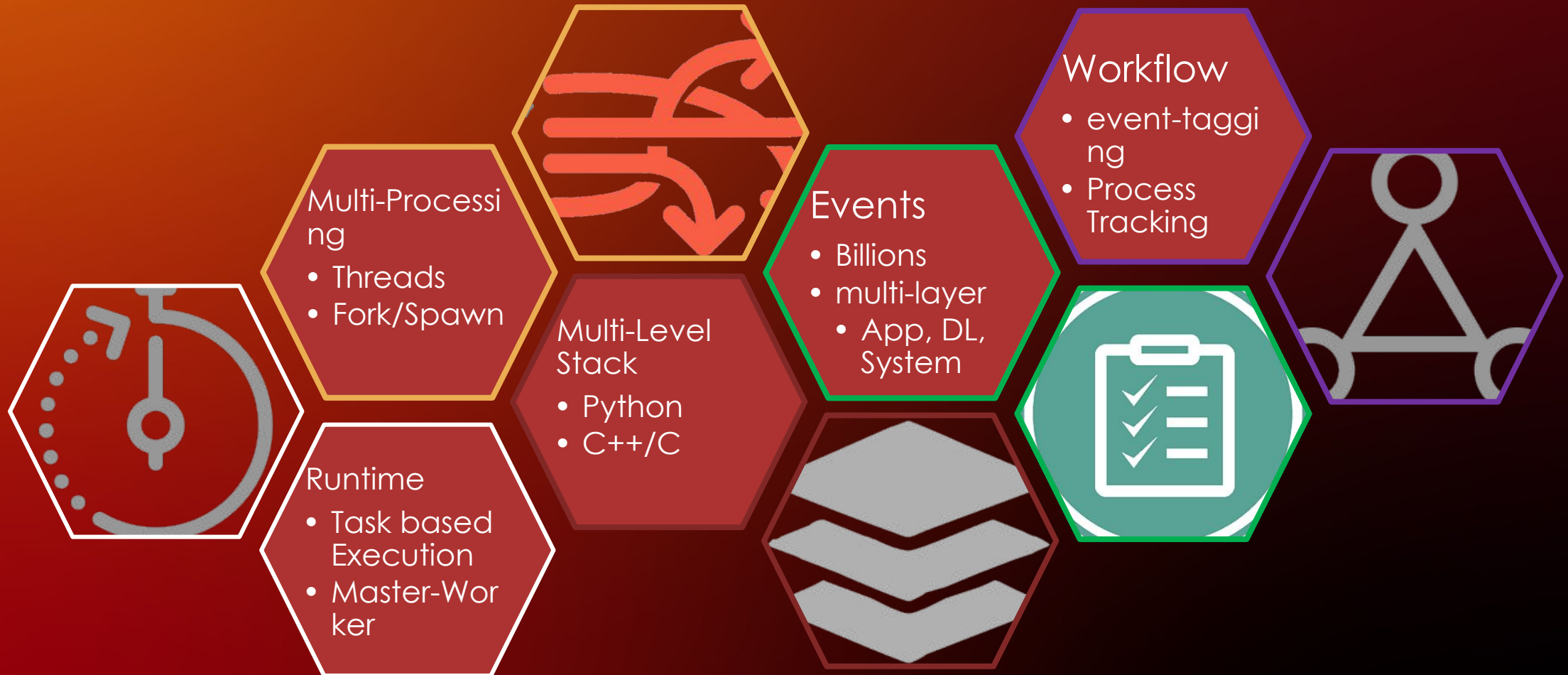Birds of Feather

SCAN ME

SC24
Atlanta, GA | hpc creates.

