Quintupling the speed of the PDP-8 DF32 disk system for real-time use

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The author has noted some inefficiencies in the operation of the DF32 hardware/software disk system on the PDP-8. While such inefficiencies are not significant when the disk is used only as a store for programs which are called into core from the keyboard, they become important when the disk is used as a real-time backup for core. This paper isolates some of the problems, gives rules for avoiding them, and then describes how the system software was modified to obey these rules. The speed of the modified system is noticeable even when SAVEing and CALLing programs from the keyboard; successive blocks can be transferred between disk and core in one-fifth the previously required time.

HARDWARE

The DEC DF32 disk¹ for the PDP-8 is capable of storing 32,768 words. It has a maximum access time (revolution time) of 33 msec and a transfer rate of 66 microsec/word. Each word on the disk is individually addressable, and once core field, starting core address, (negative) word count, and starting disk address have been specified, the disk will read or write the specified number of words (1-4,096) independently of the central processor. At the conclusion of the read or write operation, the word count (which is incremented by one every time a word is transferred) will have been incremented to 0, and the disk completion flag will come up (and cause an interrupt if interrupts are enabled).

For purposes of this paper, and as far as its actual operation, the disk is best thought of as consisting of 16 tracks of 2,048 (4000₈) words each, even though computation shows that $(2,048 \text{ words per track} \times .066 \text{ msec per word}) / (33 \text{ msec per revolution}) = 4$ revolutions are required to read or write one track. Apparently the hardware reads or writes only every fourth word during any one revolution.

The reason for considering the disk to be divided into tracks is that experiments by the author have shown that *when a track must be crossed during a read or write, one extra revolution (33 msec) is required to perform this track crossing.* This only applies to crossing a track during the actual read or write operation. If a read terminates in one track and a new read is initiated in another track, this extra revolution is not incurred.

Thus, our first rule for real-time use of the disk is: *Rule 1—Don't cross tracks during individual reads or writes.* Nonobservance of this rule can cost up to 15 track crossings (among 16 tracks), or even 15 extra

revolutions to read or write the entire disk (which would theoretically take $4 \times 16 = 64$ revolutions), or $15/64 = 23\%$ extra time.

SOFTWARE

For use with most of the DEC-supplied software, the disk is divided into 254 blocks of 129 words each. The blocks are numbered from 0 to 375₈ and can be linked together to form files. Each block contains 128 words of useful information, and the 129th word contains the number of the next block in the file, or 0 if there are no more blocks in the file.

The method used to allocate blocks to files is straightforward: the first available block is allocated first, then the next available block, etc. This scheme tends to allocate sequential sets of blocks to files, so that the first word of Block $n + 1$ of a file is likely to be the word immediately after Word 129 (the link word) of Block n of that same file. When reading Block n , the system waits until the link has been read, decodes the link word into the starting address of the next block, and initiates the reading of the next block. However, when Block $n + 1$ is physically the next block, by the time the decoding is completed, the first word of the block has already passed the reading heads, and another revolution must be taken before the reading is actually initiated. An unconfirmed experiment by the author has shown that even if the link decoding could be done instantaneously, the disk hardware would still not be able to start reading in time.

Thus we have: *Rule 2—Don't let Block $n + 1$ of a file start at the word immediately following the last word of Block n .* Disregarding this rule can cause up to one extra idle revolution for every $\frac{1}{4}$ revolution (the space occupied by one block) of reading or writing, or $1/(1/4) = 400\%$ extra time.

SOLUTION

As has been implied, the DEC-supplied disk system routine violates both of these rules. When using the disk just for saving and calling programs under user control, the 10ths of seconds wasted by this routine are insignificant. However, when using the disk under program control, for example for program overlay, these wasted intervals become significant.

At the suggestion of the author, some users temporarily patched their storage allocation maps² to indicate that every other disk block was already in use. Programs they saved then occupied alternate disk blocks, and the extra elapsed time in the Rule 2 case was reduced to 100%. However, using this procedure, unless one is willing to allocate permanently half of the disk to unused filler, deleting and restoring files will partially degrade performance for those files which are restored.

