THE SERIES AND ITS EVOLUTION

It is useful to compare the five 18-bit computer implementations made over the course of roughly ten years. Shipments (to 1976) have extended over a sixteen year period during which the machines were implemented across two generations of logic technology. It began in the early second generation and extended to the early part of the third (large scale integrated circuit) generation. Had the 18-bit computer series been extended to the fourth generation, a version of the PDP-15 ~~would~~ could have been easily implemented on a single silicon chip.

Table ~~2~~ 4 gives the characteristics of each 18-bit computer. Note that the duration of the projects generally increased with time, reflecting the increased production volumes. (The PDP-4 took the least time to produce because the circuits and mechanical packaging were based on the PDP-1.) The time between the first few implementations (half life) was about two years (19 months from PDP-1 to -4). In contrast to this the PDP-15 was produced for seven years after it was first implemented. The early (too frequent) implementations were perhaps indicative of the attention paid to low hardware cost and performance, rather than to application and software enhancements to increase the market life.

PDP-1

The goals, applications, innovations and improvements do not lend themselves to quantitative analysis, but nevertheless, are aspects worth examining. PDP-1 had a number of innovations compared to its laboratory predecessors, the Whirlwind and TX-0. PDP-1 contributed extremely straightforward I/O interfacing capability. This, combined with a multichannel interrupt structure and direct memory access, enabled high data rate I/O data transmission. These characteristics made it ideal for high performance laboratory applications. The PDP-1 also represented a major stepping stone in the early formation of timesharing computers. Its application to message switching contributed significantly to its marketability and provided impetus for the design of good communication interfaces in subsequent computers. It also served as a test model for the circuitry DEC had built earlier, making the PDP-1 modules more suitable for others to build systems.

PDP-4

The PDP-4 contributed in small ways. There were minor improvements in the ISP. Insofar as it was oriented to a much lower cost, the PDP-4 did feature some refinements in the modules. The simplified logic design of the PDP-4 contributed to the implementation of subsequent computers. It also contributed the basic notion that subsequently evolving machines should be lower cost. It also extended the marketplace to industrial control (which had not been possible at PDP-1's price levels), and improved the interface capabilities.

PDP-7 and PDP-9

The PDP-7 and PDP-9 families featured significant refinement in the wirewrap packaging technology. Their circuits were based on the early PDP-6 10 Mhz circuits, but the Flip Chip package was more cost-effective and more easily produced. The performances of both machines was significantly improved over that of any predecessor. This is the first time the number of words or bits accessed by the processor was used as the performance criterion. PDP-7 represented a 4.57 improvement over the PDP-4; and PDP-9 represented a 1.75 improvement over the PDP-7. Both improvements were the result of faster core memories. The PDP-9 was implemented as a microprogrammed machine. This really was a dubious choice given the simple ISP of the 18-bit machines. PDP-9 did change to the I/O bus structure which helped reduce its basic cost further by distributing the I/O interface to each option.

PDP-15

The improvements provided with PDP-15 came about through the use of integrated circuits. At last there was a significant reduction in size, although the power consumption did increase. In the processor, the board area decreased by a factor of three over previous implementations (board area had been relatively constant at about 3000 square inches). The PDP-15's major improvement was the notion of systems including both hardware and software, and secondly, that the machine would be supported over a range of sizes. Finally in order to extend the life of the machine, a number of improvements were made to reduce price (memory, PDP-11 I/O) and to increase performance (floating point, multiple processors).

Price

Figure Price shows that the price for the minimum system declined by more than 19 percent per year. The price of the average system has never been properly analyzed, but roughly speaking the average price declined from an initial cost of $250K for a PDP-1 to $65K for a PDP-9. Early PDP-15's were sold at an average price of $75K, while the final average price was about $125K.[2] It should be noted that the Teletype ASR with built-in paper tape reader and punch helped reduce the price of the later minimum 18-bit computers.

Strangely enough, the price of the primary memory did not decrease at a very rapid rate (see Fig. Mp.price). Its price decline of 16 percent per year can be attributed to the fact that each subsequent machine needed higher performance memories. The result was that the memories were always implemented at relatively constant price with increasing performance rather than the converse. PDP-4 shows the effect of bulding a low performance memory versus the fastest memory. While the first PDP-4s were shipped with PDP-1 memory, the next machines had 8K word memory systems that cost about half that of the PDP-1. By contrast, the PDP-10 memory had operated at about 1 Mhz, and was designed not to meet performance constraints, but rather lower cost by economy of scale. (The PDP-10 performance comes through memory parallelism and a faster processor.)

Performance

Performance (in millions of words accessed per second by the processor) is shown in Fig. Perf. showing a 29 percent yearly increase. Neither the PDP-15 nor PDP-4 fall on the line, since both were oriented to lower price, instead of increased performance. In reality, the PDP-15 later evolved to have much greater performance when built-in floating point arithmetic was added. This feature brought its real performance to the line. This performance amounts to a factor of 2 to 10 for Fortran programs involving floating point. Midlife extensions of this sort were generally missing on the other computers.

Price/Performance

The performance/price ratio is a reasonable index for simple systems (see Fig. ~~Perf.Price~~ 34). This ratio has improved by 52 to 69 percent per year over the ten year period. The PDP-4 is the exception because while it went down in price it also gave poorer performance. A variant of this plot is shown in Fig. ~~PP18~~ 35 where price is plotted vis-a-vis the performance (in millions of accesses per second by the processor). Dates are shown at each point. The lines of constant performance/price are separated by a factor of two (keep in mind that if any measure changes by 41 percent per year, it takes two years to move from one line to another. Conversely, a yearly improvement of 26 percent takes three years to get double, etc.). Again, note that since the gain in this factor is at least 52 percent, the 9.1 year evolution crosses five factor of two lines. Only the PDP-4 stands out as being on a line of constant performance/price. (In essence it was either overpriced by a factor of two, or should have performed better by a factor of two for the same price).

Market Demand

Figures ~~Demand 18~~ 36 and ~~PrPerfDemand~~ 37 present a view of the market demand for 18-bit computers. These two plots show two views of what ~~can be~~ is being marketed. Are computers sold at a given price (Fig. ~~Demand 18~~ 36)? Or, is a computer a collection of operations with a given price per operation--hence, a user only cares about the price of an operation? Ignoring the PDP-1, there is a reasonable fit to the first curve; it appears that we are simply selling computers at a given price, and there is a completely elastic demand. Somehow, simply by being the first, more PDP-1s were sold than any of the other machines. Alternatively, there was one ~~lucky~~ (perhaps fortuitous) order for half of all the PDP-1s sold, and in reality only 20 ~~should~~ might otherwise have been sold.

