A 1 PB/s File System to Checkpoint Three Million MPI Tasks

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What is checkpointing?
&
Why do we need it?

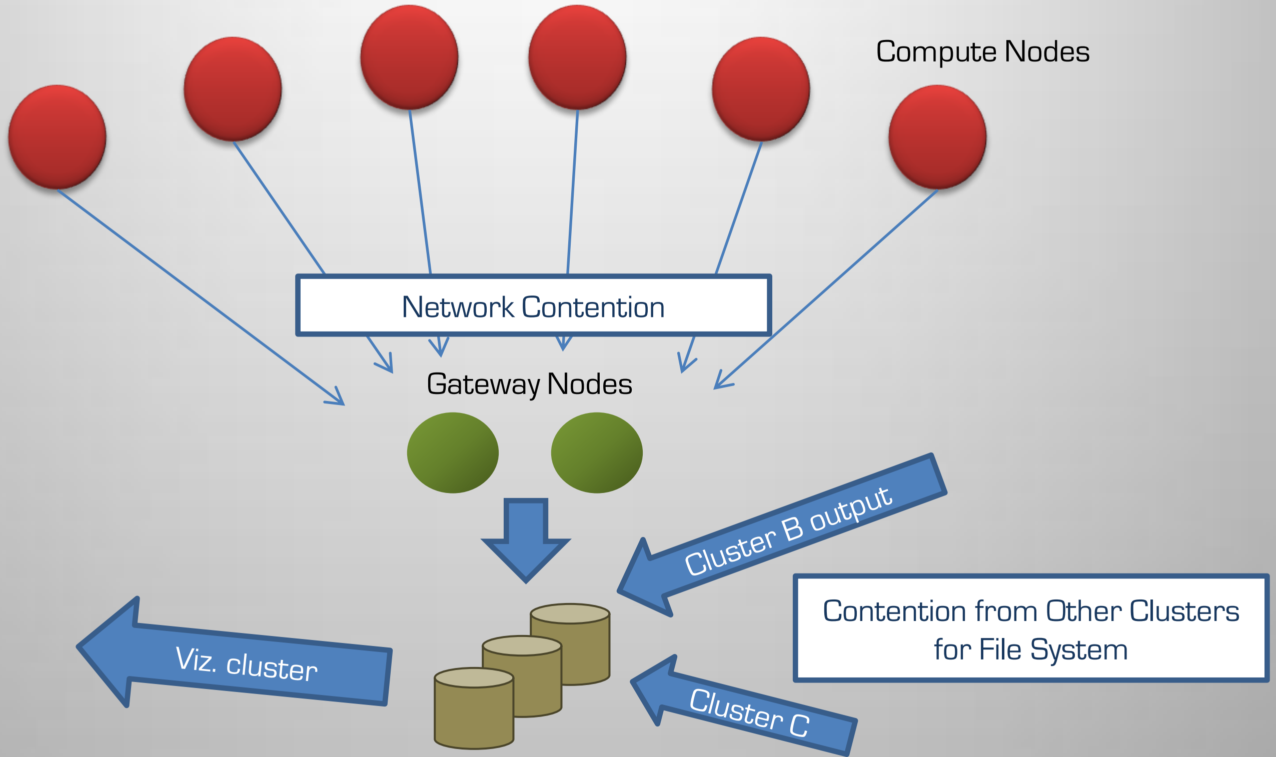
Tolerating failures with Checkpointing

- HPC architectures evolving to accommodate complex apps
  - Multi-core CPUs, GPUs, Xeon Phi, SSDs, Smart NICs…
- Failure is inevitable => Imperative to design fault-resilient systems
- Several tools and techniques are used to tolerate failures
  - Proactive and reactive
- Checkpoint-Restore mechanisms are predominantly used

That's awesome!

But, we have a problem..

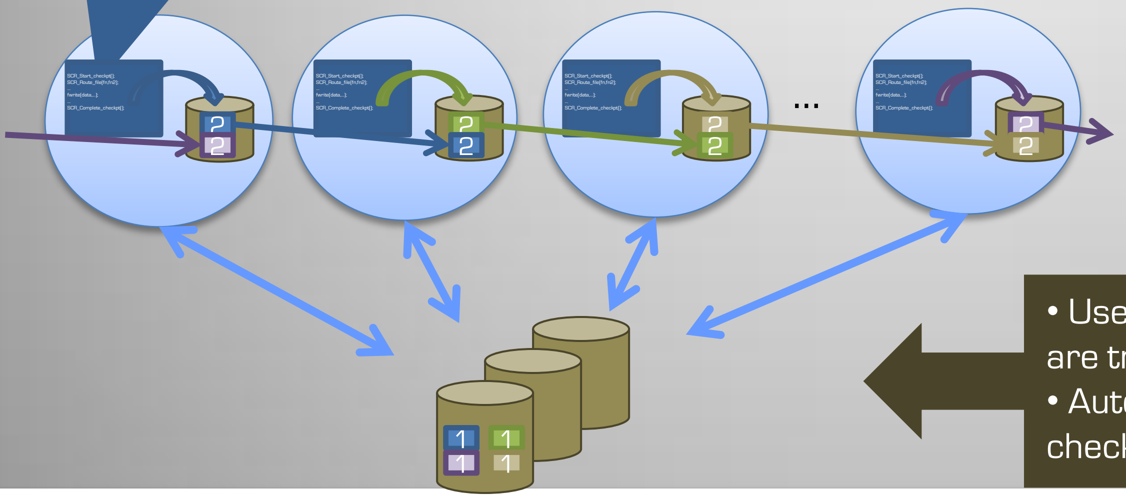
Contention for shared-storage resources



But, we also have a solution..

Scalable Checkpoint/ Restart (SCR)