11/14/24   1

Unique Features of DL Workloads

Multi-Processing
- Threads
- Fork/Spawn

Multi-Level Stack
- Python
- C++/C

Runtime
- Task based Execution
- Master-Worker

Events
- Billions
- multi-layer
- App, DL, System

Workflow
- event-tagging
- Process Tracking

Recent Tools developed for I/O in AI

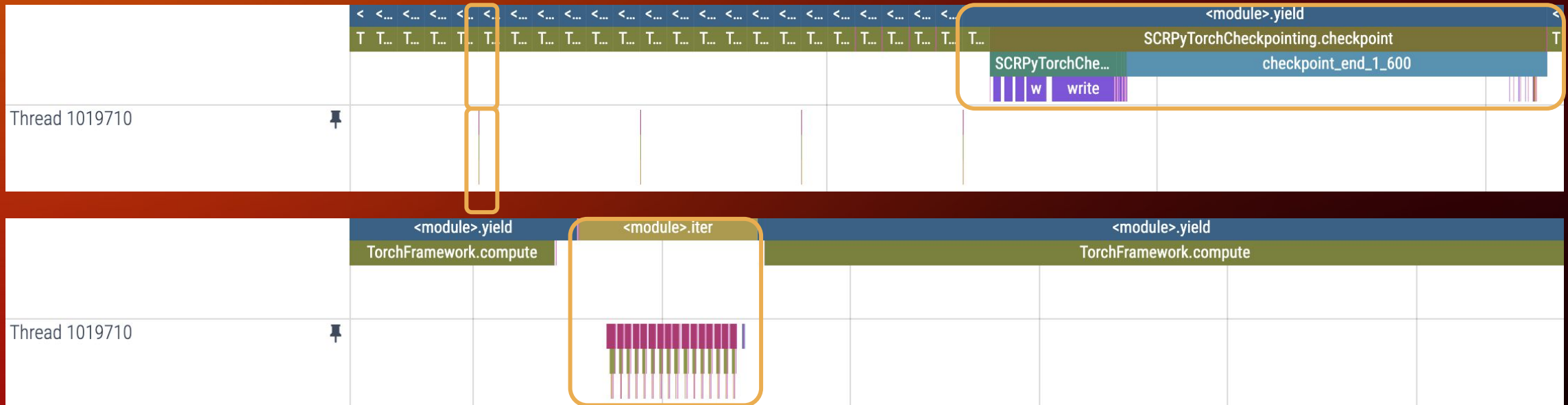DFTracer: A multi-level dataflow tracer for capturing I/O calls from AI-driven workflows.

WisIO: An automatic bottleneck detector for large-scale workloads

DFAnalyzer: A multi-level analyzer for understanding I/O from multiple levels of the hierarchy

Visualization of Megatron Deepspeed with SCR (DFTracer + Perfetto)

Capture multiple data-centric layers of the workload

- Application layer (python code)
- System layer (POSIX and STDIO interface)

Optimizing Megatron Deepspeed with SCR (DFTracer + WisIO)

Difference between overall I/O and Unoverlapped or perceived I/O

```
Runtime: 8428.34 seconds (100%)
├── Application I/O Time: 1487.00 seconds (17.64%)
├── Checkpoint I/O Time: 1485.76 seconds (17.63%)
├── Compute Time: 7327.39 seconds (86.94%)
├── I/O Time: 938.97 seconds (11.14%)
├── Read I/O Time: 1.69 seconds (0.02%)

├── Unoverlapped Application I/O Time: 297.31 seconds (3.53%)
├── Unoverlapped Checkpoint I/O Time: 297.31 seconds (3.53%)
├── Unoverlapped Compute Time: 6469.93 seconds (76.76%)
├── Unoverlapped I/O Time: 81.50 seconds (0.97%)
├── Unoverlapped Read I/O Time: 0.00 seconds (0.00%)
├── Unoverlapped Application Compute Time: 6137.71 seconds (72.82%)
```

```
Runtime: 9773.62 seconds (100%)
├── Application I/O Time: 4424.42 seconds (45.27%)
├── Checkpoint I/O Time: 4405.64 seconds (45.08%)
├── Compute Time: 7345.04 seconds (75.15%)
├── I/O Time: 2218.73 seconds (22.70%)
├── Read I/O Time: 29.65 seconds (0.30%)

├── Unoverlapped Application I/O Time: 3162.50 seconds (32.36%)
├── Unoverlapped Checkpoint I/O Time: 3162.50 seconds (32.36%)
├── Unoverlapped Compute Time: 5934.06 seconds (60.72%)
├── Unoverlapped I/O Time: 807.75 seconds (8.26%)
├── Unoverlapped Read I/O Time: 0.00 seconds (0.00%)
├── Unoverlapped Application Compute Time: 6083.12 seconds (62.24%)
```

Reduced overall runtime is a result of increasing overlap between checkpoint I/O and Computation

