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Linux Asynchronous I/O Design: Evolution & Challenges

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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

Question: Can you detect other blocking points besides the ones marked above ?

- **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

(inode sem locking, journal)

Linux File System Direct IO - Recap

- **O_DIRECT 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

Quick Check: Can you identify the AIO design model used here ?

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

AIO Results – OLTP example

Configuration	Relative throughput	Page cleaner writes (%)
1 page cleaner with AIO	133	100
55 page cleaners without AIO	122	70

- 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

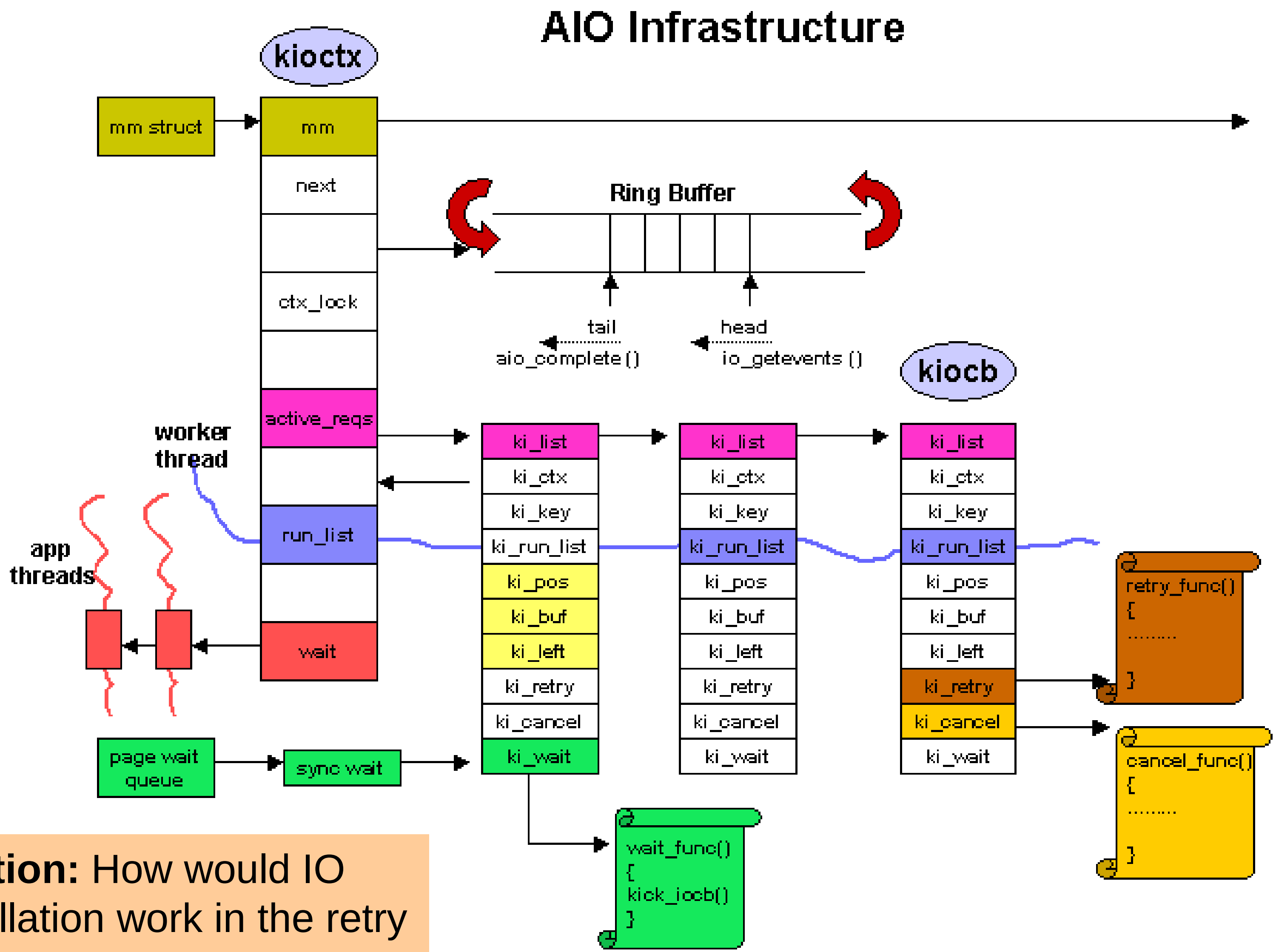
- **Basic mechanism**
  - wait_queue_head
  - wait_queue_t
    - wait_queue_function, task to wakeup
  - prepare_to_wait(), finish_wait(), wakeup()
    - Flags: TASK_INTERRUPTIBLE, TASK_UNINTERRUPTIBLE
  - io_schedule()
- **Hashed wait queues**
  - Filtered wakeups
  - Example: page wait queue

Question: What purpose does the wait_queue_function serve ?