Alternatively, the standard price-based demand curve may not be correct. Computers may be regarded like power generators: demand for them is based on the amount of work they can do per unit of cost. (This would explain why roughly the same number of both PDP-1s and PDP-4s were sold.) Note that more PDP-9s and PDP-15s were sold than the curve would have predicted. This is because both machines had longer lives before successors were introduced, and hence did not have arbitrarily shortened lives. (A better measure of demand might be the maximum number shipped in any one year, taking into account other marketplace limits.) Because of the relatively large number of variables that can be evaluated (size of DEC, the economy, market maturity, etc.) it hardly seems worthwhile to try for more insight from what is probably quite weak data. These plots should simply be regarded as providing interesting insight...and a basis for speculation.

<u>Other Characteristics</u>

Table ~~7~~ 4 has other data that could be plotted. The input power (with the exception of PDP-4) is constant over all implementations. The weight is correlated with size (volume in cubic feet) reflecting a relatively constant weight per bay. The volume has declined with time consistently reflecting improvements in packing density. In this respect, the PDP-4 was a better implementation than the PDP-1. The PDP-7 was better than the ~~-4~~ PDP-4 in high packing density than either PDP-1 or PDP-4. The PDP-9 improvement in implementation used the same logic as in the PDP-7. PDP-15 achieved its volume reduction using integrated circuit technology. The ~~number~~ weight/# appears to have risen and is correlated with inflation. Power and weight density measurments are given in the table together as are several ratios involving cost, weight, power and performance. Note that measurement of performance changes most. The calculated mean time between failures has declined by over a factor of two between the PDP-1 and PDP-15.

The reader should compare the implementations. Of special interest is the number of logic module types and power supply types. With the exception of PDP-1, all required about 5000 sq.in. of printed circuit board area. The innovation of PDP-4 to use a bit slice approach added two specialized modules, making possible a major reduction in backpanel interconnections. All subsequent implementations used the bit slice approach with a few special purpose modules. Similarly, use of integrated circuits in the PDP-15 resulted in another major reduction in the PDP-15's size. All required about the same number of explanatory logic diagrams and all had about 40 different logic types, although the PDP-15 had 54 types. This low number of part numbers and relatively low cost per module meant that the cost of a complete package of spare modules for a computer represented a small fraction of the price.

Options

Table 5 shows the options available for the various machines. Note that PDP-1 was relatively complete, and subsequent machines followed the PDP-1 fairly closely. PDP-1, 4 and 7 were relatively compatible and slowly evolved the same set of options. PDP-9 changed to an I/O Bus structure requiring new options and while PDP-15 used the same I/O Bus structure and signals, the voltages were different necessitating the redevelopment of logic options. Also, note from the start, that the displays have been major options. Only since the PDP-15 were moving head disks added.

Although a number of card options were available, few were sold.

Evolution

While the 18-bit computers evolved over both a wide price and performance range, they must be contrasted with the clear evolution of the 12-bit computer whose evolution has been quite clearly based on decreasing price. The 18-bit evolution has been neither decreased price (providing larger and newer markets) nor constant price with much greater performance, but rather a combination. The PDP-11 has evolved to both increased performance at constant price and constant performance (or even decreased performance) at decreased price.

The 18-bit series has been a middle of the (price-performance) road design. Nor has it had a continuity of designers or architects of the other DEC machines. Each implementation has been made by a member of the previous implementation group.

The PDP-15's identity came up clearly in the face of a 16-bit word length competitor. The PDP-11 required more IC's to implement, but because the PDP-15 remained packaged in a large cabinet with small modules (and few IC's per board) versus a small metal box structure, the cost did not decline rapdily enough to be competitive with the metal-boxed minis. On the other hand, some felt the market demand was only for 16 or module (8) bits. As a result the 18-bit machines are no longer manufactured.

Acknowledgments

Several people helped get the data together for this paper and critiqued its design: Dick Devlin, Dick Best, Carl Noelcke (reliability calculations), Jack Shields, Don White, Don Zereski, Craig Mudge, and Earl Cain. Mary Jane Forbes and Louise Principe deserve thanks for typing the numerous drafts.

Table 4 - CHARACTERISTICS OF DEC's 18-BIT COMPUTERS.

	1	4	7	9;9/L	15
Project start; first ship	8/59;11/60	11/61;7/62	;12/64	;8/66;-,12/68	~~;12/69~~ 5/68; 2/70
Goals	cost;short word length; speed	cost	speed; cost	speed; cost; producibility	cost;range of machines, hdw/sw sys.
Applications	lab control message switch time-sharing dev.	process cont lab control indust.test-ing	+ time-	+ graphics	+computation >graphics process
Innovation/ improvements	ckt.use package, ISP, interrupts, direct mem. access i/o interface;	functional (bit slice) modules, ISP trend to mini; 3 cycle DMA; i/o interface	package & modules; perf	microprogram; I/O BUS	IC use; floating point; multiprocessor
Price with Rdr, 4K Pch, Typ, 4 Kword	120	65.5(56.5)	45	25+;24.4(19.9)	19.8(16.2)
Price/Mp word	7.32	3.66	3.99	2.19;1.95	1.71;1.32

Table ~~C~~ 4 - CHARACTERISTICS OF 18-BIT COMPUTERS.

	1	4	7	9;9/L	15
MTBF (hrs.)	2800	-	-	-	5400
Mp. cycle time	5	8	1.75	1;1.5	0.8
Mp access/sec x M	0.2	.125	.57	1;.67	1.25
Multiply/divide time (microsec.)	25/40		4.4/9	4.5-12.5/12.5	4.5/4.5
Mp.size(Kwords)	1,4;...,65	1,4,8,...,32	4,...,32	8,4,...,32	4,...,131
Bits accessed per sec/$	30(.033)	34.5(.029)	227(.0044)	714(.0014)	1135(.00088)
Perf/price improve	-	1.1	6.6	3.1	1.7
Price improve	-	1.8	1.45	1.8	1.3(1.5)
Perf improve	-	.62	4.57	1.75	1.25
Product Life	4	3	4	4	7
Number produced	50	45	120 (165?)	445	790
Power (watts)	2160	1125	2100	2000	2875

Table 4 - CHARACTERISTICS OF 18-BIT COMPUTERS.