DFAnalyzer: Multi-Level analysis of AI workloads

Stromer application from ANL

Initial Conditions   **5-day Forecast**   **Ground Truth**
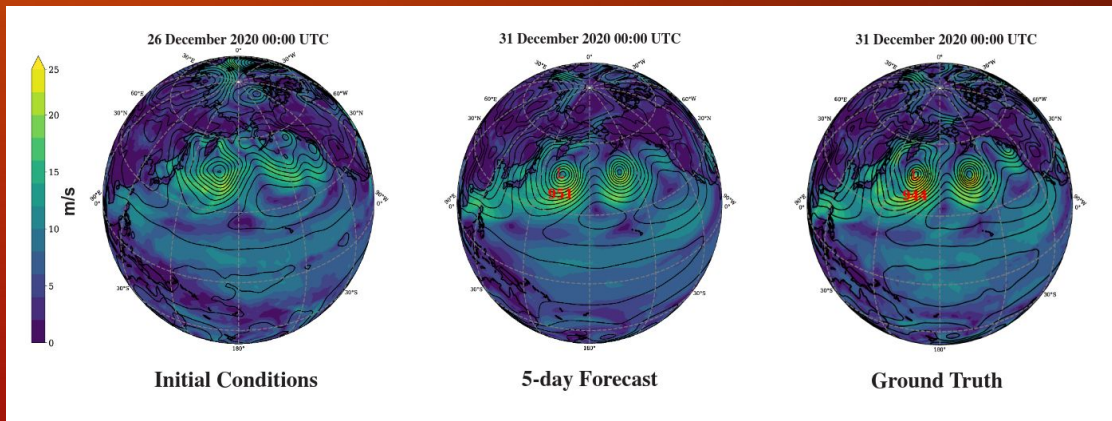
HDF5 Dataset with PyTorch Data Loader

We need to look at multiple layers and different metrics to understand performance.

| Level	Item	Metric	Stormer
App	Compute	Num Instances Agg. Time	2920 15.04 min
	Data Loading	Num Instances Agg. Time	2920 4.32 min
Data Loader	Num Workers	Num Instances	32
	Preprocess	Num Instances Agg. Time	2920 2.66 min
	Get Item	Num Instances Agg. Time	2920 17.93 min
System Call	IO Size	Total	2.93 TB
	All POSIX	Num Instances Agg. Time Agg. Size	82756 16.19 min 2.93 TB
	Data > 4KB	Dur. wrt POSIX Num Instances Agg. Time Agg. Size Transfer Size Bandwidth	98.87 % 5904 16.05 min 2.93 TB 521.05 MB 0.88 GB/s
	Data <= 4KB	Dur. wrt POSIX Num Instances Agg. Time Agg. Size	0.60 % 29244 6.85 secs 6.03 MB
	Others	Dur. wrt POSIX Num Instances Agg. Time	0.53 % 47588 7.76 secs

Questions or Comments

DFTracer

SCAN ME

Analyzer

SCAN ME
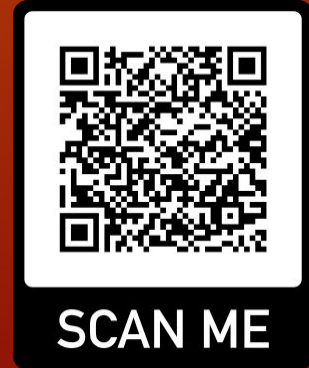
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Detailed Characterization and Analysis (DFTracer + WisIO)


```
                ─ POSIX I/O Characteristics ─

Runtime              9773.62 seconds
I/O Time             2218.73 seconds (100%)
                     ├── Read: 612.49 seconds (27.61%)
                     ├── Write: 1409.17 seconds (63.51%)
                     └── Metadata: 773.33 seconds (34.85%)
I/O Ops.             114,626,459 ops
                     ├── Read - 24,729,700 ops (21.57%)
                     ├── Write - 4,478,320 ops (3.91%)
                     └── Metadata - 65,177,974 ops (56.86%)
I/O Size             86.64 TiB
                     ├── Read - 41.83 TiB (48.27%)
                     └── Write - 44.82 TiB (51.73%)
Read Requests        4 kiB→64 MiB - 24,729,700 ops
                     ├── >64 MiB: 24,696,810 ops (99.87%)
                     └── [Others: 32,890 ops (0.13%)]
Write Requests       4 kiB→64 MiB - 4,478,320 ops
                     ├── <4 kiB: 233,346 ops (5.21%)
                     ├── >64 MiB: 4,227,808 ops (94.41%)
                     └── [Others: 17,166 ops (0.38%)]
Time Periods         151 time periods (Time Granularity: 65.00 seconds)
Access Pattern       Sequential: 29,208,020 ops (100.00%) - Random: 0 ops (0.00%)

─ R: Read - W: Write - M: Metadata ─
```

```
                ─ POSIX I/O Characteristics ─

Runtime                  9773.62 seconds
Unoverlapped I/O Time    807.75 seconds (100%)
                         ├── Read: 148.93 seconds (18.44%)
                         ├── Write: 229.07 seconds (28.36%)
                         └── Metadata: 294.69 seconds (36.48%)
Unoverlapped I/O Ops.    84,805,998 ops
                         ├── Read - 21,718,805 ops (25.61%)
                         ├── Write - 3,233,634 ops (3.81%)
                         └── Metadata - 57,117,804 ops (67.35%)
Unoverlapped I/O Size    47.29 TiB
                         ├── Read - 26.41 TiB (55.83%)
                         └── Write - 20.89 TiB (44.17%)
Read Requests            4 kiB→64 MiB - 21,718,805 ops
                         ├── >64 MiB: 21,717,137 ops (99.99%)
                         └── [Others: 1,668 ops (0.01%)]
Write Requests           4 kiB→64 MiB - 3,233,634 ops
                         ├── >64 MiB: 3,218,930 ops (99.55%)
                         └── [Others: 14,704 ops (0.45%)]
Time Periods             36 time periods (Time Granularity: 65.00 seconds)
Access Pattern           Sequential: 24,952,439 ops (100.00%) - Random: 0 ops (0.00%)

─ R: Read - W: Write - M: Metadata ─
```