A more complicated but more permanent solution depends on the fact that the programs do not generally perform disk I/O operations directly, but usually call on the system I/O routine resident on the last page of Field O to transfer a particular block. Thus, if the block structure is somehow modified to obey our rules, it is only necessary to modify the disk I/O routine's block number decoding algorithm, and all such programs will continue to operate. Unfortunately, PIP and EDIT, two of DEC's supplied programs, and some other programs do perform some of their own disk I/O, and therefore do require further modification, which we have not performed.

In addition to the restrictions implied by our two rules, we are constrained by the fact that we don't want our modified disk I/O routine to extend over the last page of Field O, which is customarily reserved for this routine.

Our solution is based on the following considerations: (1) A maximum of 15 129-word blocks will fit into a 2,048-word track without overlapping tracks. This reduces us to 15 blocks/track $\times$ 16 tracks = 240 blocks, numbered 0 to 357₈; or $240/254 = 94\%$ of total disk space is still available. (2) If we intersperse a few unused words between blocks, we will have time to decode the disk address of the next block before we have passed its first word. (3) If the spaces between blocks are uniform, then the starting address of any block will remain a linear function of its block number.

A formula which satisfies all of these considerations is: (1) Start Block 0 at Location 10₈ of the disk.

Table 1
Disk Addresses for the Implemented Routine*

TRACK NO. 00			TRACK NO. 04			TRACK NO. 10			TRACK NO. 14		
BLOCK NO.	FIRST WORD	LAST WORD	BLOCK NO.	FIRST WORD	LAST WORD	BLOCK NO.	FIRST WORD	LAST WORD	BLOCK NO.	FIRST WORD	LAST WORD
000	0004	0205	074	0003	0204	170	0002	0203	264	0001	0202
001	0214	0415	075	0213	0414	171	0212	0413	265	0211	0412
002	0425	0626	076	0424	0625	172	0423	0624	266	0422	0623
003	0635	1036	077	0634	1035	173	0633	1034	267	0632	1033
004	1046	1247	100	1045	1246	174	1044	1245	270	1043	1244
005	1256	1457	101	1255	1456	175	1254	1455	271	1253	1454
006	1467	1670	102	1466	1667	176	1465	1666	272	1464	1665
007	1677	2100	103	1676	2077	177	1675	2076	273	1674	2075
010	2110	2311	104	2107	2310	200	2106	2307	274	2105	2306
011	2320	2521	105	2317	2520	201	2316	2517	275	2315	2516
012	2531	2732	106	2530	2731	202	2527	2728	276	2526	2727
013	2741	3142	107	2740	3141	203	2737	3140	277	2736	3137
014	3152	3353	110	3151	3352	204	3150	3351	300	3147	3350
015	3362	3563	111	3361	3562	205	3360	3561	301	3357	3560
016	3573	3774	112	3572	3773	206	3571	3772	302	3570	3771

TRACK NO. 01			TRACK NO. 05			TRACK NO. 11			TRACK NO. 15		
BLOCK NO.	FIRST WORD	LAST WORD	BLOCK NO.	FIRST WORD	LAST WORD	BLOCK NO.	FIRST WORD	LAST WORD	BLOCK NO.	FIRST WORD	LAST WORD
017	0003	0204	113	0002	0203	207	0001	0202	303	0000	0201
020	0214	0415	114	0213	0414	210	0212	0413	304	0211	0412
021	0424	0625	115	0423	0624	211	0422	0623	305	0421	0622
022	0635	1036	116	0634	1035	212	0633	1034	306	0632	1033
023	1045	1246	117	1044	1245	213	1043	1244	307	1042	1243
024	1256	1457	120	1255	1456	214	1254	1455	310	1253	1454
025	1466	1667	121	1465	1666	215	1464	1665	311	1463	1664
026	1677	2100	122	1676	2077	216	1675	2076	312	1674	2075
027	2107	2310	123	2106	2307	217	2105	2306	313	2104	2305
030	2320	2521	124	2317	2520	220	2316	2517	314	2315	2516
031	2530	2731	125	2527	2730	221	2526	2727	315	2525	2726
032	2741	3142	126	2740	3141	222	2737	3140	316	2736	3137
033	3151	3352	127	3150	3351	223	3147	3350	317	3146	3347
034	3362	3563	130	3361	3562	224	3360	3561	320	3357	3560
035	3572	3773	131	3571	3772	225	3570	3771	321	3567	3770