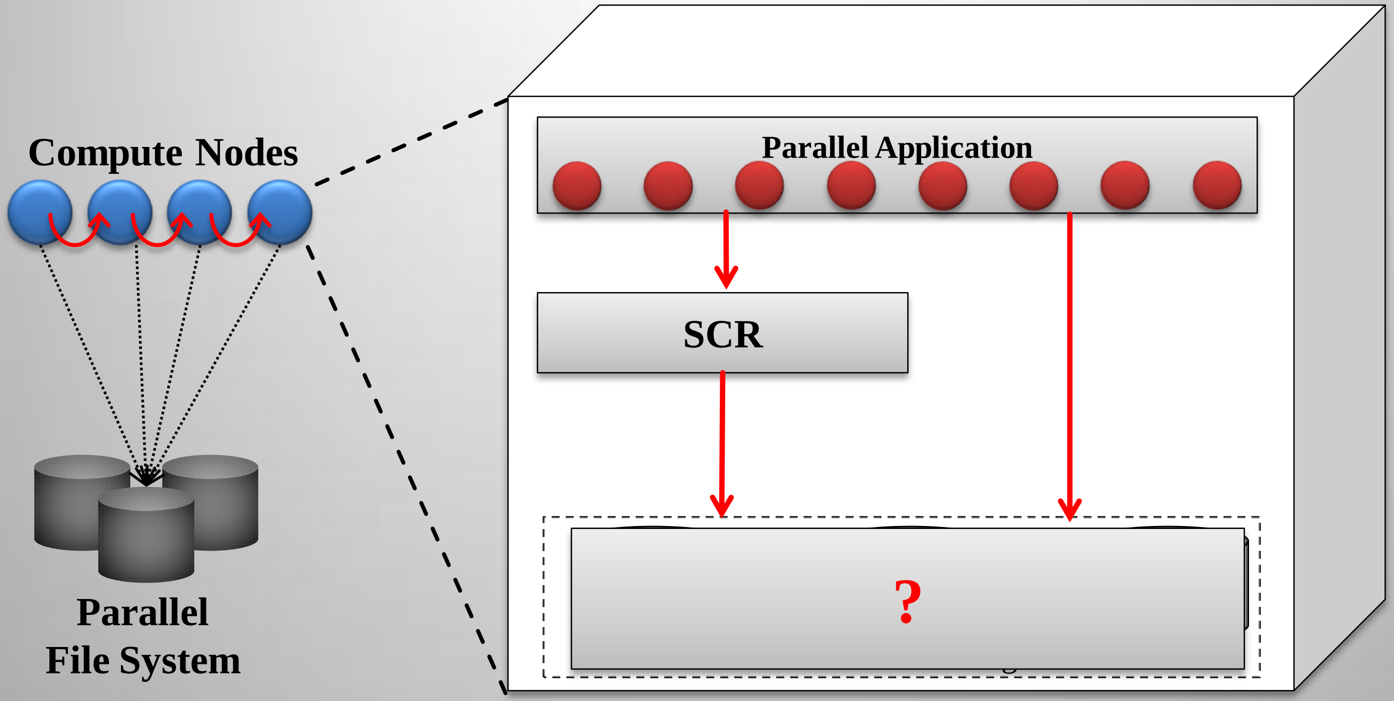
```
SCR_Start_checkpt();
SCR_Route_file(fn,fn2);
…
fwrite(data,…);
…
SCR_Complete_checkpt();
```



- First write checkpoints to node-local storage
- When checkpoint is complete, apply redundancy schemes

- Users select which checkpoints are transferred to global storage
- Automatically drain last checkpoint of the job

Node-local storage with SCR



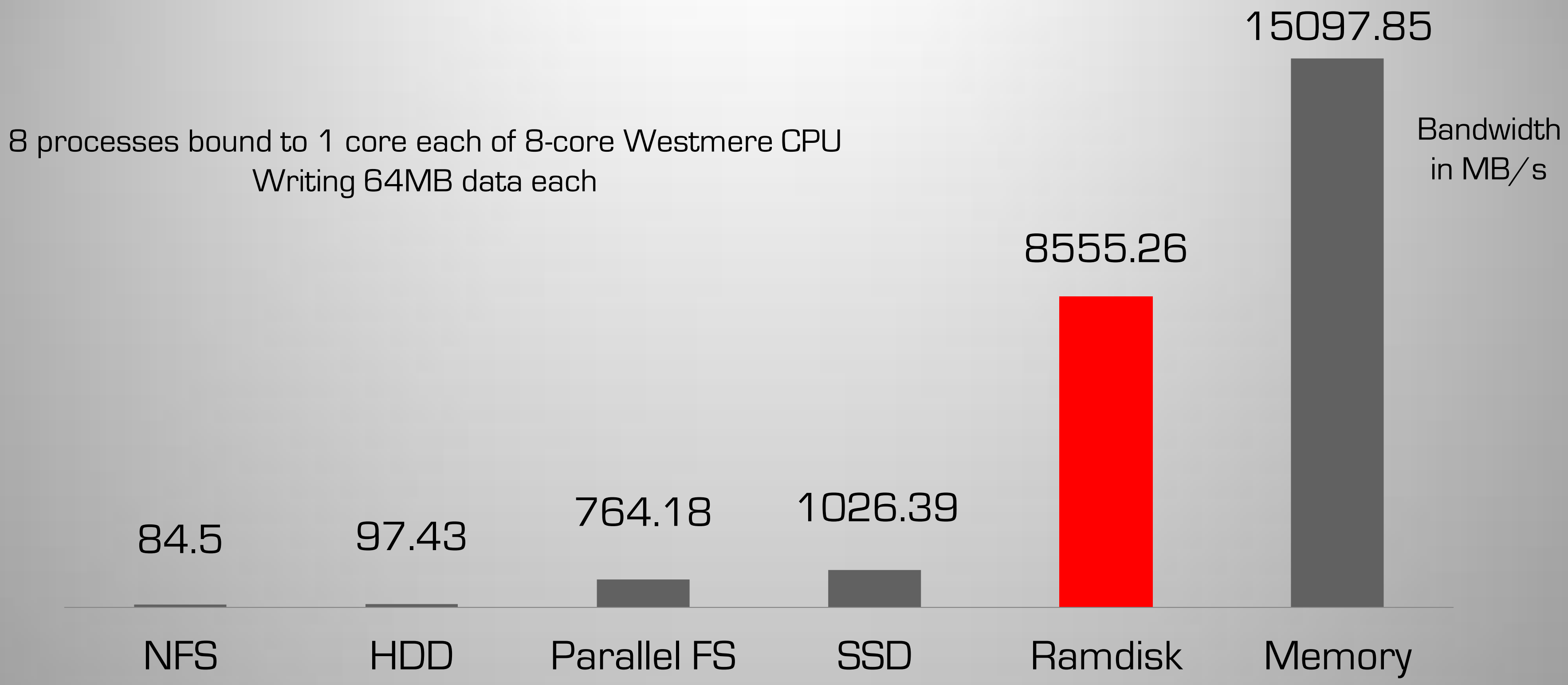
Design Goals

- Large checkpoints -- small memory
- Leverage the node-local storage hierarchy
- Asynchronous copy-out capability
- Portability
- Future-proof
- Improve checkpointing throughput

