Data Models and I/O

ATPESC 2018

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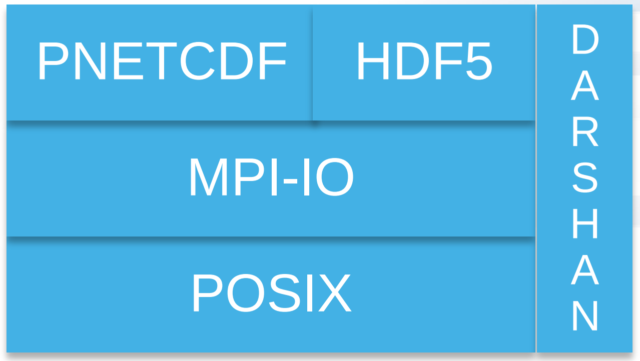
Plan of attack

- Bottom-up tour of I/O interfaces
  - POSIX routines called by MPI-IO implementations
  - Parallel-NetCDF routines build on top of MPI-IO
- Simple toy programs
  - Refining example several times throughout day
  - We can apply these lessons to your own code in evening session
- Demonstrating some tools for understanding what's going on
- "Game of Life" for your reference

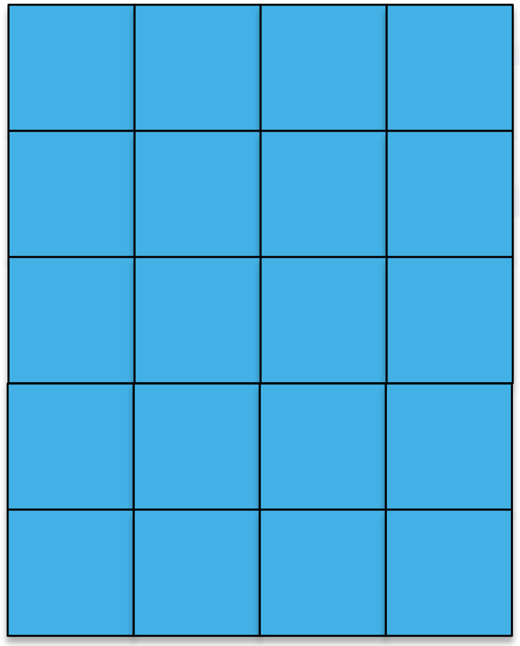


Hands on materials

- Code for this …
  - Simple array I/O
- … and other sections available on our gitlab site:
  - Game of Life I/O
  - Darshan
  - Burst buffers
  - Globus
- https://xgitlab.cels.anl.gov/ATPESC-IO/hands-on
- I’m going to give you a few minutes to try each hands-on. Can continue working in evening session if you need more time.

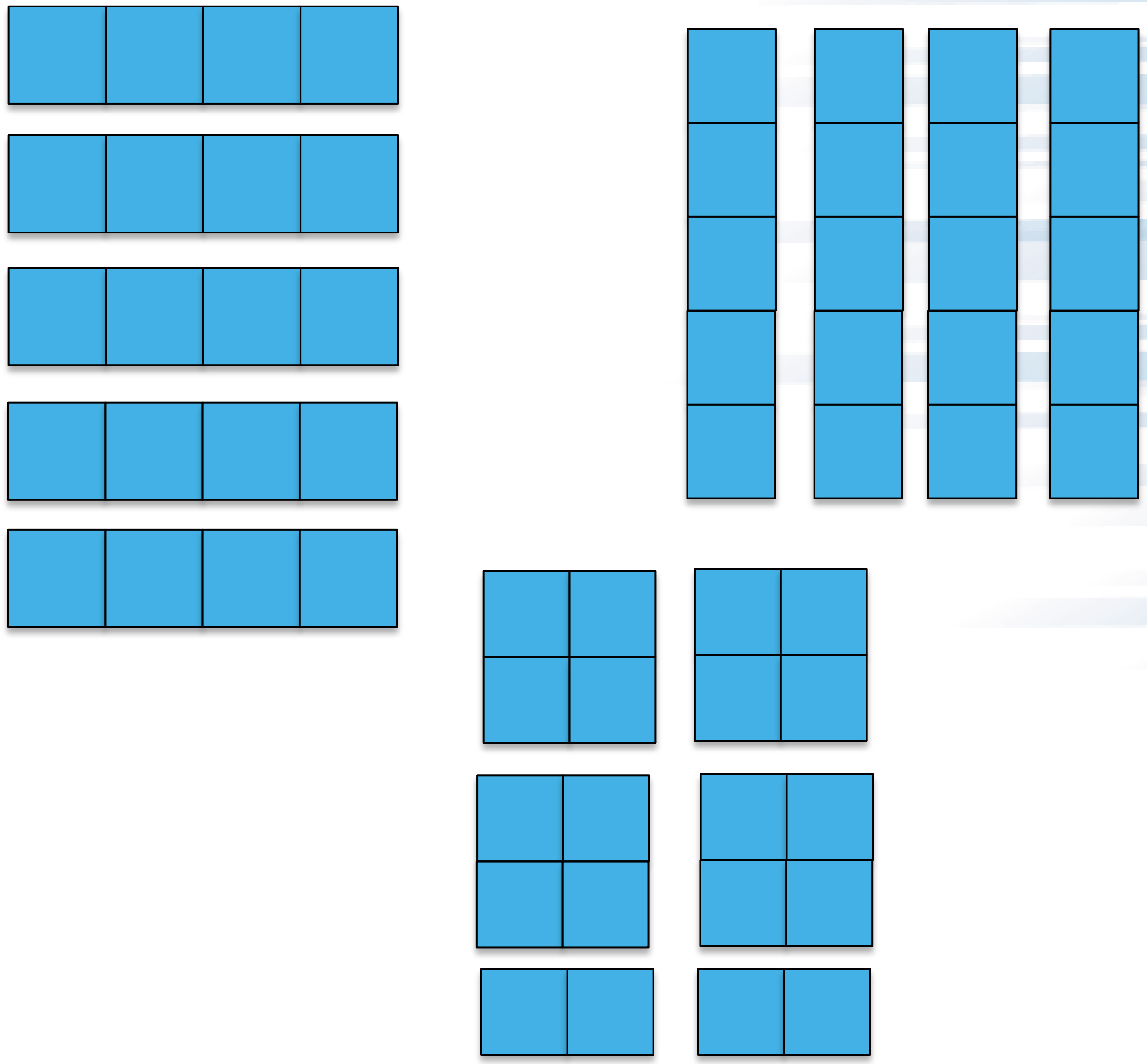
Operating on Arrays

- Arrays show up in many scientific applications
  - Matrix operations
  - Particle maps
  - Regions of space
  - Time series
  - Images
- Probably your real application more complicated but an array or two (or more) is in there somewhere, I'd wager.