	1	4	7	9;9/L	15
Weight (lbs.)	1350	1030	1150	790	750
Size(in.69"x21" x28" bays)	4	2	3	1.5(special)	1
Vol.(cu.ft.)	94	47	70.5	36	23.5
Power dens. =watts/cu.ft.	22.9	23.9	29.8	55.5	122.3
Wt.dens. =lbs./cu.ft.	14.4	21.9	16.3	21.9	31.9
Watts/$	.018	.017	.046	.08	.15
lbs./$	.011	.016	.026	.032	.038
KBits accessed per watt	1.6	1.1	4.9	9.0	7.8
KBits accessed per lb.	2.6	2.2	8.9	22.8	30.
KBits accessed per cu.ft.xK	38.3	47.9	146.	500.	957.
Logic technology	sat.MADT	C-D gates;	sat.trans.		7400,74H00

Table ~~6~~ 4 - CHARACTERISTICS OF 18-BIT COMPUTERS.

	1	4	7	9;9/L	15
	trans.	diode trans.			
Logic speed(Mhz)	5, .5	1,0.5,5	10,1,.5	10,1	10,20
Module size	5.25x4=23	5.25x4=22	2.25,5 (x 3.875);	2.25,5,10 (x 3.875)	same
# power supply/ # types	8/4	4/2	9/4	1/1	1/1
# modules/ # types	544/34	236/41	614/39	644/44	300/54
# transistors, diodes, IC's	3.5K,4.3K	-	-	-	350, 200, ~~?,?~~,3.4K
Modules space Pc	18x25	6x25	12x32	8x44	4x32
Modules space, I/O Interface	3x25	3x25	-	-	4x32
Modules space, Rdr,Pch,Typ.	3x25	3x25	8x32	8x44	7
Modules space, 4Kw Mp	4x25	4x25(8K)	3x32	3x44	4x32

Table 4 - CHARACTERISTICS OF 18-BIT COMPUTERS.

	1	4	7	9;9/L	15
Total Logic area(sq.in xK)	11.9	5.2	5.3	5.6	3.4
Processor area	8.9	3.3	3.3	3.1	2.1
# logic prints	18	16	27	44/2=22	75/2

Table 5 - OPTIONS For DEC's 18-BIT COMPUTERS

	1	4	7	9	15
CPU OPTIONS					
Multiply/Divide	Std.	[18] EAE	[177]		EAE opt,flt.pt. opt.
Priority interrupt	1ch.std.; [120]-16ch; also 256ch.	1ch.std.	1ch.std [172] 16ch;	1ch.std;8 opt.	1ch.std;8 opt.
Direct Mem. access	[19] 3 ch.	1 std.; 3 opt.	[173] 3 ch.	+1 to mem.(std.)	up to 64
Clock	yes	1 std; [132] 16 ch.	opt.	opt.	opt.
Power failure	N/A	std.	-	-	opt.
Memory protect	4K blocks	none	[KA 70A] base & bounds	same	same
Ms					
Magtape (prog. control)	[51]-[50] 200 b/i	[54]-[50] 200 b/i			
Magtape (DMA)	[52]-[50] [510]-[IBM 729]	[57A]-[50 or 570] 556 b/i	[57A]-[50 or 570]	[TC59]-[TU20]	[TC59]-[TU20 or TU30]

Table 5 - OPTIONS OF 18-BIT COMPUTERS

	1	4	7	9	15
Drums	[23]	[24] 16Kw ...65Kw	[24] 32Kw ...131Kw	32Kw...524Kw	
Disks	N/A			[RS09] 1Mw	[RS09]-262Kw ...2Mw
Disk pak					[RP02]10Mw
DECtape	N/A	[550]-[555]	[550A] -[555]	[TC02]-[TU55]	[TC02]- [TU55]
<u>LINKS</u>					
Inter-Computer			[195] DB97	DB98,99	DB98,99
To 7090	[150] 10Kw/s				
Communications	8ch. up to 256		[630] 64ch. [634] 8ch.	[630] 64ch. [LT09] 5ch	 [LT19]
To other computer busses				to PDP-7	[DW15] to PDP-9
<u>TRANSDUCERS</u>					
Papertape reader	std. 400c/s	std.300c/s	std. 300c/s	std.300c/s	std.300c/s
Papertape punch	std. 63c/s	[75] 63c/s	[75] 63c/s	[PC09] 50c/s	[PC15] 50c/s
typewriter	std. 10 c/s	[65] 28KSR,	[643] 33KSR	33 KSR, ASR	33,35,ASR,KSR

Table 9 - OPTIONS OF 18-BIT COMPUTERS

	1	4 10 c/s	7	9	15
CRT's.					
pt. plot	[30] 16"1Kx1K	[30D]	[30D] [340] vector plot	[30D] [340C],	[VP15]
storage	[34]Tektronix storage	[34]	[34]	[34H]	
DMA				[339]P.display with 340	[VT15]
precision	[31] 5" 4Kx4K				
Alphanumeric					[VT05]
Card reader	[421]200c/m	[41]200c/m	[421]200 or 800c/m	[CROIE] 100 or 200c/m	[CR033] 200c/m
Card punch	[40]100c/m	[40]100c/m	[410]100c/m	-	
Line printer	[64]3001/m	[64]3001/m	[64]3001/m	[647]300 or 6001/m	[647]300 o[illegible] 1000 1/m
Plotter			[350] to Calcomp	[350]	[350],[x415]

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	1	4	7	9	15
Relays	[140]18ch	[140] 18ch	[140]18ch	[DR09A]	DR09A
A/D	[138/139]64ch	[138/139]	[138/139]	64 ch	[AF02] 64ch
				1000 ch	[AF04] 1000ch
D/A					AFC 15-analog
					UDC 15-digital

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Table 4 gives the characteristics of each 18-bit computer. The first part of this section summarizes the contributions of each member of the series. Aided by time plots of the major parameters in Table 4, the second part observes trends in the series as a whole.

PART I

PDP-1

The goals, applications, innovations, and improvements do not lend themselves to quantitative analysis, but nevertheless, are aspects worth examining. PDP-1 had a number of innovations compared to its laboratory predecessors, the Whirlwind and TX-0. PDP-1 contributed extremely straightforward I/O interfacing capability. This, combined with a multichannel interrupt structure and direct memory access, enabled high data rate I/O data transmission. These characteristics made it ideal for high performance laboratory applications. The PDP-1 also represented a major stepping stone in the early formation of timesharing computers. Its application to message switching contributed significantly to its marketability and provided impetus for the design of good communication interfaces in subsequent computers. It also served as a test model for the circuitry DEC had built earlier, making the PDP-1 modules more suitable for others to build systems.

