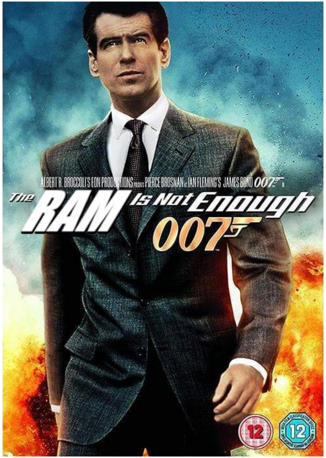
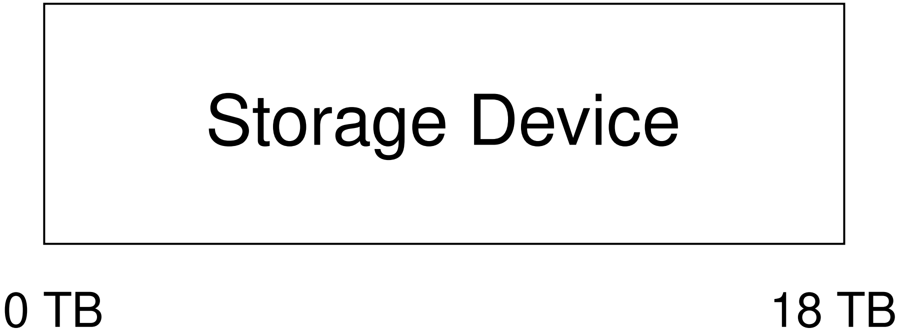
Operating Systems

File Systems

Daniel Gruss

2023-11-14


ALBERT R. BROCCOLI'S EON PRODUCTIONS
PIERCE BROSNAN
IAN FLEMING'S JAMES BOND 007
The RAM Is Not Enough
007
12
12


Storage Device
0 TB
18 TB


Storage Device
How to organize this?
0 TB
18 TB

Users view

Users view

Users view

- User does not want to see, know and understand

- User does not want to see, know and understand
  - where and

Users view

- User does not want to see, know and understand
  - where and
  - how

- User does not want to see, know and understand
  - where and
  - how
- data is stored

Users view

- User does not want to see, know and understand
  - where and
  - how
- data is stored
- must be able to refer to data

- User does not want to see, know and understand
  - where and
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→ we need names

Bild	5117 Produkte	Bewertung (Anzahl)	Testberichte	Angebote	LZ	Preis* (pro GiB)
	Samsung RDIMM 16GB, DDR3L-1600, CL11-11-11, reg ECC (M393B2G70BH0-YK0) Typ: DDR3L RDIMM 240-Pin, reg ECC • Takt: 1600MHz • Module: 1x 16GB • JEDEC: PC3L-12800R • Ranks/Bänke: dual rank, x4 • CAS Latency CL: 11 (entspricht ~13.75ns) • Row-to-Column Delay tRCD: 11 (entspricht ~13.75ns) • Row Precharge Time tRP: 11 ...	(zu wenige)		5		ab € 29,90 (€ 1,869/GB)
	Samsung RDIMM 16GB, DDR3L-1600, CL11-11-11, reg ECC (M393B2G70DB0-YK0) Typ: DDR3L RDIMM 240-Pin, reg ECC • Takt: 1600MHz • Module: 1x 16GB • JEDEC: PC3L-12800R • Ranks/Bänke: dual rank, x4 • CAS Latency CL: 11 (entspricht ~13.75ns) • Row-to-Column Delay tRCD: 11 (entspricht ~13.75ns) • Row Precharge Time tRP: 11 ...	(zu wenige)		36		ab € 35,00 (€ 2,188/GB)
	Samsung LRDIMM 32GB, DDR3-1866, CL13-13-13, ECC (M386B4G70DM0-CMA) Typ: DDR3 LRDIMM 240-Pin, ECC • Takt: 1866MHz • Module: 1x 32GB • JEDEC: PC3-14900L • Ranks/Bänke: quad rank, x4 • CAS Latency CL: 13 (entspricht ~13.93ns) • Row-to-Column Delay tRCD: 13 (entspricht ~13.93ns) • Row Precharge Time tRP: 13 ...	(zu wenige)		6		ab € 74,25 (€ 2,320/GB)
	Samsung RDIMM 32GB, DDR4-2133, CL15-15-15, reg ECC (M393A4K40BB0-CPB) Typ: DDR4 RDIMM 288-Pin, reg ECC • Takt: 2133MHz • Module: 1x 32GB • JEDEC: PC4-17000R • Ranks/Bänke: dual rank, x4 • CAS Latency CL: 15 (entspricht ~14.06ns) • Row-to-Column Delay tRCD: 15 (entspricht ~14.06ns) • Row Precharge Time tRP: 15 ...	(zu wenige)		12		ab € 79,00 (€ 2,469/GB)
	Patriot Signature Line DIMM 8GB, DDR4-2666, CL19-19-19-43 (PSD48G266681) Typ: DDR4 DIMM 288-Pin • Takt: 2666MHz • Module: 1x 8GB • JEDEC: PC4-21300U • Ranks/Bänke: single rank • CAS Latency CL: 19 (entspricht ~14.25ns) • Row-to-Column Delay tRCD: 19 (entspricht ~14.25ns) • Row Precharge Time tRP: 19 (entspricht ...	(zu wenige)		26		ab € 19,90 (€ 2,487/GB)
	Patriot Signature Line ohne Kühler DIMM 8GB, DDR3-1600, CL11 (PSD38G16002) Typ: DDR3 DIMM 240-Pin • Takt: 1600MHz • Module: 1x 8GB • JEDEC: PC3-12800U • CAS Latency CL: 11 (entspricht ~13.75ns) • Spannung: 1.5V • Modulhöhe: 30mm • Gehäuse: N/A • Beleuchtung: N/A • Besonderheiten: Standard-SPD • Garantie: (bitte ...	(zu wenige)		15		ab € 19,99 (€ 2,499/GB)
	Patriot Signature Line SO-DIMM 8GB, DDR3L-1600, CL11 (PSD38G1600L2S) Typ: DDR3L SO-DIMM 204-Pin • Takt: 1600MHz • Module: 1x 8GB • JEDEC: PC3L-12800S • CAS Latency CL: 11 (entspricht ~13.75ns) • Spannung: 1.35V • Modulhöhe: 30mm • Gehäuse: N/A • Beleuchtung: N/A • Besonderheiten: Standard-SPD • Garantie: (bitte ...	(zu wenige)		16		ab € 19,99 (€ 2,499/GB)
	Samsung RDIMM 8GB, DDR3L-1333, CL9-9-9, reg ECC (M393B1K70DH0-YH9) Typ: DDR3L RDIMM 240-Pin, reg ECC • Takt: 1333MHz • Module: 1x 8GB • JEDEC: PC3L-10667R • Ranks/Bänke: dual rank • CAS Latency CL: 9 (entspricht ~13.50ns) • Row-to-Column Delay tRCD: 9 (entspricht ~13.50ns) • Row Precharge Time tRP: 9 (entspricht ...	(zu wenige)		13		ab € 20,00 (€ 2,500/GB)

Bild	2700 Produkte	Bewertung (Anzahl)	Testberichte	Angebote	LZ	Preis* (pro TB)
	Patriot Burst Elite 1.92TB, SATA (PBE192TS25SSDR) Bauform: Solid State Drive (SSD) • Formfaktor: 2.5" • Schnittstelle: SATA 6Gb/s • Lesen: 450MB/s • Schreiben: 320MB/s • IOPS 4K lesen/schreiben: 40k/40k • Speichermodule: 3D-NAND QLC • TBW: 800TB • Zuverlässigkeitsprognose: 2 Mio. Stunden (MTBF) ...	(zu wenige)	1 Testbericht	11		ab € 103,90 (€ 54,115/TB)
	Intenso PCIe PREMIUM SSD 1TB, M.2 (3835460) Bauform: Solid State Module (SSM) • Formfaktor: M.2 2280 • Schnittstelle: M.2/M-Key (PCIe 3.0 x4) • Lesen: 2100MB/s • Schreiben: 1700MB/s • Speichermodule: 3D-NAND TLC • TBW: 600TB • Protokoll: NVMe 1.3 • Leistungsaufnahme: keine Angabe ...	(zu wenige)		40		ab € 55,99 (€ 55,990/TB)
	Intenso Top Performance SSD 2TB, SATA (3812470) Bauform: Solid State Drive (SSD) • Formfaktor: 2.5" • Schnittstelle: SATA 6Gb/s • Lesen: 520MB/s • Schreiben: 500MB/s • Protokoll: AHCI • Leistungsaufnahme: keine Angabe (maximal), keine Angabe (Betrieb), keine Angabe (Leerlauf), keine Angabe ...	(zu wenige)		41		ab € 117,03 (€ 58,515/TB)
	Patriot P210 1TB, SATA (P210S1TB25) Bauform: Solid State Drive (SSD) • Formfaktor: 2.5" • Schnittstelle: SATA 6Gb/s • Lesen: 520MB/s • Schreiben: 430MB/s • IOPS 4K lesen/schreiben: 50k/50k • Speichermodule: 3D-NAND (verschiedene Bestückungen möglich) • TBW: keine Angabe ...	(zu wenige)	1 Testbericht	35		ab € 58,89 (€ 58,890/TB)
	Intenso Top Performance SSD 1TB, SATA (3812460) Bauform: Solid State Drive (SSD) • Formfaktor: 2.5" • Schnittstelle: SATA 6Gb/s • Lesen: 520MB/s • Schreiben: 500MB/s • Protokoll: AHCI • Leistungsaufnahme: keine Angabe (maximal), keine Angabe (Betrieb), keine Angabe (Leerlauf), keine Angabe ...	★★★★★ 1 Bewertung		95		ab € 58,90 (€ 58,900/TB)
	TeamGroup CX2 SSD 2TB, SATA (T253X6002T0C101) Bauform: Solid State Drive (SSD) • Formfaktor: 2.5" • Schnittstelle: SATA 6Gb/s • Lesen: 540MB/s • Schreiben: 490MB/s SLC-Cached • Speichermodule: 3D-NAND TLC, Toshiba/WD, 64 Layer (BiCS3) • TBW: 1.6PB • Zuverlässigkeitsprognose: 1 Mio. Stunden ...	(zu wenige)	1 Testbericht	24		ab € 119,70 (€ 59,850/TB)
	Intenso Top Performance SSD 1TB, M.2 (3832460) Bauform: Solid State Module (SSM) • Formfaktor: M.2 2280 • Schnittstelle: M.2/B-M-Key (SATA 6Gb/s) • Lesen: 520MB/s • Schreiben: 500MB/s • Protokoll: AHCI • Leistungsaufnahme: keine Angabe (maximal), keine Angabe (Betrieb), keine Angabe	★★★★★ 2 Bewertungen		57		ab € 59,90 (€ 59,900/TB)