Decomposition

- How do we physically access locally parts of a logically larger distributed array in parallel…
  - Piecewise?
  - Chunks?
  - Rows?
- Largely dictated by application algorithm needs
  - E.g. volume rendering math requires chunks not rows.
- Choice impacts memory and I/O performance



Supporting Checkpoint/Restart

- For long-running applications, the cautious user checkpoints
- Application-level checkpoint involves the application saving its own state
  - With a bit of extra effort, can be portable
- A canonical representation is preferred
  - Independent of number of processes
- Restarting is then possible
  - Canonical representation aids restarting with a different number of processes
- Also eases data analysis (when using same output)

Defining a Checkpoint

- Need enough to restart
  - Header information
    - Size of problem (e.g. matrix dimensions)
    - Description of environment (e.g. input parameters)
  - Program state
    - Should represent the global (canonical) view of the data
- Ideally stored in a convenient container
  - Single “thing” (file, object, keyval store...)
- If all processes checkpoint at once, naturally a parallel, collective operation

HANDS-ON 1: simple data descriptions

- Consider an application that operates on a 2-d array of integers.
  1. Write code declaring a 2-d array of integers
     - Probably want to allocate on heap, not stack
     - Later steps will be easier if you make it a single allocation
  2. Define a data structure describing the experiment
     - E.g. C struct with row, column, iteration
- Use whatever language you like…
  - … but Phil and I can only be helpful if you use C
- Source "`setup-env.sh`" to load necessary modules

HANDS-ON 1 solutions

C struct holding metadata

```
typedef struct {
    int row;
    int col;
    int iter;
} science;
```

Do this: index into a single big allocation

```
int *array;
array = malloc(XDIM*YDIM*sizeof(*array));
```

Don't do this: N allocations will be slower and harder to describe

```
/* not MPI-friendly: describing this memory region will require
 * a more complicated data type description */
int **annoying;
annoying = malloc(YDIM*sizeof(*array));
for (int i=0; i<YDIM; i++)
     annoying[i] = malloc(XDIM*sizeof(*array));
```

POSIX I/O

- POSIX is the IEEE Portable Operating System Interface for Computing Environments
- “POSIX defines a standard way for an application program to obtain basic services from the operating system”
  - Mechanism almost all serial applications use to perform I/O
- POSIX was created when a single computer owned its own file system

Deficiencies in serial interfaces

POSIX:

```
fd = open("some_file", O_WRONLY|O_CREAT,
 S_IRUSR|S_IWUSR);
ret = write(fd, w_data, nbytes);
ret = lseek(fd, 0, SEEK_SET);
ret = read(fd, r_data, nbytes);
ret = close(fd);
```

FORTRAN:

```
OPEN(10, FILE='some_file',  &
    STATUS="replace", &
   ACCESS="direct", RECL=16);
WRITE(10, REC=2) 15324
CLOSE(10);
```

- Typical (serial) I/O calls seen in applications
- No notion of other processors
- Primitive (if any) data description methods
- Tuning limited to open flags
- No mechanism for data portability
  - Fortran not even portable between compilers

HANDS-ON 2: simple I/O

- We haven't talked about MPI-IO or I/O libraries, but we can still checkpoint.
  - Serial I/O, not parallel
- Implement "write_data"
  - Will create file and fill in data
  - Prototype:
    - `int write_data(char *filename)`
  - Use system calls (`open()`, `write()`, `close()`) , not "stdio" calls (`fopen()`, `fwrite()`, `fclose()`): will map more closely to MPI-IO later
  - How will you know it worked?
  - We are going to repeatedly revise "write_data" (and later "read_data") with each exercise
    - Software engineering: hide details

RUNNING

- Submit to the ‘training’ queue
- I’ve provided a ‘submit.sh’ shell script
  - `qsub -q training submit.sh <program> [filename]`
    - If you don’t give [filename], then ‘testfile’ used.
- Which Theta file system to use?
  - Tried to make scripts do right thing by default
  - Please don’t use the NFS-mounted home directory
  - `submit.sh` should already point you to the right lustre directory

Solution fragments:

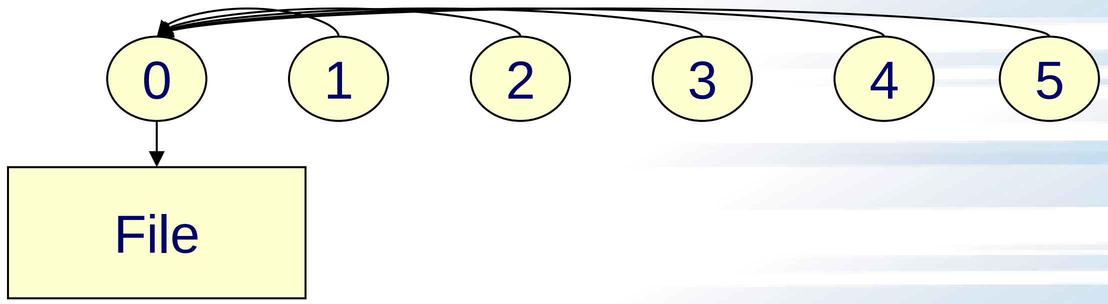
```
int write_data(char *filename)
{
    science data = {
        .row = YDIM,
        .col = XDIM,
        .iter = 1
    };

    int *array;
    int fd;
    int ret=0;

    array = buffer_create(0, XDIM, YDIM);

    fd = open(filename, O_CREAT|O_WRONLY,
         S_IRUSR|S_IWUSR);
    ret = write(fd, &data, sizeof(data));
    ret = write(fd, array, XDIM*YDIM*sizeof(int));
    ret = close(fd);

    return ret;
}
```

