Memory Management Strategies for Data Serving with RDMA

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Motivation

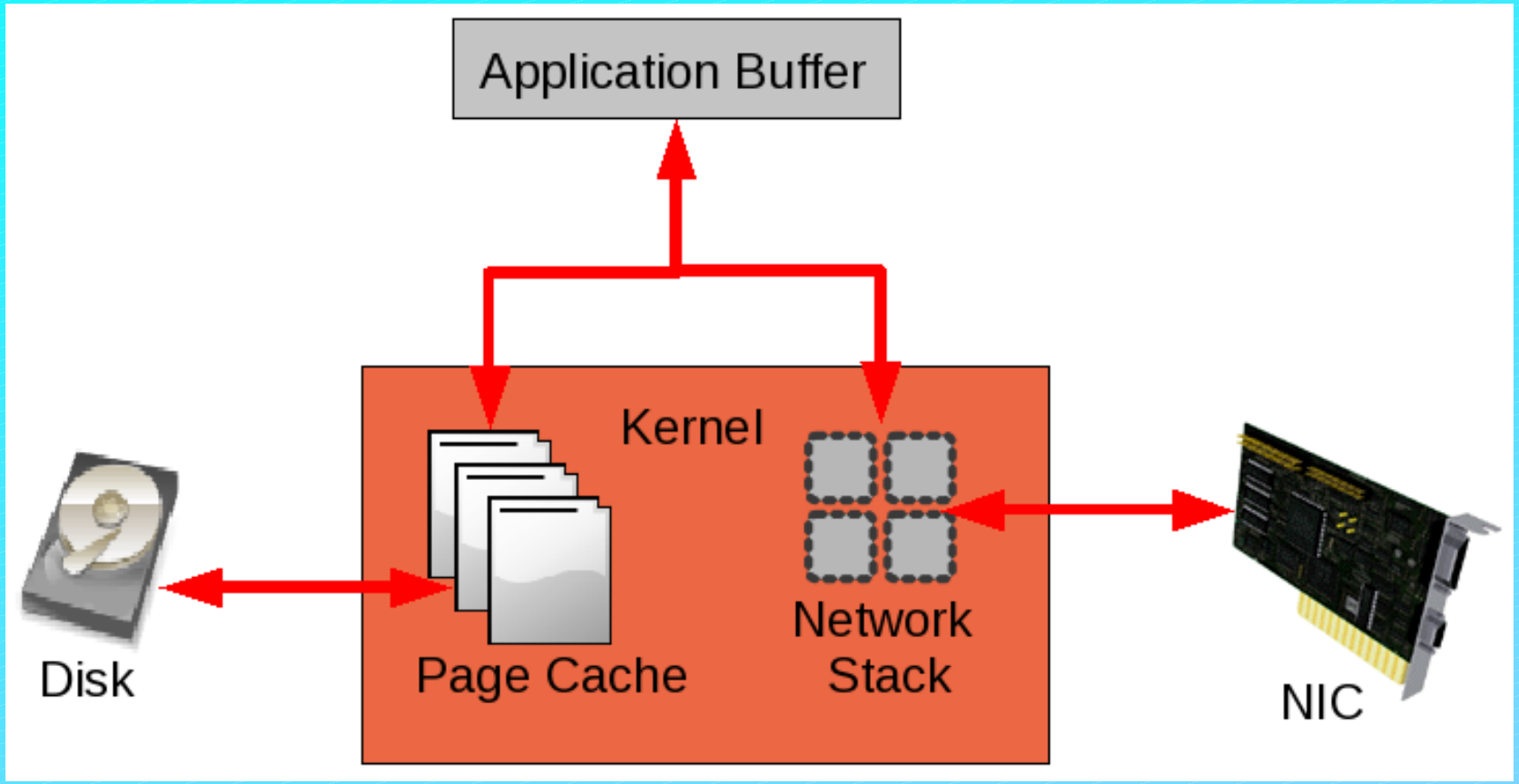
- Increasing demands for
  - bandwidth
  - client scaling
  - dynamic content
  - more interactions
- File transfer is a fundamental component
  - distributed file systems
    - NFS, PVFS, CIFS
  - distributed data-intensive protocols
    - FTP, HTTP, DAV, Bittorrent
    - video-on-demand, multicast conferencing

Can RDMA improve file transfer performance?

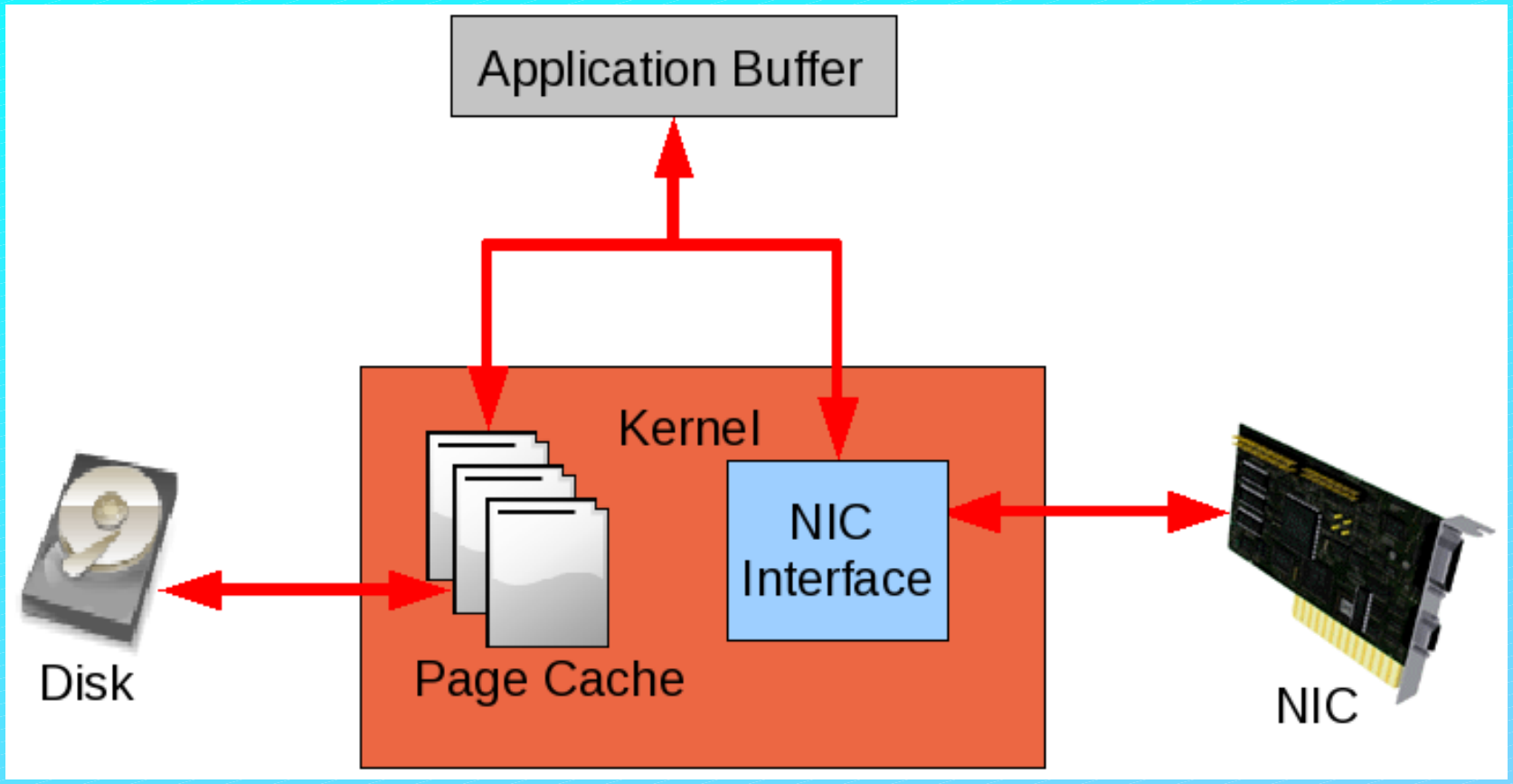
What is RDMA?

- Two major aspects
  - Protocol Offload
    - NIC handles network processing
    - Removes biggest burden from host CPU
  - Zero Copy (with or without OS bypass)
    - Data is moved directly between network and user buffers
- TCP Offload Engine (TOE)
  - TCP/IP stack processing offloaded
  - CPU still moves data from buffers to user memory
- Remote Direct Memory Access (RDMA)
  - TCP/IP offloaded
  - Data goes directly to and from user buffers

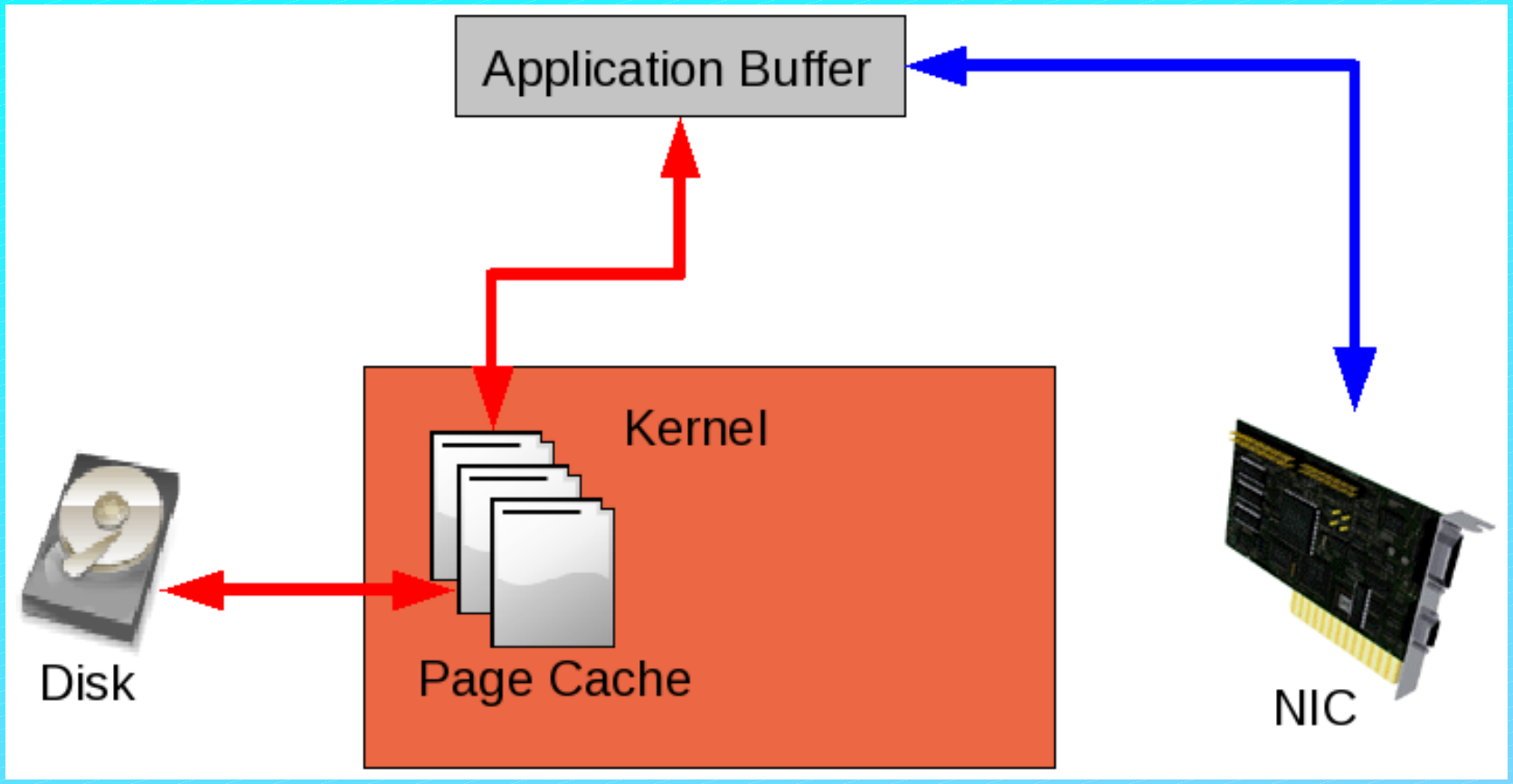
Traditional Network Processing



TCP Offload Engine Processing



RDMA Network Processing



RDMA Usage

- High-performance computing
  - Message passing (MPI)
    - InfiniBand, Myrinet, Quadrics, iWARP
  - File systems
    - PVFS, Lustre, NFSv4
- Various back-end applications
  - Database (unreliable datagrams)
  - Storage interconnect (non-switched)
  - IPoIB or SDP for sockets API on faster hardware
- Little general purpose usage
  - Web serving? back-end only
  - Wide-area communications? rare point-to-point

Why is RDMA limited to HPC?

