Linux Asynchronous I/O Design: Evolution & Challenges

Suparna Bhattacharyya
suparna@in.ibm.com
Senior Technical Staff Member,
Linux Technology Center
IBM Systems and Technology Lab, India
Can you guess: How many changes (lines of code) make their way into the mainline linux kernel every day?
Introduction to AIO

- **AIO overlaps processing with I/O Operations**
  - App can submit (batch) IO w/o waiting for completion
    - Separate calls for submission & completion indication
    - Pipeline operations for improved throughput

- **Improved utilization of CPU and devices**
  - Web servers, databases, I/O intensive applications
    - Avoid need for lots of threads, event driven model
  - Application and system performance
    - Adapt to dynamically varying loads
    - Optimize disk activity (e.g. combining/re-ordering requests)

*Food for thought:* What makes having lots of threads a problem?
AIO Architecture Decisions

- **External interface (API) choices**
  - Common interface for sync & async (Example ?)
  - Unique set of interfaces for AIO
    - Can address specific requirements, e.g. batch submission

- **Alternative system design principles**
  - Sync and async share a common code path
    - e.g. sync = async + wait
  - Sync and async paths diverge as needed
    - May be tuned for different performance characteristics
Linux AIO API

- **Native Linux AIO API (libaio)**
  - `io_setup, io_destroy` [queue setup/teardown]
  - `io_submit` (e.g. `IO_CMD_PREAD, IO_CMD_PWRITE`)
  - `io_getevents` [completion status notification]
  - `io_cancel`

- **POSIX AIO API (glibc)**
  - `aio_read/aio_write/aio_fsync`
  - `lio_listio`
  - `aio_cancel, aio_suspend, aio_return/aio_error`
Linux File System IO - Recap

**Generic file read**
- For each page in range
  - page_cache_readahead
  - lock_page
  - aops->readpage if not uptodate
    - map blocks & issue read
  - wait till page is unlocked (indicates IO completion)
  - copy data to user buffer

**Generic file write**
- For each page in range
  - map (and read) blocks
  - copy data from user buffer
  - mark pages dirty
- If (O_SYNC)
  - writeout dirty mapping pages (use radix tree)
  - sync meta-data updates
  - wait for writeback to complete on these pages

**Question:** Can you detect other blocking points besides the ones marked above?
(inode sem locking, journal)
Linux File System Direct IO - Recap

- **O_GRAPH option**
  - Streams entire IO direct to BIO
    - inode sem locking, consistency wrt concurrent/buffered IO

- **Block device FS direct IO**
  - Walk user pages and the file range
    - get_user_pages (pin some user buffer pages)
    - Map blocks to disk
    - Submit io (collated)
  - Wait for completion of all submitted IO
    - DIO structure (tracks count of BIOs)
  - Post-processing for completed IO (dirty pages)

**Question:** Can you detect other blocking points besides the ones marked here?
Alternate Design Models for AIO

- **Offload entire IO to thread pools**
  - User level threads (e.g. glibc implementation)
  - Kernel threads

- **Fully async state machine for every operation**
  - Series of event driven non-blocking steps
  - Map user buffers to process context indep. form

- **Hybrid approach with split phase I/O**
  - Async submission, pool of threads to wait for completion
    - Per-address space threads for user context dependencies
    - e.g. SGI KAIO
Linux AIO Evolution

- POSIX AIO implementation in glibc
- SGI KAIO patches
- Linux 2.4 distro add on patches (RHEL, SLES)
  - General FSAIO
- Linux 2.6 mainline
  - AIO Direct IO
- Linux 2.6 external patches
  - General FSAIO, AIO-epoll, POSIX AIO enablement
  - Syslets & threadlets (general async system calls)
Linux Kernel 2.6 AIO – Basic Infrastructure

- **Data structures**
  - IO context (ioctx)
  - IO control block (iocb)
  - Ring buffer - completion events
  - AIO workqueue

- **A few implementation issues**
  - Tricky race conditions (submit/complete/cancel paths)
  - Latency, fairness, batching, ordering
  - Resource limits and scaling
  - Process exit conditions
Linux 2.6 – Asynchronous Direct IO

- **IO completion step async**
  - Return -EIOCBQUEUED after all IO is submitted
    - BIO completion callback completes iocb from interrupt context when entire DIO is done
  - Workqueue for post-processing which cannot be from interrupt context
    - Optimization: mark pages dirty before IO, redirty if needed

- **Caveats**
  - Multiple potential blocking points not converted to async
    - Works in practice for special requirement of databases
  - DIO code fragile, AIO-DIO error handling messy