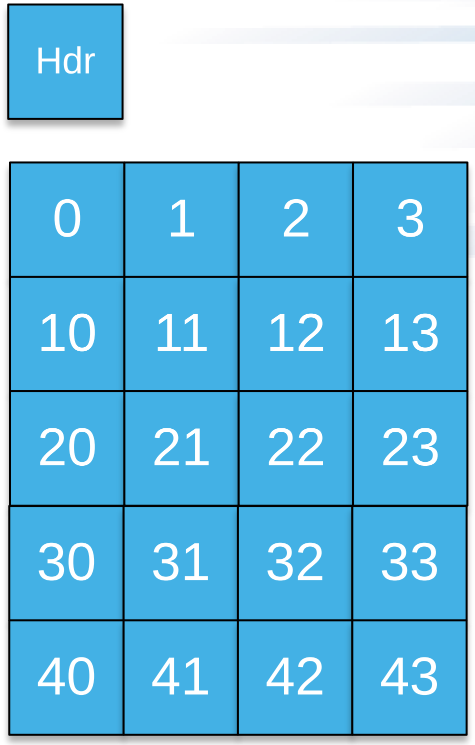
Reading a binary file: “cat” won’t work. Could write a c program to read. Several utilities available. I like ‘od’: historically it only did an “octal dump”. The (t)ype argument can select (d)ecimal

```
% od -td testfile
0000000           1           5           1           0
0000020           1           2           3           4
0000040
```

HANDS-ON 3: send-to-master

- Parallel program, but serial I/O
  1. `Write_data()` should take an MPI Communicator
  2. Call MPI_Init() and MPI_Finalize()
  3. Use MPI_Gather to collect all data onto rank 0:
- Only rank 0 does I/O; writes header and all array information
- What's good about send-to-master? What's bad?





Solution fragments: MPI_Gather, write larger data from rank 0

```
MPI_Comm_rank(comm, &rank);
MPI_Comm_size(comm, &nprocs);
/* every process creates its own buffer */
array = buffer_create(rank, XDIM, YDIM);

/* and then sends it to rank 0  */
int *buffer =
  malloc(XDIM*YDIM*nprocs*sizeof(int));

MPI_CHECK(MPI_Gather(
    /* sender (buffer,count,type) tuple */
    array, XDIM*YDIM, MPI_INT,
    /* receiver tuple */
    buffer, XDIM*YDIM, MPI_INT,
/* who gathers and across which context */
           0, comm));
```

Solution fragments: writing from rank 0

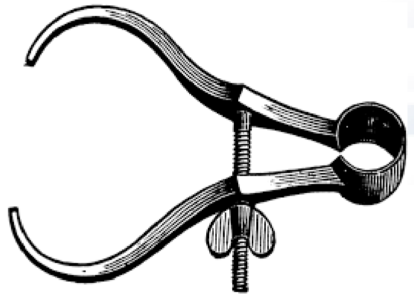
```
if (rank == 0) {
/* looks like serial with more data */
…
/* writing a global array, not just our
local piece of it */
    data.row = YDIM*nprocs;
    data.col = XDIM;
    data.iter = 1;

    ret = write(fd, &data, sizeof(data));
    ret = write(fd, buffer,
          XDIM*YDIM*nprocs*sizeof(int));

    ret = close(fd);
    return ret;
}
```

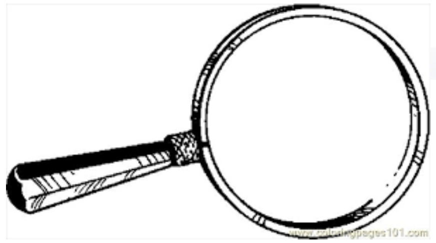
Other questions:

- Lots of machines (your laptop; Theta) represent integers as 32 bit little endian. What if you ran this code on Mira?
- We wrote row-wise. What if you wanted to write a column of data?
- What impact would a header have on data layout? Are there other options?

Understanding I/O

- **Instrumentation**:
  - What do we measure?
  - How much overhead is acceptable and when?
- **Analysis**:
  - How do we correlate data and extract actionable information?
  - Can we identify the root cause of performance problems?
- **Impact:**
  - Develop best practices and tune applications
  - Improve system software
  - Design and procure better systems





What is Darshan?

Project began in 2008, first public software release and deployment in 2009

Darshan is a scalable HPC I/O characterization tool. It captures an accurate but concise picture of ***application*** I/O behavior with minimum overhead.

- No code changes, easy to use
  - Negligible performance impact: just “leave it on”
  - Enabled by default at ALCF, NERSC, NCSA, and KAUST
  - Installed and available for case by case use at many other sites
- Produces a ***summary*** of I/O activity for each job, including:
  - Counters for file access operations
  - Time stamps and cumulative timers for key operations
  - Histograms of access, stride, datatype, and extent sizes

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Darshan design principles

- The Darshan run time library is inserted at link time (for static executables) or at run time (for dynamic executables)
- Transparent wrappers for I/O functions collect per-file statistics
- Statistics are stored in bounded memory at each rank
- At shutdown time:
  - Collective reduction to merge shared file records
  - Parallel compression
  - Collective write to a single log file
- No communication or storage operations until shutdown
- Command-line tools are used to post-process log files

JOB analysis example

Example: Darshan-job-summary.pl produces a 3-page PDF file summarizing various aspects of I/O performance