- Another incompatible fabric
  - Not with iWARP, runs on Ethernet
- High cost of 10 Gb/s Ethernet
  - Dropping rapidly, like Ethernet always does

- Sockets API
  - Completely entrenched
  - Cannot handle RDMA semantics
  - Sockets “extensions” are poor compromises
  - RDMA is not integrated into OS

RDMA in the Linux Community

Recent email from David Miller (Net maintainer)

> Isn't RDMA part of the "software net stack"

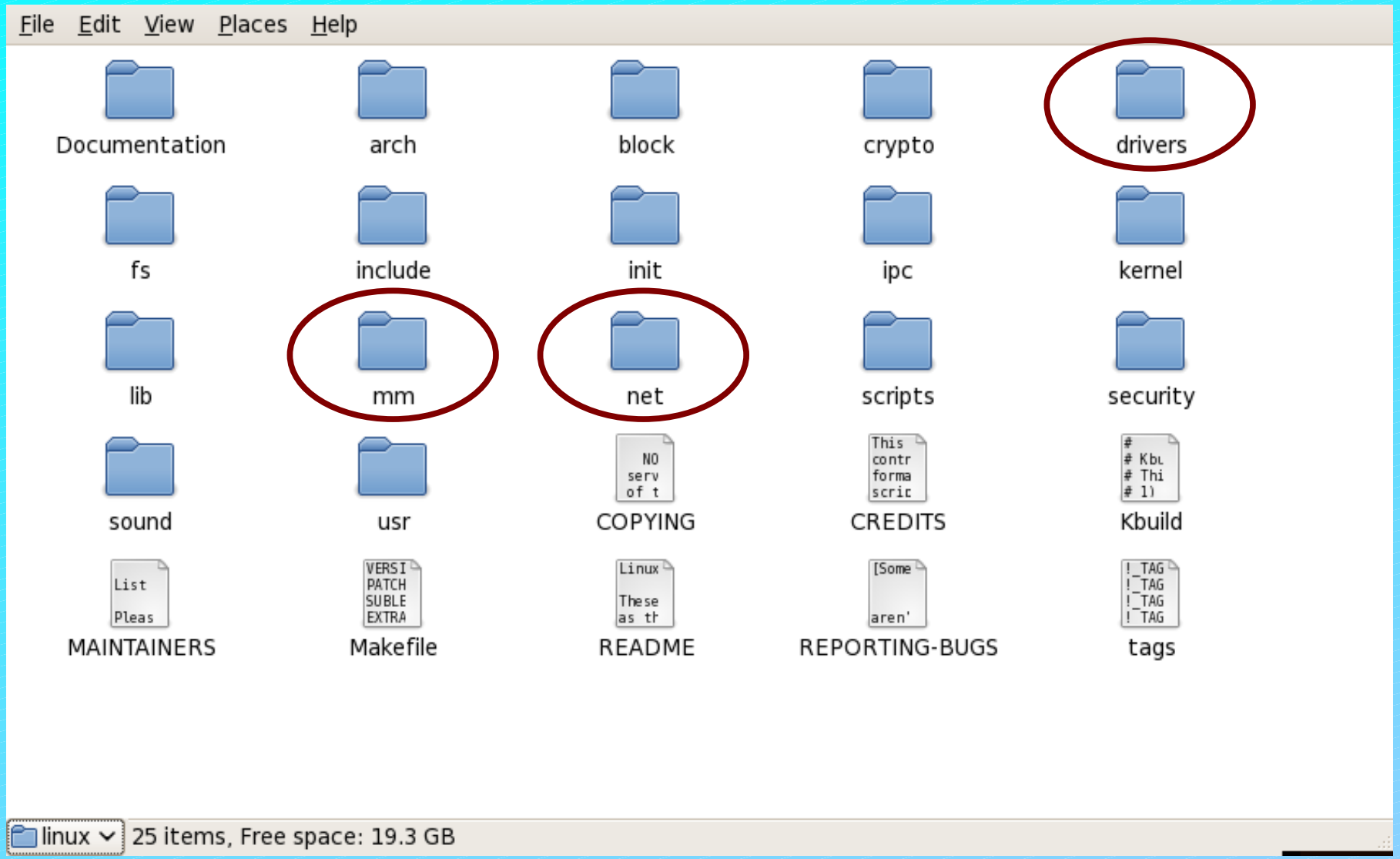
> within Linux?

It very much is not so.

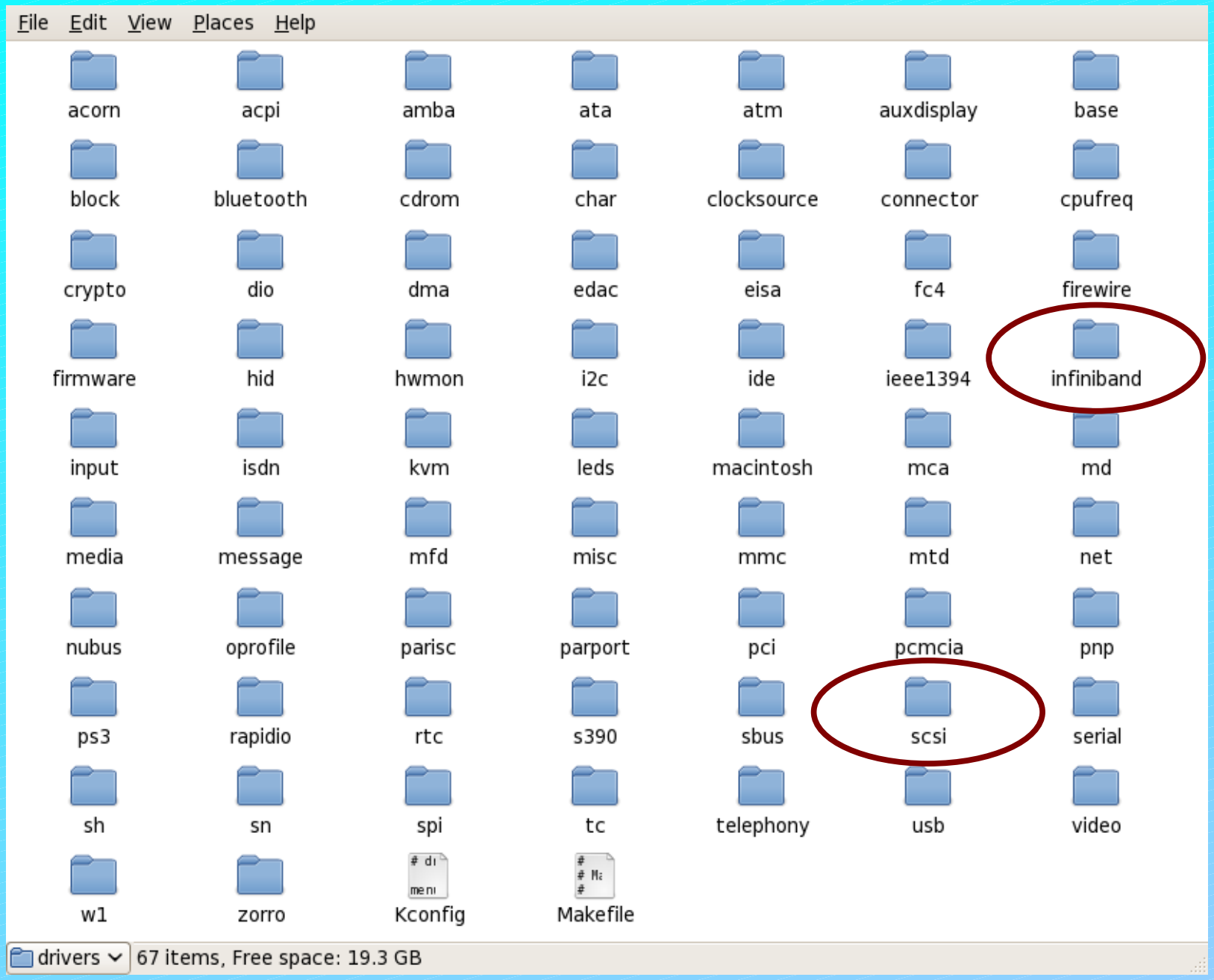
Major complaints

- Firewalling, packet shaping and classification not possible
- Stateful devices bad
- Multi-core will make RDMA obsolete

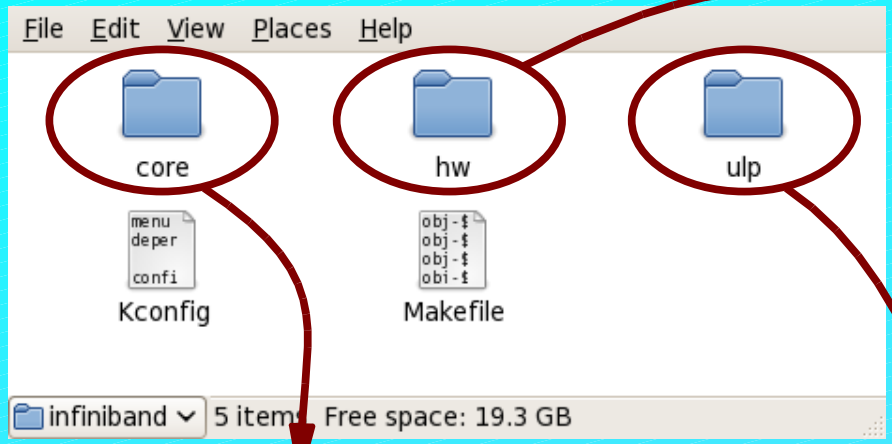
Linux kernel tree

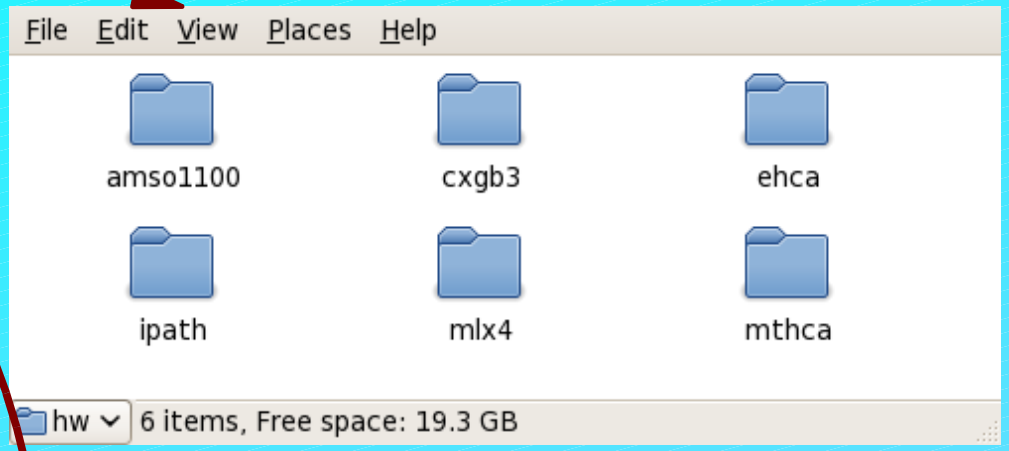


Linux “drivers”



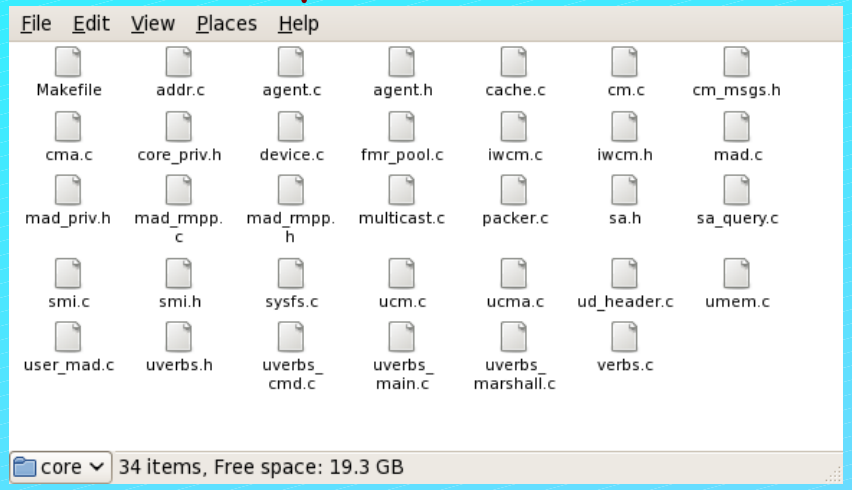
InfiniBand Components





Hardware

- True device drivers



Core

- Verbs interface
- Memory registration
- Connection manager

Upper Layer Protocols

- Ethernet interface
- SCSI transport (iSCSI)
- SCSI transport (SRP)