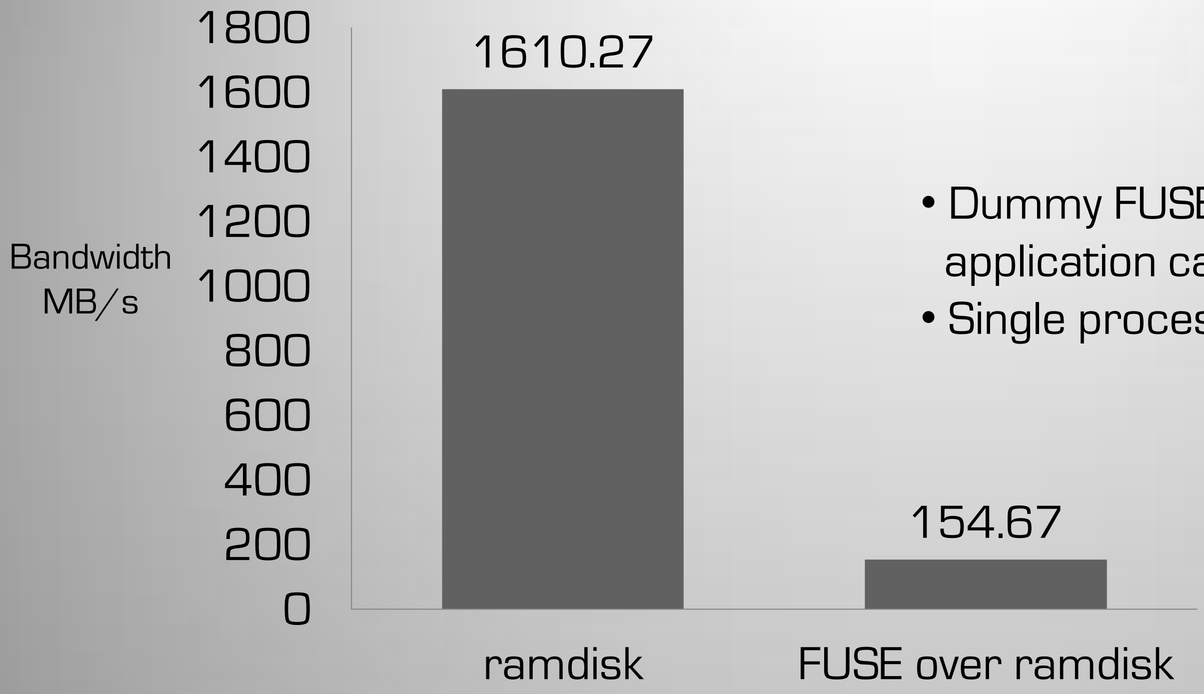
Possible Solutions

- Storage medium for the checkpoint data
  - Use kernel-provided "ramdisk"
  - Write an "in-memory" filesystem backed by an mmap'ed file
  - Just use the kernel buffer-cache
  - Manage System V IPC / Persistent memory segments
- Intercept application I/O
  - Write a FUSE-based file system
  - Trap I/O calls from the application using linker support

Can we not just use the RAM disk?



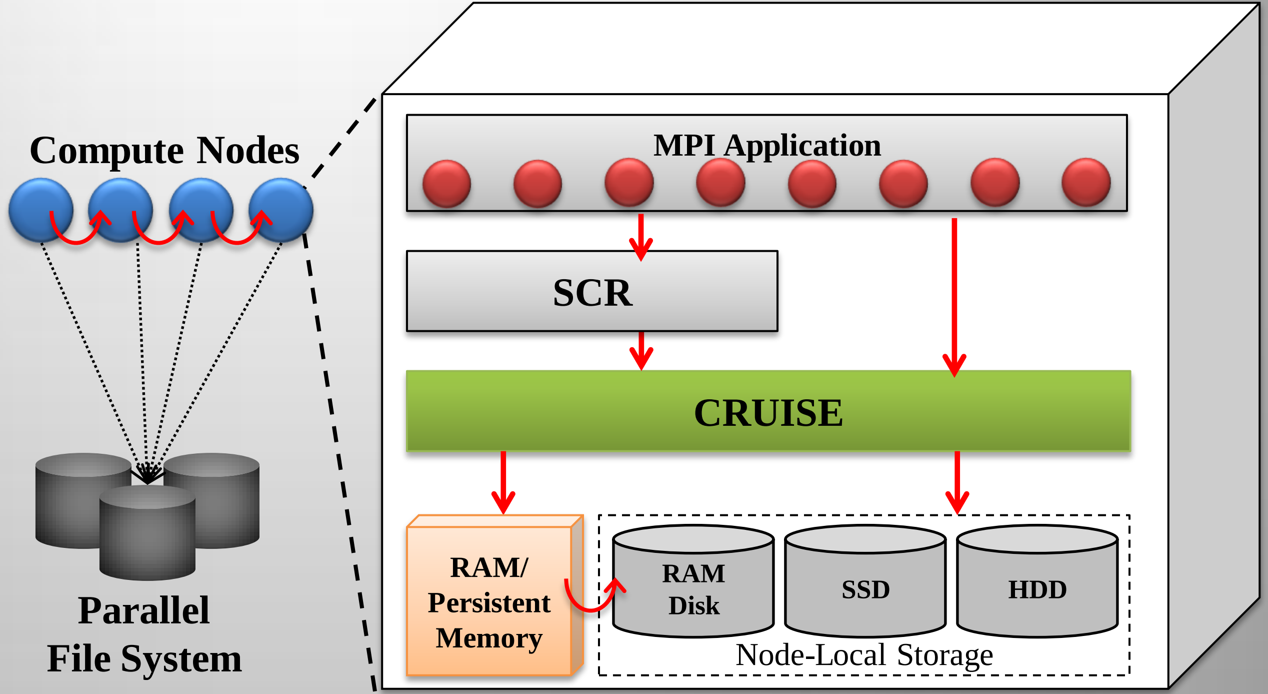
Can we not just write a FUSE file system?



- Dummy FUSE file system forwards all application calls to actual system call
- Single process writing 50MB data

CRUISE: Checkpoint-Restart in User-Space

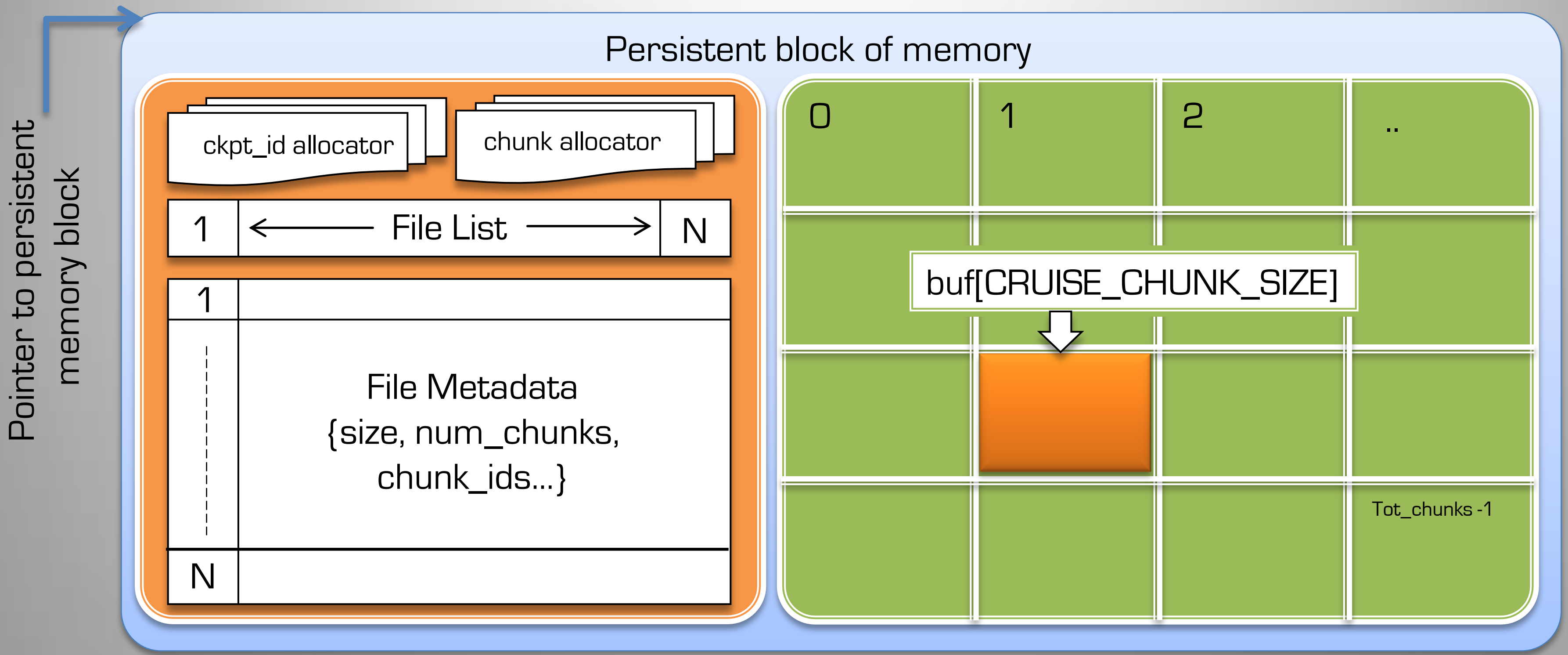
- Manages data in a byte-addressable persistent-memory region
- Library to intercept I/O operations from an application that links to it
  - Can statically / dynamically intercept I/O calls (LD_PRELOAD or -wrap,function)
  - Also implements the different calls such as open, write, read, ftruncate, lseek, etc….