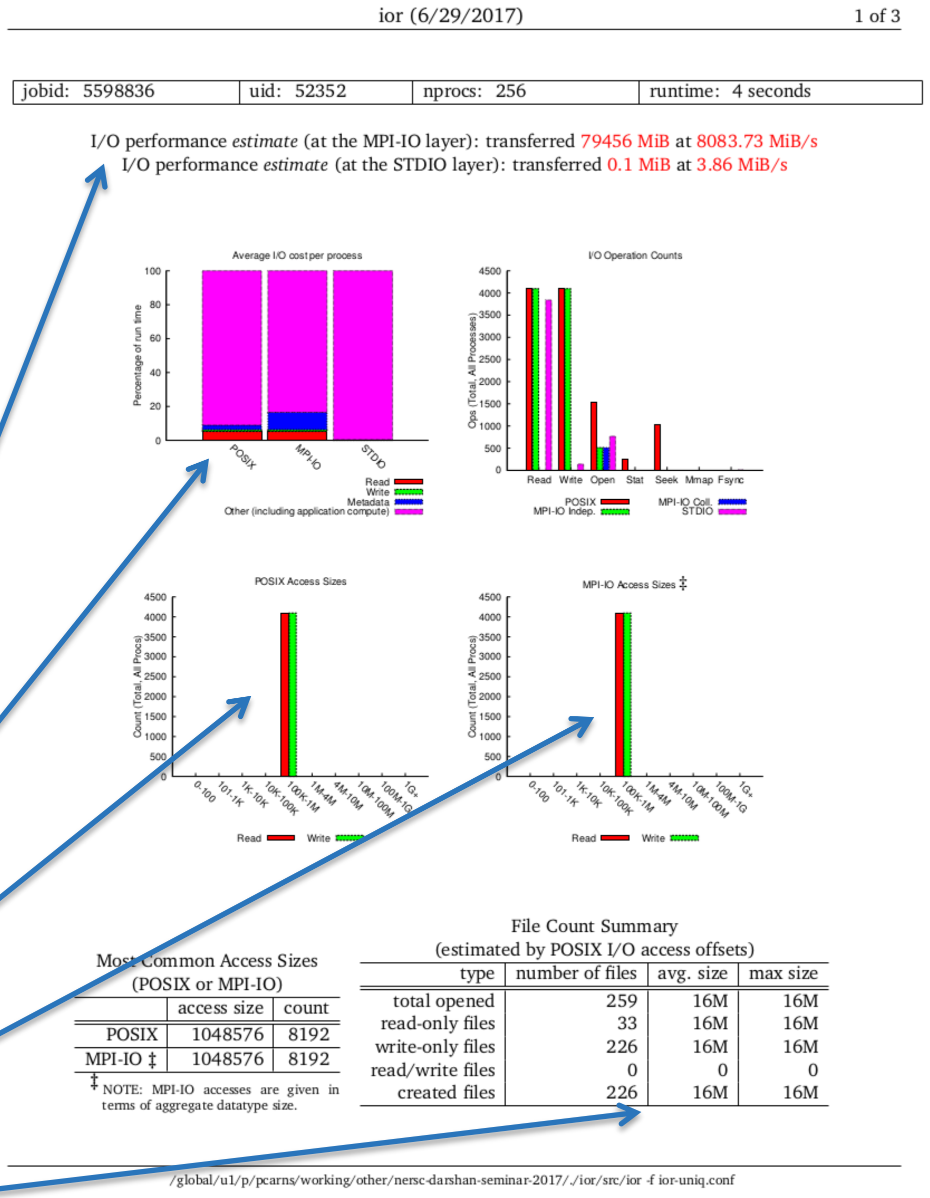
Estimated performance

Percentage of runtime in I/O

Access size histogram

Access type histograms

File usage



ior (6/29/2017) 1 of 3

jobid: 5598836	uid: 52352	nprocs: 256	runtime: 4 seconds

I/O performance *estimate* (at the MPI-IO layer): transferred 79456 MiB at 8083.73 MiB/s
I/O performance *estimate* (at the STDIO layer): transferred 0.1 MiB at 3.86 MiB/s

Average I/O cost per process
Percentage of run time
POSIX
MPI-IO
STDIO
Read
Write
Metadata
Other (including application compute)
I/O Operation Counts
Ops (Total, All Processes)
Read Write Open Stat Seek Mmap Fsync
POSIX
MPI-IO Indep.
MPI-IO Coll.
STDIO
POSIX Access Sizes
MPI-IO Access Sizes ‡
Count (Total, All Procs)
0-100 101-1K 1K-10K 10K-100K 100K-1M 1M-4M 4M-10M 10M-100M 100M-1G 1G+
Read
Write

Most Common Access Sizes
(POSIX or MPI-IO)

	access size	count
POSIX	1048576	8192
MPI-IO ‡	1048576	8192

‡ NOTE: MPI-IO accesses are given in terms of aggregate datatype size.

File Count Summary
(estimated by POSIX I/O access offsets)

type	number of files	avg. size	max size
total opened	259	16M	16M
read-only files	33	16M	16M
write-only files	226	16M	16M
read/write files	0	0	0
created files	226	16M	16M

/global/u1/p/pcarns/working/other/nersc-darshan-seminar-2017/./ior/src/ior -f ior-uniq.conf

SYSTEM analysis example

- With a sufficient archive of performance statistics, we can develop heuristics to detect anomalous behavior

Example of heuristics applied to a population of production jobs on the Hopper system in 2013:

- This example highlights large jobs that spent a disproportionate amount of time managing file metadata rather than performing raw data transfer
- Worst offender spent 99% of I/O time in open/close/stat/seek
- This identification process is not yet automated; alerts/triggers are needed in future work for greater impact

JOBS IDENTIFIED USING METADATA RATIO METRIC

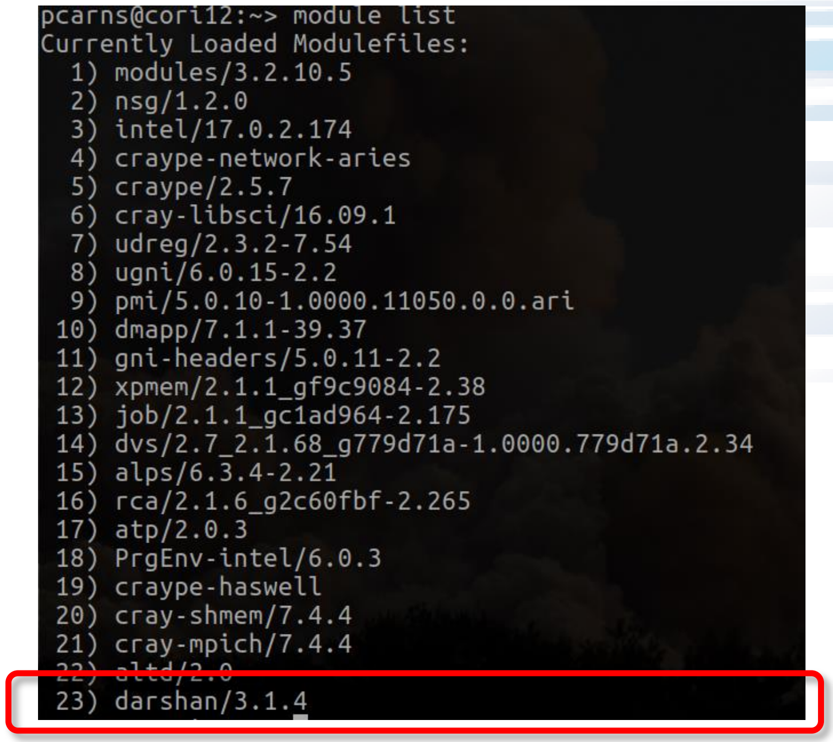
Thresholds	meta_time / nprocs $>$ 30 s
	nprocs $\geq$ 192
	metadata_ratio $\geq$ 25%
Total jobs analyzed	261,890
Jobs matching metric	252
Unique users matching metric	45
Largest single-job metadata ratio	$>$ 99%