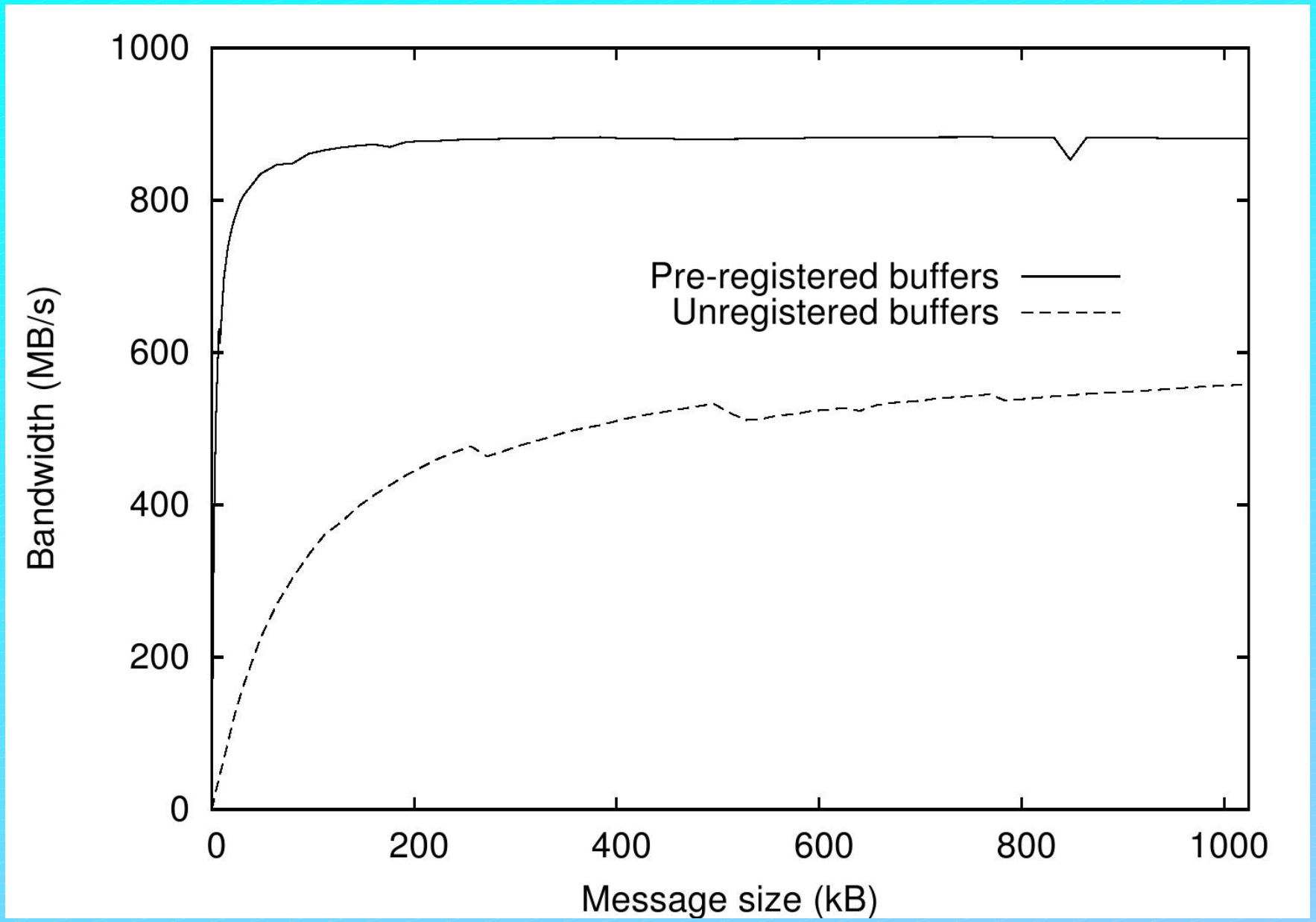
RDMA and OS Mismatches

- Memory registration
  - API exists, but is not part of memory management
    - mmap, munmap
    - mlock, munlock
    - ibv_reg_mr, ibv_dereg_mr
- Connection management
  - API exists and looks like sockets, but separate
    - socket, bind, listen, connect, accept
    - rdma_create_id, rdma_bind_addr, rdma_accept, ...
- File descriptor abstraction
  - RDMA uses Queue Pair and other entities
  - No sharing of QP across user/kernel or processes
  - No unified polling mechanism (readable/writeable)

Memory Registration

- Severe application complexity
- Two major approaches
  - static
    - copy all data into and out of fixed buffers
    - allocate per-client resources
  - dynamic
    - register buffers as they are needed
    - possibly cache previous registrations (but not in system)
- Overheads
  - 30 us to register 4 bytes
  - 100 us to register 1 MB
  - 30 to 50 us to deregister
  - 2 to 7 us network latency!

Throughput with Registration

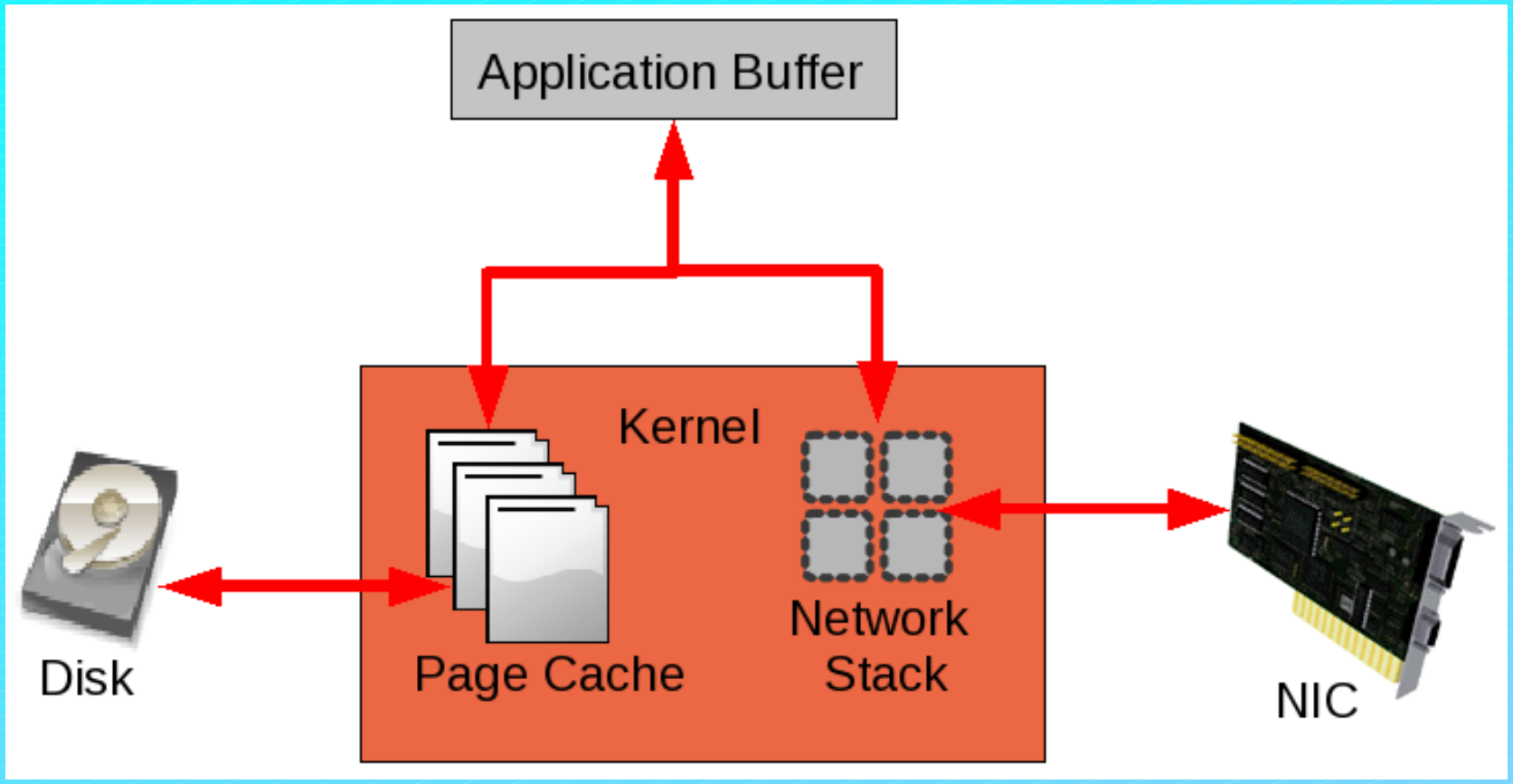


Sendfile

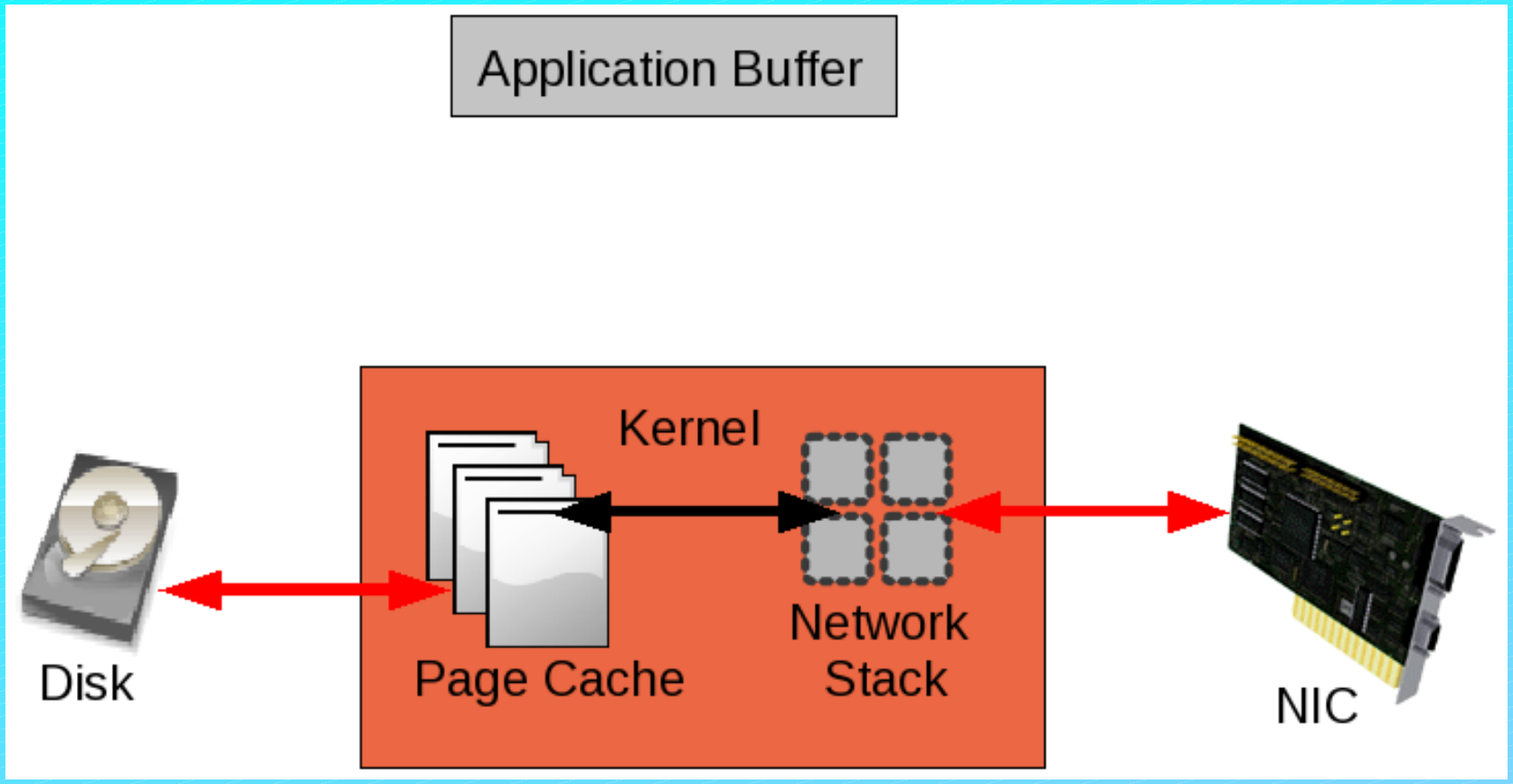
- Ship file data directly to the network
- In Linux, BSDs for many years
- Saves two memory copies for TCP
- Commonly used by Apache and other apps
- Uses file descriptors to represent
  - local file
  - socket connection