Design Assumptions

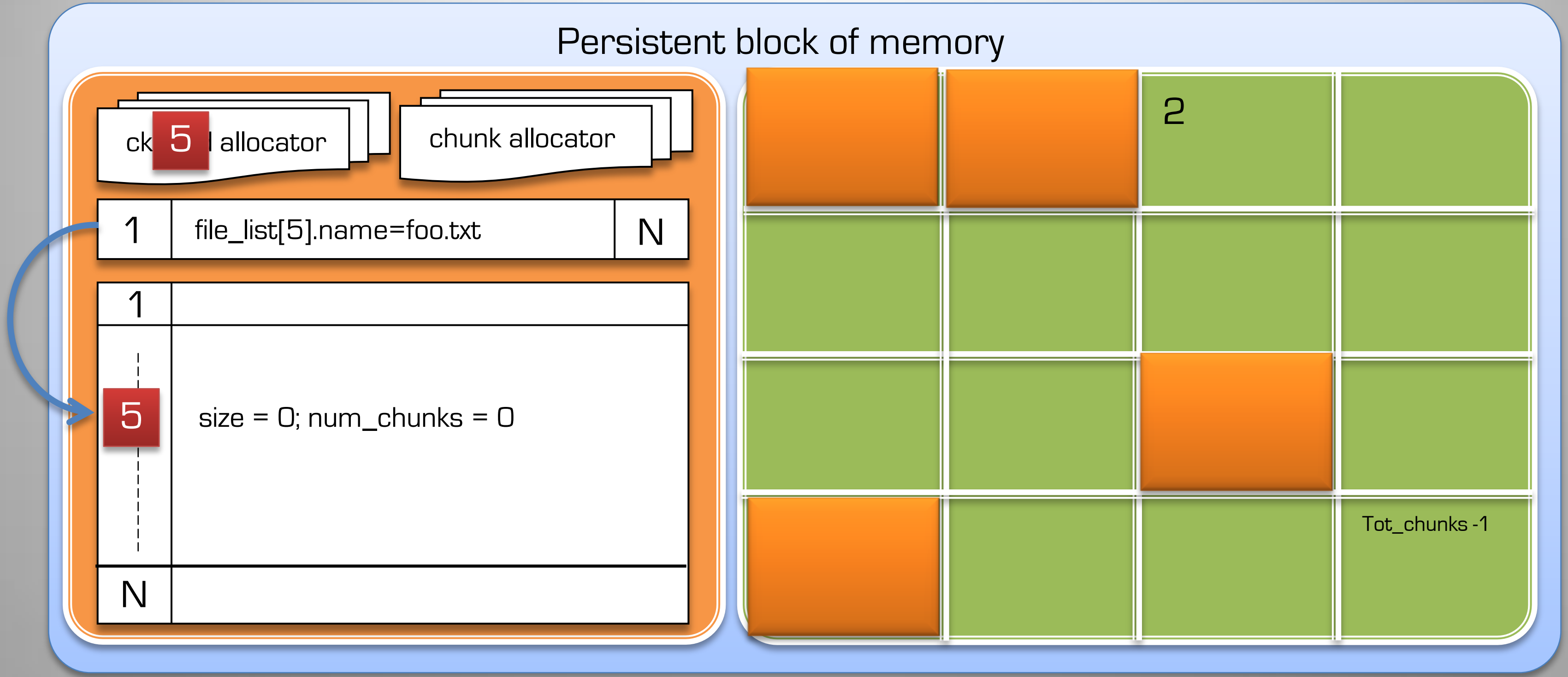
- No-shared files
  - Eliminates inter-process consistency and need for file locking
- Dense files
  - No need to optimize for potential holes
- Write-once-read-rarely model
  - Asynchronous RDMA without ensuring consistency
- Temporal nature of checkpoint data
  - No need to track POSIX timestamps, SCR handles versioning
- Globally coordinated operation
  - Can clear internal locks after a failure