TRACK NO. 02			TRACK NO. 06			TRACK NO. 12			TRACK NO. 16		
BLOCK NO.	FIRST WORD	LAST WORD	BLOCK NO.	FIRST WORD	LAST WORD	BLOCK NO.	FIRST WORD	LAST WORD	BLOCK NO.	FIRST WORD	LAST WORD
036	0003	0204	132	0002	0203	226	0001	0202	322	0000	0201
037	0214	0415	133	0213	0414	227	0212	0413	323	0211	0412
040	0424	0625	134	0423	0624	230	0422	0623	324	0421	0622
041	0635	1036	135	0634	1035	231	0633	1034	325	0632	1033
042	1045	1246	136	1044	1245	232	1043	1244	326	1042	1243
043	1256	1457	137	1255	1456	233	1254	1455	327	1253	1454
044	1466	1667	140	1465	1666	234	1464	1665	330	1463	1664
045	1677	2100	141	1676	2077	235	1675	2076	331	1674	2075
046	2107	2310	142	2106	2307	236	2105	2306	332	2104	2305
047	2320	2521	143	2317	2520	237	2316	2517	333	2315	2516
050	2530	2731	144	2527	2730	240	2526	2727	334	2525	2726
051	2741	3142	145	2740	3141	241	2737	3140	335	2736	3137
052	3151	3352	146	3150	3351	242	3147	3350	336	3146	3347
053	3362	3563	147	3361	3562	243	3360	3561	337	3357	3560
054	3572	3773	150	3571	3772	244	3570	3771	340	3567	3770

TRACK NO. 03			TRACK NO. 07			TRACK NO. 13			TRACK NO. 17		
BLOCK NO.	FIRST WORD	LAST WORD	BLOCK NO.	FIRST WORD	LAST WORD	BLOCK NO.	FIRST WORD	LAST WORD	BLOCK NO.	FIRST WORD	LAST WORD
055	0003	0204	151	0002	0203	245	0001	0202	341	0000	0201
056	0213	0414	152	0212	0413	246	0211	0412	342	0210	0411
057	0424	0625	153	0423	0624	247	0422	0623	343	0421	0622
060	0634	1035	154	0633	1034	250	0632	1033	344	0631	1032
061	1045	1246	155	1044	1245	251	1043	1244	345	1042	1243
062	1255	1456	156	1254	1455	252	1253	1454	346	1252	1453
063	1466	1667	157	1465	1666	253	1464	1665	347	1463	1664
064	1676	2077	160	1675	2076	254	1674	2075	350	1673	2074
065	2107	2310	161	2106	2307	255	2105	2306	351	2104	2305
066	2317	2520	162	2316	2517	256	2315	2516	352	2314	2515
067	2530	2731	163	2527	2730	257	2526	2727	353	2525	2726
070	2740	3141	164	2737	3140	260	2736	3137	354	2735	3136
071	3151	3352	165	3150	3351	261	3147	3350	355	3146	3347
072	3361	3562	166	3360	3561	262	3357	3560	356	3356	3557
073	3572	3773	167	3571	3772	263	3570	3771	357	3567	3770

*This table gives the address of the first and last word of each disk block relative to the start of the track in which it falls. It can be seen by inspection that each block lies completely within one track, and Rule 1 is, therefore, satisfied. It can also be seen that there is a space of at least seven words between each pair of blocks, and Rule 2 is, therefore, also satisfied. The absolute address of a disk block can be obtained by adding the relative address given here to 4000₈ times the track number. (Note: To allow standard bootstrapping techniques to also work with this system, Block 0 is moved so that it actually starts at Word 0 of the disk.)

(2) Leave 7½ words between blocks (7 one block, 8 the next).

The decoding algorithm for converting a block number into the starting address of the block on disk is then: Starting address = 210.4₈ × block number + 10₈.

By exhaustive evaluation (such an evaluation for the algorithm actually used is given in Table 1), it can be seen that all blocks numbered 0 through 357₈ will fall completely within the track they start in. The overhead time required to pass the interblock space when reading or writing consecutive blocks is only (7½ words per interblock space)/(129 words per block) = 6% of minimum time per block, a considerable improvement from the frequently occurring situations previously described.

ACTUAL IMPLEMENTATION

A slightly modified version of this scheme has actually been implemented by and is in use by the author. This version has the additional feature that the program calling it can be in any field. This is not allowed by the standard I/O routine. With this implementation, the caller's field is indicated by the setting of the data field register. Another special feature is an optional overlapped return in which the routine does not wait for the completion of the I/O operation, but merely initiates it and then immediately returns (through the error return) to the caller.