$$\frac{\sum_{n=1}^{nfiles} metadata\_time}{\sum_{n=1}^{nfiles} metadata\_time + IO\_time}$$

Carns et al., “Production I/O Characterization on the Cray XE6,” In Proceedings of the Cray User Group meeting 2013 (CUG 2013).

Typical deployment and usage

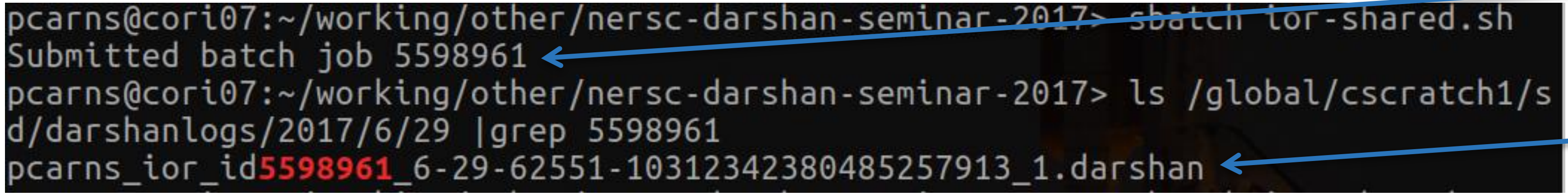
- Darshan usage on Mira, Cetus, Vesta, Theta, Cori, or Edison, abridged:
  - Run your job
  - If the job calls MPI_Finalize(), log will be stored in DARSHAN_LOG_DIR/**month**/**day**/
    - If your job does not call MPI_Finalize, you cannot use Darshan. Check out Tau.
  - Theta: /lus/theta-fs0/logs/darshan/theta
  - Use tools (next slides) to interpret log
- On Titan: “module load darshan” first
- More details:
  - https://www.alcf.anl.gov/user-guides/darshan
  - www.nersc.gov/users/software/performance-and-debugging-tools/darshan/



```
pcarns@cori12:~> module list
Currently Loaded Modulefiles:
  1) modules/3.2.10.5
  2) nsg/1.2.0
  3) intel/17.0.2.174
  4) craype-network-aries
  5) craype/2.5.7
  6) cray-libsci/16.09.1
  7) udreg/2.3.2-7.54
  8) ugni/6.0.15-2.2
  9) pmi/5.0.10-1.0000.11050.0.0.ari
 10) dmapp/7.1.1-39.37
 11) gni-headers/5.0.11-2.2
 12) xpmem/2.1.1_gf9c9084-2.38
 13) job/2.1.1_gc1ad964-2.175
 14) dvs/2.7_2.1.68_g779d71a-1.0000.779d71a.2.34
 15) alps/6.3.4-2.21
 16) rca/2.1.6_g2c60fbf-2.265
 17) atp/2.0.3
 18) PrgEnv-intel/6.0.3
 19) craype-haswell
 20) cray-shmem/7.4.4
 21) cray-mpich/7.4.4
 22) altd/2.0
 23) darshan/3.1.4
```

Generating job summaries

- Run job and find its log file:

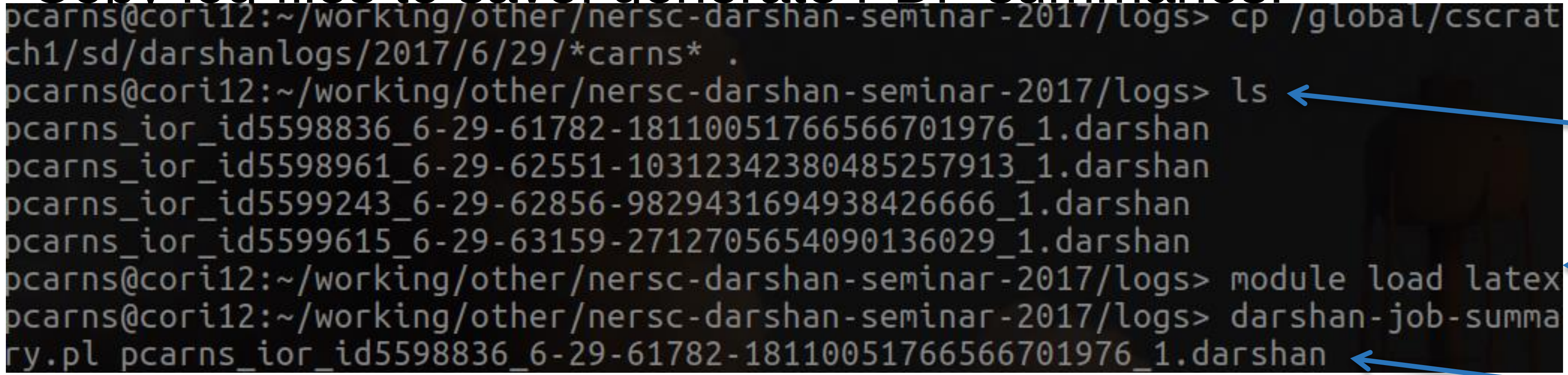


```
pcarns@cori07:~/working/other/nersc-darshan-seminar-2017> sbatch ior-shared.sh
Submitted batch job 5598961
pcarns@cori07:~/working/other/nersc-darshan-seminar-2017> ls /global/cscratch1/s
d/darshanlogs/2017/6/29 |grep 5598961
pcarns_ior_id5598961_6-29-62551-10312342380485257913_1.darshan
```