Design of CRUISE

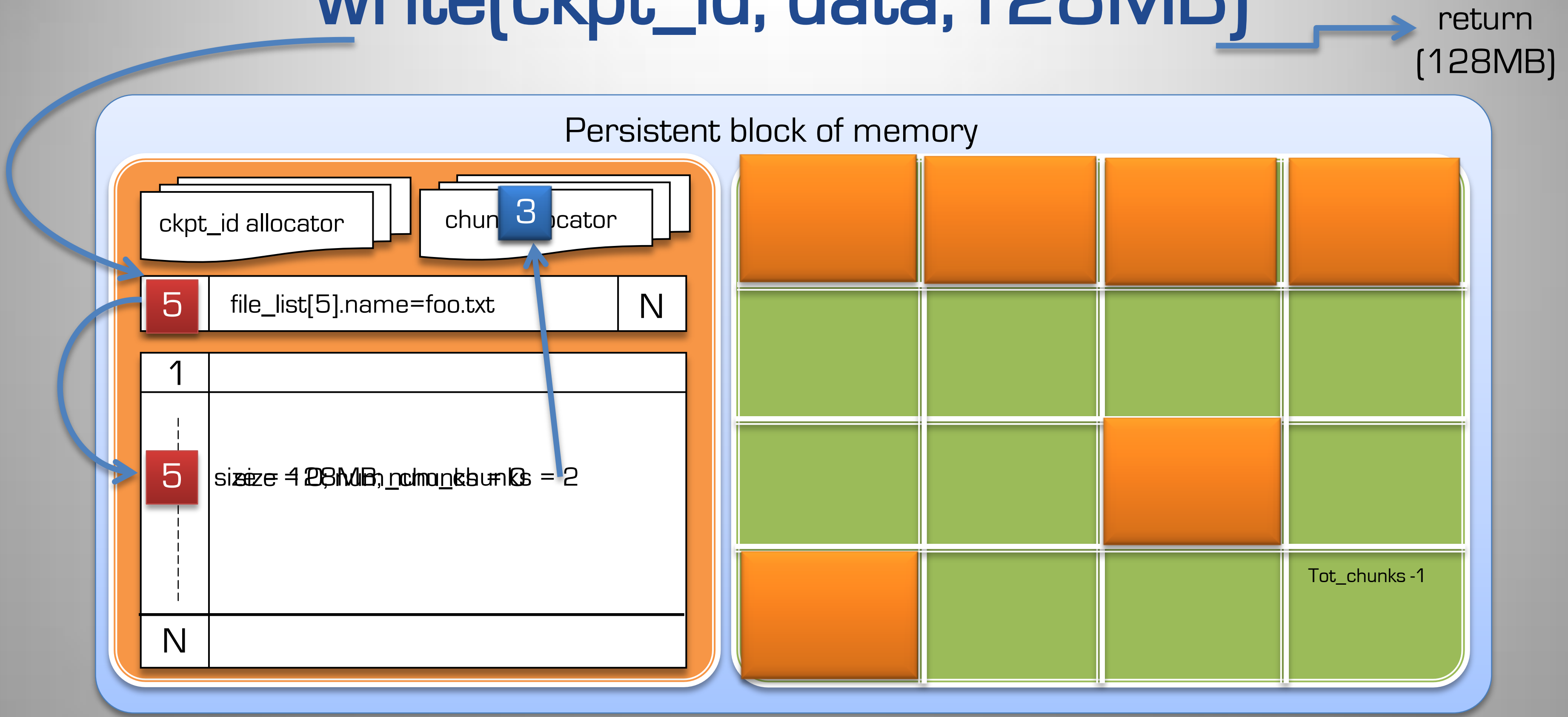


open($CRUISE/foo.txt)

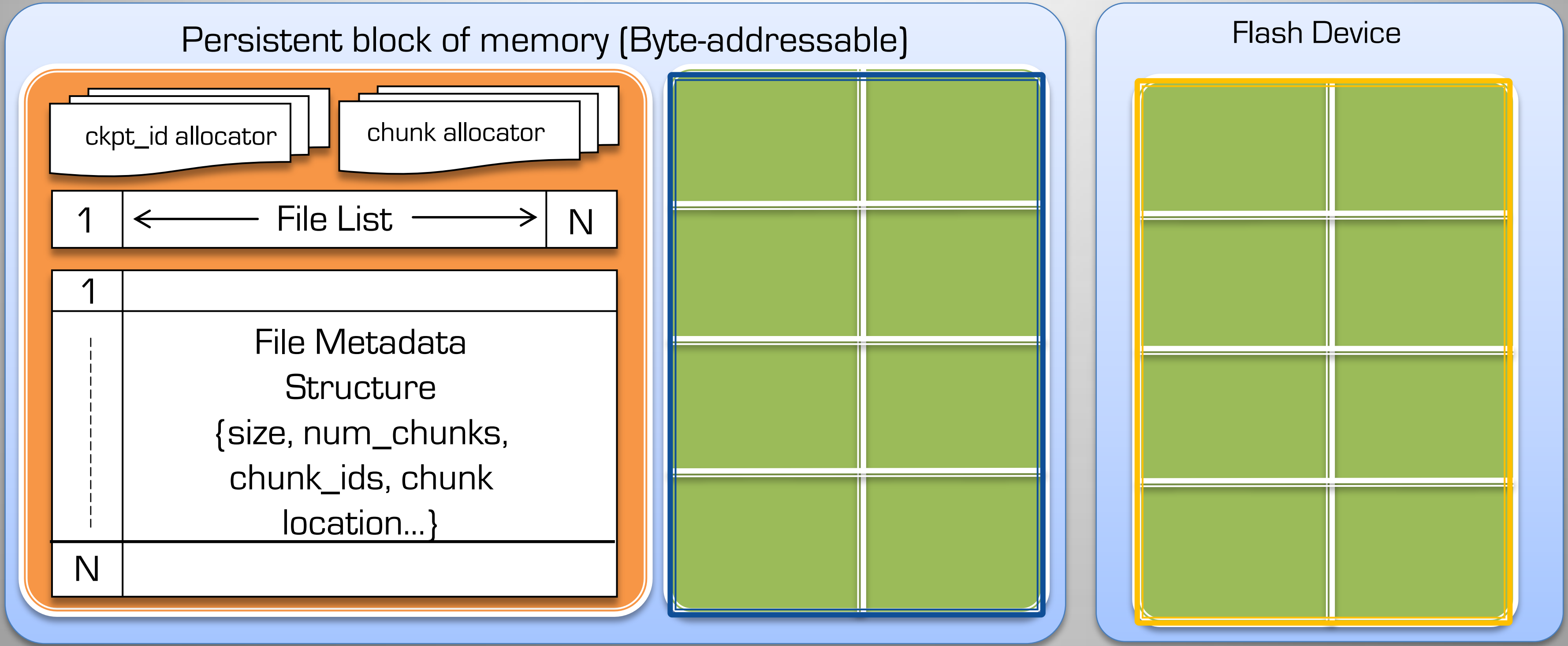
return
(ckpt_id)



write(ckpt_id, data,128MB)



Spill-over to SSD



Spill-over to SSD

$T_{spillover}$ – throughput of cruise with spillover
T_{MEM} – throughput of memory
T_{SSD} – throughput of SSD
$size_{tot}$ – total size of checkpoint
$size_{MEM}$ – size of checkpoint in memory
$size_{SSD}$ – size of checkpoint in SSD

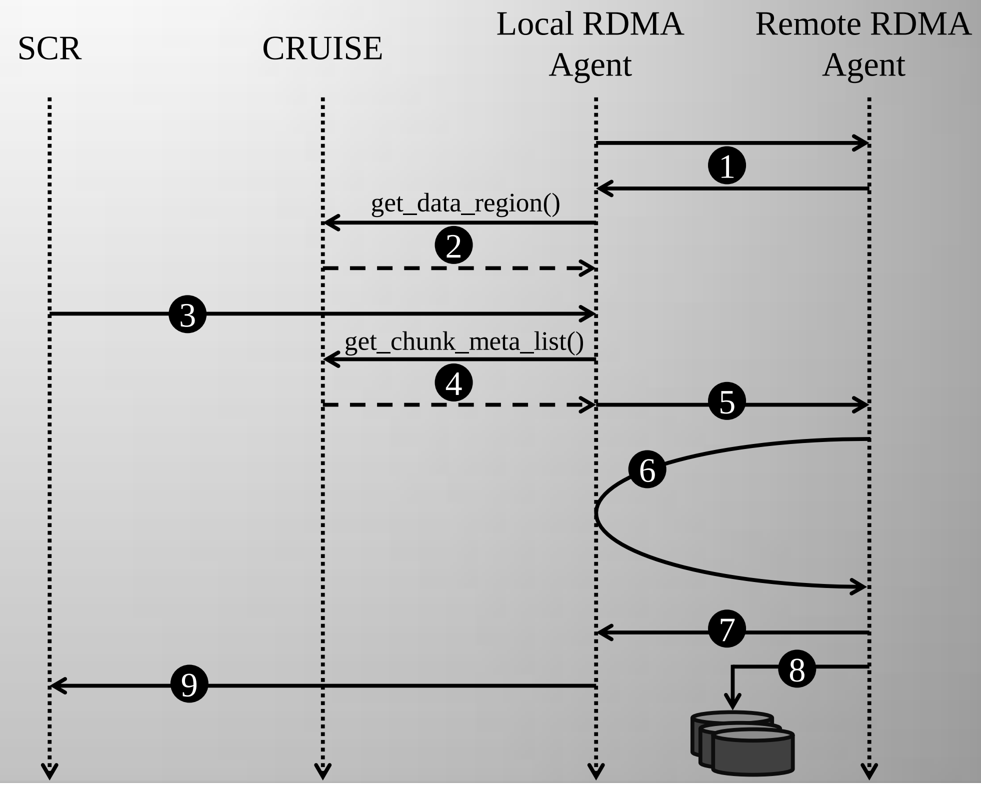
$$T_{spillover} = \frac{size_{tot}}{\frac{size_{MEM}}{T_{MEM}} + \frac{size_{SSD}}{T_{SSD}}}$$

