YAFFS
A NAND flash filesystem

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Project Genesis

- TCL needed a reliable FS for NAND
- Charles Manning is the man
- Considered Smartmedia compatibile scheme (FAT+FTL)
- Considered JFFS2
  - Better than FTL
  - High RAM use
  - Slow boot times

History

- Decided to create 'YAFFS' - Dec 2001
- Working on NAND emulator - March 2002
- Working on real NAND (Linux) - May 2002
- WinCE version - Aug 2002
- ucLinux use - Sept 2002
- Linux rootfs - Nov 2002
- pSOS version - Feb 2003
- Shipping commercially - Early 2003
- Linux 2.6 supported - Aug 2004
- YAFFS2 - Dec 2004
- Checkpointing - May 2006

Flash primer - NOR vs NAND

	NOR flash	NAND flash
Access mode:	Linear random access	Page access
Replaces:	ROM	Mass Storage
Cost:	Expensive	Cheap
Device Density:	Low (64MB)	High (1GB)
Erase block size:	8k to 128K typical	32x512b / 64x2K pages
Endurance:	100k to 1M erasures	10k to 100k erasures
Erase time:	1second	2ms
Programming:	Byte by Byte, no limit on writes	Page programming, must be erased before re-writing
Data sense:	Program byte to change 1s to 0s. Erase block to change 0s to 1s	Program page to change 1s to 0s. Erase to change 0s to 1s
Write Ordering:	Random access programming	Pages must be written sequentially within block
Bad blocks:	None when delivered, but will wear out so filesystems should be fault tolerant	Bad blocks expected when delivered. More will appear with use. Thus fault tolerance is a necessity.
OOB data:	No	Yes (16 bytes)

NAND reliabilty

NAND is unreliable - bad blocks, data errors
Affected by temp, storage time, manufacturing, voltage

- Program/erase failure
  - Detected in hardware. YAFFS copies data and retires block
- Charge Leakage - bitrot over time
  - ECC - Error Correction Codes
- Write disturb: (extra bits set to 0 in page/block)
  - YAFFS2 minimises write disturb (sequential block writes, no re-writing)
- Read disturb, other pages in block energised.
  - minor effect - needs 10*endurance reads to give errors
  - ECC (not sufficient)
  - count page reads, rewriting block at threshold
  - Read other pages periodically (e.g. every 256 reads)

MLC makes all this worse - multiple program and read voltages

Mechanisms to deal with NAND problems

	Chip Fault	Degre-dation	Prog/Erase failure	Leakage	Write Disturb	Read Disturb
NAND self-check	Yes		Yes			
Block Retirement	Yes	Yes	Yes			
Wear Levelling		Yes				
Write Verification					Yes	
Read counting /re-write						Future
Infrequent Read Checking				Future	Future	Future
ECC		Yes		Yes	Yes	Yes

Design approach

- OS and compiler neutral
- Portable - OS interface, guts, hardware interface, app interface
- Log-structured - Tags break down dependence on physical location
- Configurable - chunk size, file limit, OOB layout, features
- Single threaded (don't need separate GC thread like NOR)
- Follow hardware characteristics (OOB, no re-writes)
- Developed on NAND emulator in userspace
- Abstract types allow Unicode or ASCII operation

Terminology

- Flash-defined
  - Page - 2k flash page (512 byte YAFFS1)
  - Block - Erasable set of pages (typically 64 on 2K NAND)
- YAFFS-defined
  - Chunk - YAFFS tracking unit.
    usually==page.
    Can be bigger, e.g. 2x2K NAND in parallel as 4K chunks)

Process

- Each file has an id - equivalent to inode. id 0 indicates 'invalid'
- File data stored in chunks, same size as flash pages (2K/512 bytes)
- Chunks numbered 1,2,3,4 etc - 0 is header.
- Header gives type (device/file/dir) and hold mode/uid/length etc
- Each flash page is marked with file id and chunk number
- These tags are stored in the OOB - file id, chunk number, write serial/sequence number, tag ECC and bytes-in-page-used
- When changing a file the relevant chunks are replaced by writing new pages with new data but same tags - the old page is marked 'discarded'
- Pages have a serial number incremented on write (2-bit serial in YAFFS1, sequence in YAFFS2). Allows crash-recovery when two pages have same tags.
- Discarded blocks are garbage-collected.
- Deleted items placed in 'deleted' dir (YAFFS2)

Log-structured Filesystem (1)

Imagine flash chip with 4 pages per block.
First we'll create a file.

Flash Blocks

Block	Chunk	ObjId	ChunkId	DelFlag	Comment
0	0	500	0	Live	Object header for this file (length 0)

Next we write a few chunks worth of data to the file.

Flash Blocks

Block	Chunk	ObjId	ChunkId	DelFlag	Comment
0	0	500	0	Live	Object header for this file (length 0)
0	1	500	1	Live	First chunk of data
0	2	500	2	Live	Second chunk of data
0	3	500	3	Live	Third chunk of data

Log-structured Filesystem (2)

Next we close the file. This writes a new object header for the file. Notice how the previous object header is deleted.