Bild	1468 Produkte	Bewertung (Anzahl)	Testberichte	Angebote	LZ	Preis* (pro TB)
	Toshiba Enterprise Capacity MG08ACA 16TB, 512e, SATA 6Gb/s (MG08ACA16TE) Formfaktor: 3.5", 26.1mm • Drehzahl: 7200rpm • Cache: 512MB • Leistungsaufnahme: 7.63W (Betrieb), 4W (Leerlauf) • Lautstärke: keine Angabe (Betrieb), 20dB(A) (Leerlauf) • Aufnahmeverfahren: Conventional Magnetic Recording (CMR), Two Dimensional …	45 Bewertungen	80 aus 1 Test	90		ab € 259,79 (€ 16,237/TB)
	Toshiba Enterprise Capacity MG09ACA 18TB, 512e, SATA 6Gb/s (MG09ACA18TE) Formfaktor: 3.5", 26.1mm • Drehzahl: 7200rpm • Cache: 512MB • Leistungsaufnahme: 8.35W (Betrieb), 4.16W (Leerlauf) • Lautstärke: keine Angabe (Betrieb), 20dB(A) (Leerlauf) • Aufnahmeverfahren: Flux Control Microwave Assisted Conventional Magnetic …	34 Bewertungen	2 Testberichte	81		ab € 295,89 (€ 16,438/TB)
	Toshiba Enterprise Capacity MG09ACA 18TB, 4Kn, SATA 6Gb/s (MG09ACA18TA) Formfaktor: 3.5", 26.1mm • Drehzahl: 7200rpm • Cache: 512MB • Leistungsaufnahme: 8.35W (Betrieb), 4.16W (Leerlauf) • Lautstärke: keine Angabe (Betrieb), 20dB(A) (Leerlauf) • Aufnahmeverfahren: Flux Control Microwave Assisted Conventional Magnetic …	(zu wenige)	2 Testberichte	2		ab € 296,79 (€ 16,488/TB)
	Seagate Exos X - X18 18TB, 512e/4Kn, SATA 6Gb/s (ST18000NM000J) Formfaktor: 3.5" • Drehzahl: 7200rpm • Cache: 256MB • Leistungsaufnahme: 6.4W (Betrieb), 5.3W (Leerlauf) • Lautstärke: keine Angabe (Betrieb), keine Angabe (Leerlauf) • Aufnahmeverfahren: Conventional Magnetic Recording (CMR) • Sektoren: 4KB mit …	25 Bewertungen	1 Testbericht	114		ab € 299,98 (€ 16,666/TB)
	Toshiba Enterprise Capacity MG07ACA 14TB, 512e, SATA 6Gb/s (MG07ACA14TE) Formfaktor: 3.5", 26.1mm • Drehzahl: 7200rpm • Cache: 256MB • Leistungsaufnahme: 7.8W (Betrieb), 4.22W (Leerlauf) • Lautstärke: keine Angabe (Betrieb), 20dB(A) (Leerlauf) • Aufnahmeverfahren: Conventional Magnetic Recording (CMR) • Sektoren: 4KB …	19 Bewertungen	2 Testberichte	103		ab € 244,29 (€ 17,449/TB)
	Seagate SkyHawk +Rescue 4TB, SATA 6Gb/s (ST4000VX007) Formfaktor: 3.5" • Drehzahl: 5900rpm • Cache: 64MB • Leistungsaufnahme: 5.5W (Betrieb), 3.2W (Leerlauf) • Lautstärke: 34dB(A) (Betrieb), 30dB(A) (Leerlauf) • Aufnahmeverfahren: Conventional Magnetic Recording (CMR) • Sektoren: 4KB mit Emulation …	18 Bewertungen		106		ab € 69,86 (€ 17,465/TB)
	Seagate Exos X - X16 16TB, 512e/4Kn, SATA 6Gb/s (ST16000NM001G) Formfaktor: 3.5" • Drehzahl: 7200rpm • Cache: 256MB • Leistungsaufnahme: 6.3W (Betrieb), 5.0W (Leerlauf) • Lautstärke: keine Angabe (Betrieb), keine Angabe (Leerlauf) • Aufnahmeverfahren: Conventional Magnetic Recording (CMR) • Sektoren: 4KB mit …	21 Bewertungen	80 aus 1 Test	118		ab € 284,94 (€ 17,809/TB)
	Seagate Exos X - X16 14TB, 512e/4Kn, SATA 6Gb/s (ST14000NM001G) Formfaktor: 3.5" • Drehzahl: 7200rpm • Cache: 256MB • Leistungsaufnahme: 6.3W (Betrieb), 5.0W (Leerlauf) • Lautstärke: keine Angabe (Betrieb), keine Angabe (Leerlauf) • Aufnahmeverfahren: Conventional Magnetic Recording (CMR) • Sektoren: 4KB mit …	9 Bewertungen	80 aus 1 Test	93		ab € 249,48 (€ 17,820/TB)

Illusions

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- **fast**, but actually slow
- **names** for files and directories, but actually just bits and bytes

Performance

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What to do when performance is bad?

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DRAM cache inside modern storage devices

Performance

What to do when performance is bad? Caches!

- DRAM cache inside modern storage devices
- Page cache in software, in the OS

Yet another cache: the page cache

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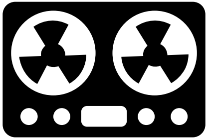
  - Pages are freed on demand
- Deduplicate pages (copy-on-write)

```
00000000: 25 50 44 46 2D 31 2E 35|0A 25 B5 ED AE FB 0A 31   %PDF-1.5.%.....1
00000010: 32 20 30 20 6F 62 6A 0A|3C 3C 20 2F 4C 65 6E 67   2 0 obj.<< /Leng
00000020: 74 68 20 31 33 20 30 20|52 0A 20 20 20 2F 46 69   th 13 0 R.   /Fi
00000030: 6C 74 65 72 20 2F 46 6C|61 74 65 44 65 63 6F 64   lter /FlateDecod
00000040: 65 0A 3E 3E 0A 73 74 72|65 61 6D 0A 78 9C ED 5D   e.>>.stream.x..]
00000050: 6D 8F 1C B7 91 FE BE BF|82 30 2E C0 2C A0 ED E5   m........0..,...
00000060: 3B D9 BE 20 86 63 FB 9C|1C 6C 24 B6 94 04 38 6D   ;.. .c...l$...8m
00000070: 10 8C 76 7B 76 27 1A CD|AC 66 66 25 CB BF FE 9E   ..v{v'...ff%....
00000080: 62 BF 4C 77 4F 93 D3 BD|A3 03 0E 97 93 EC D5 BC   b.LwO...........
00000090: B0 8A C5 AA 62 D5 53 24|9B 2B 18 C7 DF 2B 81 1F   ....b.S$.+...+..
000000A0: 5E 4B 76 FB EE E2 FD C5|4F EC FD 85 B2 0C FF 19   ^Kv.....O.......
000000B0: A9 B2 3C 97 CC 39 CE B6|05 FB 1B 5B 5F 08 46 7F   ..<..9.....[_.F
000000C0: B7 F7 EC 7A CE D9 FD 6E|B8 E1 A2 FA 58 78 97 79   ...z...n....Xx.y
000000D0: AF 98 10 99 54 BA FA 26|E7 99 E0 86 59 9E 49 EE   ....T..&....Y.I.
000000E0: 98 96 19 CF 35 E3 99 B2|AE DB C0 49 B0 B4 43 0D   ....5......I..C.
000000F0: 1C 3E F1 4C 48 93 71 2B|D1 B7 C8 3C 17 4C F2 4C   .>.LH.q+...<.L.L
00000100: 5B D1 6D A2 6D 66 A5 68|9A 08 95 09 23 3B 4D A4   [.m.mf.h....#;M.
00000110: E0 99 E5 72 B0 89 16 99|06 13 2E 33 0D 1E 3C CF   ...r.......3..<.
00000120: B4 73 9D 6E 0C 68 72 83|16 3E D3 CA 33 63 32 6B   .s.n.hr..>..3c2k
00000130: 49 B0 CC F9 BC 6C 81 C6|DE 4A 67 D8 F1 0B E8 50   I....l...Jg....P
00000140: F9 CC 41 EB 52 E6 41 3F|46 E0 5F BC 6F 8F F5 D0   ..A.R.A?F._.o...
00000150: 82 A4 2C BF E1 59 2E 74|CD DF 29 FA C3 8E 5F 80   ..,..Y.t..)..._.
00000160: BF 31 2E B3 C2 35 1D 1C|91 D7 EC 15 54 8E A1 0E   .1...5......T...
00000170: 08 D0 D8 DB 9A CC 98 1C|4D 4D 69 96 5C 64 36 C7   ......MMi.\d6.
```

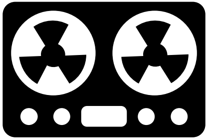
```
00000000: 46 6C 61 74 20 70 72 6F|66 69 6C 65 3A 0A 0A 45   Flat profile:..E
00000010: 61 63 68 20 73 61 6D 70|6C 65 20 63 6F 75 6E 74   ach sample count
00000020: 73 20 61 73 20 30 2E 30|31 20 73 65 63 6F 6E 64   s as 0.01 second
00000030: 73 2E 0A 20 20 25 20 20|20 63 75 6D 75 6C 61 74   s..  %   cumulat
00000040: 69 76 65 20 20 20 73 65|6C 66 20 20 20 20 20 20   ive   self
00000050: 20 20 20 20 20 20 20 20|73 65 6C 66 20 20 20 20           self
00000060: 20 74 6F 74 61 6C 20 20|20 20 20 20 20 20 20 20    total
00000070: 20 0A 20 74 69 6D 65 20|20 20 73 65 63 6F 6E 64    . time   second
00000080: 73 20 20 20 73 65 63 6F|6E 64 73 20 20 20 20 63   s   seconds    c
00000090: 61 6C 6C 73 20 20 6D 73|2F 63 61 6C 6C 20 20 6D   alls  ms/call  m
000000A0: 73 2F 63 61 6C 6C 20 20|6E 61 6D 65 20 20 20 20   s/call  name
000000B0: 0A 20 36 30 2E 30 30 20|20 20 20 20 20 30 2E 30   . 60.00      0.0
000000C0: 33 20 20 20 20 20 30 2E|30 33 20 31 36 37 37 37   3     0.03 16777
000000D0: 32 31 36 20 20 20 20 20|30 2E 30 30 20 20 20 20   216     0.00
000000E0: 20 30 2E 30 30 20 20 66|61 73 74 0A 20 32 30 2E    0.00  fast. 20.
000000F0: 30 30 20 20 20 20 20 20|30 2E 30 34 20 20 20 20   00      0.04
00000100: 20 30 2E 30 31 20 20 20|20 20 20 20 20 31 20 20    0.01        1
00000110: 20 20 31 30 2E 30 30 20|20 20 20 34 30 2E 30 30     10.00    40.00
00000120: 20 20 73 6C 6F 77 0A 20|32 30 2E 30 30 20 20 20     slow. 20.00
00000130: 20 20 20 30 2E 30 35 20|20 20 20 20 30 2E 30 31      0.05     0.01
00000140: 20 20 20 20 20 20 20 20|20 20 20 20 20 20 20 20
00000150: 20 20 20 20 20 20 20 20|20 20 20 20 20 5F 69 6E                _in
00000160: 69 74 0A 0A 20 25 20 20|20 20 20 20 20 20 20 74   it.. %         t
```

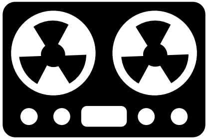
```
dgruss@hpx360dg / % mount
sysfs on /sys type sysfs (rw,nosuid,nodev,noexec,relatime)
proc on /proc type proc (rw,nosuid,nodev,noexec,relatime)
udev on /dev type devtmpfs (rw,nosuid,relatime,size=7954268k,nr_inodes=1988567,mode=755,inode64)
devpts on /dev/pts type devpts (rw,nosuid,noexec,relatime,gid=5,mode=620,ptmxmode=000)
tmpfs on /run type tmpfs (rw,nosuid,nodev,noexec,relatime,size=1602616k,mode=755,inode64)
/dev/mapper/ubuntu--vg-root on / type ext4 (rw,noatime,errors=remount-ro)
securityfs on /sys/kernel/security type securityfs (rw,nosuid,nodev,noexec,relatime)
tmpfs on /dev/shm type tmpfs (rw,nosuid,nodev,inode64)
tmpfs on /run/lock type tmpfs (rw,nosuid,nodev,noexec,relatime,size=5120k,inode64)
cgroup2 on /sys/fs/cgroup type cgroup2 (rw,nosuid,nodev,noexec,relatime,nsdelegate,memory_recursiveprot
pstore on /sys/fs/pstore type pstore (rw,nosuid,nodev,noexec,relatime)
efivarfs on /sys/firmware/efi/efivars type efivarfs (rw,nosuid,nodev,noexec,relatime)
bpf on /sys/fs/bpf type bpf (rw,nosuid,nodev,noexec,relatime,mode=700)
systemd-1 on /proc/sys/fs/binfmt_misc type autofs (rw,relatime,fd=30,pgrp=1,timeout=0,minproto=5,maxprot
mqueue on /dev/mqueue type mqueue (rw,nosuid,nodev,noexec,relatime)
hugetlbfs on /dev/hugepages type hugetlbfs (rw,relatime,pagesize=2M)
debugfs on /sys/kernel/debug type debugfs (rw,nosuid,nodev,noexec,relatime)
tracefs on /sys/kernel/tracing type tracefs (rw,nosuid,nodev,noexec,relatime)
fusectl on /sys/fs/fuse/connections type fusectl (rw,nosuid,nodev,noexec,relatime)
configfs on /sys/kernel/config type configfs (rw,nosuid,nodev,noexec,relatime)
none on /run/credentials/systemd-sysusers.service type ramfs (ro,nosuid,nodev,noexec,relatime,mode=700)
tmpfs on /run/qemu type tmpfs (rw,nosuid,nodev,relatime,mode=755,inode64)
```

accessing data



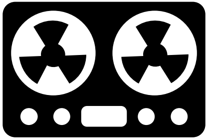
accessing data



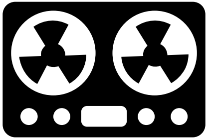


tape drives, disks, ...