Test #	% in SSD	Spill size (MB)	Expected Throughput	Achieved Throughput
1	0	0	15074.17	15074.17
2	3.125	16	10349.12	10586.61
3	6.25	32	7879.33	8134.46
4	12.5	64	5333.61	5312.26
5	25	128	3240.00	3110.58
6	50	256	1815.06	2163.93
7	100	512	965.67	965.67

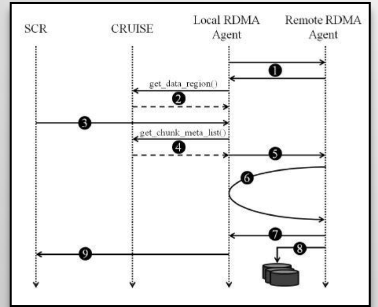
- 300GB OCZ VeloDrive PCIe SSD
- 8 processes writing 512 MB each
- #1,#7 – Native throughput of Memory and SSD respectively

RDMA-based Checkpoint Draining

- Asynchronous I/O without competing with application for CPU resources
- Data-staging architectures
- Job-/Process-migration frameworks



Implementation specifics




```
open(const char *path, int flags, ...)
if path matches CRUISE mount prefix then
    lookup corresponding FileID
    if path not in File List then
        pop new FileID from free_fid_stack
        if out of FileIDs then
            return EMFILE
        end if
        insert path in File List at FileID
        initialize File Metadata for FileID
    end if
    return FileID + RLIMIT_NOFILE
else
    return __real_open(path, flags, ...)
end if
```

Figure 4: Pseudo-code for open() function wrapper

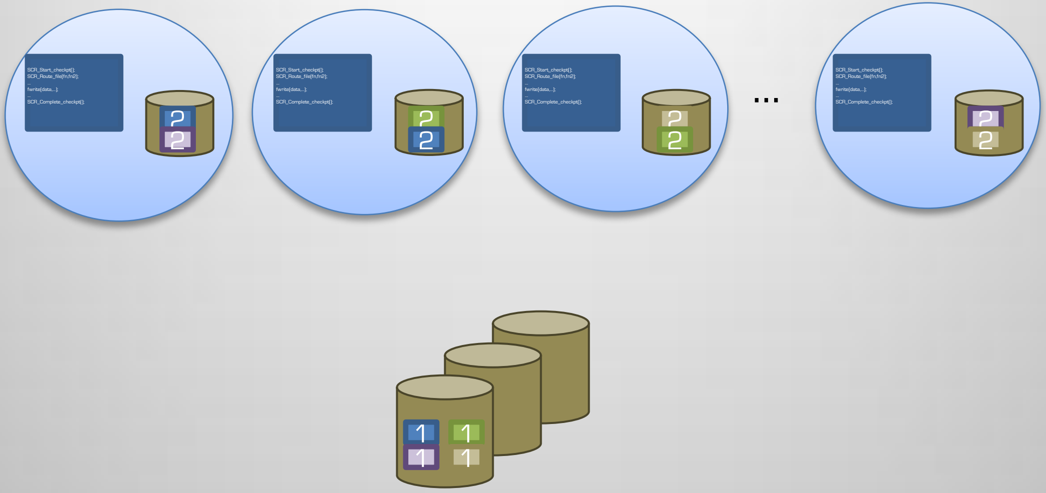
```
write(int fd, const void *buf, size_t count)
if fd more than RLIMIT_NOFILE then
    FileID = fd - RLIMIT_NOFILE
    get File Metadata for FileID
    compute number of additional data-chunks
    required to accommodate the write
    if additional data-chunks needed then
        pop data-chunks from free_chunk_stack
        if out of memory data-chunks then
            pop data-chunks from
            the free_spillover_stack
        end if
        store new ChunkIDs in File Metadata
    end if
    copy data to chunks
    update file size in File Metadata
    return number bytes written
else
    return __real_write(fd, buf, count)
end if
```

Figure 5: Pseudo-code for write() function wrapper

Please refer to the paper for more details on the implementation!

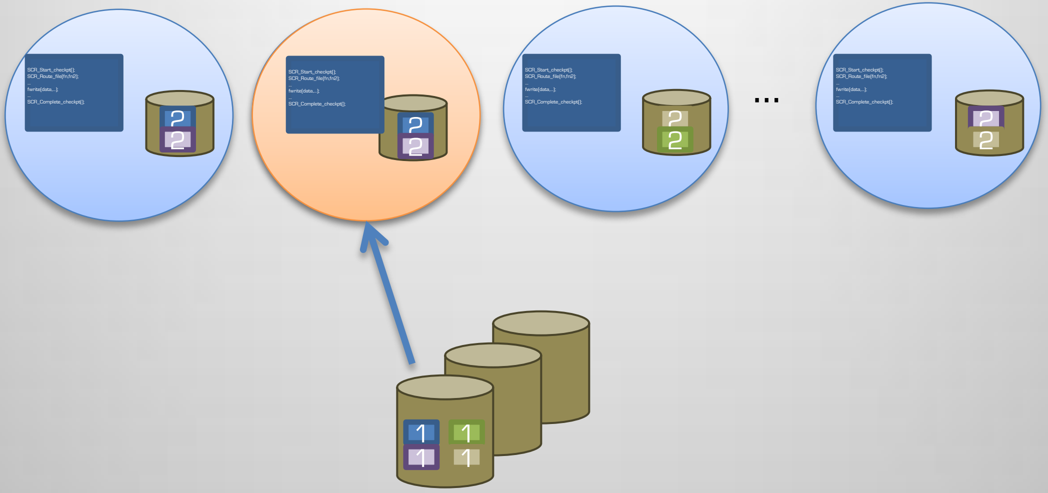
What happens when things fail?