Flash Blocks

Block	Chunk	ObjId	ChunkId	DelFlag	Comment
0	0	500	0	Del	Obsoleted object header (length 0)
0	1	500	1	Live	First chunk of data
0	2	500	2	Live	Second chunk of data
0	3	500	3	Live	Third chunk of data
1	0	500	0	Live	New object header (length n)

Log-structured Filesystem (3)

Let's now open the file for read/write, overwrite part of the first chunk in the file and close the file. The replaced data and object header chunks become deleted.

Flash Blocks

Block	Chunk	ObjId	ChunkId	DelFlag	Comment
0	0	500	0	Del	Obsoleted object header (length 0)
0	1	500	1	Del	Obsoleted first chunk of data
0	2	500	2	Live	Second chunk of data
0	3	500	3	Live	Third chunk of data
1	0	500	0	Del	Obsoleted object header
1	1	500	1	Live	New first chunk of file
1	2	500	0	Live	New object header

Log-structured Filesystem (5)

Now let's resize the file to zero by opening the file with O_TRUNC and closing the file. This writes a new object header with length 0 and marks the data chunks deleted.

Flash Blocks

Block	Chunk	ObjId	ChunkId	DelFlag	Comment
0	0	500	0	Del	Obsoleted object header (length 0)
0	1	500	1	Del	Obsoleted first chunk of data
0	2	500	2	Del	Second chunk of data
0	3	500	3	Del	Third chunk of data
1	0	500	0	Del	Obsoleted object header
1	1	500	1	Del	Deleted first chunk of file
1	2	500	0	Del	Obsoleted object header
1	3	500	0	Live	New object header (length 0)

Note all the pages in block 0 are now marked as deleted.
So we can now erase block 0 and re-use the space.

Log-structured Filesystem (6)

We will now rename the file.
To do this we write a new object header for the file

Flash Blocks

Block	Chunk	ObjId	ChunkId	Del	Comment
0	0				Erased
0	1				Erased
0	2				Erased
0	3				Erased
1	0	500	0	Del	Obsoleted object header
1	1	500	1	Del	Deleted first chunk of file
1	2	500	0	Del	Obsoleted object header
1	3	500	0	Del	Obsoleted object header
2	0	500	0	Live	New object header showing new name

YAFFS2

- Specced Dec 2002, working Dec 2004
- Designed for new hardware:
  - >=1k page size
  - no re-writing
  - simultaneous page programming
  - 16-bit bus on some parts
- Main difference is ‘discarded’ status tracking
- ECC done by driver (MTD in Linux case)
- Extended Tags (Extra metadata to improve performance)
- RAM footprint 25-50% less
- faster (write 1-3x, read 1-2x, delete 4-34x, GC 2-7x)

YAFFS2 - Discarded status mechanism

- Zero re-writes means can't use 'discarded' flag
- Genuinely log-structured
- Instead track block allocation order (with sequence number)
- Delete by making chunks available for GC and move file to special 'unlinked' directory until all chunks in it are 'stale'
- GC gets more complex to keep 'sense of history'
- Scanning runs backwards - reads sequence numbers chronologically

Filesystem Limits

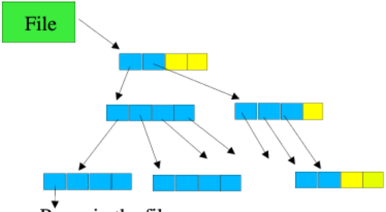
- YAFFS1
  - 2^{18} files (>260,000)
  - 2^{20} max file size (512MB)
  - 1GB max filesystem size
- YAFFS2 - All tweakable
  - 2GB max file size
  - filesystem max size set by RAM footprint (4TB flash needs 1GB RAM)
  - 4GB max filesystem size set by MTD (32-bit)
  - 8GB shipping, 16GB tested

OOB data

- YAFFS1:
  - Derived from Smartmedia, (e.g byte 5 is bad block marker)
  - 16 bytes: 7 tags, 2 status, 6 ECC
  - YAFFS/Smartmedia or JFFS2 format ECC
- YAFFS2:
  - 64 bytes available in 2k page
  - MTD-determined layout (on linux)
  - MTD or hardware does ECC - 38 bytes free on 2.6.21
  - Tags normally 28 bytes (16 data, 12ecc)
  - Sometimes doesn't fit (eg oneNAND - 20 free)

RAM Data Structures

- Not fundamental - needed for speed
- Yaffs_Object - per file/directory/link/device
- T-node tree covering all allocated chunks
  - As the file grows in size, the levels increase.
  - The T-nodes are 32 bytes. (16bytes on 2k arrays <=128MB)
  - Level 0 is 16 2-byte entries giving an index to chunkId.
  - Higher level T-nodes are 8 4-byte pointers to other tnodes
  - Allocated in blocks of 100 (reduced overhead & fragmentation)