Maps poorly to RDMA

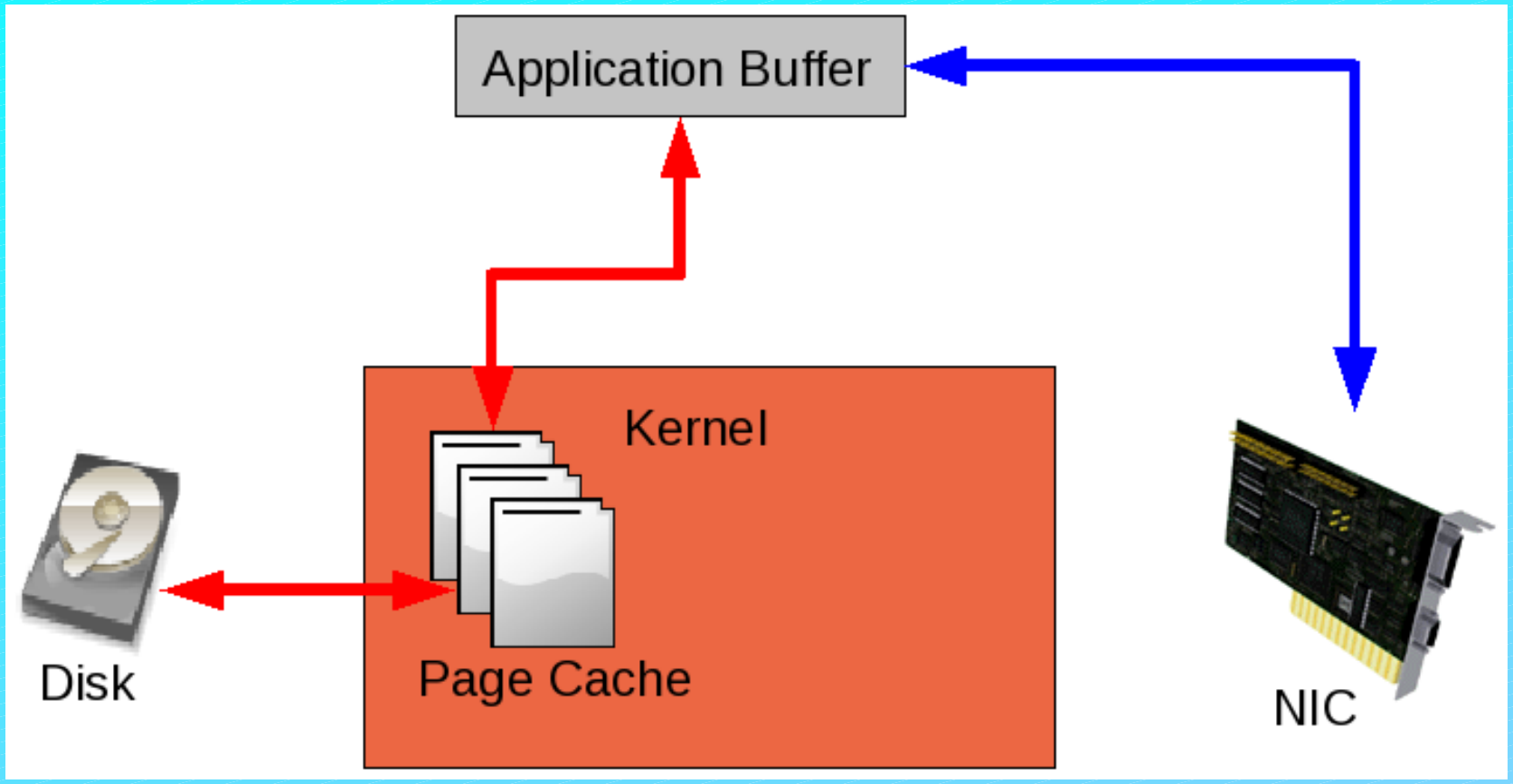
TCP Network Processing



TCP Sendfile Processing

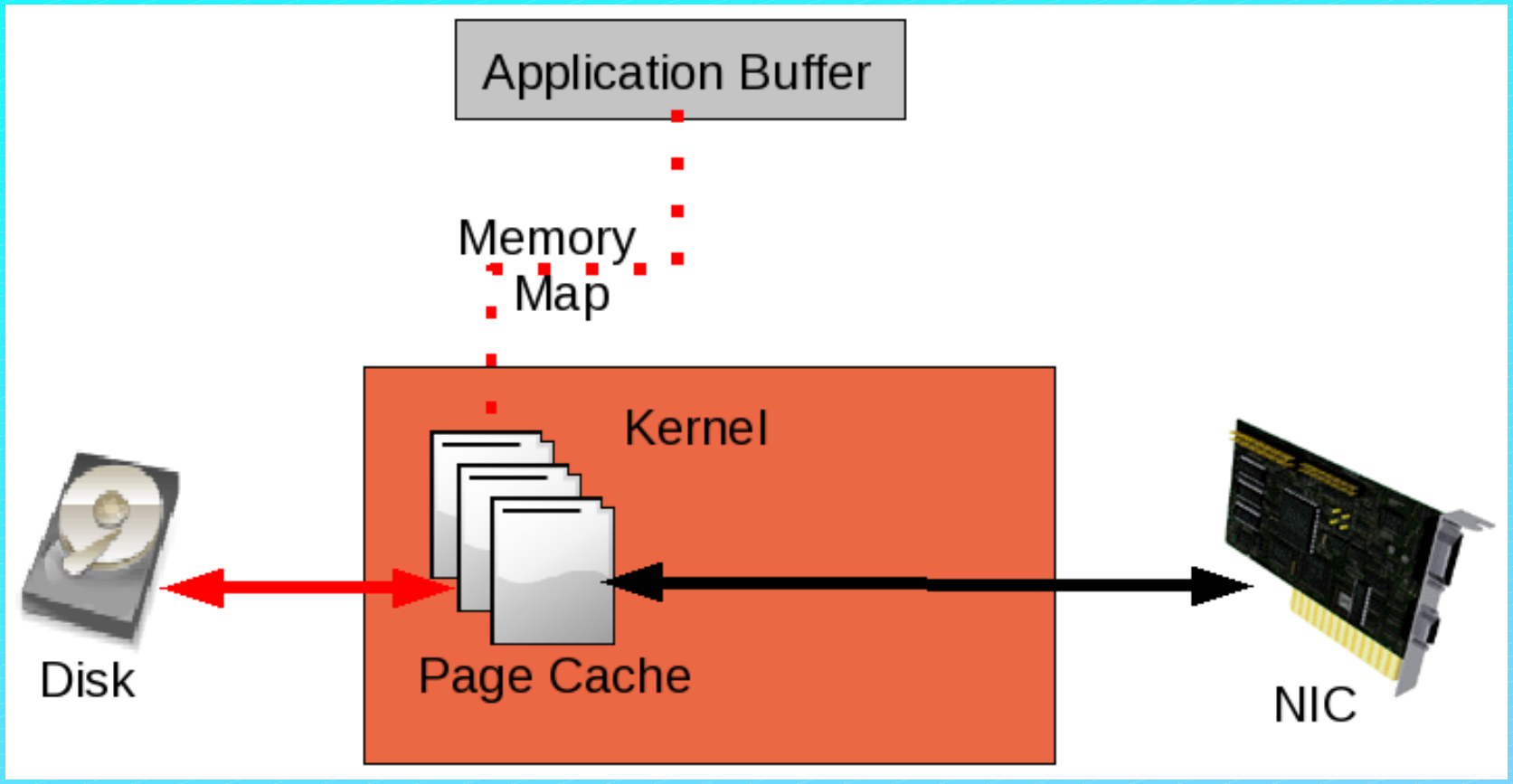


RDMA Network Processing



RDMA requires a memory copy to send a file!

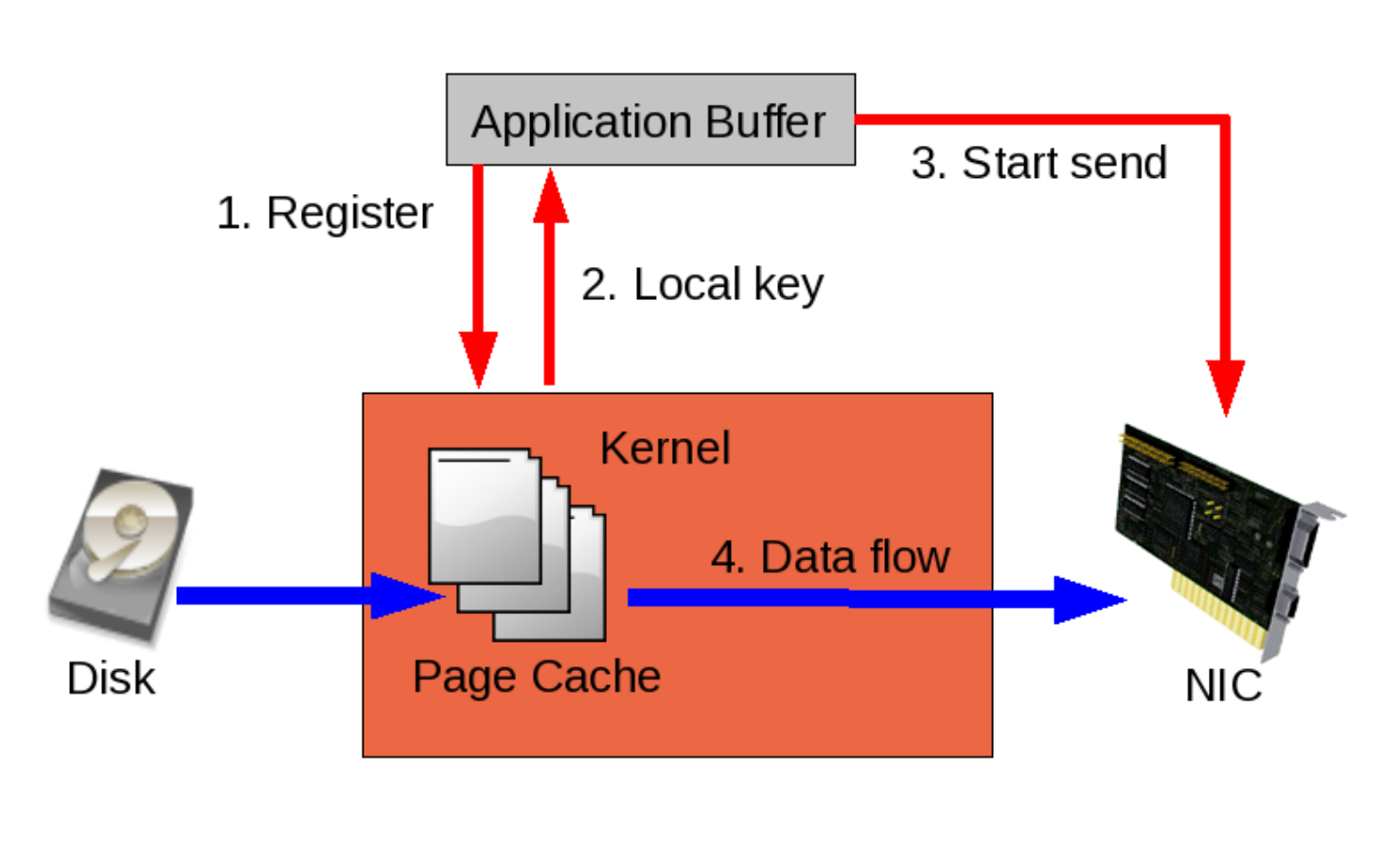
RDMA Sendfile Processing



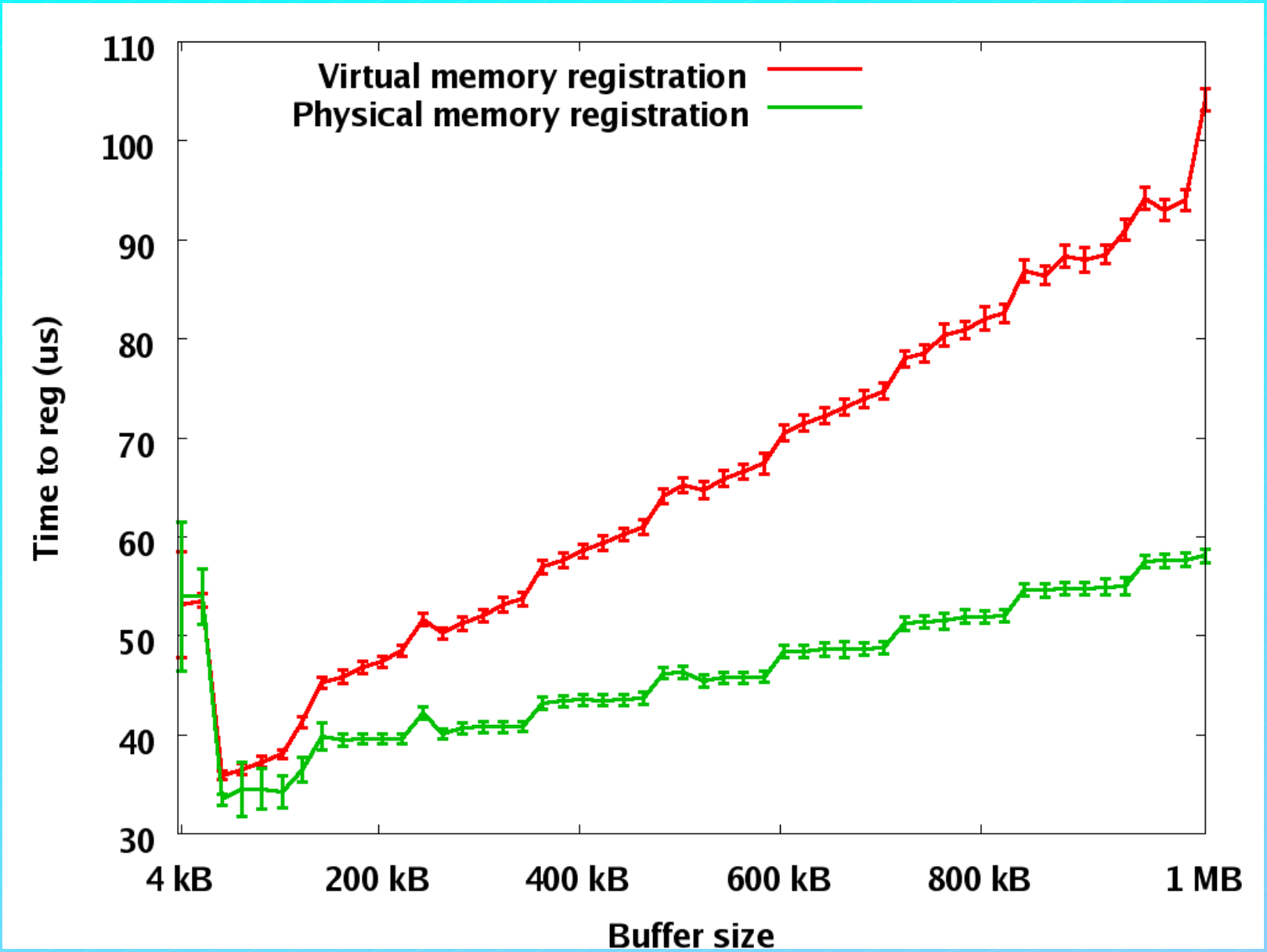
RDMA Sendfile Design

- User space application
  - Handles all connection management and errors
  - Sends and receives all data (including files)
  - Invokes kernel to map file data
  - Issues work requests to NIC using lkey from kernel
  - Never sees or copies file data
- Kernel module
  - Usual open/close/command on character device
  - Map takes PD, fd, offset, len; returns lkey
  - Unmap similar
  - Cleanup code to unmap on application failure
  - Uses physical address directly, no translation

Sendfile Steps



Key Observation



Virtual to physical translation is slow.