*Quick Check:* Can you identify the AIO design model used here?
AIO Results – OLTP example

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Relative throughput</th>
<th>Page cleaner writes (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 page cleaner with AIO</td>
<td>133</td>
<td>100</td>
</tr>
<tr>
<td>55 page cleaners without AIO</td>
<td>122</td>
<td>70</td>
</tr>
</tbody>
</table>

- Update-intensive OLTP database workload, Derived from a TPC benchmark, but in no way comparable to any TPC results
- DB2 V8, Linux 2.6.1, 2-way AMD Opteron, QLogic 2342 FC, 2 storage servers x 8 disk enclosures x 14 disks each, RAID-0 configuration, stripe size 256KB
Generalized File System AIO – Linux 2.4 patches

- **Work-to-do callback driven async state machine**
  - (Almost) fully asynchronous but complex & hard to debug

- **Separate code paths for sync and async**
  - Allow special tuning for AIO, but duplication => maintainability issues

- **Pin user buffers**
  - Avoids extra threads for completing IO in caller's context but causes inefficient utilization of TLB for small buffers

- **Per filesystem impact**
  - *Why does that matter?*
Linux wait queue mechanism - Recap

- **Basic mechanism**
  - `wait_queue_head`
  - `wait_queue_t`
    - `wait_queue_function`, task to wakeup
  - `prepare_to_wait()`, `finish_wait()`, `wakeup()`
    - Flags: `TASK_INTERRUPTIBLE`, `TASK_UNINTERRUPTIBLE`
  - `io_schedule()`

- **Hashed wait queues**
  - Filtered wakeups
  - Example: page wait queue

**Question:** What purpose does the `wait_queue_function` serve?
Generalized File System AIO – Linux 2.6 patches

- **Retry based AIO model**
  - Convert main blocking points to retry exits in AIO context
    - Return no. of bytes completed or -EIOCBRETRY
  - Series of non-blocking iterations through an IO request
    - async wait callback schedules reissue of `fop->aio_read/write` with modified arguments representing the remaining IO
  - Retry threads take on caller's address space (use_mm)

- **AIO and Sync IO share a common code path**
  - AIO = Sync IO – wait + retry (vs Sync IO = AIO + wait)
    - e.g. `iocb = container_of(current_wait())` in AIO context

**Question:** Is there a pre-requisite for the retry model to be applicable?
Question: How would IO cancellation work in the retry model?
Filesystem AIO Results (Random read/write)

- Filesystem: Ext3, blocksize: 4KB, file: 1GB
- 4-way Pentium(tm) III, 700MHz, 512MB, AIC7896 Ultra2 SCSI
- Interesting issues: IO ordering with readahead, writeback & concurrency
Combining Network & File AIO – Linux 2.6 patches

- **Typical event loop**
  - Epoll (scalable file event polling) EPOLL_CTL_ADD/DEL
  - Socket read/write
    - O_NONBLOCK (readiness to send, available data to read)

- **Experimental**
  - AIO epoll: IO_CMD_EPOLL_WAIT
  - Simulating AIO using async poll & O_NONBLOCK retries
  - Kevent

- **Eventfd (now in mainline, 2.6.22 onwards)**

**Food for thought:** What makes network IO and file IO so different? Why have so many alternatives emerged?
Building POSIX AIO over Kernel AIO – Linux 2.6 patches

- Signal notification
- lio_listio
  - IO_CMD_GROUP
- aio_cancel_fd

- AIO support for all types of file-descriptors
  - Fallback implementation
Syslets & Threadlets: Generalized asynchronous systems calls – Linux 2.6 patches

- “Cache miss” concept applied to threading
  - On-demand parallelism (Only if the original context blocks)
  - Switch caller's user space context to a cache miss thread which continues user space execution without stopping
    - Spares users from setting up, sizing and feeding a thread pool

- Threadlets (“Optional threads”)
  - Small functions of execution

- Syslets
  - Small, kernel-side, scripted "syscall plugins"
“So all in one, I used to think that AIO state-machines have a long-term place within the kernel, but with syslets I think I've proven myself embarrassingly wrong =B-)

- Ingo Molnar, Feb 2007

**Food for thought:** Are there real situations where the overheads matter?
Observations

- Many challenges beyond conversion to async
  - API decisions, compatibility implications
  - AIO exposes scenarios and IO patterns less likely with synchronous workloads
    - Inherent concurrency, contextual assumptions

- Shaped by real use cases that matter
  - AIO direct IO driven by database requirements

Food for thought: Why has getting real use cases been a challenge?
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