Difference between overall I/O and Unoverlapped or perceived I/O

Megatron Deepspeed: Characterization and Analysis (DFTracer + WisIO)

WisIO

APP I/O Characteristics

App Time   Runtime: 9773.62 seconds (100%)
            ── Application I/O Time: 4424.42 seconds (45.27%)
            ── Checkpoint I/O Time: 4405.64 seconds (45.08%)
            ── Compute Time: 7345.04 seconds (75.15%)
            ── I/O Time: 2218.73 seconds (22.70%)
            ── Read I/O Time: 29.65 seconds (0.30%)
            ── Time: 23268.77 seconds (238.08%)
            ── Unoverlapped Application I/O Time: 3162.50 seconds (32.36%)
            ── Unoverlapped Checkpoint I/O Time: 3162.50 seconds (32.36%)
            ── Unoverlapped Compute Time: 5934.06 seconds (60.72%)
            ── Unoverlapped I/O Time: 807.75 seconds (8.26%)
            ── Unoverlapped Read I/O Time: 0.00 seconds (0.00%)
            ── Unoverlapped Application Compute Time: 6083.12 seconds (62.24%)

Look at workloads with different lenses.

Details Characterization and Analysis with SCR (DFTracer + WisIO)

```
┌─────────────────────── POSIX I/O Characteristics ───────────────────────┐
│                                                                          │
│ Runtime                  8428.34 seconds                                 │
│ Unoverlapped I/O Time    81.50 seconds (100%)                            │
│                          ├── Read: 3.27 seconds (4.02%)                  │
│                          ├── Write: 40.36 seconds (49.52%)               │
│                          └── Metadata: 22.56 seconds (27.68%)            │
│                                                                          │
│ Unoverlapped I/O Ops.    16,543,145 ops                                  │
│                          ├── Read - 1,224,090 ops (7.40%)                │
│                          ├── Write - 73,755 ops (0.45%)                  │
│                          └── Metadata - 13,926,874 ops (84.19%)          │
│                                                                          │
│ Unoverlapped I/O Size    4.20 TiB                                        │
│                          ├── Read - 6.47 GiB (0.15%)                     │
│                          └── Write - 4.20 TiB (99.85%)                   │
│                                                                          │
│ Read Requests            4 kiB→64 MiB - 1,224,090 ops                    │
│                          ├── 16-64 MiB: 177,796 ops (14.52%)             │
│                          ├── >64 MiB: 1,037,568 ops (84.76%)             │
│                          └── [Others: 8,726 ops (0.71%)]                 │
│                                                                          │
│ Write Requests           4 kiB→64 MiB - 73,755 ops                       │
│                          ├── 4-16 MiB: 13,701 ops (18.58%)               │
│                          ├── >64 MiB: 59,919 ops (81.24%)                │
│                          └── [Others: 135 ops (0.18%)]                   │
│                                                                          │
│ Time Periods             10 time periods (Time Granularity: 65.00 seconds) │
│ Access Pattern           Sequential: 1,297,845 ops (100.00%) - Random: 0 ops (0.00%) │
│                                                                          │
└─ R: Read - W: Write - M: Metadata ──────────────────────────────────────┘
```