RDMA Sendfile Design Alternatives

- Pass QP to kernel and let it send
  - Architecturally not permitted in RDMA
  - Handling completion and errors would be complex
- Open new connection from kernel
  - Then just send directly and close
  - Lots of complex code to stick in the kernel
  - Overhead for each new connection
- Open entire session in kernel
  - Send all other data through kernel, as well as files
  - So much for OS bypass
- Just use pipelining and overlap the registration

Experimental Results

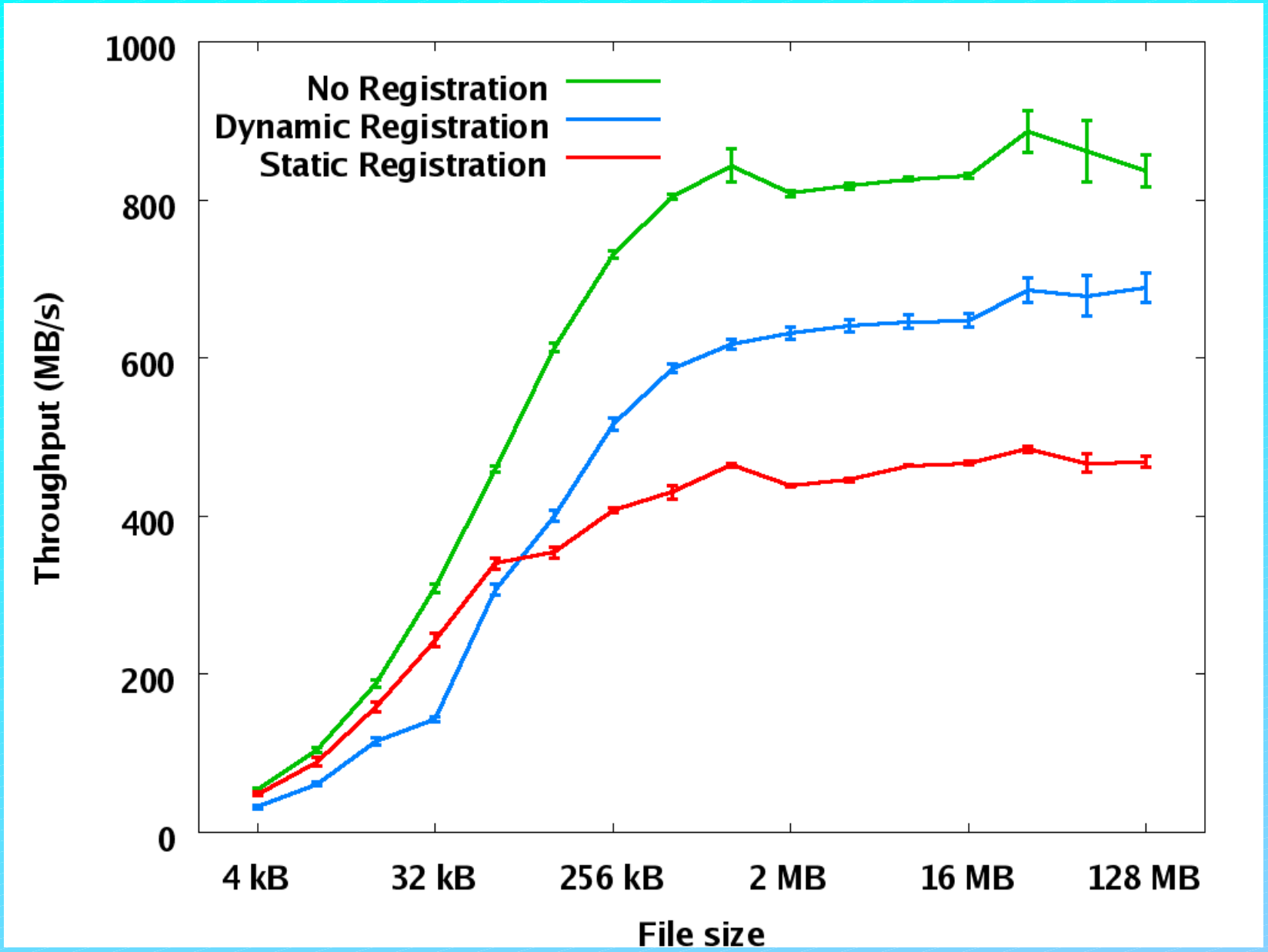
- Library of alternative implementations
  - Traditional, with or without pipelining
  - RDMA Sendfile, with or without pipelining
- Single test application

- Two Opteron 250 hosts
  - 2.4 GHz
  - 2 GB memory
  - Linux 2.6.20
- Mellanox mem-free 4x SDR InfiniBand
- Mellanox-based 24-port switch

Traditional Approach

- No registration
  - Memory registration overheads out of timing loop
  - As seen in most network benchmarks
- Static registration
  - Fixed buffer registered at startup
  - Files are read directly into that buffer
  - No registration overhead, but memory copy
- Dynamic registration
  - Files are mmap-ed into application address space
  - New address range is registered
  - No memory copy, but virtual-to-physical translation
  - (Current kernels have bug requiring copy, not shown here)

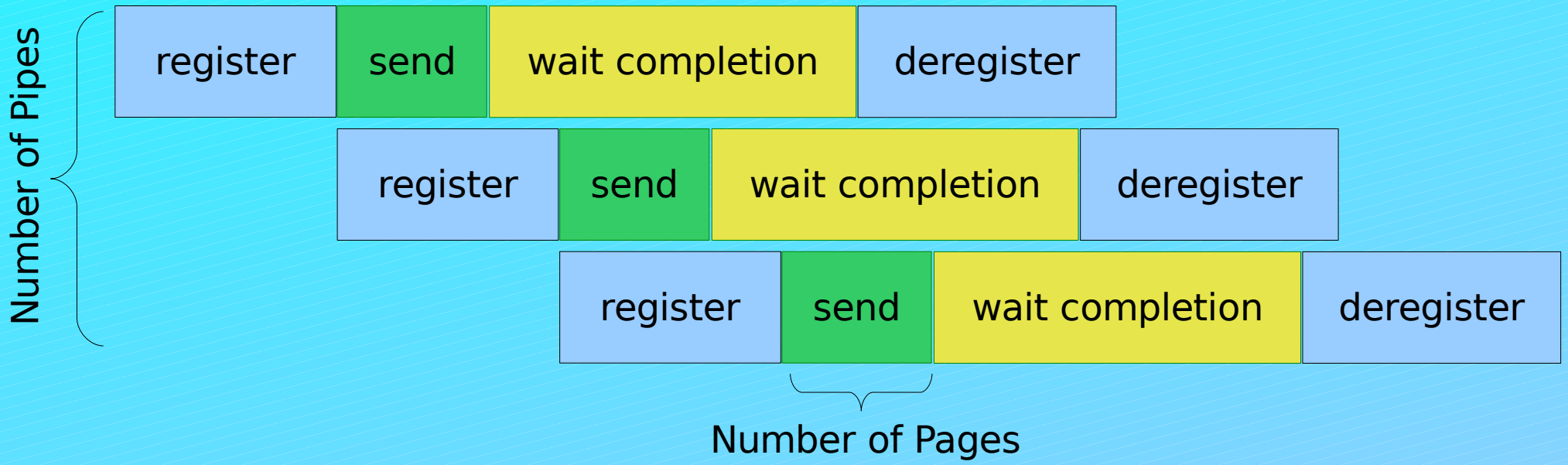
Traditional Approach



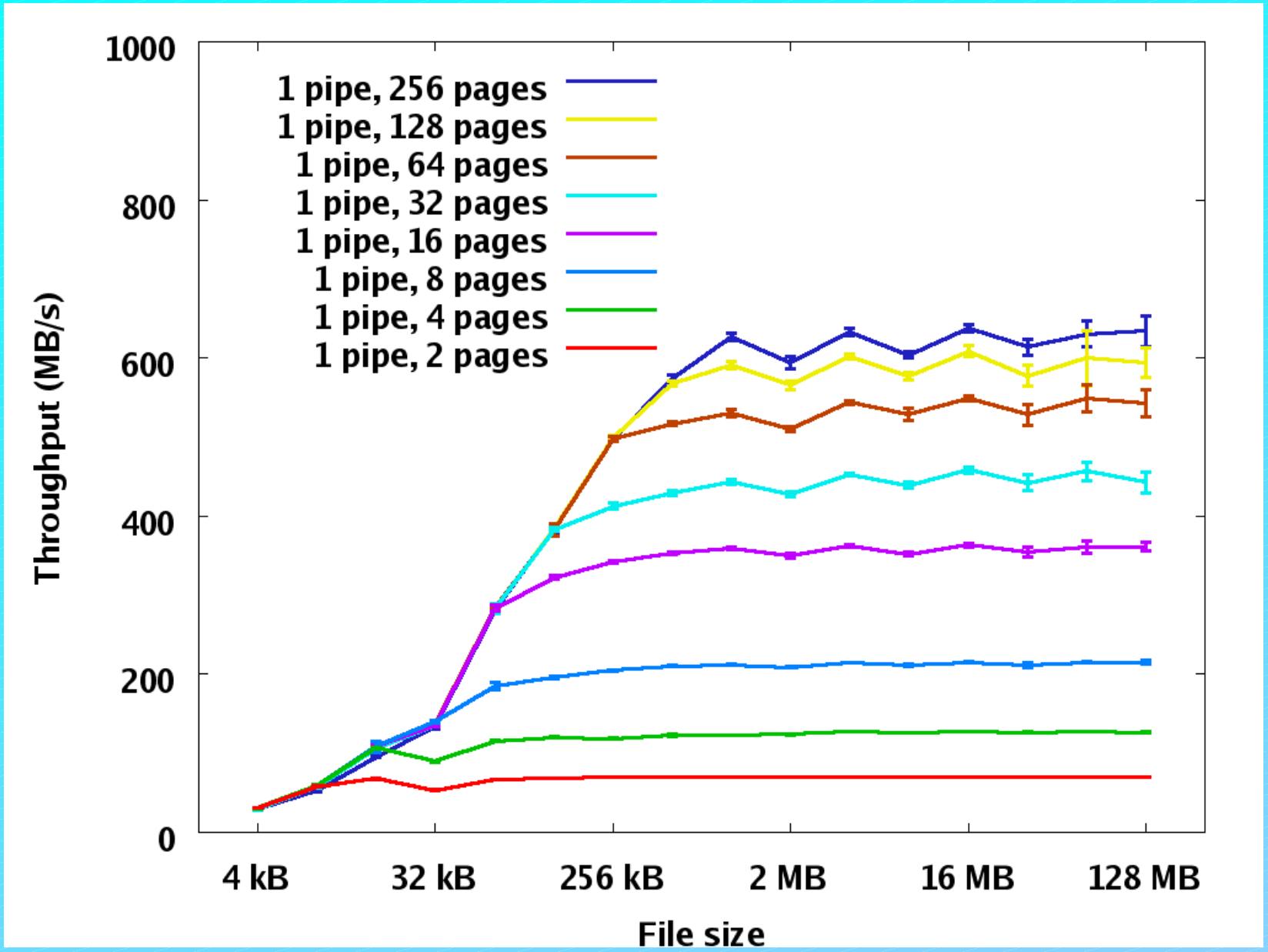
Static initially faster, until out of processor cache.
Dynamic registration overhead clearly visible.