Pages in the file

RAM usage

- Level0-Tnodes:

Chunksize	RAM use/MB NAND	256MB NAND
512b	4K	1MB
2k	1K	256K
4k	0.5K	128K

  Can change chunk size, and/or parallel chips.
- Higher-level Tnodes: 0-Tnodes/8, etc
- Objects: 24bytes (+17 with short name caching) per file
- For 256MB 2K chunk NAND with 3000 files/dirs/devices
  - 128k chunks needs 18bits per Tnode cell, so
  - Level 0-Tnodes: 288K
  - Level 1-Tnodes: 36K
  - Level 2-Tnodes: 5K
  - Objects: 120K
  - 449K total

Partitioning

- Internal - give start and end block
- MTD partitioning (partition appears as device)

Checkpointing

- RAM structures saved on flash at unmount (10 blocks)
- Structures re-read, avoiding boot scan
- sub-second boots on multi-GB systems
- Invalidated by any write
- Lazy Loading also reduces mount time.

Garbage Collection and Threads

- Single threaded - Gross locking, matches NAND
- 3 blocks reserved for GC (384K)
- If no deleted blocks, GC dirtiest
- Soft Background deletion:
  - Delete/Resize large files can take up to 0.5s
  - Incorporated with GC
  - Spread over several writes
- GC is determinsitic - does one block for each write (default)
- Worst case - nearly full disk, blocks have n-1 chunks valid
- Can give GC own thread, so operates in 'dead time'

Caching

- Linux VFS has cache, WinCE and RTOS don't
- YAFFS internal cache
  - 15x speed-up for short writes on WinCE
  - Allows non-aligned writes
  - `while(program_is_being_stupid)`
    `write(f,buf,1);`
- Choose generic read/write (VFS) or direct read/write (MTD)
  - Generic is cached (*usually* reads much faster 10x, writes 5% slower)
  - Direct is more robust on power fail

ECC

- Needs Error Correction Codes for reliable use
- ECC on Tags and data
- 22bits per 256 bytes, 1-bit correction, 2-bit detection
- CPU/RAM intensive
- Lots of options:
  - Hardware or software
  - YAFFS or MTD
  - New MTD, old MTD or YAFFS/Smartmedia positioning
- Make sure bootloader, OS and FS generation all match!
- Can be disabled - not recommended!

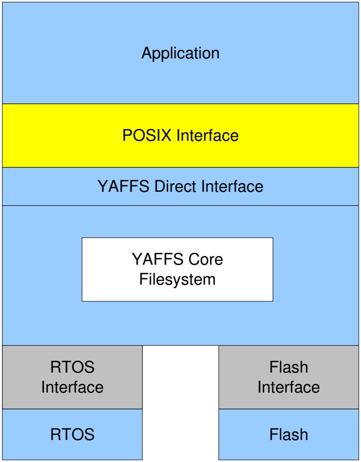
OS portability

- Native
  - Linux
  - WinCE
  - NetBSD
- Yaffs Direct Interface
  - pSOS
  - ThreadX
  - DSP_BIOS
  - Others
- Bootloaders - simple read-only YAFFS

YAFFS in use

- Formatting is simpy blanking
- `mount -t yaffs /dev/mtd0 /`
- Creating a filesystem image needs to generate OOB data
  - YAFFS1: mkyaffsimage tool - generates images
  - YAFFS2: mkyaffs2image - often customised
  - Use nandutils if possible

YAFFS Architecture



YAFFS Direct Interface

- YDI replaces Linux VFS/WinCE FSD layer
- open, close, stat, read, write, rename, mount etc
- Caching of unaligned accesses
- Port needs 5 OS functions, 6 NAND functions:
    - Lock and Unlock (mutex)
    - current time (for time stamping)
    - Set Error (to return errors)
    - Init to initialise RTOS context
    - NAND access (read, write, markbad, queryblock, initnand, erase).

Embedded system use - YAFFS Direct Interface (2)

- No CSD - all filenames in full
- Configurable case sensitivity
- No UID/GIDS
- Flat 32-bit/64-bit time
- Thread safe - one mutex
- Multiple devices - eg /ram /boot /flash

Licensing

- GPL - Good Thing (TM)
- Bootloader/headers LGPL to allow incorporation
- YAFFS in proprietary OSes (pSOS, ThreadX, VxWorks)
  - Wider use
  - Aleph One Licence - MySQL/sleepycat-style:
    ‘If you don’t want to play then you can pay’

Future Developments

- In-band tags (Done, being tested now)
- Counter Read-/write- disturb
- Continuous block summaries for checkpointing
- BCH codes instead of ECC
- RAM reduction - mixed chunk sizes
- Small files in headers - less wasted space
- Mainlining

The end

`http://yaffs.net`

Questions?