Failure Model – Process Failures



- MPI runtime is required to clean the environment
- Data persists across process death => can be restarted directly

Failure Model – Node Failures

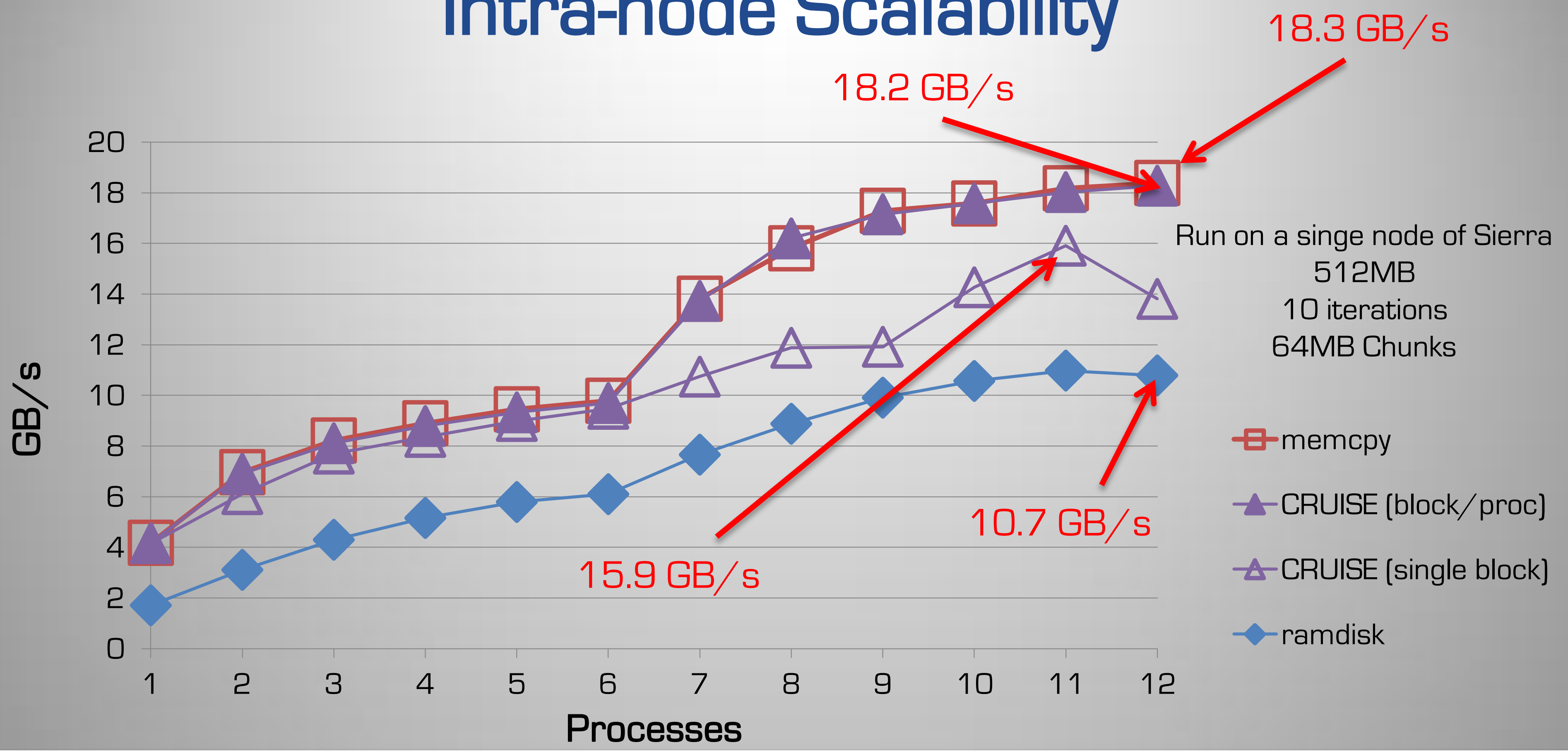


- Redundancy schemes applied by SCR rebuilds lost CRUISE files
- If unable to rebuild, fetches latest copy from parallel file system

Performance Evaluation

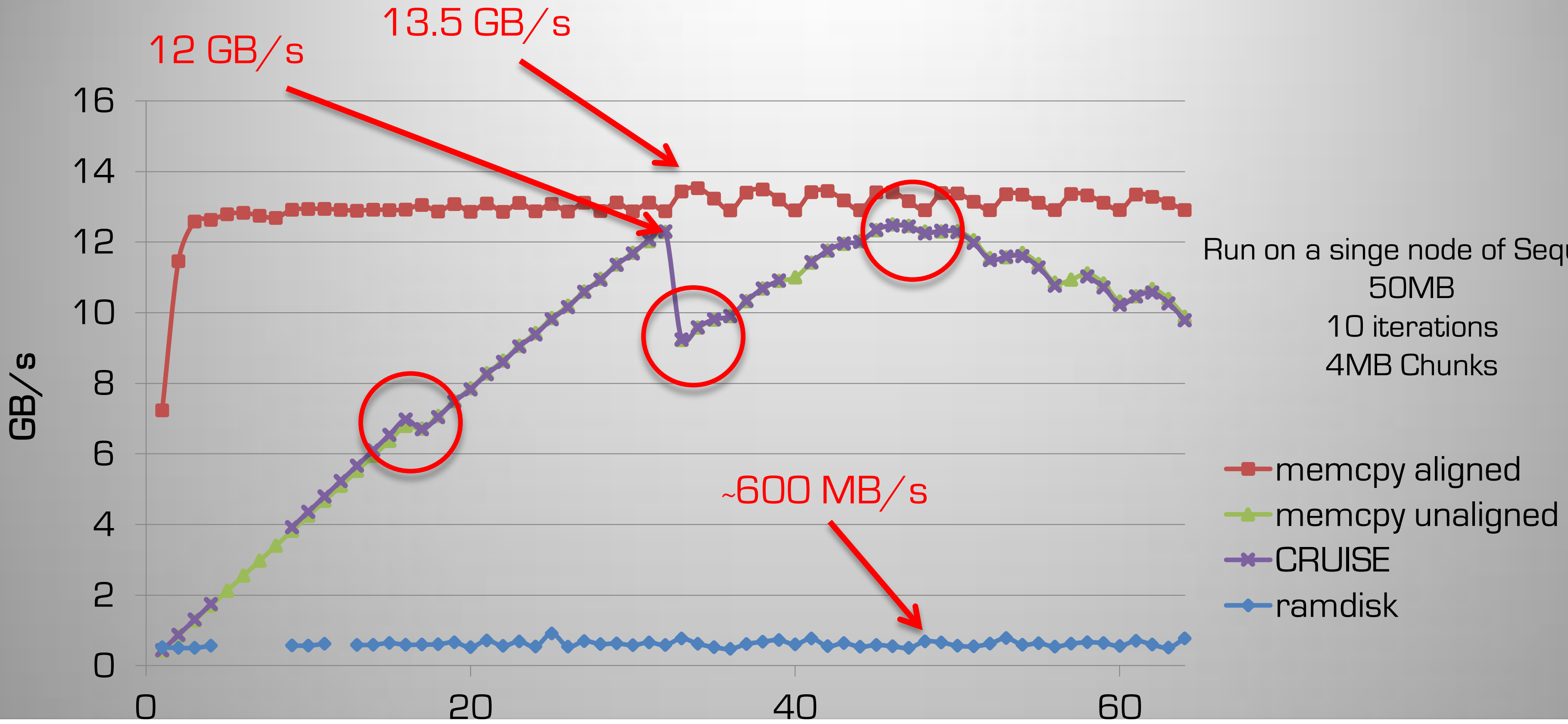
- Sierra (1,944 nodes) - #150 in Top500 (Nov'12)
  - TOSS 2.0 | 6-core Intel Xeon | 24GB RAM/node | InfiniBand QDR | ICC v11.1
- Zin (2,916 nodes) - #29 in Top500 (Nov'12)
  - TOSS 2.0 | 8-core Intel Xeon | 32GB RAM/node | InfiniBand QDR | ICC v11.1
- Sequoia (98,304 nodes) - #3 in Top500 (#1 last year)
  - IBM BG/Q – CNK | 16 cores/node | 16GB RAM/node | IBM BG -Torus | IBM compiler v12.1