The calling sequence for the modified DISKIO routine is similar to that for the standard routine. It is called by setting the data field to the caller's field and executing an effective JMS to Location 7642 of Field 0, followed by six words: Word 1—Bit 1 = 1 for overlapped return to error return, = 0 for normal return; Bit 2 = 1 for indirect return to contents of link word minus 1, = 0 for normal return; Bits 6-8 = core memory field for transfer; Bits 9-11 = 2 or 3 for read, 4 or 5 for write; other bits should be 0. Word 2—Block number. Word 3—First memory address. Word 4—Link word. Word 5—Error return is to here. Word 6—Normal return is to here.

A PAL-D listing of the implemented modified routine is given in Table 2. Since it was inserted into the BUILDER⁴ which was then used to set up the disk, it was assembled starting at Location 5600, rather than at 7600 where it actually runs. As with the standard routine, a monitor head resides at the beginning of the page, starting at 7600.

Because coding for this modified routine became so "right," the actual disk address computation algorithm was modified somewhat to take advantage of certain end-around bit rotations. The mapping from block

Table 2
PALD Listing of Modified DISKIO Routine

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/THIS DISKIO ALLOWS BLOCK NOS. 0-357
/ CALL FROM ANY FIELD, INDIRECT + OVERLAPPED RETURNS AVAILABLE
DCEL=6614
M3=CLL CLA CMA RTL
M2=CLL CLA CMA RAL
M1=CLA CMA
TWO=STL CLA RTL
*5400
5600 0006 P6,6
      M200,
5601 7400 MONITOR,7400 /OLA
5602 1200 TAD P6
5603 3217 DCA RW
5604 1252 TAD SCRM1
5605 3220 B,DCA BLK
5606 7344 M2
5607 1217 TAD RW
5610 7450 SNA
5611 5421 JMP I MEM
5612 3217 DCA RW /ONLY 2 OR 4 BUT WORKS FOR OUR IO
5613 1344 L,TAD P7200
5614 3221 DCA MEM
5615 2220 ISZ BLK
5616 4242 JMS IO
5617 0000 RW,0
5620 0000 BLK,0
      C2CA,0
5621 0000 MEM,0
5622 0000 0
5623 7402 HLT
5624 1221 TAD MEM
5625 1232 TAD P377 /RSLT=7577 OR 7777
5626 7040 CMA /RSLT=200 OR 0
5627 7450 SNA
5630 5205 JMP B
5631 5213 JMP L
5632 0377 P377,377
5633 3700 P3700,3700
5634 0000 C2DEAL,0
      ERR,
5635 2377 ISZ ERRSW
5636 5367 JMP RET
5637 1234 TAD C2DEAL
5640 6615 DEAL
5641 5322 JMP ERRON
5642 0000 IO,0
5643 7240 M1 /MUST B THIS CAUSE OF WAY OKD
5644 3377 DCA ERRSW
5645 1642 TAD I IO
5646 0200 AND P6
5647 1367 TAD P6601
5650 3330 DCA DMARV /DMAR OR DNARV
5651 1642 TAD I IO
5652 0352 SCRM1,AND P70
5653 6615 DEAL /MEM FLD
5654 1642 TAD I IO
5655 7006 RTL /SHIFT BIT 1 INTO LINK,BIT 2 INTO 0
5656 7710 SPA CLA
5657 7326 TWO /INDRCT RET, IRET=7775,CLRS LNK(NO OVLAP RET POSSBL)
5660 7040 CMA /NRML RET, IRET=7777
5661 3373 DCA IRET
5662 7420 SNL /SKP IF OVLAP DESIRED
5663 7240 M1 /NO OVLAP,WILL WAIT FOR COMPLETION
5664 3347 DCA OVLAP
5665 2242 ISZ IO
5666 1642 TAD I IO /BLK
5667 7001 P7001,1AC
5670 7106 CLL RTL
5671 7006 RTL
5672 1642 TAD I IO
5673 3353 DCA R21111 /21*(BLK+1)-1
5674 1353 TAD R21111
5675 0267 AND P7001
5675 0267 AND P7001
5676 7110 CLL RAR
5677 7112 CLL RTR
5700 6614 DCEL /3 LD ORD XTEND
5701 3234 DCA C2DEAL
5702 1353 TAD R21111
5703 7126 STL RTL /ADD 4
5704 7006 RTL /M1 ORD BITS SHFT AROUND + ADD DELTA .LT. 4
5705 1642 TAD I IO
5706 7010 RAR
5707 1201 TAD M200 /21*(BLK+1)+BLK/2+DELTA-200=210+BLK+BLK/2+4
5710 3353 DCA C2DEAL
5711 2242 ISZ IO
5712 1642 TAD I IO /MEM
5713 3221 DCA C2CA
5714 7326 TAD
5715 1242 TAD IO
5716 3246 DCA RETAD
5717 7446 TAD I RETAD
5720 2373 ISZ IRET /SKP IF NRML RET
5721 3346 DCA RETAD /PP ERROR RETURN
5722 7240 ERRON,M1
5723 1221 TAD C2CA
5724 3351 DCA CA
5725 1375 TAD M201
5726 3350 DCA XCIF
5727 1353 TAD C2DMAX
5730 0000 DMARV,0
5731 1347 TAD OVLAP
5732 7450 SNA CLA
5733 5370 JMP RET+1 /OVERLAPPED RET RTNS TO ERROR RET
5734 1350 TAD KC
5735 7040 CMA
5736 7440 SZA CLA
5737 5334 JMP -3
5740 6614 DFAC
5741 0233 AND P3700
5742 6214 RDF
5743 6615 DFAL
5744 7000 P7000,CLA
5745 5356 JMP CNT
5746 0000 RETAD,0
5747 0000 OVLAP,0
5750 7751 KC,7751
5751 7751 CA,7751
5752 0070 P70,70
      C2DMAX,
5753 0000 R21111,0
5754 0000 DCTPC,0
5755 0000 DCTPCA,0
      CNT,
5756 1373 TAD IRET /NOW 0=NRML RET, 7776=INDPCT RET
5757 7450 SNA
5760 1242 TAD IO
5761 3351 DCA CA
5762 6622 DFSC
5763 5340 JMP -1
5764 6621 DFSE
5765 5235 JMP FRV
5766 2346 ISZ RETAD
      RET,
5767 6601 P6601,DCA
5770 1376 TAD XCIF
5771 6214 RDF
5772 3373 DCA -+1
5773 0000 IRET,0 /CIF
5774 5746 JMP I RETAD
5775 7577 M201,-201
5776 4202 XCIF,CIF
5777 5201 ERRSW, JMP MONITOR /FOR BOOTSTRAP