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Part VI

Length of Development Project

Note that The duration of the projects generally increased with time, reflecting the longer tooling time for increased production volumes. (The PDP-4 is an exception; it had the shortest design time took the least time to produce because the circuits and mechanical packaging were based on the PDP-1.) The time between the first few implementations (half life) was about two years. (19 months from PDP-1 to -4). The final implementation, the In contrast to this the PDP-15 was produced for seven years, after it was first implemented. The early (too frequent) implementations were perhaps indicative of the attention paid to low hardware cost and performance, rather than to application and software enhancements to increase the market life. [GB: an alternative to this last sentence is:]

[GB: half life?]

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Printer error (left margin)

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Market Demand

Replace with α

Figures 36 and 37 present a view of the market demand for 18-bit computers. These two plots show two views of what is being marketed. Are computers sold at a given price (Fig. 36)? Or, is a computer a collection of operations with a given price per operation--hence, a user only cares about the price of an operation? Ignoring the PDP-1, there is a reasonable fit

In order to speculate on a theory of demand for small computers, two demand curves are given. Fig 36 is ~~a~~ the classic demand curve: price of the unit versus quantity. If we ignore the PDP-1, it appears that there is complete price elasticity of demand. We offer two reasons for the PDP-1 anomaly.

Twenty of the PDP-1's are accounted for by a single, perhaps fortuitous, order ~~was received~~ for the ADX 7300 systems (?). If we subtract this amount from the PDP-1 quantity, the classic demand model fits the data. The second conjecture is that sales were higher than the model projection because the PDP-1 was first into the market.

An alternative to the above demand model is given in Fig 37 where price <u>per unit of performance</u> is plotted against quantity. This model is based on the thesis that computers are like power generators (or tractors): demand is based to the first curve; it appears that we are simply selling computers at a given price, and there is a completely elastic demand. Somehow, simply by being the first, more PDP-1s were sold than any of the other machines. Alternatively, there was one (perhaps fortuitous) order for half of all the PDP-1s sold, and in reality only 20 might otherwise have been sold.

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[GB: The section on demand is flaky; we should talk to an economist before we discuss models. However the plots themselves are interesting. What references can we give?]

Other Characteristics

Table 4 has other data that could be plotted. The input power (with the exception of PDP-4) is constant over all implementations. The weight is correlated with size (volume in cubic feet) reflecting a relatively constant weight per bay. The volume has declined with time consistently reflecting improvements in packing density. In this respect, the PDP-4 was a better implementation than the PDP-1. The PDP-7 was better than the

PDP-4 in high packing density than either PDP-1 or PDP-4. The PDP-9 improvement in implementation used the same logic as in the PDP-7. PDP-15 achieved its volume reduction using integrated circuit technology. The weight/$ appears to have risen and is correlated with inflation. Power and weight density measurments are given in the table together as are several ratios involving cost, weight, power and performance. Note that measurement of performance changes most. The calculated mean time between failures has declined by over a factor of two between the PDP-1 and PDP-15.

The reader should compare the implementations. Of special interest is the number of logic module types and power supply types. With the exception of PDP-1, all required about 5000 sq.in. of printed circuit board area. The innovation of PDP-4 to use a bit slice approach added two specialized modules, making possible a major reduction in backpanel interconnections; however All subsequent implementations used the bit slice approach with a few special purpose modules. Similarly, Use of integrated circuits in the PDP-15 resulted in another major reduction in the PDP-15's size. All required about the same number of explanatory logic diagrams and All had about 40 different logic types, although the PDP-15 had 54 types. This low number of part numbers and relatively low cost per module meant that the cost of a complete package of spare modules for a computer represented a small fraction of the price.

Options

Table 5 shows the options available for the various machines. Note that PDP-1 was relatively complete, and Subsequent machines followed the PDP-1 fairly closely. PDP-1, 4 and 7 were relatively compatible and slowly evolved the same set of options. PDP-9 changed to an I/O Bus structure requiring new options and while PDP-15 used the same I/O Bus structure and signals, the voltages were different; necessitating the redevelopment of logic options. Also, note from the start, that the displays have been major options. Only since the PDP-15 were moving head disks added. Although a number of card options were available, few were sold.

Evolution

While the 18-bit computers evolved over both a wide price and performance range, they must be contrasted with the clear evolution of the 12-bit computer whose evolution has been quite clearly based on decreasing price. The 18-bit evolution has been neither decreased price (providing larger and newer markets) nor constant price with much greater performance, but rather a combination. The PDP-11 has evolved to both increased performance at constant price and constant performance (or even decreased performance) at decreased price.

The 18-bit series has been a middle of the (price-performance) road design. Nor has it had a continuity of designers or architects of the other DEC machines. Each implementation has been made by a member of the previous implementation group.

The PDP-15's identity came up clearly in the face of a 16-bit word length competitor. The PDP-11 required more IC's to implement, but because the PDP-15 remained packaged in a large cabinet with small modules (and few IC's per board) versus a small metal box structure, the cost did not decline rapdily enough to be competitive with the metal-boxed minis. On the other hand, some felt the market demand was only for 16 or modulo (8) bits. As a result the 18-bit machines are no longer manufactured.

B

We conclude this chapter by relating the 18-bit series evolution to the model of minicomputer evolution presented in Chapter ~~0~~ 1. Three design styles are distinguished in the model, as can be seen in Figure 38. As we shall see in Part III, the 12-bit family (PDP-8) evolved consistently along the decreasing price curve. The ~~PDP-11~~ 16-bit PDP-11 family, presented in Part IV, evolved ~~along~~ with all three ~~curves of~~ design styles.

For a family to evolve ~~along~~ in more than one design style, design resources must be available for parallel development efforts. The PDP-11 family has ~~had~~ the ~~a~~ multiplicity of designers and architects to do this; the 18-bit series ~~PDP-15~~ has not. Each new implementation has been designed by a member of ~~the~~ a previous implementation team. For such a single-thread approach ~~, it appears~~ to be successful, it appears that that one of the three design styles of the evolution model ~~be~~ must be chosen and <u>consistently</u> followed. Instead, the 18-bit series has ~~been middle of the~~ followed a middle-of-the-road style: price-performance.

It appears that a clear identity is needed to guide design decisions. Consider the physical packaging of the PDP-15. Although a comparable-speed performance PDP-11 requires more i.c.'s to implement (the PDP-11 has more modes of addressing, more instructions, and more data types) the PDP-15 processor costs more. The ~~pa~~ PDP-15 remained packaged in a large cabinet, it used smaller modules, and its i.c. density per module was lower. Had the evolution been identified as consistently lower cost, ~~stringent box~~ metal box packaging would have been set as a stringent goal. As it was, the PDP-15 had to compete against the PDP-11 with the handicap of an extra level of integration in its physical packaging.