Pipelining Effect

- Split up registration and sending
- Break each file size into sets of *pages*
- Keep some number of *pipes* outstanding

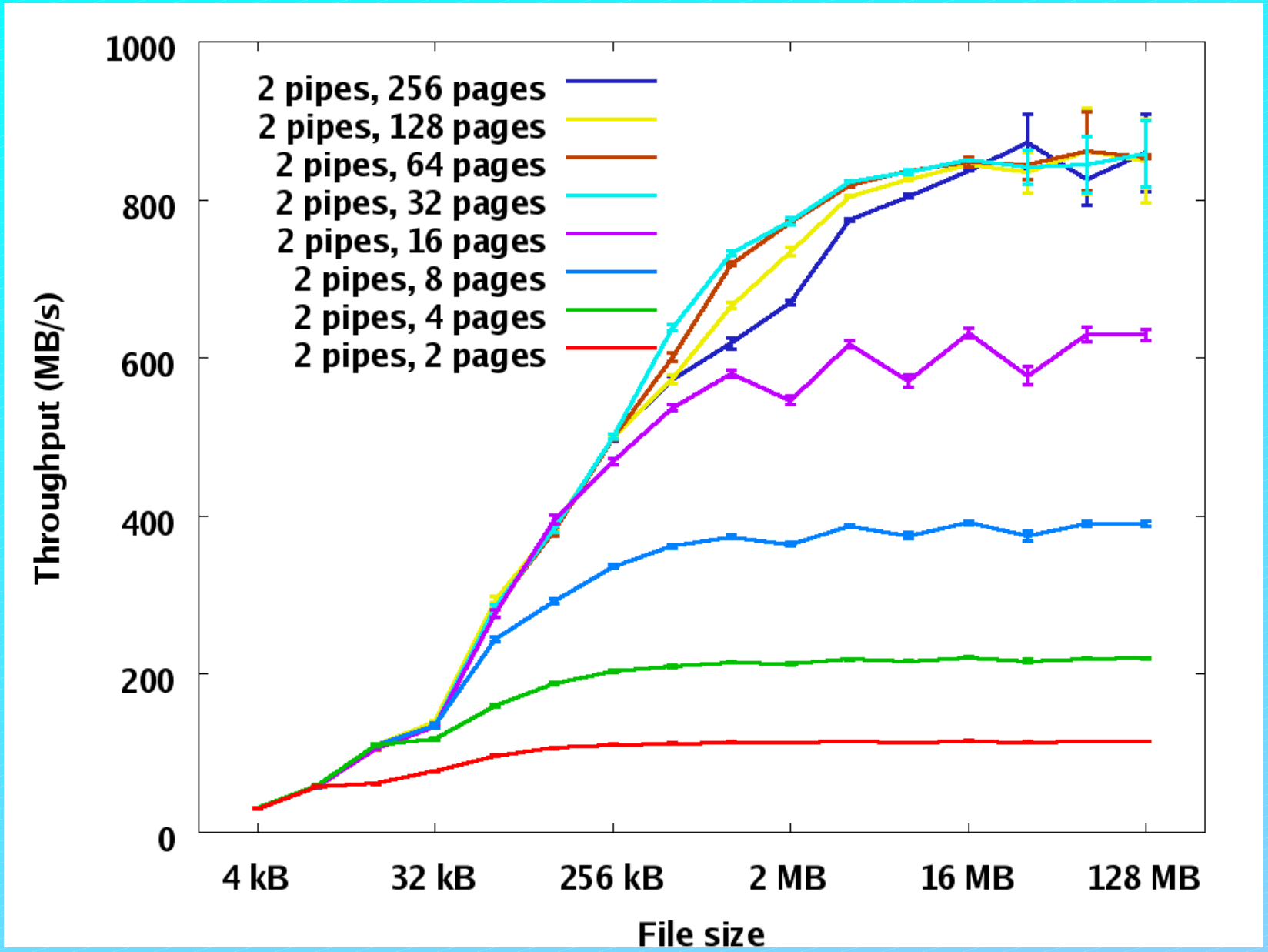


Traditional Pipelining: 1 pipe



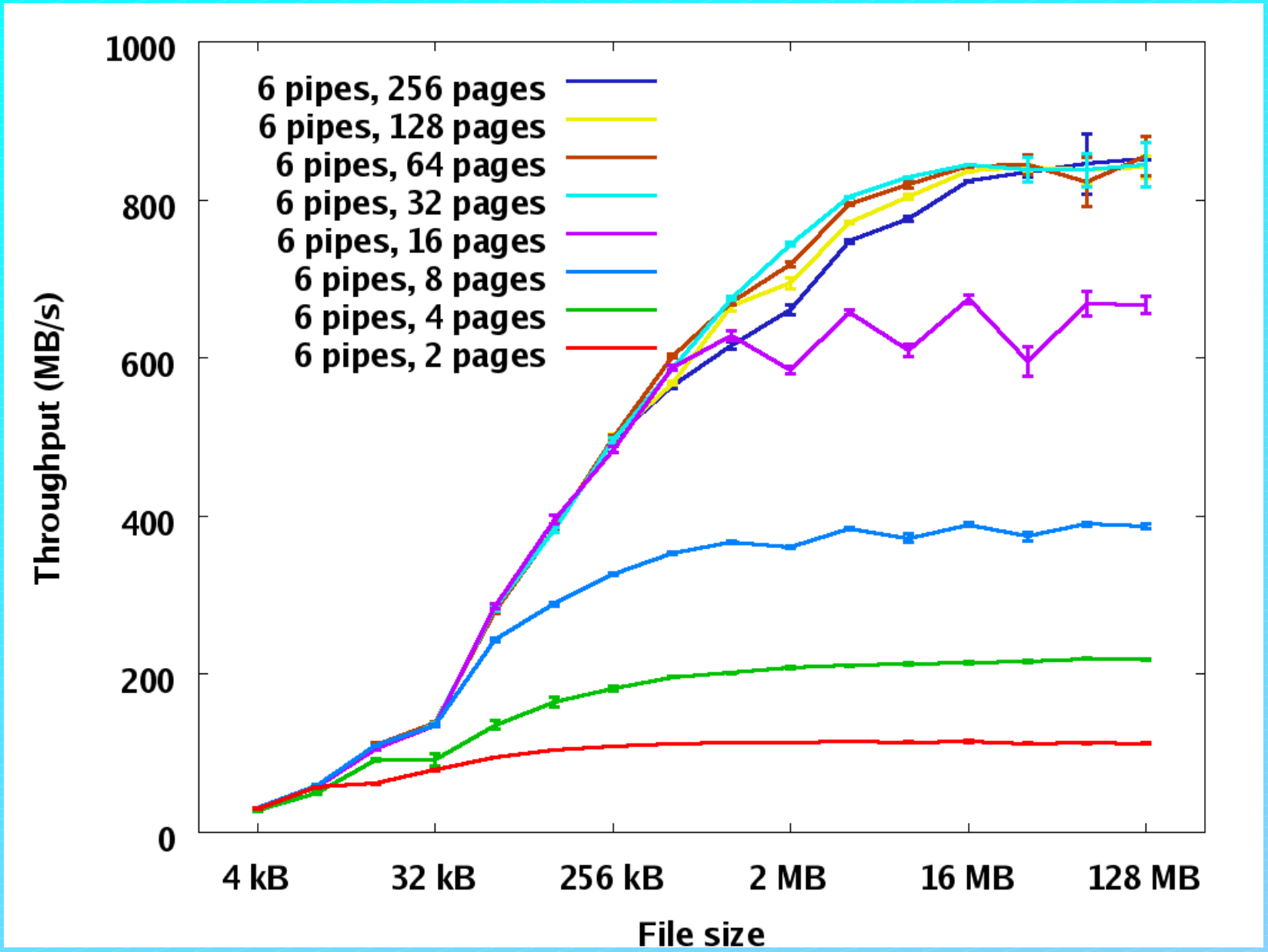
Need large operations to get good throughput.

Traditional Pipelining: 2 pipes



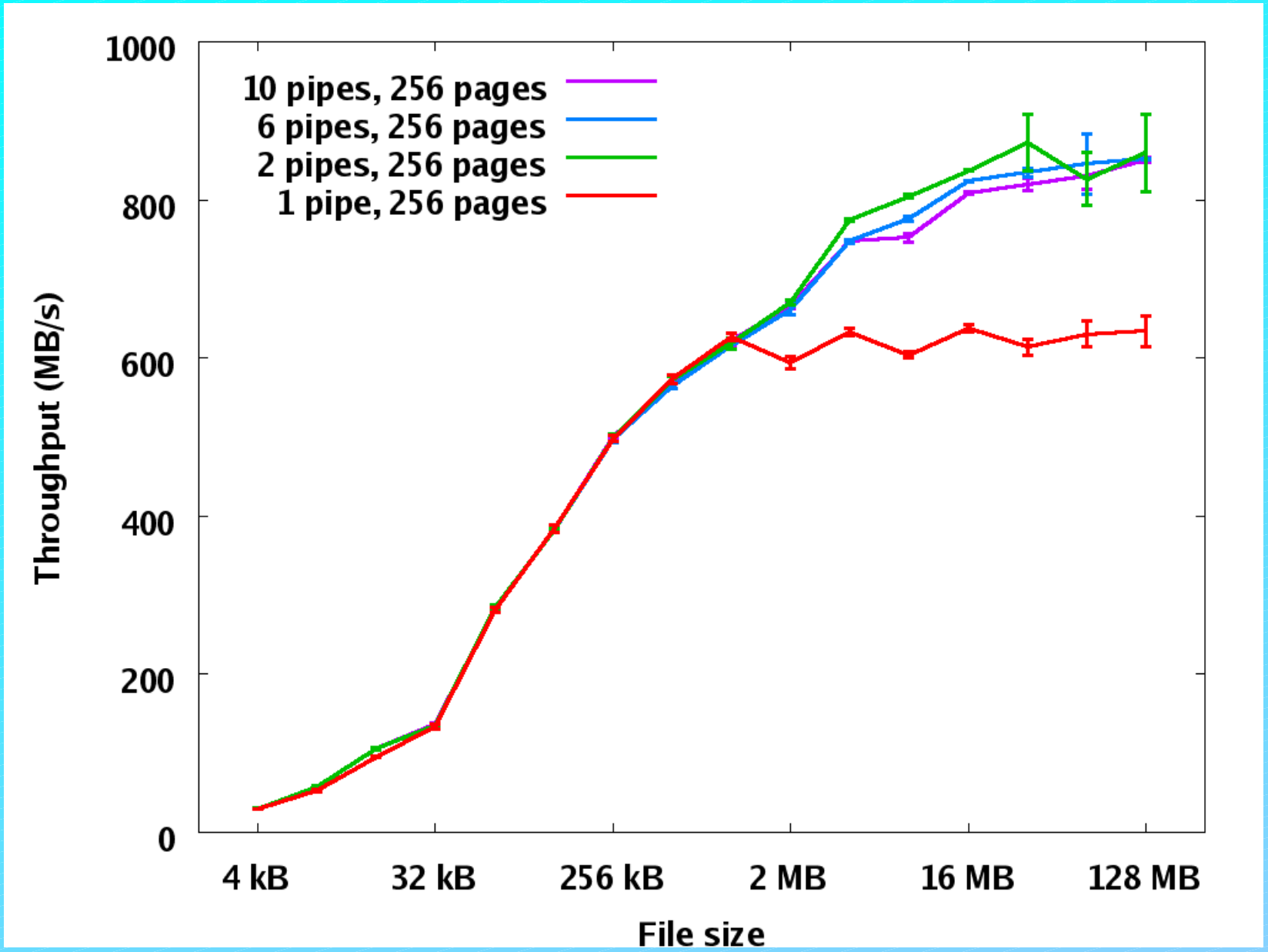
Just two pipes significantly improve throughput.