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numbers to track addresses performed by the implemented algorithm is given in Table 1, from which it can be seen that our rules are satisfied.

Since Blocks 373₈, 374₈, and 375₈, which are normally system scratch blocks, are nonexistent in our system, program references to these blocks had to be changed. And, naturally, the storage allocation map had to be changed to indicate the additional nonexistent blocks.

The difference in speed when using the modified routine is detectable even when using the SAVE and CALL programs from the keyboard, since the noticeable pause which usually occurs between the entering of a SAVE or CALL instruction and the completion

of its execution is now absent. Reads or writes of consecutive blocks under the new system can be done in about one-fifth the time required under the old system.

AVAILABILITY

The author regrets that only the SAVE, CALL, and DISKIO (SYSIO) routines have been modified to take advantage of these results; other routines which perform their own block-oriented disk I/O will not work properly under this system.

If there is sufficient demand, a DECTape SWAP⁵ image of a basic modified disk system could be made available to the DECUS library.

NOTES

1. This paper deals only with the DF32 disk. Because of the hardware restrictions on changing the core field addressed by the disk during a disk read or write, the user must restrict himself either to using only Disk 0 or to reading and writing only from the core field which contains the disk I/O routine, in order to use effectively the results of this paper. Since the author had a configuration which contained only one disk, the former was the course chosen.

2. With standard Moore School operating procedure, each user has his own DECTape SWAP³ image of the disk, and can therefore modify it as he pleases, without adversely affecting other users.

3. Kristol, D. M. SWAP, DECUS, Program 8-154, 1968.

4. PDP-8 Disc System Builder Listing, Document No. DEC-08-SBAB-LA, 1967.

5. PDP-8/I Disk Monitor System, Document No. DEC-D8-SDAA-D, 1968.