Job id

Corresponding log file in today's directory

- Copy log files to save, generate PDF summaries:



```
pcarns@cori12:~/working/other/nersc-darshan-seminar-2017/logs> cp /global/cscrat
ch1/sd/darshanlogs/2017/6/29/*carns* .
pcarns@cori12:~/working/other/nersc-darshan-seminar-2017/logs> ls
pcarns_ior_id5598836_6-29-61782-18110051766566701976_1.darshan
pcarns_ior_id5598961_6-29-62551-10312342380485257913_1.darshan
pcarns_ior_id5599243_6-29-62856-9829431694938426666_1.darshan
pcarns_ior_id5599615_6-29-63159-2712705654090136029_1.darshan
pcarns@cori12:~/working/other/nersc-darshan-seminar-2017/logs> module load latex
pcarns@cori12:~/working/other/nersc-darshan-seminar-2017/logs> darshan-job-summa
ry.pl pcarns_ior_id5598836_6-29-61782-18110051766566701976_1.darshan
```

Copy out logs

List logs

Load "latex" module, (if needed)

Generate PDF

HANDS-ON 4: introduction to Darshan

1. Find the darshan log for the last exercise
2. View the raw counters with “darshan-parser”
3. Generate a report
   - You might have to transfer PDF locally to view
4. Find the darshan log for the exercise #2
   - Hint: you can’t!

I/O benchmarking challenges

- Variability
  - Storage systems shared, mechanical
- Caching
  - Watch out for “speed of light” violations
- Ganging
  - Be sure you are timing what you think you are timing

I/O benchmarking: variability

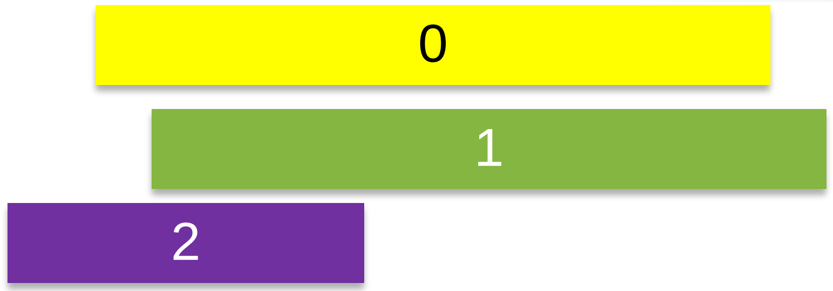
- Silicon (e.g. Read from DRAM, multiply 100 integers) pretty stable
  - E.g. easy to observe register, L1, L2, memory, swap behavior
- Write to disk… less stable
  - How many users are also writing? How full is disk?
- I/O experiments cannot be short, one-offs
  - Ideal: run each experiment cfg a dozen times, sized to run for about a minute
  - Reality: supercomputer time is precious
- Try out the `variance` example in hands-on repository

I/O benchmarking: caching

- Caching at every layer of storage
  - Disk drive, Raid controller, Server RAM, Compute node SSD
- Storage expensive; vendors don’t give stuff away
  - If spec says “240 GB/sec”, you ain’t getting 250 GB/sec

I/O benchmarking: ganging

- Fast-finisher problem
  - Maybe a caching or aggregation layer resulted in less work for one process
- Staggered-start problem
  - Probably want all processes writing/reading at once
- `variance` code example
  - MPI_Barrier() before timing
  - MPI_Reduce() to find maximum time

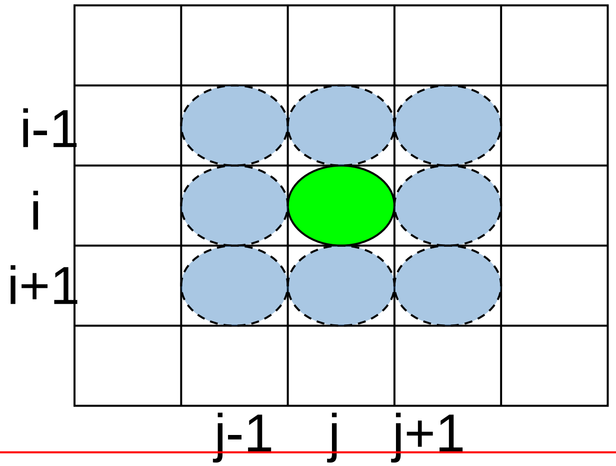


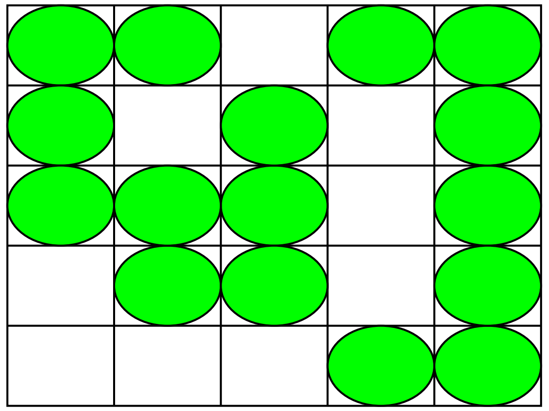
Bonus topic: “Game of Life” I/O

- Next stepping stone between toy array i/o and full application
- More sophisticated use of MPI datatypes, communication
  - “ghost cell” optimization heavily used in nearest-neighbor pattern
- Using “duplicated communicator” to separate library, application communication
- Also demonstrates a way to link different approaches

Rules for Life (you've probably seen this before)

- Matrix values A(i,j) initialized to 1 (live) or 0 (dead)
- In each iteration, A(i,j) is set to
  - 1 (live) if either
    - the sum of the values of its 8 neighbors is 3, or
    - the value was already 1 and the sum of its 8 neighbors is 2 or 3
  - 0 (dead) otherwise