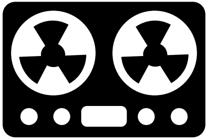
accessing data



- tape drives, disks, ...
  - sequential access

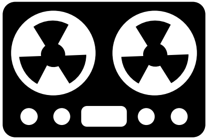


- tape drives, disks, ...
  - sequential access
  - one byte after the other



- tape drives, disks, ...
  - sequential access
  - one byte after the other
  - `seek()` other positions to access other parts

accessing data



- tape drives, disks, ...
  - sequential access
  - one byte after the other
  - `seek()` other positions to access other parts
  - random access possible, but slow

File System Workload

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Optimize for small files or large files?

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We want the best of both worlds!

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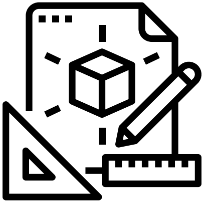

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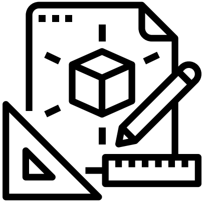

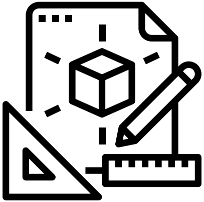

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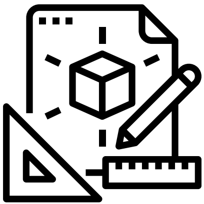

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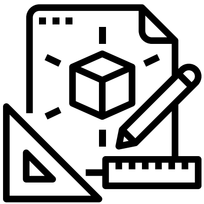

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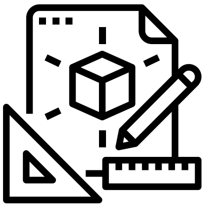

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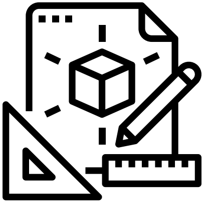

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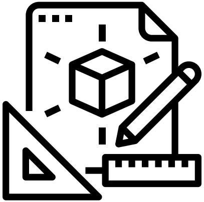

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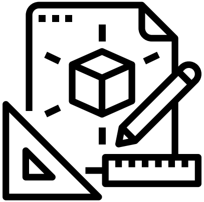

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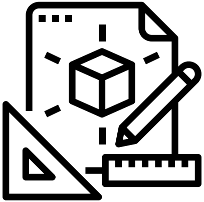

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File System Abstraction

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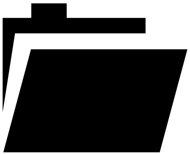

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- `/var/www/teaching/courses/os`

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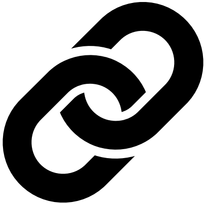

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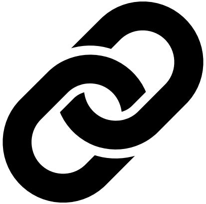

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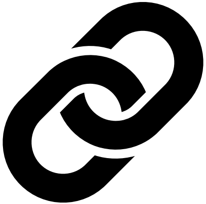

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File System Abstraction

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  - Link name in one file system to root of another

Accessing files - API

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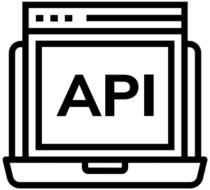

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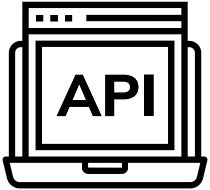

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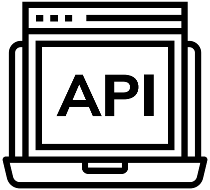

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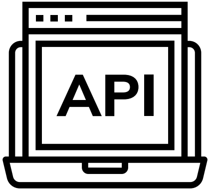

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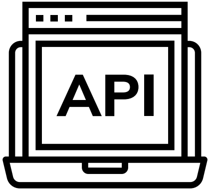

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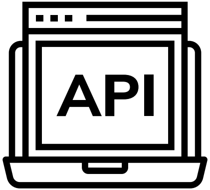

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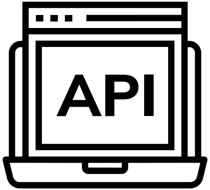

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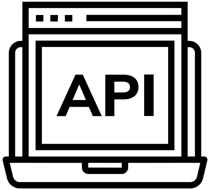

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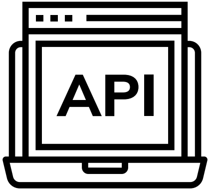

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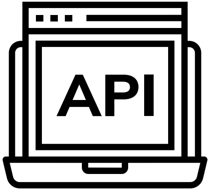

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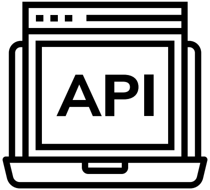

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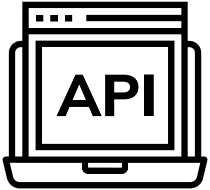

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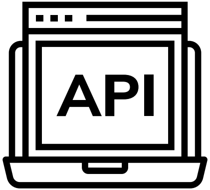

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- force modification to storage: `fsync()`

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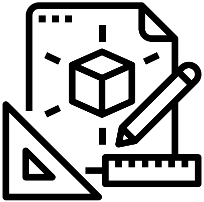

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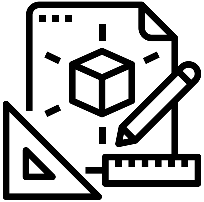

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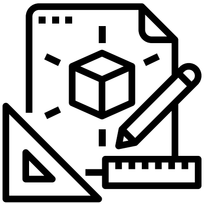

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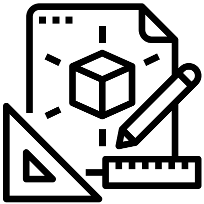

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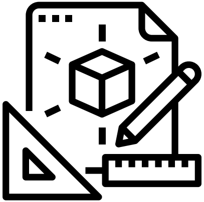

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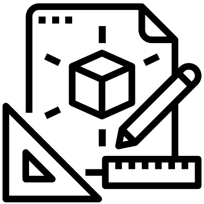

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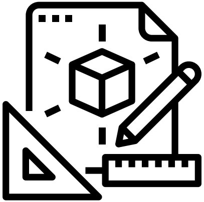

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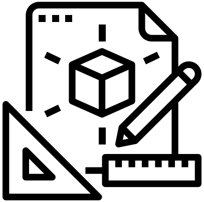

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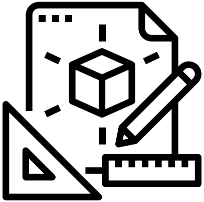

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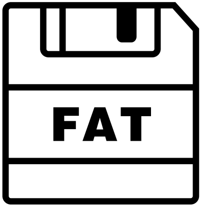

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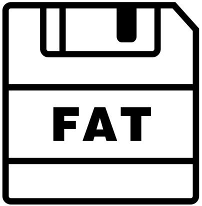

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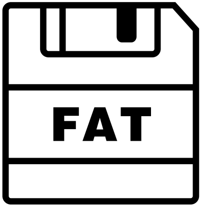

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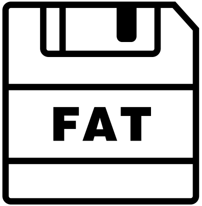

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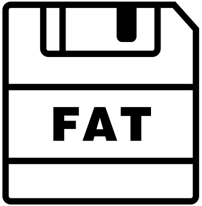

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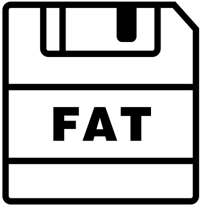

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- Today: exFAT for SD-cards, USB sticks, ...

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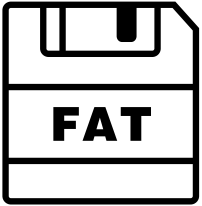

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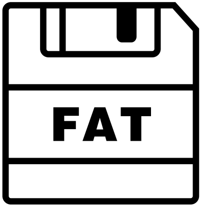

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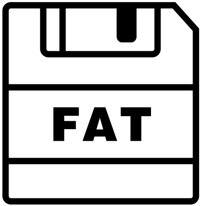

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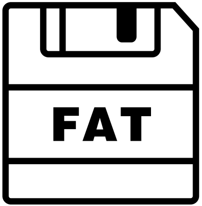

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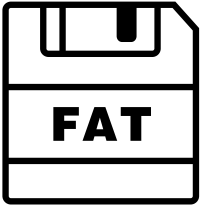

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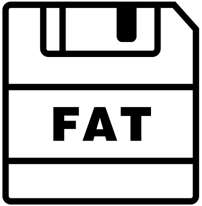

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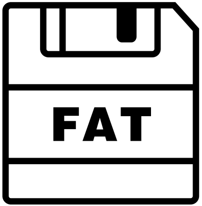

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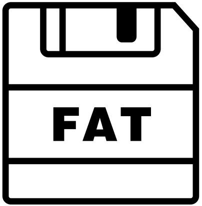

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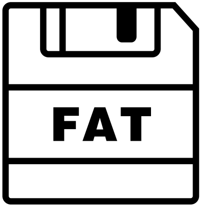

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- Directory: file name, starting cluster, length

FAT Limits

- FAT12: 12bit FAT entry $\rightarrow 2^{12}$ clusters (512B-4KB) $\rightarrow$ max. 16 MB

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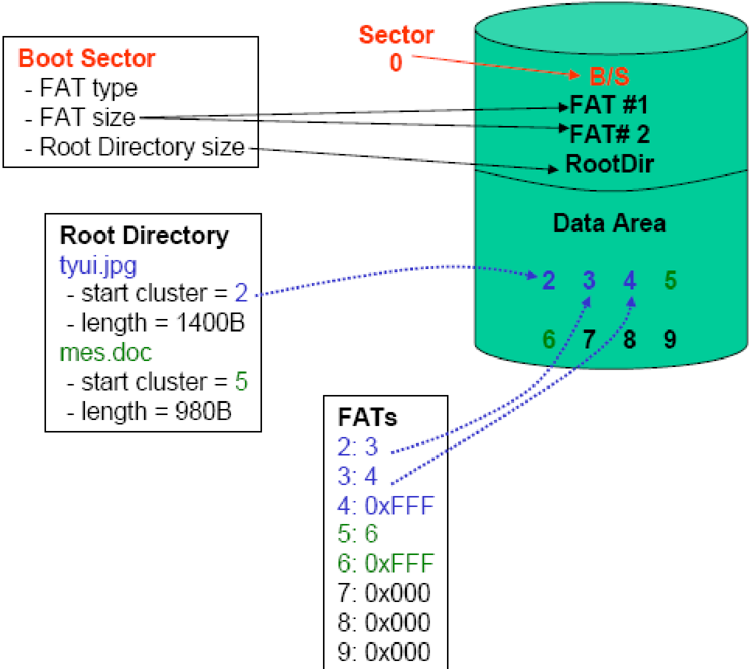
- FAT32: 28bit FAT entry $\rightarrow 2^{28}$ (4KB-32KB) $\rightarrow$ max. 2 TB (limited by a 32-bit sector count field)

Entry	Pointer
2	0
3	0
4	0
:	:
40	0
41	0
42	43
43	44
44	45
: :	: :
70	71

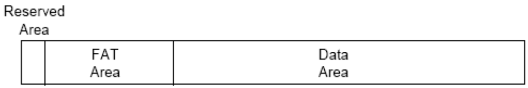
1st cluster chain starts at cluster 42 (length 31)

2nd cluster chain starts at cluster 73 (length 5)

Entry	Pointer
71	72
72	0xfff
73	74
74	75
75	76
76	77
77	0xfff
78	0
79	0
80	0
:	0

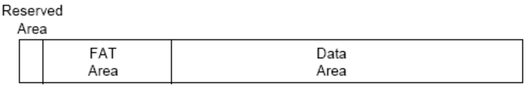


Boot Sector
- FAT type
- FAT size
- Root Directory size
Sector 0
B/S
FAT #1
FAT# 2
RootDir
Data Area
2 3 4 5
6 7 8 9
Root Directory
tyui.jpg
- start cluster = 2
- length = 1400B
mes.doc
- start cluster = 5
- length = 980B
FATs
2: 3
3: 4
4: 0xFFF
5: 6
6: 0xFFF
7: 0x000
8: 0x000
9: 0x000