In addition, some product planners felt that the market demand was only for 16-bits or ~~modulus (8) a~~ higher multiples of 8 bits. As a result, the 18-bit ~~[illegible]~~ machines are no longer manufactured & [GB: or designed].

Acknowledgments

Several people helped ~~get~~ gather the data ~~together~~ for this paper and critiqued its design: Dick Devlin, Dick Best, Carl Noelcke (reliability calculations), Jack Shields, Don White, Don Zereski, Craig Mudge, and Earl Cain. Mary Jane Forbes and Louise Principe deserve thanks for typing the numerous drafts.

Table 4 - CHARACTERISTICS OF DEC's 18-BIT COMPUTERS.

	1	4	7	9;9/L	15
Project start; first ship	8/59;11/60	11/61;7/62	4/64;12/64	;8/66;-,12/68	5/68;2/70
Goals	cost;short word length; speed	cost	speed; cost	speed; cost; producibility	cost;range of machines, hdw/sw sys.
Applications	lab control, message switch, time-sharing dev.	process control, lab control, indust. testing	+ time-sharing	+ graphics	+ computation + graphics processing
Innovation/ improvements	ckt. use; package; ISP; interrupts; direct memory access; i/o interface	functional (bit slice) modules; ISP trend to mini; 3 cycle DMA; i/o interface	package; modules; perf	microprogram; I/O BUS	IC use; floating point; multiprocessor
Price with Rdr, 4K Pch, Type, 4 Kword	120	65.5(56.5)	45	25+;24.4(19.9)	19.8(16.2)
Price/Mp word	7.32	3.66	3.99	2.19;1.95	1.71;1.32
MTBF (hrs.)	2800	-	-	-	5400
Mp cycle time (μsec)	5	8	1.75	1;1.5	0.8
Mp access/sec (M)	0.2	.125	.57	1;.67	1.25
Multiply/divide time (microsec.)	25/40		4.4/9	4.5-12.5/12.5	4.5/4.5
Mp size(Kwords)	1,4,...,65	1,4,8,...,32	4,...,32	8,4,...,32	4, ..,131
Bits accessed per sec/$	30(.033)	34.5(.029)	227(.0044)	714(.0014)	1135(.00088)
Perf/price improve*	1	1.1	6.6	3.1	1.7
Price improve*	1	1.8	1.45	1.8	1.3(1.5)
Perf. improve*	1	.62	4.57	1.75	1.25
Product Life	4	3	4	4	7
Number produced	50	45	120 (165?)	445	790
Power (watts)	2160	1125	2100	2000	2875

* over predecessor

Table 4 - CHARACTERISTICS OF DEC's 18-BIT COMPUTERS.

	1	4	7	9;9/L	15
Weight (lbs.)	1350	1030	1150	790	750
Size(in.69"x21" x28" bays)	4	2	3	1.5(special)	1
Vol.(cu ft.)	94	47	70.5	36	23.5
Power dens. (watts/cu.ft)	22.9	23.9	29.8	55.5	122.3
Wt.dens. (lbs./cu.ft.)	14.4	21.9	16.3	21.9	31.9
Watts/$	.018	.017	.046	.08	.15
Pounds lbs./$	.011	.016	.026	.032	.038
KBits accessed per watt	1.6	1.1	4.9	9.0	7.8
KBits accessed per lb.	2.6	2.2	8.9	22.8	30.
KBits accessed per cu.ft.xK	38.3	47.9	146.	500.	957.
Logic technology	~~sat.~~ saturating MADT transistors	~~C-D~~ capacitor-diode gates; diode transistors	~~sat.trans.~~ saturating transistors		7400,74H00 series integrated circuits
Module series	1000		B		M
Logic speed(Mhz)	5, .5	1,0.5,5	10,1,.5	10,1	10,20
Module size	5.25x4=23	5.25x4=22	2.25,5 (x 3.875);	2.25,5,10 (x 3.875)	same
# power supply/ # types	8/4	4/2	9/4	1/1	1/1
# modules/ # types	544/34	236/41	614/39	644/44	300/54
# transistors, diodes, IC's	3.5K,4.3K	-	-	-	350,200,3.4K
Modules space Pc	18x25	6x25	12x32	8x44	4x32
Modules space, I/O Interface	3x25	3x25	-	-	4x32
Modules space, ~~Rdr,Pch,Typ.~~ Reader, Punch, Typewriter	3x25	3x25	8x32	8x44	7
Modules space, 4Kw Mp	4x25	4x25(8K)	3x32	3x44	4x32

Table 4 - CHARACTERISTICS OF DEC's 18-BIT COMPUTERS.

	1	4	7	9;9/L	15
Total Logic area(sq.in xK)	11.9	5.2	5.3	5.6	3.4
Processor area	8.9	3.3	3.3	3.1	2.1
# logic prints	18	16	27	44/2=22	75/2

Table 5 - OPTIONS FOR DEC's 18-BIT COMPUTERS*

	1	4	7	9	15
CPU OPTIONS					
Multiply/Divide	Std.	[18] EAE	[177]		EAE opt, flt.pt. opt.
Priority interrupt	1ch.std.; [120]-16ch; also 256ch.	1ch.std.	1ch.std [172] 16ch;	1ch.std; 8 opt.	1ch.std; 8 opt.
Direct Memory access	[19] 3 ch.	1 std.; 3 opt.	[173] 3 ch.	+1 to mem.(std.)	up to 64
Clock	yes	1 std; [132] 16 ch.	opt.	opt.	opt.
Power failure	N/A	std.	-	-	opt.
Memory protect	~~4K blocks~~ ~~(?)~~ 4 Kword core images	none	[KA 70A] base & bounds	[KA70A] ~~same~~	[KA70A] same
Ms					
Magtape (prog. control)	[51]-[50] 200 b/i	[54]-[50] 200 b/i			
Magtape (DMA)	[52]-[50] [510]-[IBM 729]	[57A]-[50 or 570] 556 b/i	[57A]-[50 or 570]	[TC59]-[TU20]	[TC59]-[TU20 or TU30]
Drums	[23]	[24] 16Kw ...65Kw	[24] 32Kw ...131Kw	32Kw...524Kw	
Disks	N/A			[RS09] 1Mw	[RS09]-262Kw ...2Mw
Disk pak					[RP02]10Mw
DECtape	N/A	[550]-[555]	[550A] -[555]	[TC02]-[TU55]	[TC02]-[TU55]
LINKS					
Inter-Computer			[195] DB97	DB98,99	DB98,99
To 7090	[150] 10Kw/s				
Communications	8ch. up to 256		[630] 64ch. [634] 8ch.	[630] 64ch. [LT09] 5ch	[LT19]
To other computer busses				to PDP-7	[DW15] to PDP-9
TRANSDUCERS					
Papertape reader	std. 400c/s	std.300c/s	std. 300c/s	std.300c/s	std.300c/s
Papertape punch	std. 63c/s	[75] 63c/s	[75] 63c/s	[PC09] 50c/s	[PC15] 50c/s

* The DEC-assigned option number is given in square brackets, e.g., [177].