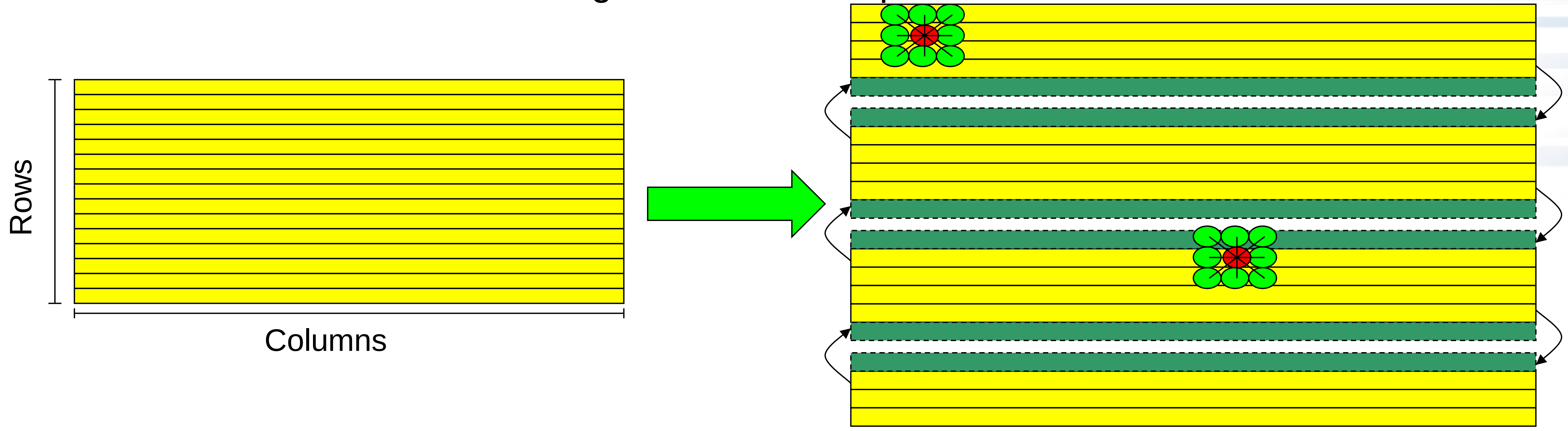


All code examples in this tutorial can be found in hands-on repo:

xgitlab.cels.anl.gov/ATPESC-IO/hands-on

Decomposition and Boundary Regions

- Decompose 2d array into rows, shared across processes
- In order to calculate next state of cells in edge rows, need data from adjacent rows
- Need to communicate these regions at each step



Life Checkpoint/Restart API

- Define an interface for checkpoint/restart for the row-block distributed Life code
- Five functions:
  - MLIFEIO_Init
  - MLIFEIO_Finalize
  - MLIFEIO_Checkpoint
  - MLIFEIO_Can_restart
  - MLIFEIO_Restart
- All functions are collective
  - i.e., all processes must make the call

- We can implement API for different back-end formats
  - Insulate main code from I/O details:
  - back-end also makes good spot for tuning

Life Checkpoint

-
  ```
  MLIFEIO_Checkpoint(char     *prefix,
                     int     **matrix,
                     int        rows,
                     int        cols,
                     int        iter,
                     MPI_Info info);
  ```

- Prefix is used to set filename
- Matrix is a reference to the data to store
- Rows, cols, and iter describe the data (header)
- Info is used for tuning purposes

Life stdout “checkpoint”

- The first implementation is one that simply prints out the “checkpoint” in an easy-to-read format
- MPI standard does not specify that all stdout will be collected in any particular way
  - Pass data back to rank 0 for printing
  - Portable!
  - Not scalable, but ok for the purpose of stdio

```
# Iteration 9

 1:    **        **              **              ** *
 2:  * **         * *            * *      ****   *    *    ***    **
 3:   **           **            **     *    *  * **  *         **
 4:               **                   *   * ** ** ***
 5:               * *    **         **  * *  ***  * * *
 6:             *    *   **         *       *  *  ** *
 7:             ***                  *   ** *     ***
 8:       ***  *   ** ***              *    * *****   *** ***
 9:         *** *                     * ** *   ***    ** **
10:       * *  *   *                            ***  * *
11:        *    **         **         **           * *
12:              * **     ****          *   ** ****    *
13:              **       *** * **       *    *** *   *
14:                     *    ** *      *     * ***
15:          ** **        ******         *     *   *
16:           ****       *****      *     *   *
17:     ***     *** *            ***       ****
18:     ***      **  **
19:        *   **         **         *         **            *
20:  *         *         * **       **                      ***
21: * *  * **         *  * * **                  ***         * * **
22: * *   **    *    ****    *         **         *     *    ***  **
23:  *         **    **** ***    ***     *              * *   **    *
24:            ***      *  *          **              *     **** *
25:                    ***           **                     ****
```

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stdio Life Checkpoint Code Walkthrough

- Points to observe:
  - All processes call checkpoint routine
    - Collective I/O from the viewpoint of the program
  - Interface describes the global array
  - Output is independent of the number of processes

See mlife-io-stdout.c pp. 1-3 for code example.