- FAT area for table

FAT



- FAT area for table
- Data area for the data of files, in clusters

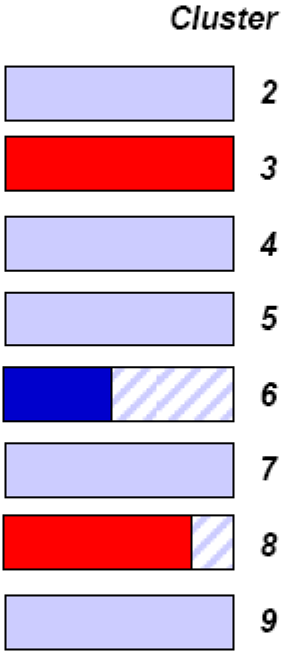
Root Directory

File Name	Size	Cluster
gary.txt	1034	6
hello.jpg	3973	3

File Allocation Table

Cluster	Next
2	0
3	8
4	0
5	0
6	0xFF
7	0
8	0xFF
9	0

Cluster = 2048 B = 4 sectors



FAT Boot Sector

Bytes	Purpose
0-2	Assembly code instructions to jump to boot code (mandatory in bootable partition)
3-10	OEM name in ASCII
11-12	Bytes per sector (512, 1024, 2048, or 4096)
13	Sectors per cluster (Must be a power of 2 and cluster size must be ¡=32 KB)
14-15	Size of reserved area, in sectors
16	Number of FATs (usually 2)
17-18	Maximum number of files in the root directory (FAT12/16; 0 for FAT32)
19-20	Number of sectors in the file system; if 2 B is not large enough, set to 0 and use 4 B value in bytes 32-35 below
21	Media type (0xf0=removable disk, 0xf8=fixed disk)
22-23	Size of each FAT, in sectors, for FAT12/16; 0 for FAT32
24-25	Sectors per track in storage device
26-27	Number of heads in storage device
28-31	Number of sectors before the start partition
32-35	Number of sectors in the file system; this field will be 0 if the 2B field above (bytes 19-20) is non-zero

FAT Boot Sector (FAT12/FAT16)

Bytes	Purpose
0-35	(See previous table)
36	BIOS INT 13h (low level disk services) drive number
37	Not used
38	Extended boot signature to validate next three fields (0x29)
39-42	Volume serial number
43-53	Volume label, in ASCII
54-61	File system type level, in ASCII. (Generally "FAT'', "FAT12'', or "FAT16")
62-509	Not used
510-511	Signature value (0xaa55)

Sector Assignments

Sector(s)	Address	Function
0	0x0000-0x01ff	Boot Sector
1-9	0x0200-0x13ff	File Allocation Table (primary)
10-18	0x1400-0x25ff	File Allocation Table (secondary)
19-32	0x2600-0x41ff	Root Directory (this is the maximum size!)
33-2879	0x4200-0x167fff	File storage space

Root Directory

- after FAT(s) - or in FAT32: specified in boot sector

Root Directory

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- new file entry needed? first / next-available search

Root Directory

- after FAT(s) - or in FAT32: specified in boot sector
- new file entry needed? first / next-available search
- Root directory (32 bytes each):

Root Directory SFN Entry Data Structure

Bytes	Purpose
0	First character of file name (ASCII) *or* allocation status (0x00=unallocated, 0xe5=deleted)
1-10	Characters 2-11 of the file name (ASCII); the "." is implied between bytes 7 and 8
11	File attributes (see File Attributes table)
12	Reserved
13	File creation time (in tenths of seconds)*
14-15	Creation time (hours, minutes, seconds)*
16-17	Creation date*
18-19	Access date*
20-21	High-order 2 bytes of address of first cluster (0 for FAT12/16)*
22-23	Modified time (hours, minutes, seconds)
24-25	Modified date
26-27	Low-order 2 bytes of address of first cluster
28-31	File size (0 for directories)

File Attributes

Flag Value	Description
0000 0001 (0x01)	Read-only
0000 0010 (0x02)	Hidden file
0000 0100 (0x04)	System file
0000 1000 (0x08)	Volume label
0000 1111 (0x0f)	Long file name
0001 0000 (0x10)	Directory
0010 0000 (0x20)	Archive

** Bytes 13-22 are unused by DOS*

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** Bytes 13-22 are unused by DOS*

- Root directory (32 bytes each):
- also possible: extra 32 bytes for "long" filename

Allocating Files

1. Find free entry in directory

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2. Find free entry in FAT for cluster, write sector number there and EOF into FAT

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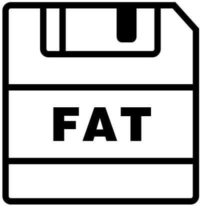
Extending files? if next FAT entry is free, move EOF to that instead

FAT discussion

FAT discussion



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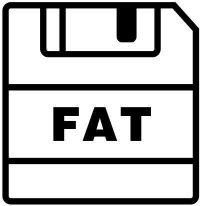

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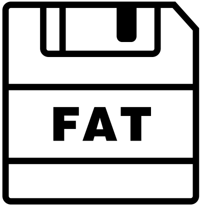
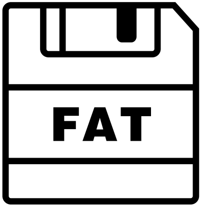


- widely used - simple, wide supporting



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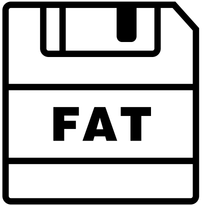

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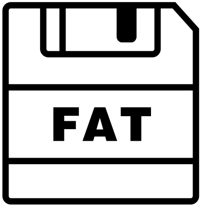

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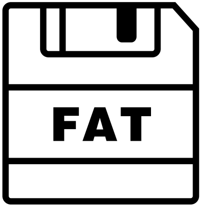

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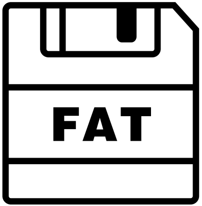

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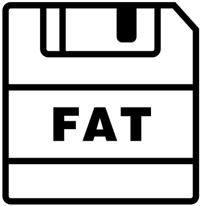

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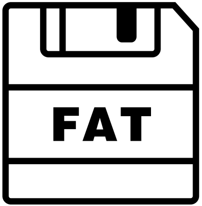

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- limitation of volume and file size
- reliability techniques??

UNIX FFS

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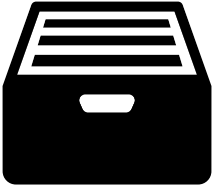

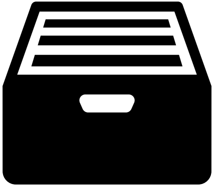

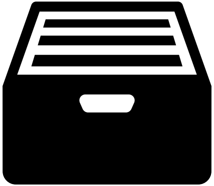

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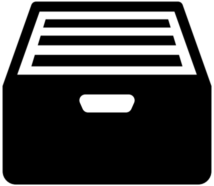

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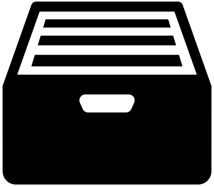

- Unix Fast File System - released mid 1980
- many data-structures identical to Ritchie/Thomposon's original UNIX FS (1970ies)
- Tree-based multi-level index

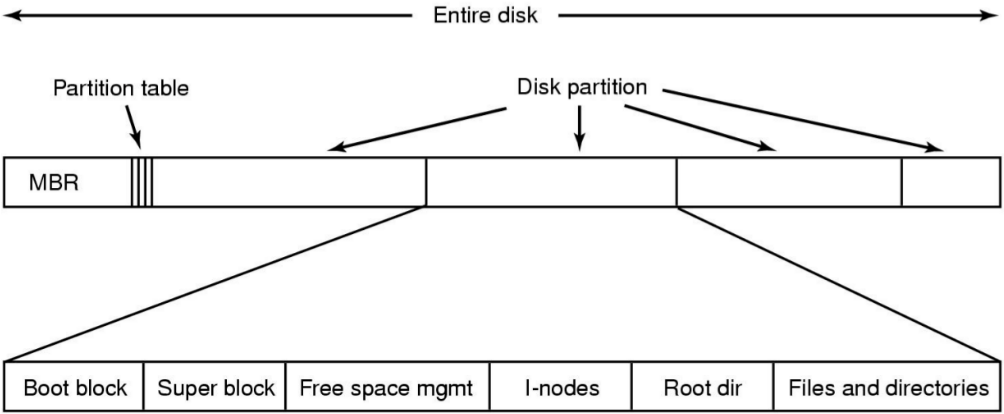

Figure 1: Disk layout, classical example

Implementation (“classical Unix”)

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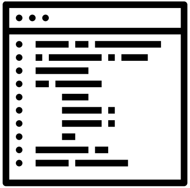

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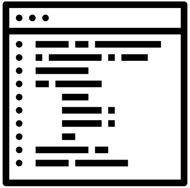

- boot block: Boot Loader, to boot system

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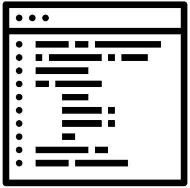

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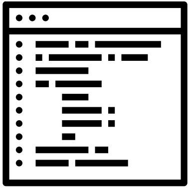

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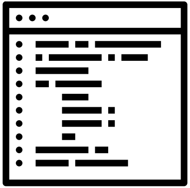

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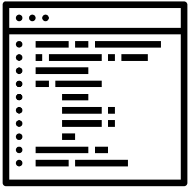

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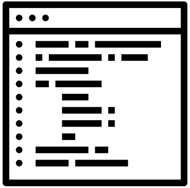

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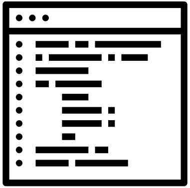

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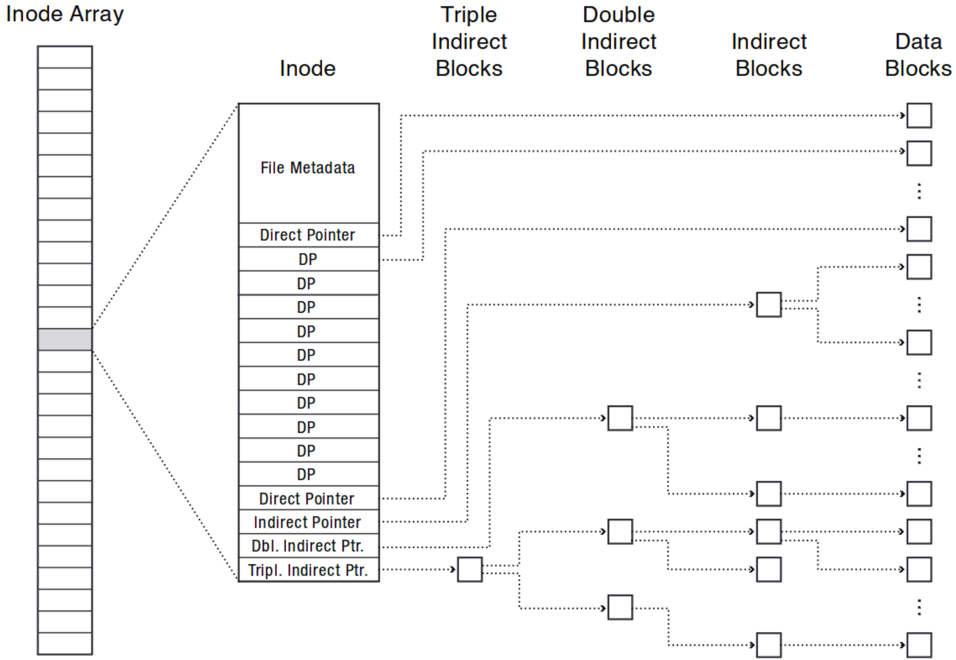
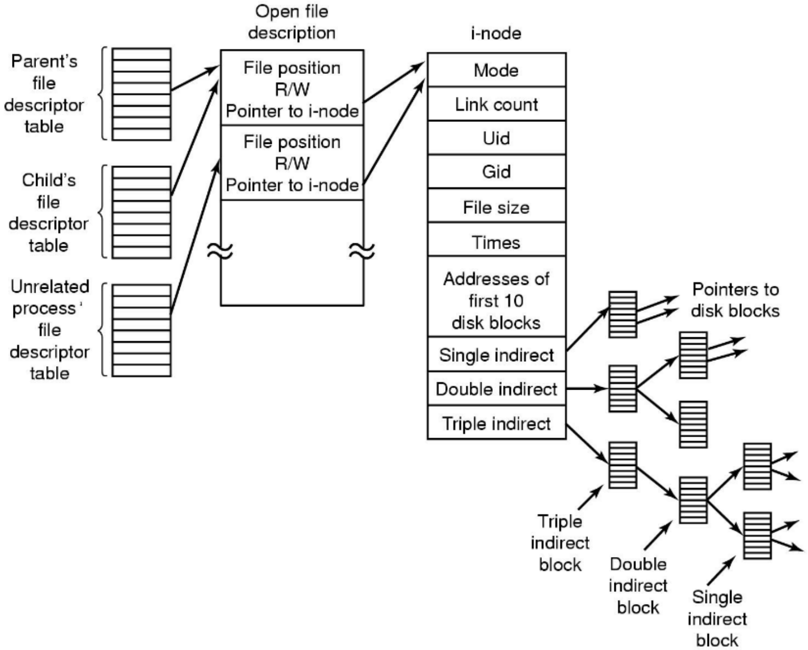
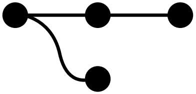


Inode Array
Inode
Triple Indirect Blocks
Double Indirect Blocks
Indirect Blocks
Data Blocks
File Metadata
Direct Pointer
DP
DP
DP
DP
DP
DP
DP
DP
DP
DP
Direct Pointer
Indirect Pointer
Dbl. Indirect Ptr.
Tripl. Indirect Ptr.