Table 5 - OPTIONS FOR DEC's 18-BIT COMPUTERS

	1	4	7	9	15
typewriter	std. 10 c/s	[65] 28KSR, 10 c/s	[643] 33KSR	33 KSR, ASR	33,35,ASR,KSR
CRT's.					
pt. plot	[30] 16"1Kx1K	[30D]	[30D] [340] vector plot	[30D] [340C],	[VP15]
storage	[34]Tektronix storage	[34]	[34]	[34H]	
DMA				[339]P.display with 340	[VT15]
precision	[31] 5" 4Kx4K				
Alphanumeric					[VT05]
Card reader	[421]200c/m	[41]200c/m	[421]200 or 800c/m	[CROIE] 100 or 200c/m	[CR033] 200c/m
Card punch	[40]100c/m	[40]100c/m	[410]100c/m	-	
Line printer	[64]3001/m	[64]3001/m	[64]3001/m	[647]300 or 6001/m	[647]300 or 1000 1/m
Plotter			[350] to Calcomp	[350]	[350],[x415]
Relays	[140]18ch	[140] 18ch	[140]18ch	[DR09A]	DR09A
A/D	[138/139]64ch	[138/139]	[138/139]	64 ch 1000 ch	[AF02] 64ch [AF04] 1000ch
D/A					AFC 15-analog UDC 15-digital

THE SERIES AND ITS EVOLUTION 12/2/77

It is useful to compare the five 18-bit computers designed over the course of roughly ten years. The sixteen year period of shipments spanned two generations of logic technology. The series began in the early second generation and extended to the early part of the third (integrated circuit) generation. Had the 18-bit computer series been extended to the (large scale integrated circuit) fourth generation, a version of the PDP-15 could have been easily implemented on a single silicon chip.*1

Table 4 gives the characteristics of each 18-bit computer.

PDP-1

The PDP-1 had a number of innovations over its laboratory predecessors, the Whirlwind and TX-0. It contributed extremely straightforward I/O interfacing capability together with a multichannel interrupt structure and direct memory access capability which enabled a high ~~data rate~~ I/O data rate. ~~transmission.~~ These characteristics made it ideal for high performance laboratory applications. The PDP-1 also represented a major stepping stone in the early days of timesharing computers. The message switching application contributed significantly to its market success and motivated the design of good communication interfaces in subsequent computers. Since the PDP-1 served as a thorough test vehicle for the circuitry of the 1,000 series system modules, these modules were more suitable for their general application in building digital systems.

*1 The single chip CMOS-8 (1977) contains n,000 transistors; the ~~PDP-4~~ PDP-1 used about 3500 ~~m,000~~ transistors and 4300 ~~[illegible]~~ diodes.

(call Gale to get a # here or Don White or)

PDP-4

The PDP-4 contributed in small ways: there were minor improvements in the ISP, and because the PDP-4 was oriented to a much lower cost, some of the modules were refined. The simplified logic design of the PDP-4 was a major influency on the implementation style of subsequent computers. It also contributed the fundamental minicomputer notion that successor machines should be lower cost. Moreover, the PDP-4 extended the marketplace to industrial control, which had not been possible at PDP-1's price levels, and improved the ease of I/O interfacing.

PDP-7 and PDP-9

The PDP-7 and PDP-9 families exploited a significant refinement in the wirewrap packaging technology. Although the circuits were based on the early PDP-6 10 Mhz circuits, the more cost-effective and producible Flip Chip package was used. Both machines had significant performance gains over all predecessors. For the first time, the number of words or bits accessed by the processor was used as the performance criterion. Using this measure the PDP-7: PDP-4 ratio was 4.57 and the PDP-9: PDP-7 ratio was 1.75. Both gains were due to the use of faster core memories. The PDP-9 used microprogrammed control, a dubious choice given the simple ISP. The change to an I/O bus structure in the PDP-9 distributed the I/O interface to each option and so further reduced the basic cost.

The single chip CMOS-8 (1977) contains n,000 transistors; the PDP-4 used m,000 transistors.

PDP-15

The use of integrated circuits provided an 18-bit series improvement; at last there was a significant reduction in size, although the power consumption did increase. The board area in the processor decreased by a factor of three over previous implementations, where it had been relatively constant at about 3000 square inches. The two major contributions of the PDP-15 were the notion that systems include both hardware and software, and that the machine would span a range of sizes. Finally, in order to extend the life of the machine, a number of improvements were made later to reduce price (memory, PDP-11 I/O) and to increase performance (floating point, multiple processors).

Length of Development Project

The duration of the projects generally increased with time, reflecting the longer tooling time for increased production volumes. The PDP-4 is an exception; it had the shortest design time because the circuits and mechanical packaging were based on the PDP-1. The time between the first few implementations was only about two ~~[GB: half life?]~~ years. The final implementation, the PDP-15 was produced for seven years. The early (too frequent) implementations were perhaps indicative of the attention paid to low hardware cost and performance, rather than to application and software enhancements to increase the market life.

~~[GB: an alternative to this last sentence is:]~~

Price

Figure 31 shows that the price for the minimum priced system declined by more than 19 percent per year. The price of the average priced system has never been properly analyzed, but roughly speaking the average price declined from an initial cost of $250K for a PDP-1 to $65K for a PDP-9. Early PDP-15's were sold at an average price of $75K, while the final average price was about $125K. It should be noted that the Teletype ASR 33 (?) with built-in paper tape reader and punch helped reduce the price of the ~~later~~ minimum configurations of later 18-bit computers as much as any component.

The primary memory price decline (Fig. 32) of just 16 percent per year can be attributed to the fact that each subsequent machine needed higher performance memories. Memories were always implemented at relatively constant price with increasing performance. Again, the PDP-4 is an exception; it shows the effect of bulding a low performance memory versus the fastest memory. While the first PDP-4s were shipped with PDP-1 memory, the next machines had 8 Kword memory systems that cost about half that of the PDP-1. The price of the 18-bit memory systems decreased at a rate slightly less than the 12-bit computers. The rate of decrease for the 36-bit computers was faster, perhaps reflecting an economy of scale.