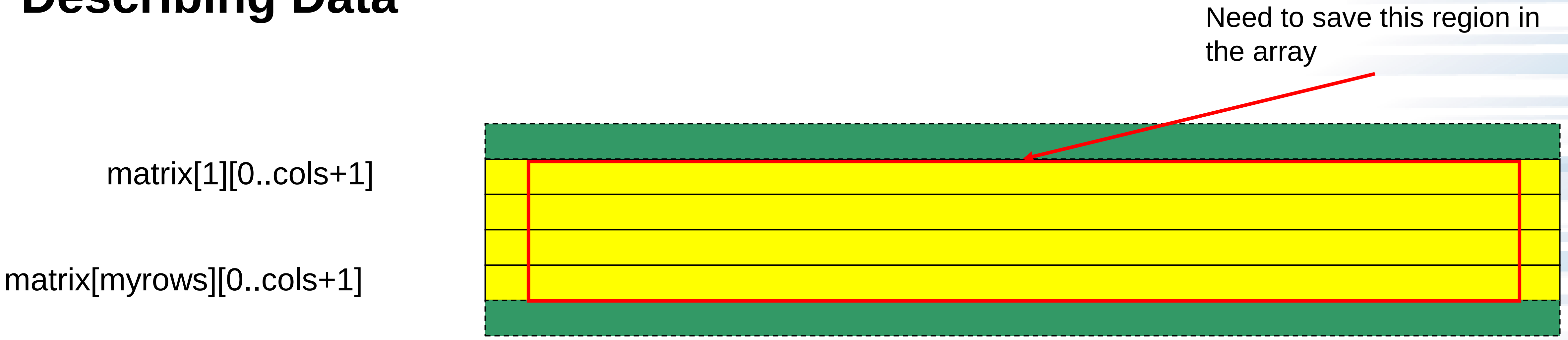
```c
/* SLIDE: stdio Life Checkpoint Code Walkthrough */
/* -*- Mode: C; c-basic-offset:4 ; -*- */
/*
 *   (C) 2004 by University of Chicago.
 *       See COPYRIGHT in top-level directory.
 */

#include <stdio.h>
#include <stdlib.h>
#include <unistd.h>

#include <mpi.h>

#include "mlife.h"
#include "mlife-io.h"

/* stdout implementation of checkpoint (no restart) for MPI Life
 *
 * Data output in matrix order: spaces represent dead cells,
 * '*'s represent live ones.
 */
static int MLIFEIO_Type_create_rowblk(int **matrix, int myrows,
                                      int cols,
                                     MPI_Datatype *newtype);
static void MLIFEIO_Row_print(int *data, int cols, int rownr);
static void MLIFEIO_msleep(int msec);

static MPI_Comm mlifeio_comm = MPI_COMM_NULL;
```

```
/* SLIDE: stdio Life Checkpoint Code Walkthrough */
int MLIFEIO_Init(MPI_Comm comm)
{
    int err;

    err = MPI_Comm_dup(comm, &mlifeio_comm);

    return err;
}

int MLIFEIO_Finalize(void)
{
    int err;

    err = MPI_Comm_free(&mlifeio_comm);

    return err;
}
```

```c
/* SLIDE: Life stdout "checkpoint" */
/* MLIFEIO_Checkpoint
 *
 * Parameters:
 * prefix - prefix of file to hold checkpoint (ignored)
 * matrix - data values
 * rows   - number of rows in matrix
 * cols   - number of columns in matrix
 * iter   - iteration number of checkpoint
 * info   - hints for I/O (ignored)
 *
 * Returns MPI_SUCCESS on success, MPI error code on error.
 */
int MLIFEIO_Checkpoint(char *prefix, int **matrix, int rows,
                       int cols, int iter, MPI_Info info)
{
    int err = MPI_SUCCESS, rank, nprocs, myrows, myoffset;
    MPI_Datatype type;

    MPI_Comm_size(mlifeio_comm, &nprocs);
    MPI_Comm_rank(mlifeio_comm, &rank);

    myrows   = MLIFE_myrows(rows, rank, nprocs);
    myoffset = MLIFE_myrowoffset(rows, rank, nprocs);

```

```
/* SLIDE: Describing Data */
    if (rank != 0) {
        /* send all data to rank 0 */

        MLIFEIO_Type_create_rowblk(matrix, myrows, cols, &type);
        MPI_Type_commit(&type);
        err = MPI_Send(MPI_BOTTOM, 1, type, 0, 1, mlifeio_comm);
        MPI_Type_free(&type);
    }
    else {
        int i, procrows, totrows;

        printf("\033[H\033[2J# Iteration %d\n", iter);

        /* print rank 0 data first */
        for (i=1; i < myrows+1; i++) {
            MLIFEIO_Row_print(&matrix[i][1], cols, i);
        }
        totrows = myrows;

/* SLIDE: Describing Data */
        /* receive and print others' data */
        for (i=1; i < nprocs; i++) {
                    int j, *data;

            procrows = MLIFE_myrows(rows, i, nprocs);
            data = (int *) malloc(procrows * cols * sizeof(int));

            err = MPI_Recv(data, procrows * cols, MPI_INT, i, 1,
                           mlifeio_comm, MPI_STATUS_IGNORE);

            for (j=0; j < procrows; j++) {
                MLIFEIO_Row_print(&data[j * cols], cols,
                                  totrows + j + 1);
            }
            totrows += procrows;

            free(data);
        }
    }

    MLIFEIO_msleep(250); /* give time to see the results */

    return err;
}
```

Describing Data


Need to save this region in the array
matrix[1][0..cols+1]
matrix[myrows][0..cols+1]

- Lots of rows, all the same size
  - Rows are all allocated as one big block
  - Perfect for MPI_Type_vector

```
MPI_Type_vector(count = myrows,
   blklen = cols, stride = cols+2, MPI_INT, &vectype);
```

  - Second type gets memory offset right (allowing use of MPI_BOTTOM in MPI_File_write_all)

```
MPI_Type_hindexed(count = 1, len = 1,
   disp = &matrix[1][1], vectype, &type);
```

See mlife-io-stdout.c pp. 4-6 for code example.

File: mlife-io-stdout.c   Page 6 of 8

```c
/* SLIDE: Describing Data */
/* MLIFEIO_Type_create_rowblk
 *
 * Creates a MPI_Datatype describing the block of rows of data
 * for the local process, not including the surrounding boundary
 * cells.
 *
 * Note: This implementation assumes that the data for matrix is
 *       allocated as one large contiguous block!
 */
static int MLIFEIO_Type_create_rowblk(int **matrix, int myrows,
                                      int cols,
                                      MPI_Datatype *newtype)
{
    int err, len;
    MPI_Datatype vectype;
    MPI_Aint disp;

    /* since our data is in one block, access is very regular! */
    err = MPI_Type_vector(myrows, cols, cols+2, MPI_INT,
                          &vectype);
    if (err != MPI_SUCCESS) return err;

    /* wrap the vector in a type starting at the right offset */
    len = 1;
    MPI_Address(&matrix[1][1], &disp);
    err = MPI_Type_hindexed(1, &len, &disp, vectype, newtype);

    MPI_Type_free(&vectype); /* decrement reference count */

    return err;
}

static void MLIFEIO_Row_print(int *data, int cols, int rownr)
{
    int i;

    printf("%3d: ", rownr);
    for (i=0; i < cols; i++) {
        printf("%c", (data[i] == BORN) ? '*' : ' ');
    }
    printf("\n");
}

int MLIFEIO_Can_restart(void)
{
    return 0;
}

int MLIFEIO_Restart(char *prefix, int **matrix, int rows,
                    int cols, int iter, MPI_Info info)
{
    return MPI_ERR_IO;
}
```

EXASCALE COMPUTING PROJECT

Next steps: thinking about I/O interfaces for parallel programming (MPI-IO)