Open file description
i-node
Parent's file descriptor table
Child's file descriptor table
Unrelated process' file descriptor table
File position
R/W
Pointer to i-node
File position
R/W
Pointer to i-node
Mode
Link count
Uid
Gid
File size
Times
Addresses of first 10 disk blocks
Single indirect
Double indirect
Triple indirect
Pointers to disk blocks
Triple indirect block
Double indirect block
Single indirect block

Inode

Inode



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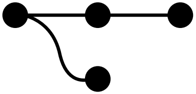

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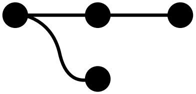
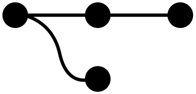


- Attributes:

Inode



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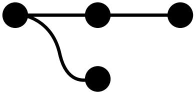

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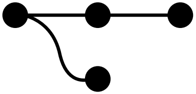
Inode



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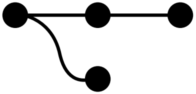
  - created, modified, accessed times

Inode



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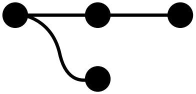
  - created, modified, accessed times
  - size: in bytes and blocks

Inode



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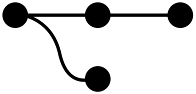
  - created, modified, accessed times
  - size: in bytes and blocks
  - permissions (rwx)

Inode



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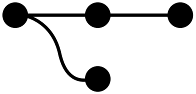
    - owner: user, group
    - created, modified, accessed times
    - size: in bytes and blocks
    - permissions (rwx)
    - NO filename

Inodes

Inodes



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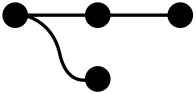

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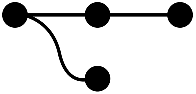
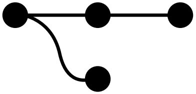


- files may have multiple names

Inodes



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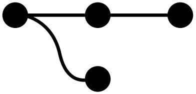
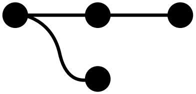
Inodes



- files may have multiple names
  - directories contain names and numberings
  - multiple occurrences possible

Inodes



- files may have multiple names
  - directories contain names and numberings
  - multiple occurrences possible
  - “hard link”

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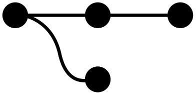
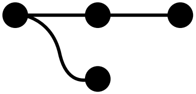


- files may have multiple names
  - directories contain names and numberings
  - multiple occurrences possible
  - “hard link”
  - inode contains link count

Inodes



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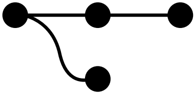

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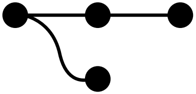

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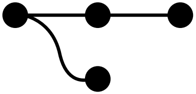

- Inode link-count 0:
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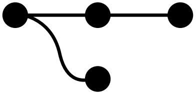

- Inode link-count 0:
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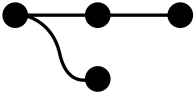
  - file can be deleted

Inodes



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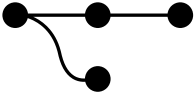

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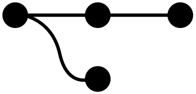

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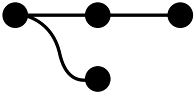
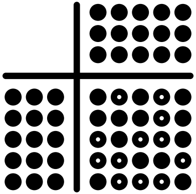


- Inode link-count 0:
  - no more reference within file system exists
  - file can be deleted
- number of inodes limited
  - file system may be full, because
    - no free inode
    - all blocks used

Sparse files



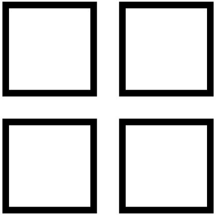
- Sparse file: one or more empty spaces are surrounded by file data
- empty space: needs not consume disk spaces

```
fd=creat("test.file",777);
lseek(fd,1000000000,SEEK_SET);
write(fd,"test",2);
close(fd);
```

- Should create a file of size ~1GB using one block
  - does the file system support it?

Block group placement

Block group placement



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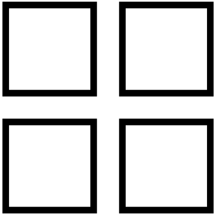

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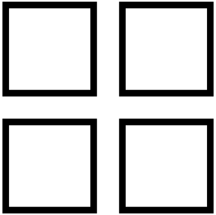

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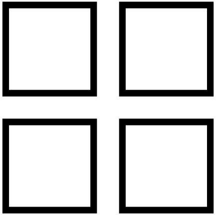

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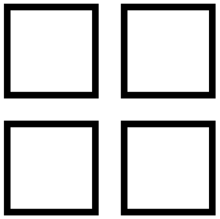
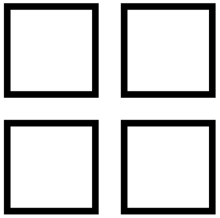


- places data to optimize concurrent access to
  - data blocks of a file
  - metadata of a file

Block group placement



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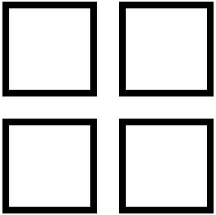
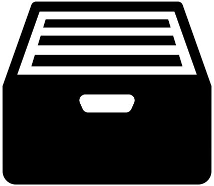


- places data to optimize concurrent access to
  - data blocks of a file
  - metadata of a file
  - different files from the same directory
- different directories may be far from each others

NTFS

NTFS



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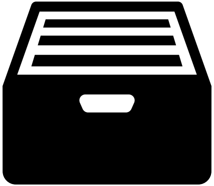

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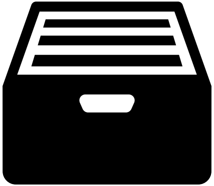
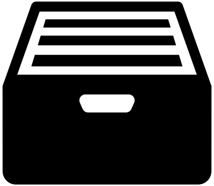


- Microsoft **N**ew **T**echnology **F**ile **S**ystem

NTFS



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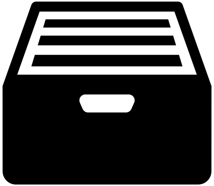

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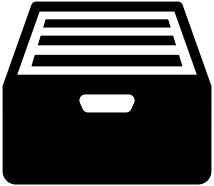
NTFS



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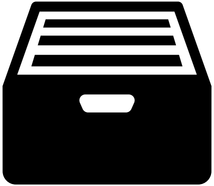

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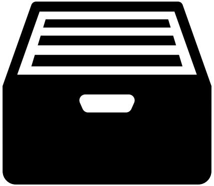

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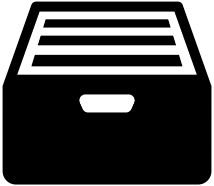

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NTFS

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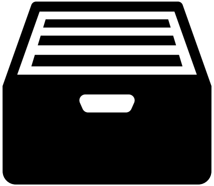
  - improved reliability
- still the primary file system for Windows

NTFS Index Structures

NTFS Index Structures



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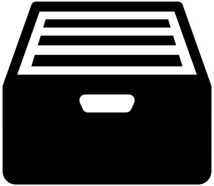

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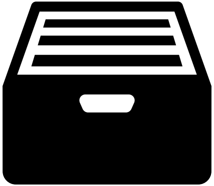

- **Extents**: variable sized region of a file stored in a contiguous region on the storage device

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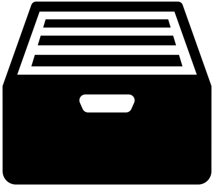

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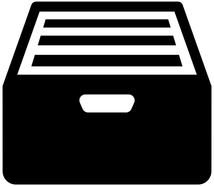

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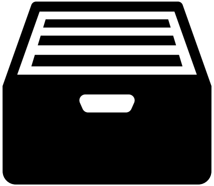

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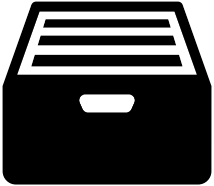

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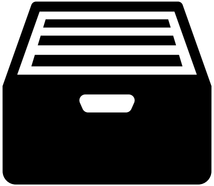

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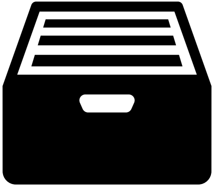

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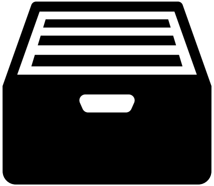

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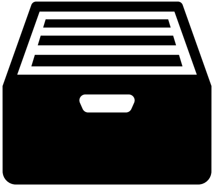

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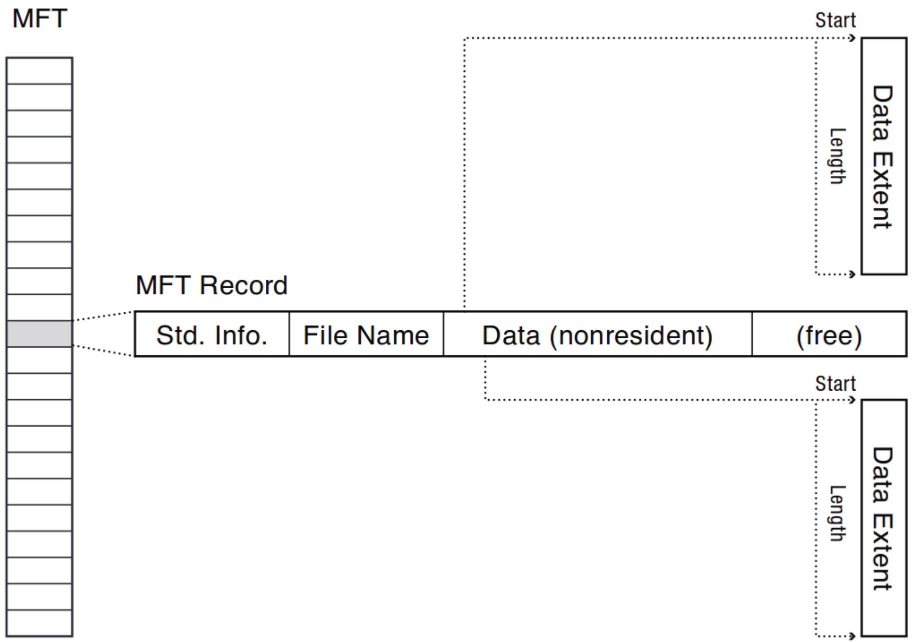
  - contains sequence of variable-size attribute records
    - can contain data and metadata
    - data is an attribute of a file-system