Traditional Pipelining: 6 pipes



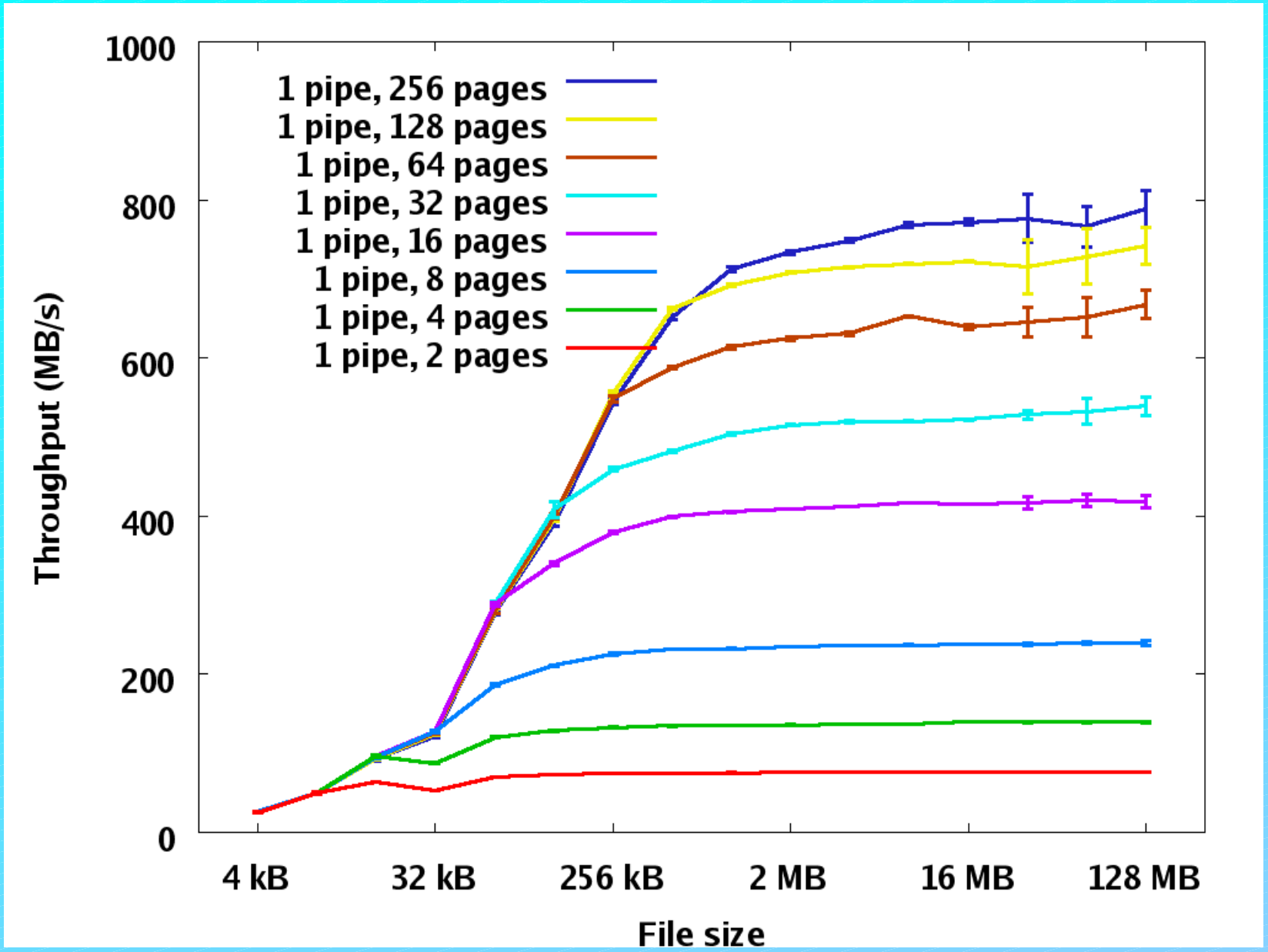
Little difference beyond two pipes.

Traditional Page count: 256 pages



Transpose of previous few graphs.

Sendfile Pipelining: 1 pipe



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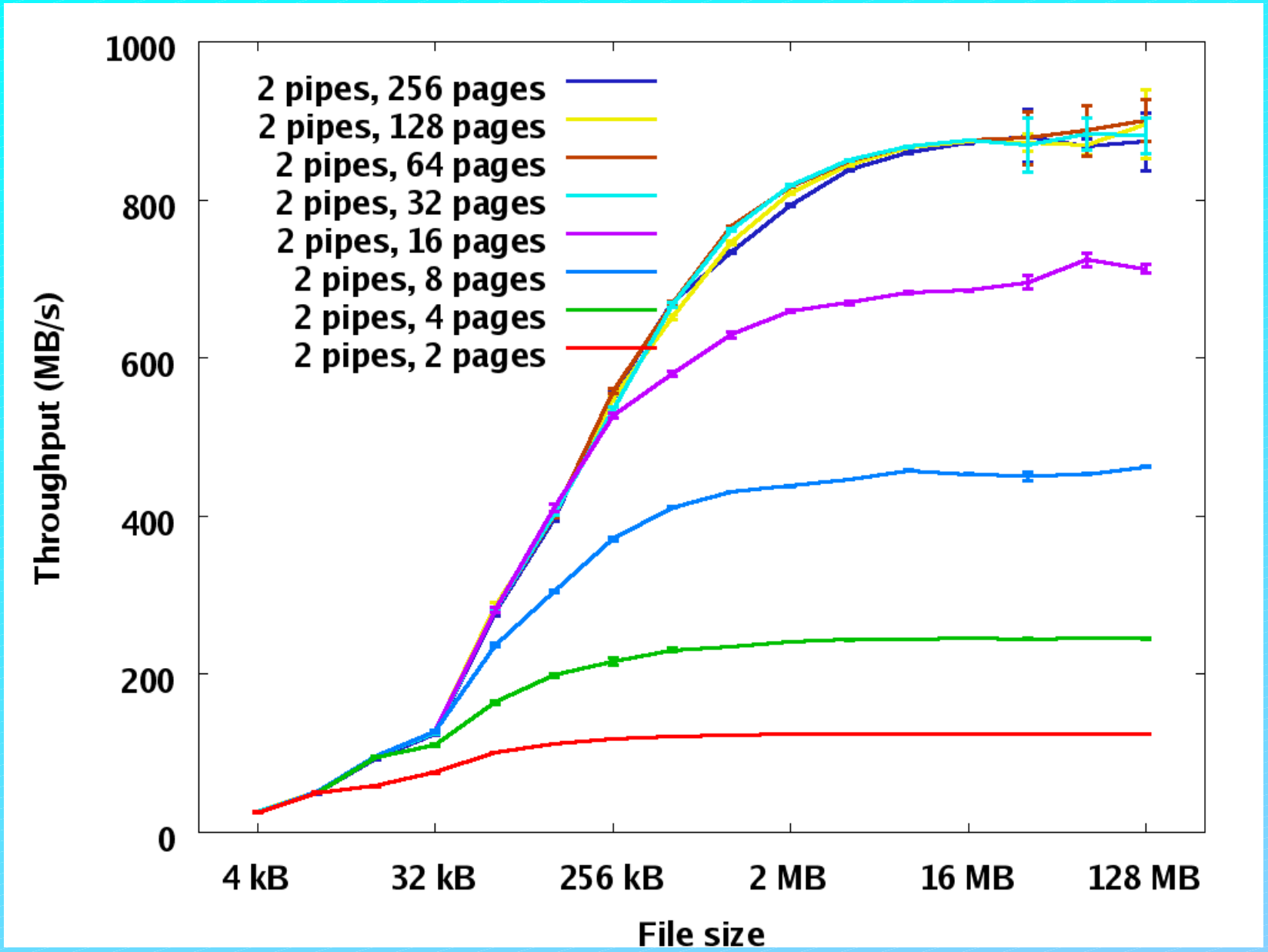
Sendfile Pipelining: 2 pipes



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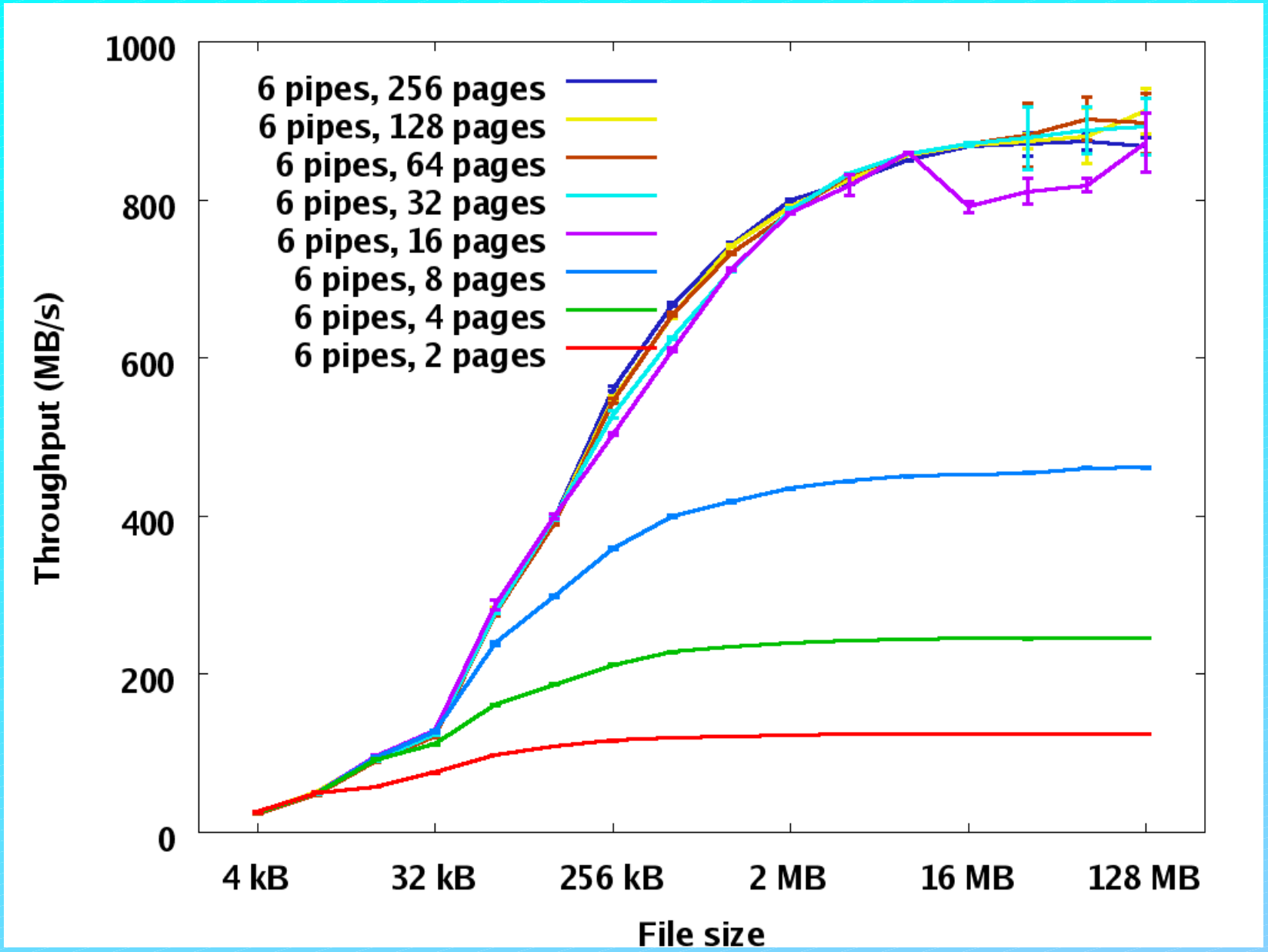