Performance

Performance (in millions of words accessed per second by the processor) is shown in Fig. 33. showing a 29 percent yearly increase. Neither the PDP-15 nor PDP-4 fall on the line, since both were oriented to lower price, rather than increased performance. In reality, the PDP-15 later evolved to have much greater effective performance when built-in floating point arithmetic was added. Then its real performance (a factor of 2 to 10 better for Fortran programs involving floating point) exceeded the line position. Midlife extensions of this sort were generally missing on the other 18-bit computers as design resources went into developing new processors.

Price/Performance

The performance/price ratio, a reasonable index for simple systems, is shown in Fig. 34. This ratio has improved by 52 to 69 percent per year over the ten year period. A variant of this plot is shown in Fig. 35 where price is plotted against the performance (in millions of accesses per second by the processor). Dates are shown at each point[1].

Since the gain in price/performance is at least 52 percent per year, the 9.1 year evolution crosses five factor of two lines. Only the PDP-4 stands out as being on a line of constant performance/price. It was either overpriced by a factor of two, or should have performed better by a factor of two for the same price.

Market Demand

In order to speculate on a theory of demand for small computers, two demand curves are given. Figure 36 is the classic ~~term and~~ demand curve: price of the

leave more space

[1] The lines of constant performance/price are separated by a factor of two (keep in mind that if any measure changes by 41 percent per year, it takes two years to move from one line to another. Conversely, a yearly improvement of 26 percent takes three years to get double, etc.). ~~[GB: give the mathematics of this, or is it in Chapter 0?]~~

unit versus quantity. If we ignore the PDP-1, it appears that there is complete price elasticity of demand. We offer two reasons for the PDP-1 anomaly. Twenty of the PDP-1s are accounted for by a single, perhaps fortuitous, order for the ADX 7300 systems (?). If we subtract this amount from the PDP-1 quantity, we obtain the second conjecture: ~~is that~~ sales were higher than the model projection because the PDP-1 was first into the market.

An alternative to the above demand model is given in Fig. 37 where price <u>per unit of performance</u> is plotted against quantity. This model is based on the thesis that computers are like power generators (or tractors): demand is based on the amount of work they can do per unit of cost. (This would explain why roughly the same number of both PDP-1s and PDP-4s were sold.) Note that more PDP-9s and PDP-15s were sold than the curve would have predicted. Because both machines had longer lives before successors were introduced, a better ordinate might be the maximum number shipped in any one year, which would take into account other marketplace limits.

Because of the relatively large number of variables that pertain (size of DEC, strength of the economy, market maturity, etc.) it hardly seems worthwhile to try for more insight from what are probably quite weak models.

[GB: The section on demand is flaky; we should talk to an economist before we discuss models. However the plots themselves are interesting. What references can we give?]

The lines of constant performance/price are separated by a factor of two (keep in mind that if any measure changes by 41 percent per year, it takes two years to move from one line to another. Conversely, a yearly improvement of 26 percent takes three years to get double, etc.). [GB: give the mathematics of this, or is it in Chapter 0?] will not be on this page when single spaced

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Other Characteristics

Table 4 has other data which has not been plotted. The input power (with the exception of PDP-4) is constant over all implementations. The weight is correlated with size reflecting a relatively constant weight per bay. The volume has declined, which reflects consistently improvements in packing density. In this respect, the PDP-4 was a better implementation than the PDP-1. The PDP-7 was better in packing density than either the PDP-1 or PDP-4. The PDP-9 improvement ~~in implementation~~ used the same logic ~~as in the PDP-7[??].~~ PDP-15 achieved its volume reduction using integrated circuit technology. The weight/$ appears to have risen and ~~is~~ correlated with inflation. Power and weight density measurements are given in the table together as are several ratios involving cost, weight, power and performance. Note that ~~measurement of~~ performance changes most[??]. The calculated mean time between failures has declined by over a factor of two between the PDP-1 and PDP-15.

The reader should compare the implementations. With the exception of PDP-1, all required about 5000 sq.in. of printed circuit board area. The bit slice approach of the PDP-4 made possible a major reduction in backpanel interconnections; ~~moreover it added~~ two specialized modules. All subsequent implementations used the bit slice approach with a few special purpose modules. Of special interest is the number of logic module types and power supply types. All had about 40 different logic types, although the PDP-15 had 54 types. ~~Of special interest is the number of logic module types and power supply types.~~ This low number of part numbers and relatively low cost per module meant that the cost of a complete package of spare modules for a computer represented a small fraction of the price.

In the fourth and fifth generations, (e.g. CMOS 8, page 00) a single module contains the whole computer and therefore the cost of spare modules is a large fraction of the computer's price.

Options

Table 5 shows the options available for the various machines. Note that PDP-1 ~~was relatively complete in the sense of~~... ~~Subsequent machines followed the PDP-1 fairly closely,~~ PDP-1, 4 and 7 were relatively compatible and ~~slow~~ly evolved the same set of options. PDP-9 changed to an I/O Bus structure, so requiring new option interfaces. While PDP-15 used that same I/O Bus structure and signals, the voltages were different; again new option interfaces were required.

Displays have been major options throughout the series. Moving head disks were first available on the PDP-15. Although a number of card options were available, few were sold,

Evolution

We conclude this chapter by relating the 18-bit series evolution to the model of minicomputer evolution presented in Chapter 1. Three design styles are distinguished in the model, as can be seen in Fig. 38. ~~As we shall see in~~ Part III, the 12-bit family (PDP-8) ~~evolved consistently~~ along the decreasing price curve. The 16-bit PDP-11 family, presented in Part IV, evolved ~~with~~ all three design styles.

For a family to evolve in more than one design style, design resources must be available for parallel development efforts. The PDP-11 family has had the multiplicity of designers and architects to do this, the 18-bit series ~~has~~ not. Each new implementation has been designed by a member of a previous implementation team. For such a single-thread approach to be successful, it appears that one of the three design styles of the evolution

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model must be chosen and consistently followed. Instead, the 18-bit series has followed a middle-of-the-road style: price-performance.

It appears that a clear identity is needed to guide design decisions. Consider the physical packaging of the PDP-15. Although a comparable-speed performance PDP-11 requires more i.c.'s to implement (the PDP-11 has more modes of addressing, more instructions, and more data types) the PDP-15 processor costs more. The PDP-15 remained packaged in a large cabinet, it used smaller modules, and its i.c. density per module was lower. Had the evolution been identified as consistently lower cost, metal box packaging would have been set as a stringent goal. As it was, the PDP-15 had to compare against the PDP-11 with the handicap of an extra level of integration in its physical packaging.