MFT
MFT Record
Std. Info.
File Name
Data (nonresident)
(free)
Start
Length
Data Extent
Start
Length
Data Extent

index for NTFS basic file

index for NTFS basic file

index for NTFS basic file

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index for NTFS basic file

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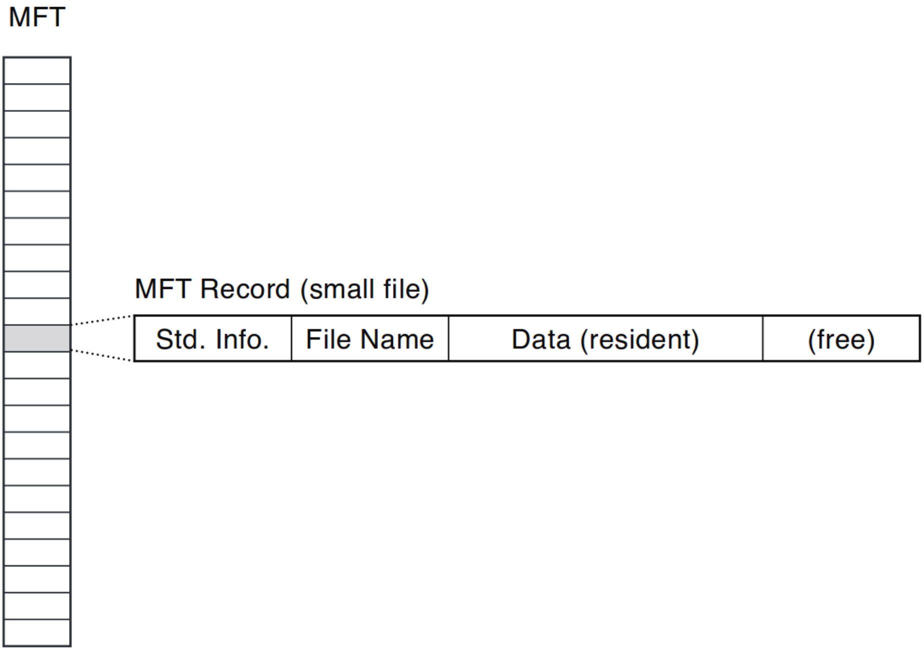
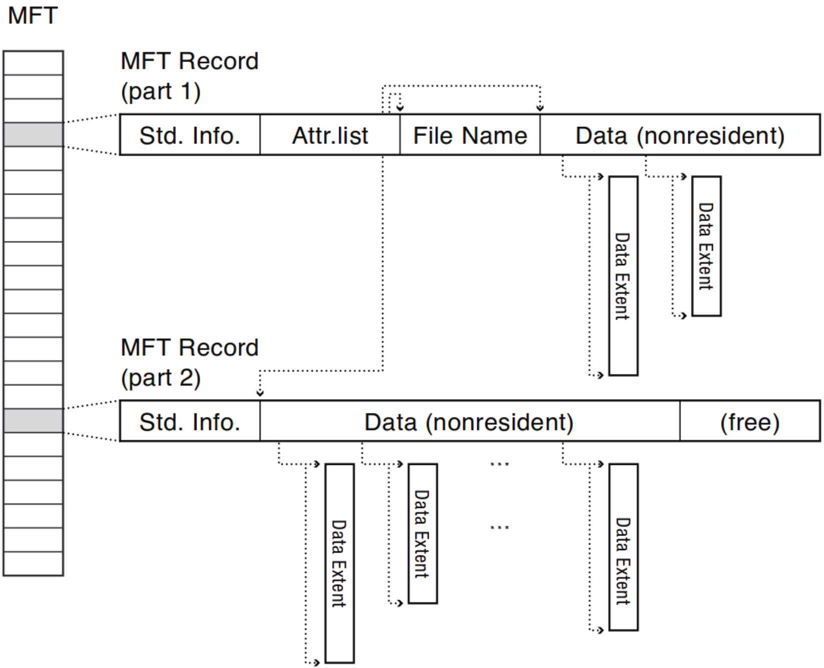
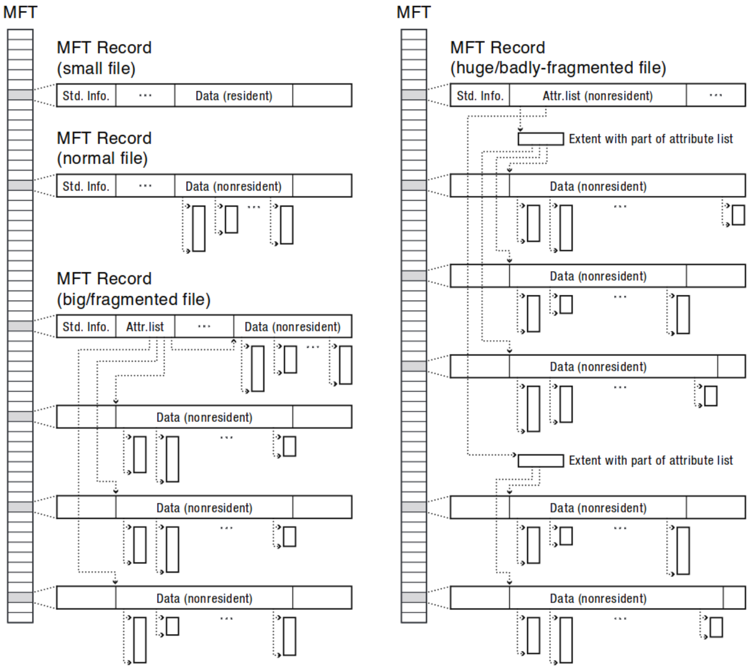
- File small? attribute may even contain data

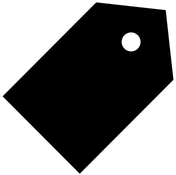

MFT
MFT Record (small file)
Std. Info.
File Name
Data (resident)
(free)


MFT
MFT Record
(part 1)
Std. Info.
Attr.list
File Name
Data (nonresident)
Data Extent
Data Extent
MFT Record
(part 2)
Std. Info.
Data (nonresident)
(free)
Data Extent
Data Extent
...
...
Data Extent


MFT
MFT Record
(small file)
Std. Info.
Data (resident)
MFT Record
(normal file)
Std. Info.
Data (nonresident)
MFT Record
(big/fragmented file)
Std. Info.
Attr.list
Data (nonresident)
Data (nonresident)
Data (nonresident)
Data (nonresident)
MFT
MFT Record
(huge/badly-fragmented file)
Std. Info.
Attr.list (nonresident)
Extent with part of attribute list
Data (nonresident)
Data (nonresident)
Data (nonresident)
Extent with part of attribute list
Data (nonresident)
Data (nonresident)

Metadata files

Metadata files



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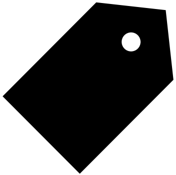

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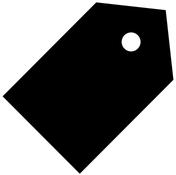
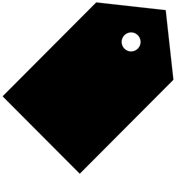


- no special regions for file system metadata

Metadata files



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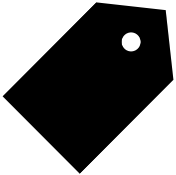

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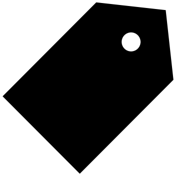
Metadata files



- no special regions for file system metadata
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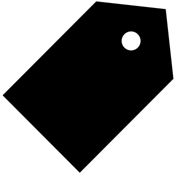
Metadata files



- no special regions for file system metadata
- all metadata in ordinary files:
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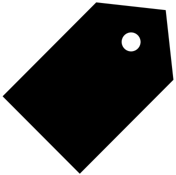
  - file 8: bad block list

Metadata files



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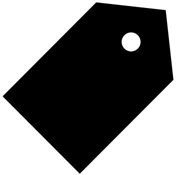

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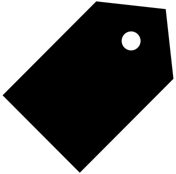
  - file 0: master file tableofcontents

Metadata files



- no special regions for file system metadata
- all metadata in ordinary files:
  - file 5: root directory
  - file 6: free space bitmap
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  - file 9: security and access control information
  - file 0: master file tableofcontents
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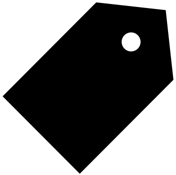

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    - first sector contains a pointer to first MFT entry
- makes it easier to dynamically grow metadata

NTFS locality heuristics

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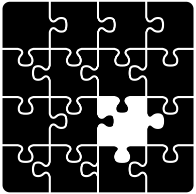

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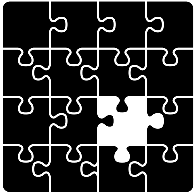

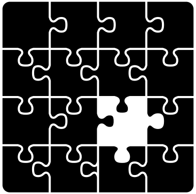

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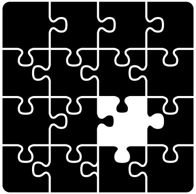

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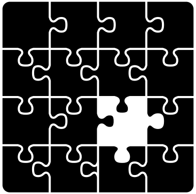

- variation of “best fit” - place a newly allocated file in the smallest free region large enough
- applications can indicate expected file size
- start of volume reserved for MFT table to avoid fragmentation

COW File systems

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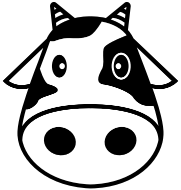

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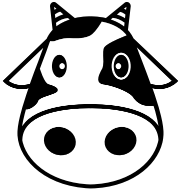

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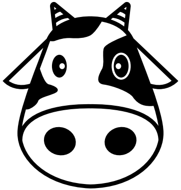

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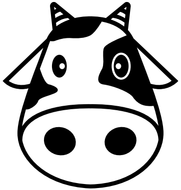

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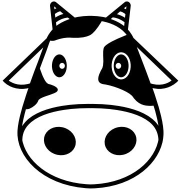

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  - Example - append a block to a file

Why would we need COW file systems?

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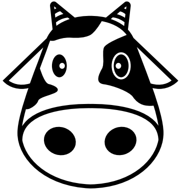

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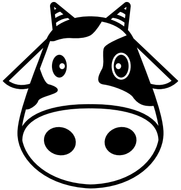

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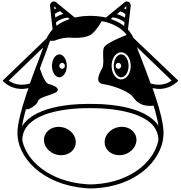

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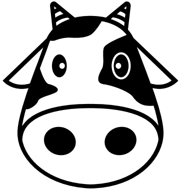

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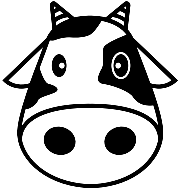

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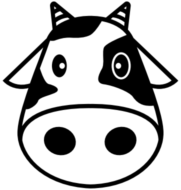

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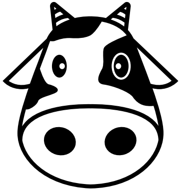

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- Versioning

ext/ext2/ext3/ext4

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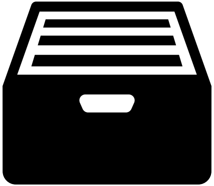

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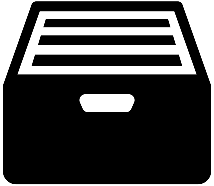

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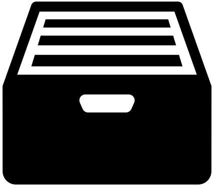

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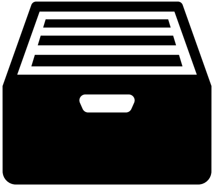

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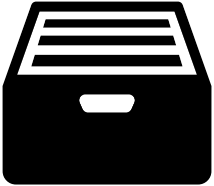

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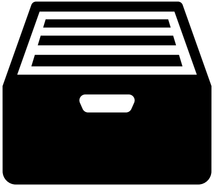