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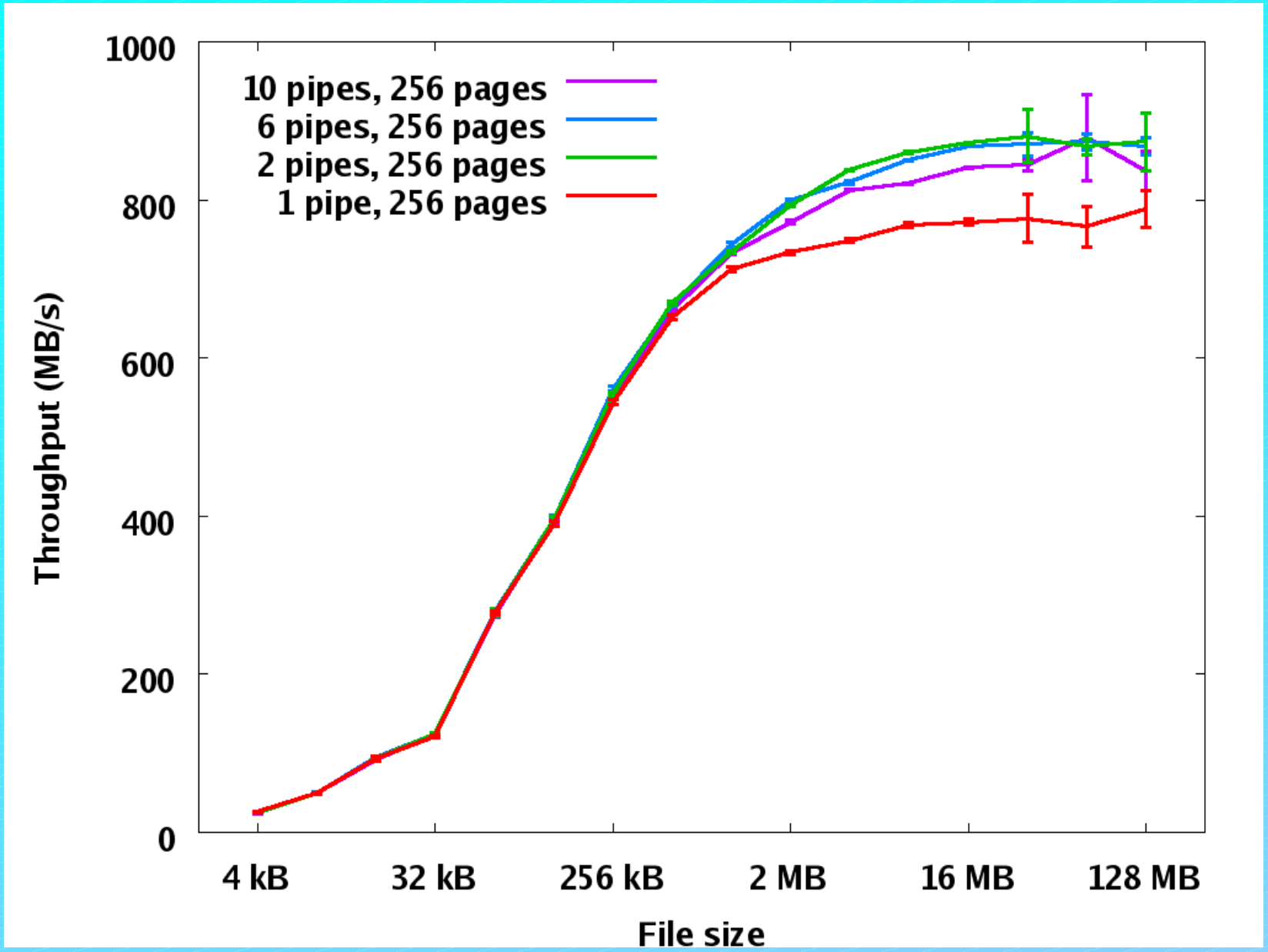
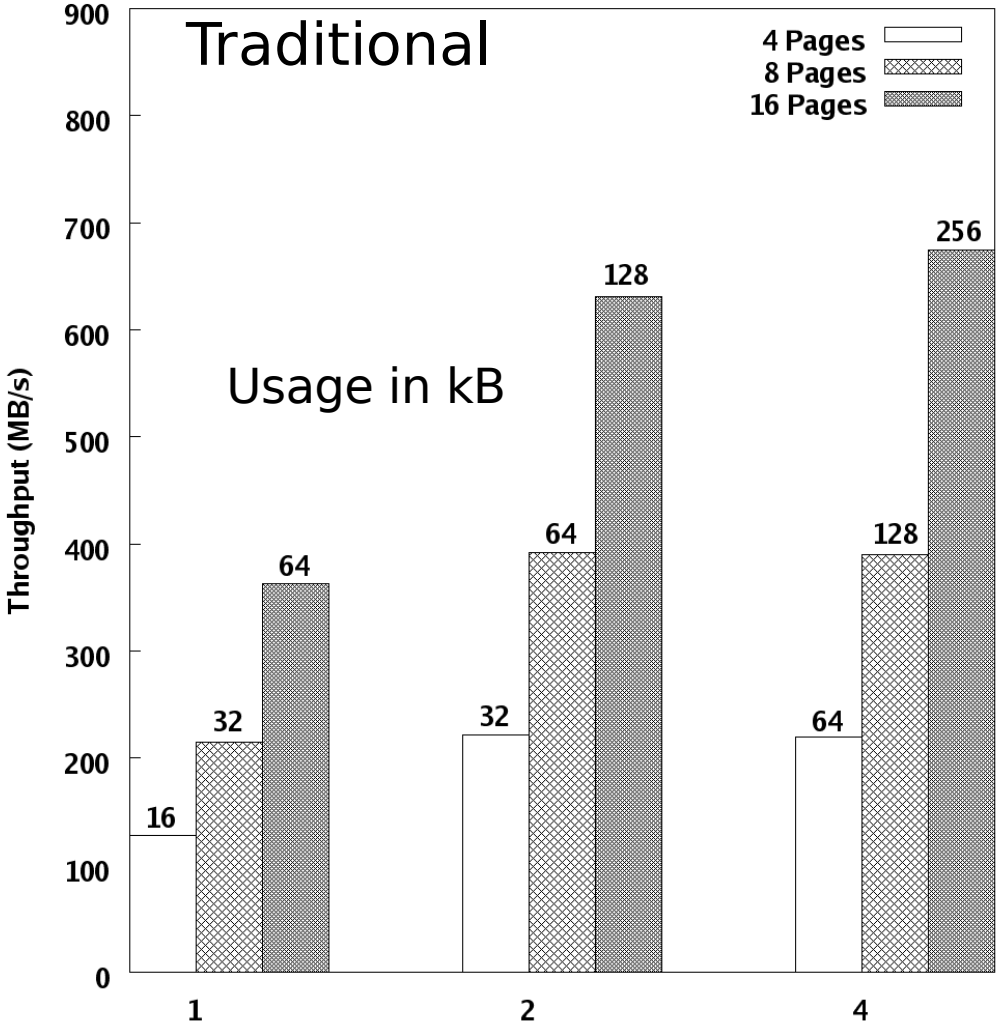


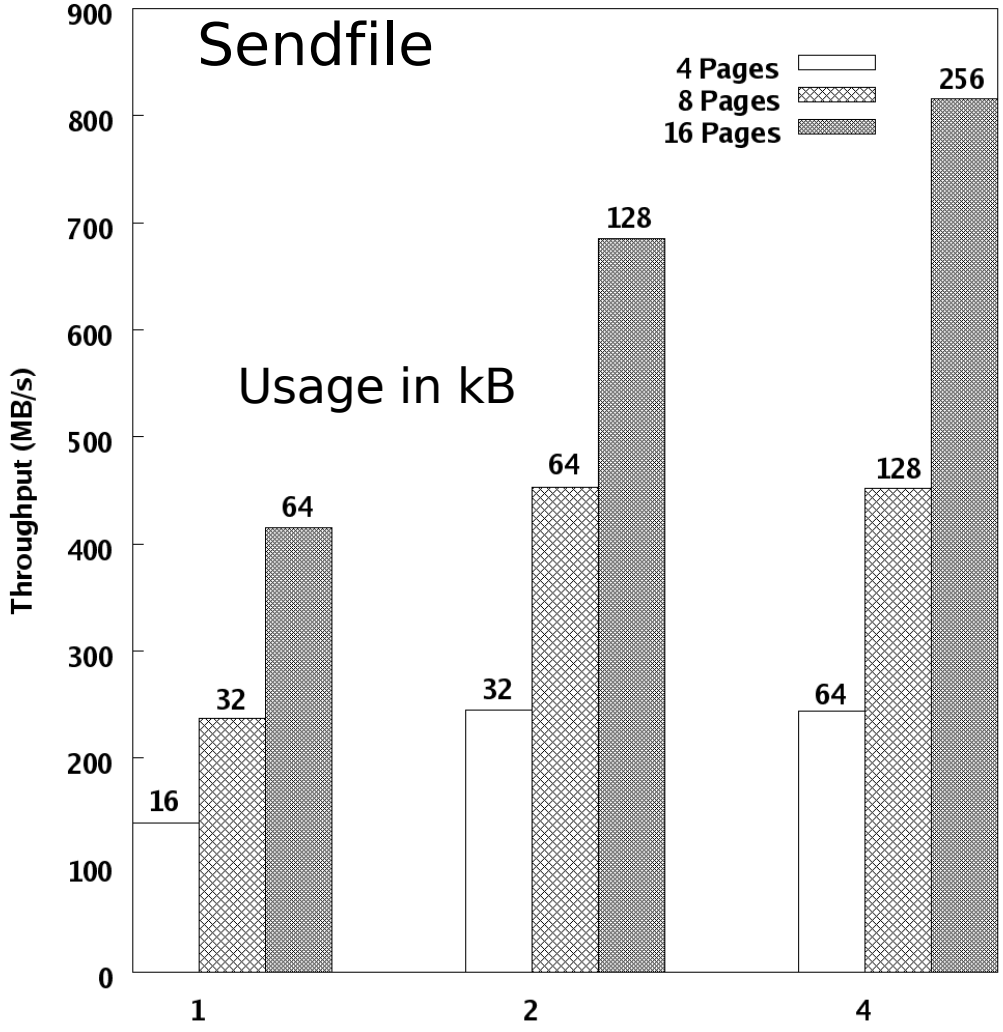
Transpose of previous few graphs.

Per-connection Memory Requirements

- Real TCP-based servers
  - Many connections
  - Small state per connection
  - Send socket buffer size offers tunable memory
- RDMA approach
  - Both static and dynamic require much more
  - Small message sizes deliver little performance
- Sendfile as a way to limit resource consumption

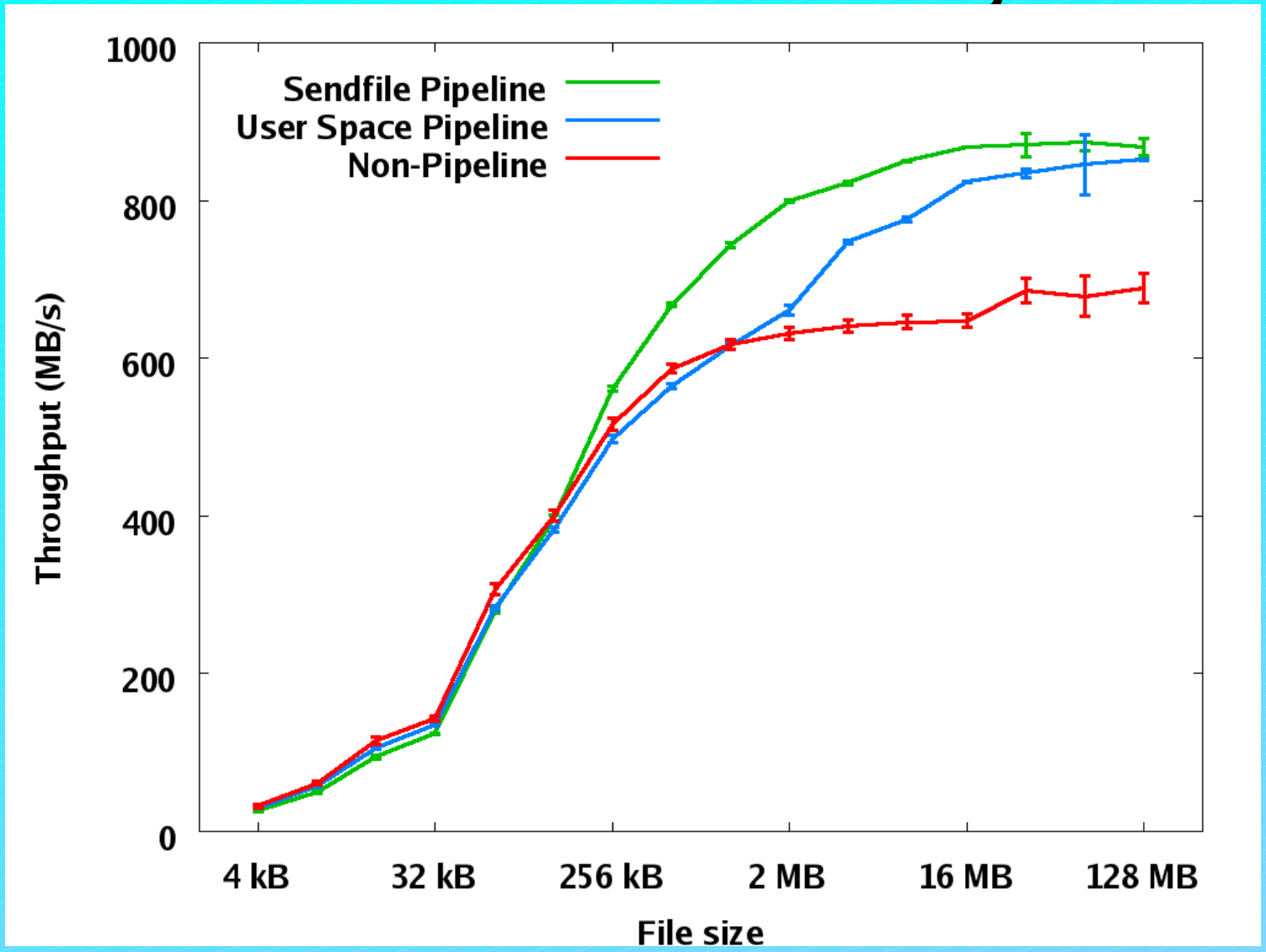
Memory Usage





RDMA performance needs memory.
Sendfile is better for small (and large) buffers).

Results Summary



All dynamic registration.
Pipelining: 6 pipes, 256 pages each (1 MB).
At higher network speeds, gap should enlarge.
Less CPU utilization and memory overhead with sendfile.

Promising Related Work

- Registered memory allocator (Tipparaju)
  - User-space prototype
  - Could be part of kernel
  - Path to integrate with other memory functions
- Hugepages (Rex)
  - Minimizes virtual-to-physical translation
- Other in-kernel file sending (Park)
  - Even less integrated with existing OS

Conclusions

- Cautionary Tale
  - Is this really a good idea?
  - If you want to do this, our way performs best.
  - App cache, disable page cache, avoid OS bypass
- Sendfile and splice
  - Exist to work around problems in sockets API
  - RDMA has different problems
- Must consider integrated system
  - Networking
  - Memory management
  - File system