Details Characterization and Analysis with SCR (DFTracer + WisIO)

Megatron Deepspeed (DFTracer + DFAnalyzer)

Allocation
```
Scheduler Allocation Details
├── Nodes: 16
├── Processes: 256
├── Thread allocations across nodes (includes d
│   ├── Compute: 128
│   └── I/O: 31067
└── Events Recorded: 135M
```

Dataset
```
Description of Dataset Used
└── Files: 484081
```

I/O Behavior
```
Behavior of Application
└── Split of Time in application
    ├── Total Time: 9773.622 sec
    ├── Overall App Level I/O: 4514.237 sec
    ├── Unoverlapped App I/O: 3659.268 sec
    ├── Unoverlapped App Compute: 6487.549 sec
    ├── Compute: 7342.518 sec
    ├── Overall I/O: 2338.010 sec
    ├── Unoverlapped I/O: 1035.517 sec
    └── Unoverlapped Compute: 6040.025 sec
```

- Checkpointing + Reading (App I/O)
- Overlapped I/O is Reading uses MMap
  - We cannot see kernel's page faults
- Checkpointing is Unoverlapped
  - It is synchronous wrt the computation.

Megatron Deepspeed w/wo SCR (WisIO)

Reduced overall runtime is a result
of increasing overlap between
checkpoint I/O and Computation

```
Runtime    8428.34 seconds
App Time   App Time Breakdown
          ├── Compute Time: 7327.39 seconds (86.94%)
          ├── I/O Time: 938.97 seconds (11.14%)
          ├── Application I/O Time: 1487.00 seconds (17.64%)
          ├── Read I/O Time: 1.69 seconds (0.02%)
          ├── Checkpoint I/O Time: 1485.76 seconds (17.63%)
          ├── Unoverlapped Application Compute Time: 6137.71 seconds (72.82%)
          ├── Unoverlapped Application I/O Time: 297.31 seconds (3.53%)
          ├── Unoverlapped Compute Time: 6469.93 seconds (76.76%)
          ├── Unoverlapped I/O Time: 81.50 seconds (0.97%)
          ├── Unoverlapped Checkpoint I/O Time: 297.31 seconds (3.53%)
          └── Unoverlapped Read I/O Time: 0.00 seconds (0.00%)
```

```
Runtime    9773.62 seconds
App Time   App Time Breakdown
          ├── Compute Time: 7345.04 seconds (75.15%)
          ├── I/O Time: 2218.73 seconds (22.70%)
          ├── Application I/O Time: 4424.42 seconds (45.27%)
          ├── Read I/O Time: 29.65 seconds (0.30%)
          ├── Checkpoint I/O Time: 4405.64 seconds (45.08%)
          ├── Unoverlapped Application Compute Time: 6083.12 seconds (62.24%)
          ├── Unoverlapped Application I/O Time: 3162.50 seconds (32.36%)
          ├── Unoverlapped Compute Time: 5934.06 seconds (60.72%)
          ├── Unoverlapped I/O Time: 807.75 seconds (8.26%)
          ├── Unoverlapped Checkpoint I/O Time: 3162.50 seconds (32.36%)
          └── Unoverlapped Read I/O Time: 0.00 seconds (0.00%)
```

Megatron Deepspeed with SCR

```
Allocation    Scheduler Allocation Details
              ├── Nodes: 16
              ├── Processes: 256
              ├── Thread allocations across nodes (includes dy
              │   ├── Compute: 128
              │   └── I/O: 14784
              └── Events Recorded: 64M
Dataset       Description of Dataset Used
              └── Files: 462527
I/O Behavior  Behavior of Application
              ├── Split of Time in application
              │   ├── Total Time: 8641.546 sec
              │   ├── Overall App Level I/O: 1932.854 sec
              │   ├── Unoverlapped App I/O: 993.126 sec
              │   ├── Unoverlapped App Compute: 6392.047 sec
              │   ├── Compute: 7331.776 sec
              │   ├── Overall I/O: 1529.879 sec
              │   ├── Unoverlapped I/O: 445.952 sec
              │   └── Unoverlapped Compute: 6247.848 sec
```

- Performs more I/O first to SSD then async to PFS
- Improves overall time by 1132 secs.
- 2x speed up on Checkpointing
- Improved overlapping: from 20% to 50%.