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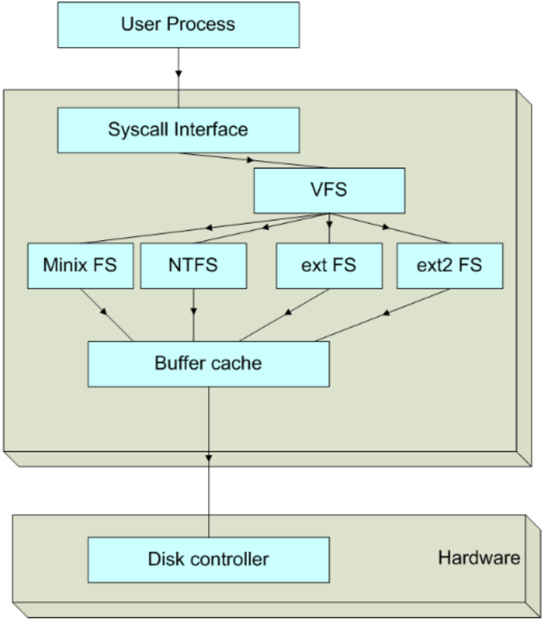
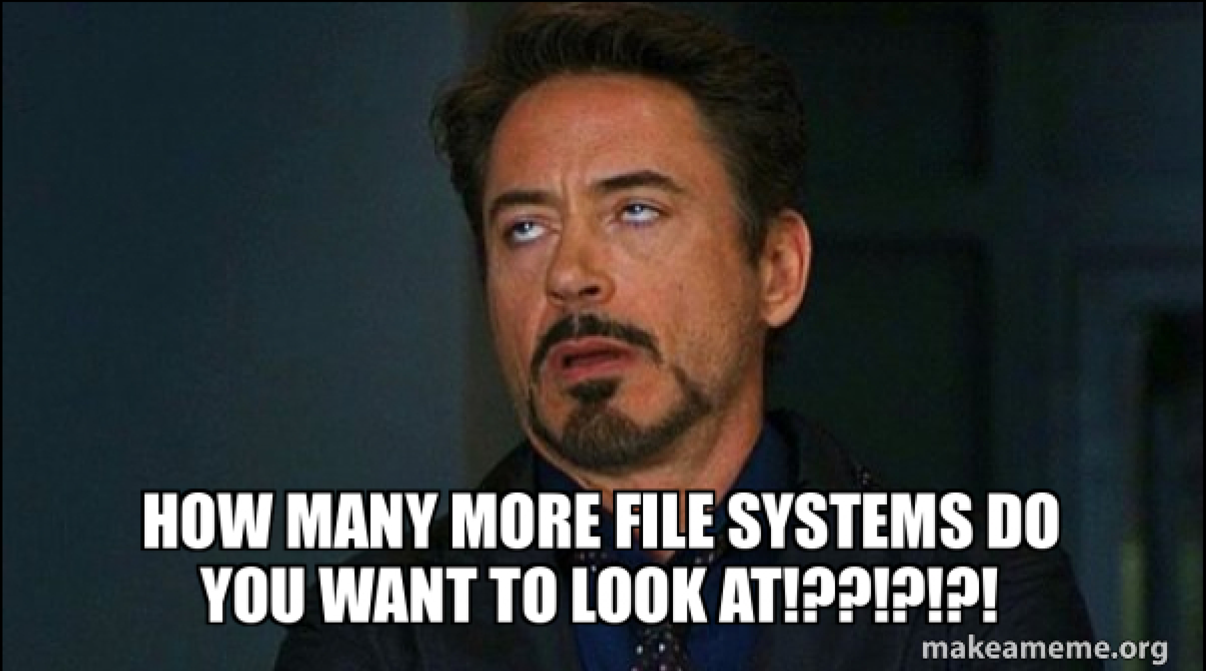
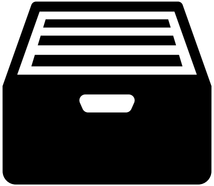
- VFS: virtual file system layer

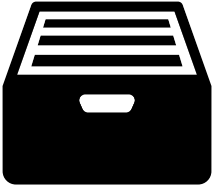

User Process
Syscall Interface
VFS
Minix FS
NTFS
ext FS
ext2 FS
Buffer cache
Disk controller
Hardware


HOW MANY MORE FILE SYSTEMS DO
YOU WANT TO LOOK AT!??!?!?!
makeameme.org

ext

ext





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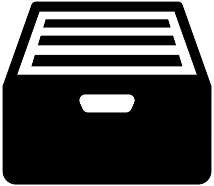

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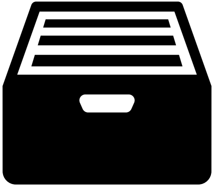

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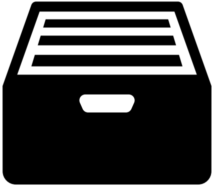

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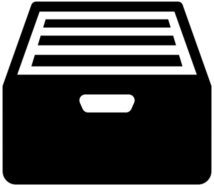
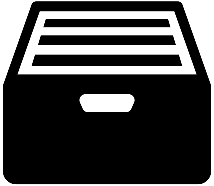
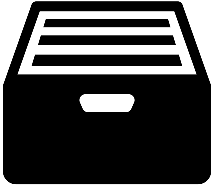


ext2





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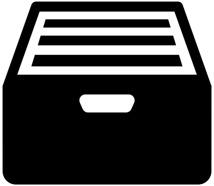

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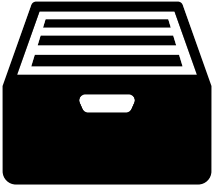

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- also uses cylinder groups, superblocks, inodes, ...

ext2 has more attributes!

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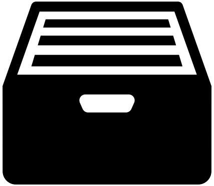

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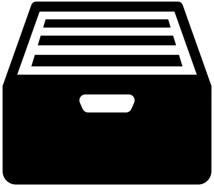

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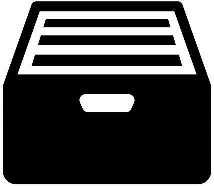

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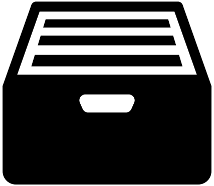

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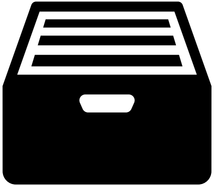

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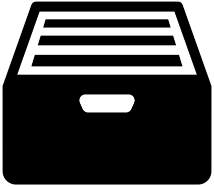

- c: compressed
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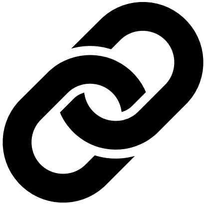
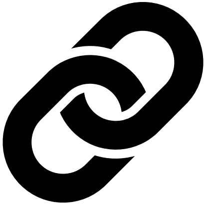
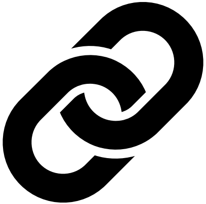
- A: append mode





symbolic links



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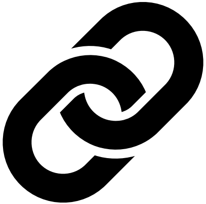

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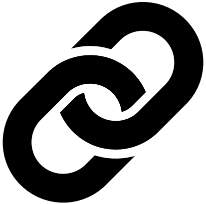

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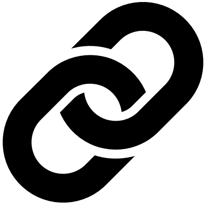

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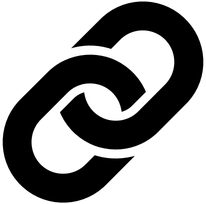

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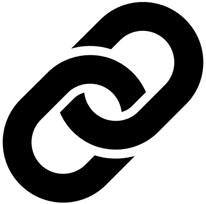
clean/dirty state ($\rightarrow$ kind of a simple journal)

- after OS crash: fsck recommended/enforced



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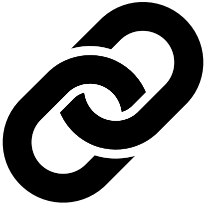

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ext2 performance

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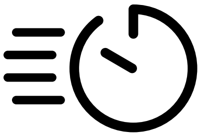

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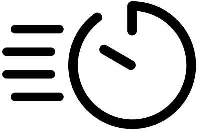

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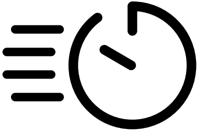

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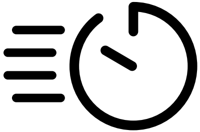

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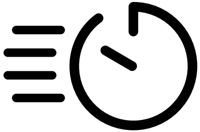

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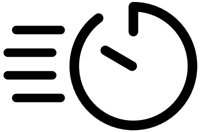

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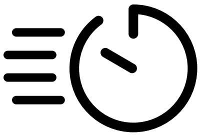

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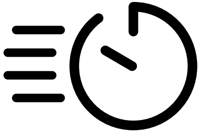

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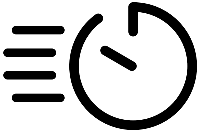

- inodes and data blocks "close" to each other on hard disk
- on magnetic disks: reduces seek times

Preallocation:

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Bitmaps for

- inode allocation

ext2 performance

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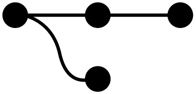
Bitmaps for

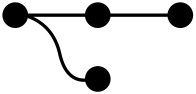
- inode allocation
- data allocation

ext2 limits

ext2 limits

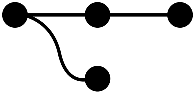


ext2 limits



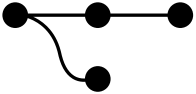
maximum file size

ext2 limits



maximum file size

- depends on block size *b*



maximum file size

- depends on block size b
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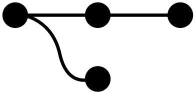

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  - b=1KB: 16GB

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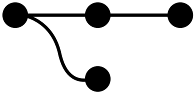

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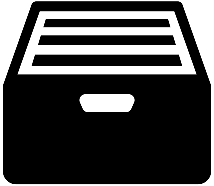
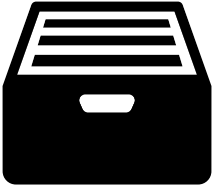
  - b=1KB: 16GB
  - b=4KB: 2 TB

ext3

ext3



ext3



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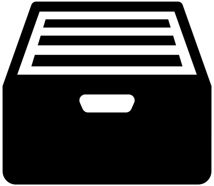
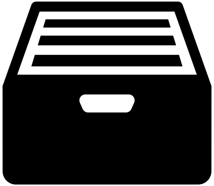
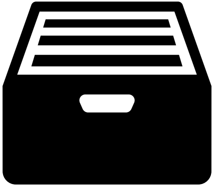


- based on ext2



- based on ext2
- **journaling** file system



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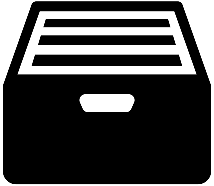
ext3



- based on ext2
- **journaling** file system
- file systems can grow dynamically
- hash tree for big directories

ext3 Journal

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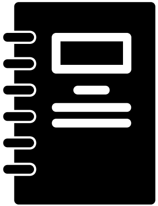

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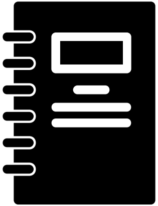

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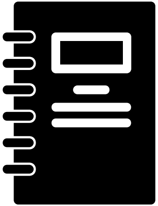

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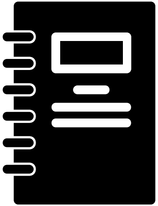
ext3 Journal



- changes to files stored in a journal
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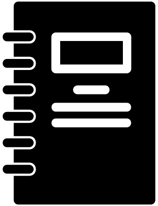

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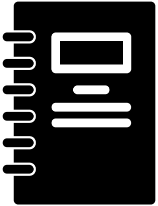

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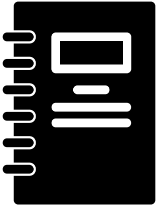

- changes to files stored in a journal
  - in principle a cyclic log
- first change noted in journal
- then executed in file system
- after crash: allows fixing inconsistencies easier

Journal - typical scenario

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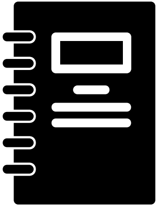

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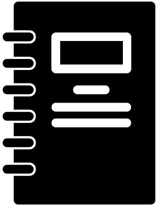

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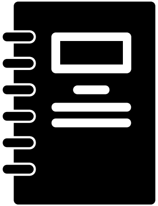
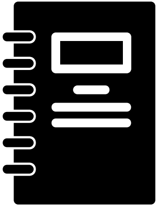


- file system is consistent



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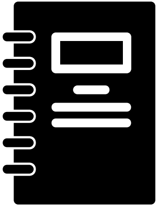

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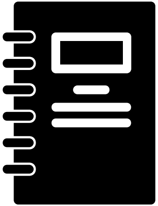

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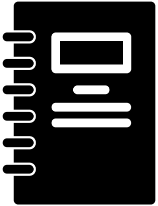
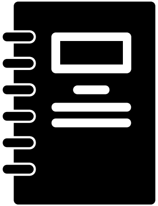


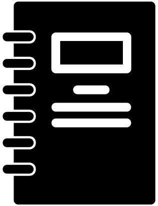
- file system is consistent
- changes are requested
- changes noted in journal
- changes executed in file system
- similar to stable storage concept

journaling - delete file example



journaling - delete file example

deleting a file may need two steps:



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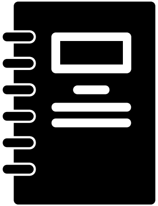

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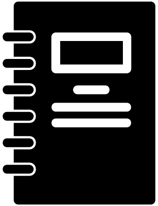

deleting a file may need two steps:

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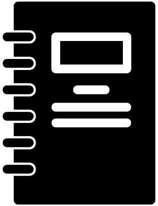
2. delete inode



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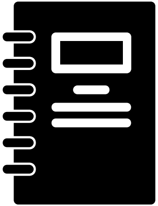

deleting a file may need two steps:

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Crash between the two steps?