Generalized File System AIO – Linux 2.6 patches

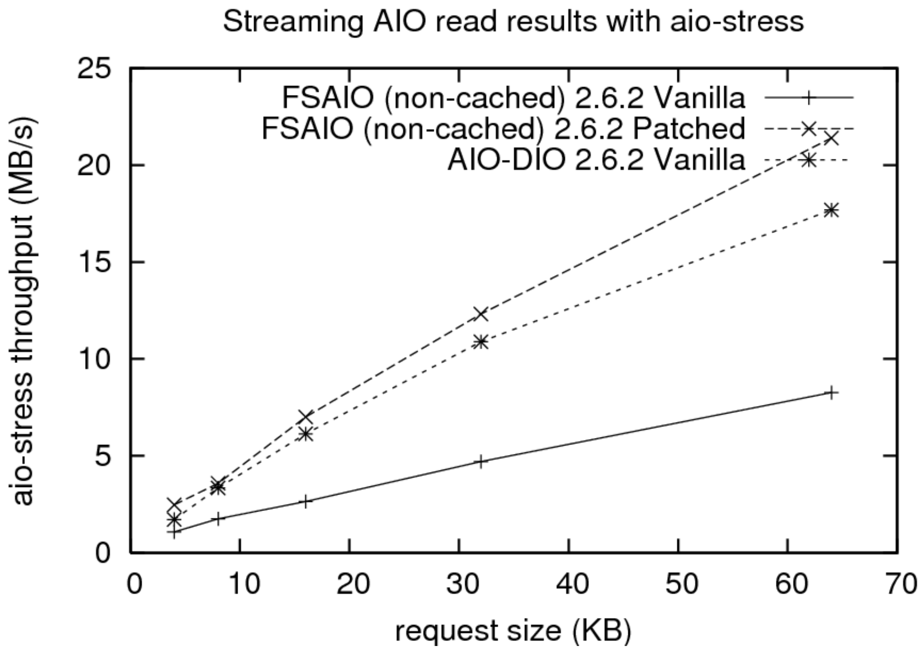
- **Retry based AIO model**
  - Convert main blocking points to retry exits in AIO context
    - Return no. of bytes completed or -EIOCBRETRY
  - Series of non-blocking iterations through an IO request
    - async wait callback schedules reissue of ***fop->aio_read/write*** with modified arguments representing 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

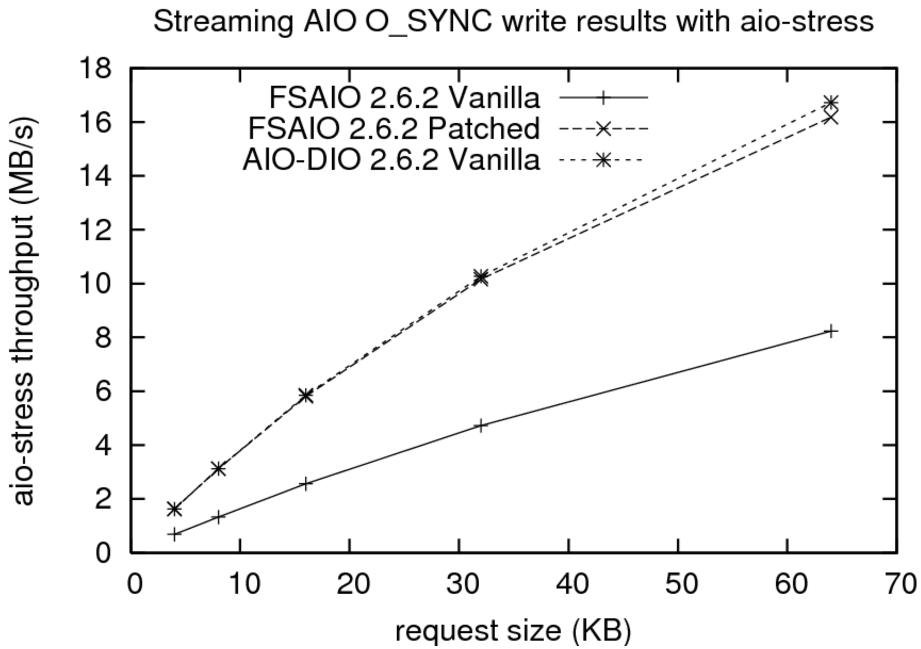
Question: Is there a pre-requisite for the retry model to be applicable ?



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 embarrasingly 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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