Intra-node Scalability



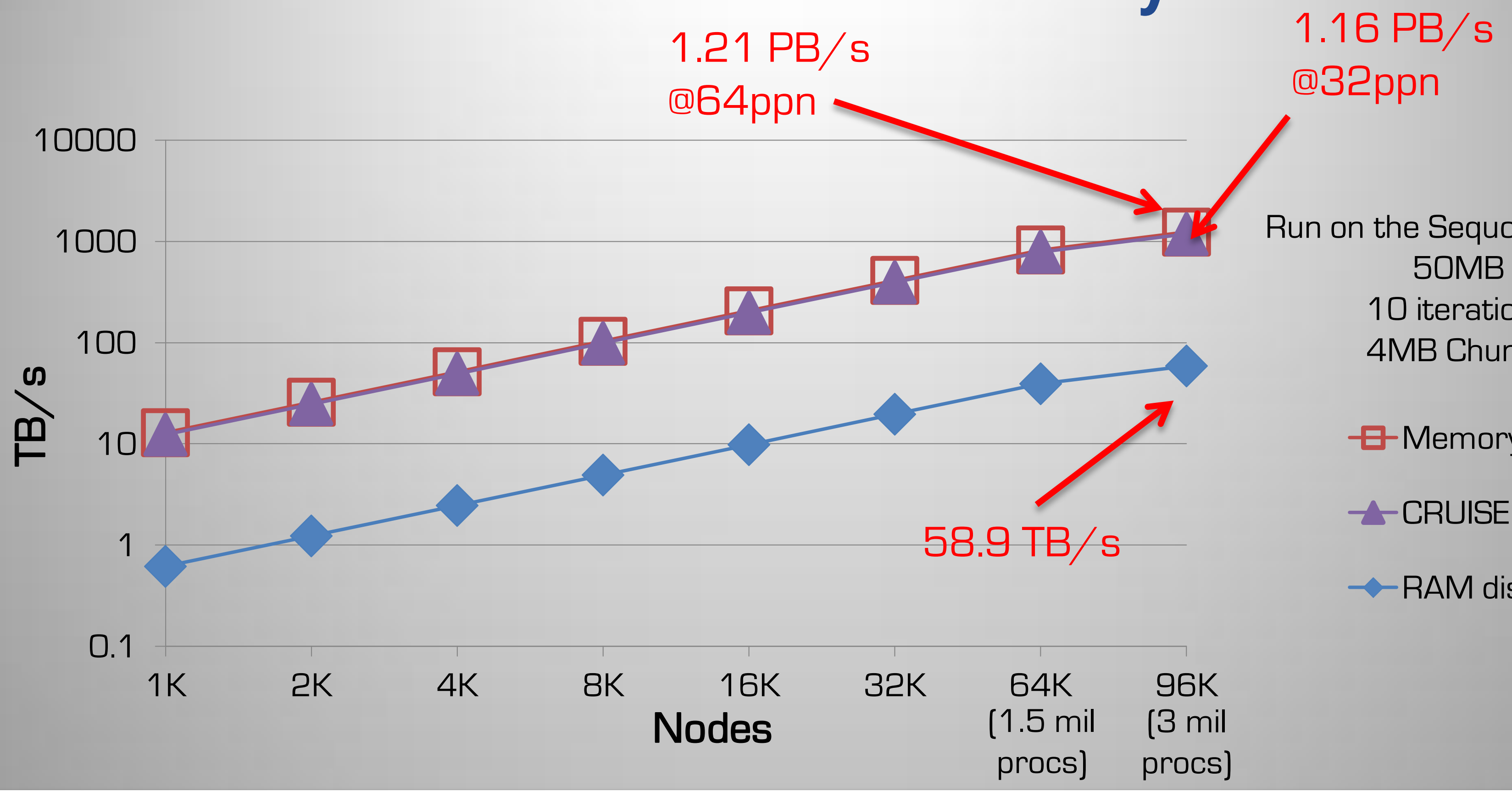
Run on a singe node of Sierra
512MB
10 iterations
64MB Chunks

Intra-node Scalability



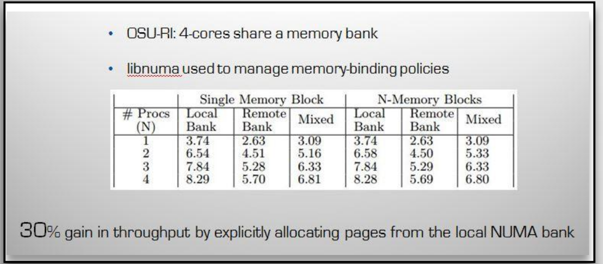
Run on a singe node of Sequoia
50MB
10 iterations
4MB Chunks

Inter-node Scalability

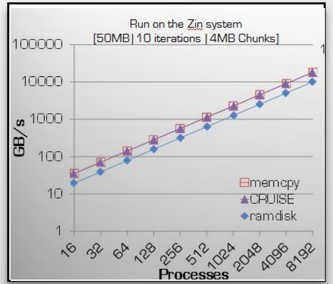


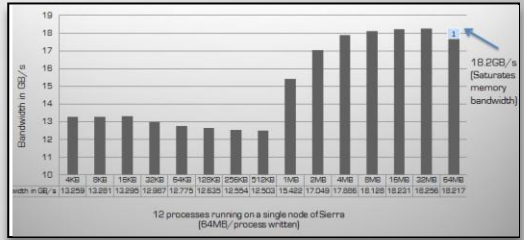
Run on the Sequoia system
50MB
10 iterations
4MB Chunks

Performance Evaluation



# Procs (N)	Single Memory Block: Local Bank	Single Memory Block: Remote Bank	Single Memory Block: Mixed	N-Memory Blocks: Local Bank	N-Memory Blocks: Remote Bank	N-Memory Blocks: Mixed
1	3.74	2.63	3.09	3.74	2.63	3.09
2	6.54	4.51	5.16	6.58	4.50	5.33
3	7.84	5.28	6.33	7.84	5.29	6.33
4	8.29	5.70	6.81	8.28	5.69	6.80





Please refer to the paper for more results!

Summary

- CRUISE: a file system to extend capabilities of multi-level checkpointing systems
- Allows asynchronous draining of checkpoints using RDMA techniques
- Checkpoint data cascades down the storage hierarchy
- **20x faster than RAM disk**, can run on systems without RAM disk
- **Scales linearly** with node-count
- **1.16PB/s** when **three million** processes checkpoint simultaneously

The path forward

- Evaluation with real-word applications (pF3D laser-plasma)
- Enhanced caching policies when data spills-over
- Impact of CRUISE on non-CR application file I/O
- Releasing the CRUISE for use by the community

Thank you!

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