- orphaned inode

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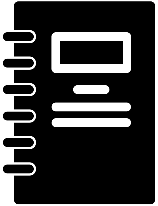

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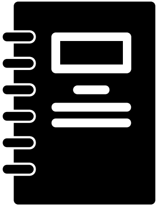

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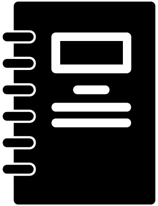

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- directory references non-existing inode

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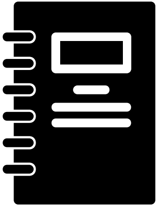

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1. remove reference from directory
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Crash between the two steps?

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Change their order?

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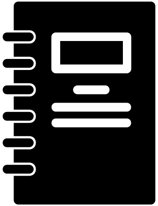
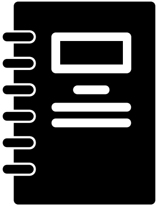
→ using that inode may have fatal consequences

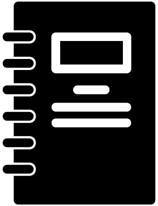
Journal

Journal



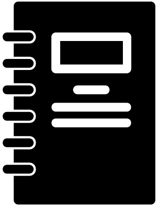
Journal





- Without Journal: fsck - file system check at reboot and **hope to find those inconsistencies**

Journal



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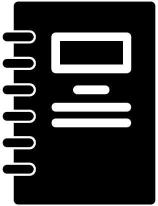
Journal



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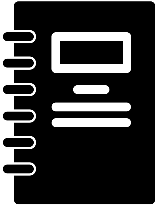

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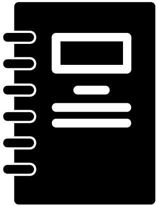

- Without Journal: fsck - file system check at reboot and **hope to find those inconsistencies**
- Now:
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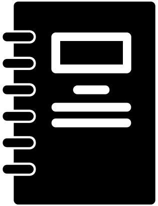
- much faster than fsck



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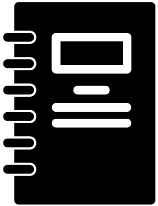

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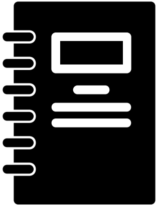
Journal



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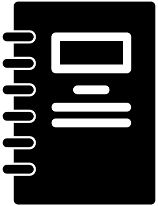

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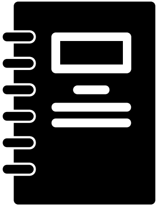
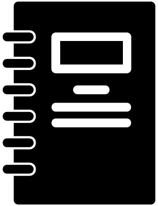
  - or not at all if not yet in the journal

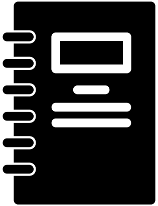
implementing journals

implementing journals



implementing journals





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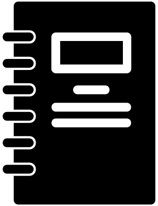
implementing journals



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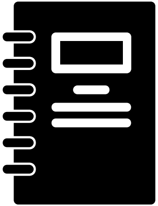
implementing journals



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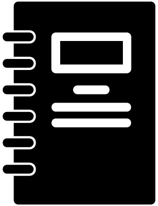

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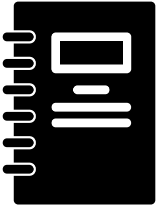
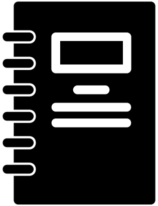
implementing journals



- storage: regular file, hidden file, special disk area, separate device?
- do we need a journal for the journal?
- must be able to check the integrity of the journal
  - checksum
  - ignore entries with incorrect checksum

physical journals



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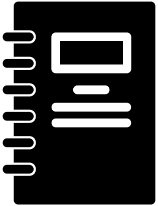
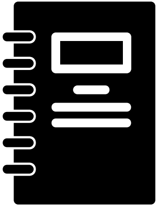
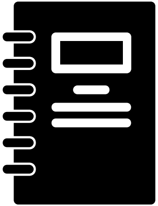


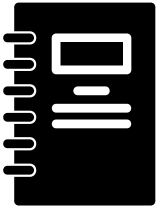


- writes a copy of each block

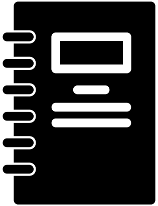


- writes a copy of each block
  - first into the journal

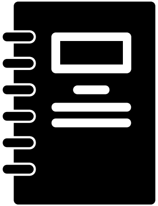
physical journals



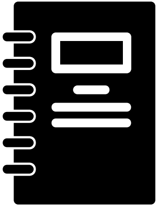
- writes a copy of each block
  - first into the journal
  - then on the disk



- writes a copy of each block
  - first into the journal
  - then on the disk
- Crash:

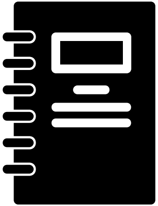


- writes a copy of each block
  - first into the journal
  - then on the disk
- Crash:
  - neither in journal nor on disk: no change



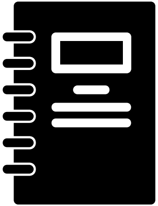
- writes a copy of each block
  - first into the journal
  - then on the disk
- Crash:
  - neither in journal nor on disk: no change
  - only in journal: copy to disk

physical journals



- writes a copy of each block
  - first into the journal
  - then on the disk
- Crash:
  - neither in journal nor on disk: no change
  - only in journal: copy to disk
  - already on disk: nothing to do

physical journals



- writes a copy of each block
  - first into the journal
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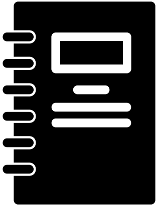
- Crash:
  - neither in journal nor on disk: no change
  - only in journal: copy to disk
  - already on disk: nothing to do
- high overhead

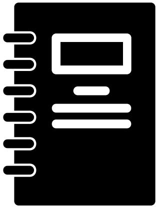
physical journals



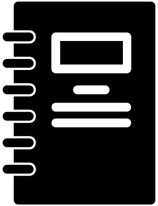
- writes a copy of each block
  - first into the journal
  - then on the disk
- Crash:
  - neither in journal nor on disk: no change
  - only in journal: copy to disk
  - already on disk: nothing to do
- high overhead
- acceptable for high correctness requirements

logical journals

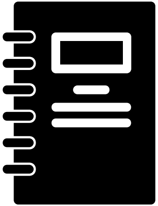
logical journals



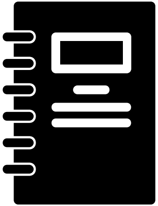
logical journals



logical journals

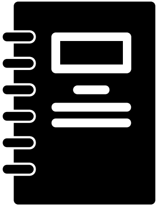


- only meta-data written to journal



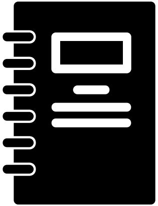
- only meta-data written to journal
- trades safety against performance

logical journals



- only meta-data written to journal
- trades safety against performance
- may lead to asynchronicity between meta-data and data

logical journals

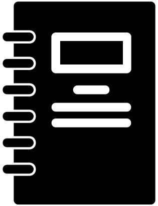


- only meta-data written to journal
- trades safety against performance
- may lead to asynchronicity between meta-data and data

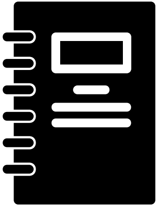
→ for example, a correctly resized file but garbage content

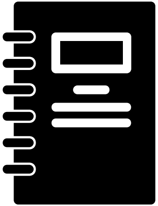
journals in ext3

journals in ext3



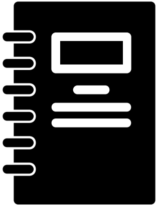
journals in ext3





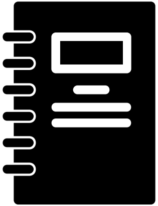
- full journal (no risk):

journals in ext3

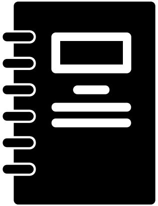


- full journal (no risk):

journals in ext3

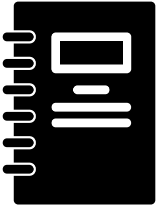


- full journal (no risk): 1. data $\rightarrow$ journal; 2. data $\rightarrow$ disk
- ordered (medium risk):



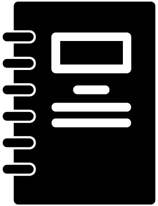
- full journal (no risk): 1. data $\rightarrow$ journal; 2. data $\rightarrow$ disk
- ordered (medium risk):

journals in ext3



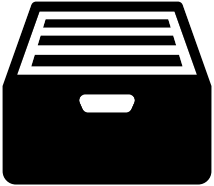
- full journal (no risk): 1. data $\rightarrow$ journal; 2. data $\rightarrow$ disk
- ordered (medium risk): 1. meta-data $\rightarrow$ journal; 2. data $\rightarrow$ disk
- write-back (highest risk): 1. meta-data $\rightarrow$ journal; 2. data "eventually" $\rightarrow$ disk (`sync`)

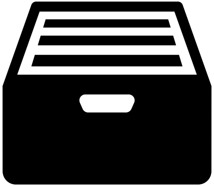
journals in ext3



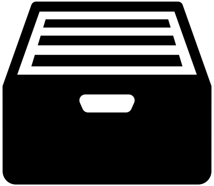
- full journal (no risk): 1. data → journal; 2. data → disk
- ordered (medium risk): 1. meta-data → journal; 2. data → disk
- write-back (highest risk): 1. meta-data → journal; 2. data "eventually" → disk (`sync`)
- no checksums on journal

ext4



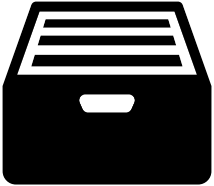


ext4



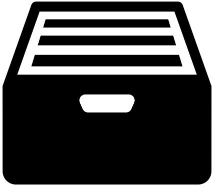
- successor of ext3

ext4



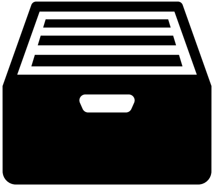
- successor of ext3
- volume size up to 1 exibyte (2^{60})

ext4



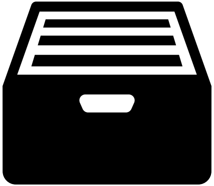
- successor of ext3
- volume size up to 1 exibyte (2^{60})
- file size up to 16 tebibytes (2^{40})

ext4



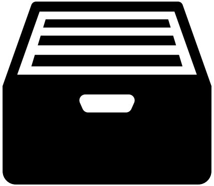
- successor of ext3
- volume size up to 1 exibyte (2^{60})
- file size up to 16 tebibytes (2^{40})
- extents

ext4



- successor of ext3
- volume size up to 1 exibyte (2^{60})
- file size up to 16 tebibytes (2^{40})
- extents
- preallocation

ext4



- successor of ext3
- volume size up to 1 exibyte (2^{60})
- file size up to 16 tebibytes (2^{40})
- extents
- preallocation
- journals with checksum


ITS OVER
ITS FINALLY OVER