In addition, some product planners felt that the market demand was only for 16 bits or higher multiples of 8 bits. As a result, the 18-bit machines are no longer manufactured. [GB: or designed]

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Note there are some corrections in the table.

FIGURE 38 (attached)

Project start; first ship	8/59;11/60	11/61;7/62	4/64;12/64	;8/66;-,12/68	5/68;2/70
Goals	cost;short word length; speed	cost	speed; cost	speed; cost; producibility	cost;range of machines, hardware/ software systems
Applications	lab control; message switching; timesharing	process control; industrial testing	improved time-sharing	graphics	numerical computation; graphics processing
Innovations/ improvements	circuit use; package; ISP; interrupts; direct memory access; i/o interfacing ease	functional (bit slice) modules; ISP trend to mini; 3 cycle DMA; i/o interfacing ease	package; modules; performance	micro-programming I/O Bus	integrated circuits; floating point; multiprocessor
Price with	120	65.5(56.5)	45	25+;24.4(19.9)	19.8(16.2)

Table 4 - CHARACTERISTICS OF DEC's 18-BIT COMPUTERS.

	1	4	7	9;9/L	15
Paper tape reader/punch, Typewriter, 4 Kword Mp					
Price/Mp word	7.32	3.66	3.99	2.19;1.95	1.71;1.32
MTBF (hrs.)	2800	-	-	-	5400
Mp cycle time (microsec.)	5	8	1.75	1;1.5	0.8
Mp accesses/sec (millions)	0.2	.125	.57	1;.67	1.25
Multiply/divide time (usec.) (microsec.)	25/40		4.4/9	4.5-12.5/12.5	4.5/4.5
Mp size(Kwords)	1,4,...,65	1,4,8,...,32	4,...,32	8,4,...,32	4,...,131
Bits accessed per sec/$	30(.033)	34.5(.029)	227(.0044)	714(.0014)	1135(.00088)

Table 4 - CHARACTERISTICS OF DEC's 18-BIT COMPUTERS.

	1	4	7	9;9/L	15
Perf/price improve*	-	1.1	6.6	3.1	1.7
Price improve*	-	1.8	1.45	1.8	1.3(1.5)
Perf. improve*	-	.62	4.57	1.75	1.25
Product Life	4	3	4	4	7
Number produced	50	45	120 (165?)	445	790
Power (watts)	2160	1125	2100	2000	2875
Weight (lbs.)	1350	1030	1150	790	750
Size(in.69"x21" x28" bays)	4	2	3	1.5(special)	1
Vol.(cu.ft.)	94	47	70.5	36	23.5
Power dens. (watts/cu.ft.)	22.9	23.9	29.8	55.5	122.3
Wt.dens. (lbs./cu.ft.)	14.4	21.9	16.3	21.9	31.9
Watts/$	.018	.017	.046	.08	.15

*over predecessor

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Table 4 - CHARACTERISTICS OF DEC's 18-BIT COMPUTERS.

	1	4	7	9;9/L	15
unds/$	.011	.016	.026	.032	.038
KBits accessed per watt	1.6	1.1	4.9	9.0	7.8
KBits accessed per lb.	2.6	2.2	8.9	22.8	30.
KBits accessed per cu.ft. x K	38.3	47.9	146.	500.	957.
Logic technology	saturating MADT transistors	capacitor-diode gates; diode transistors	saturating transistors		7400,74H00 series integrated circuits
Module series	1,000		B		M
Logic speed(Mhz)	5, .5	1,0.5,5	10,1,.5	10,1	10,20
Module size	5.25x4=23	5.25x4=22	2.25,5 (x 3.875);	2.25,5,10 (x 3.875)	same
# modules/ # types	544/34	236/41	614/39	644/44	300/54
# transistors, ~~*over predecessor~~	3.5K,4.3K	-	-	-	350,200,3.4K

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Table 4 - CHARACTERISTICS OF DEC's 18-BIT COMPUTERS.

	1	4	7	9;9/L	15
Diodes, IC's					
# power supply/ # types	8/4	4/2	9/4	1/1	1/1
Modules space Pc	18x25	6x25	12x32	8x44	4x32
Modules space, I/O Interface	3x25	3x25	-	-	4x32
Modules space, Reader, Punch, Typewriter	3x25	3x25	8x32	8x44	7
Modules space, 4Kw Mp	4x25	4x25(8K)	3x32	3x44	4x32
~~Total~~ Pc, Mp, I/O Logic area(sq.in xK)	11.9	5.2	5.3	5.6	3.4
Processor logic area	8.9	3.3	3.3	3.1	2.1
Logic prints	18	16	27	44/2=22	75/2

Table 5 - OPTIONS FOR DEC's 18-BIT COMPUTERS*

	1	4	7	9	15
PU OPTIONS					
Multiply/Divide	Std.	[18] EAE	[177]		EAE opt, flt.pt. opt.
Priority interrupt	1ch.std.; [120]-16ch; also 256ch.	1ch.std.	1ch.std [172] 16ch;	1ch.std;8 opt.	1ch.std;8 opt.
Direct memory access	[19] 3 ch.	1 std.; 3 opt.	[173] 3 ch.	+1 to mem.(std.)	up to 64
Clock	yes	1 std; [132] 16 ch.	opt.	opt.	opt.
Power failure	N/A	std.	-	-	opt.
Memory protect	4 Kword core images	none	[KA 70A] base & bounds	[KA70A]	[KA70A]
Ms					
Magtape (prog. control)	[51]-[50] 200 b/i	[54]-[50] 200 b/i			
Magtape (DMA)	[52]-[50] [510]-[IBM 729]	[57A]-[50 or 570] 556 b/i	[57A]-[50 or 570]	[TC59]-[TU20]	[TC59]-[TU20 or TU30]

The DEC-assigned option number is given in square brackets, e.g., [177].

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Table 5 - OPTIONS FOR DEC's 18-BIT COMPUTERS*

	1	4	7	9	15
Drums	[23]	[24] 16Kw ...65Kw	[24] 32Kw ...131Kw	32Kw...524Kw	
Disks	N/A			[RS09] 1Mw	[RS09]-262Kw ...2Mw
Disk pak					[RP02]10Mw
DECtape	N/A	[550]-[555]	[550A] -[555]	[TC02]-[TU55]	[TC02]- [TU55]
LINKS					
Inter-Computer			[195] DB97	DB98,99	DB98,99
To 7090	[150] 10Kw/s				
Communications	8ch. up to 256		[630] 64ch. [634] 8ch.	[630] 64ch. [LT09] 5ch	[LT19]
To other computer busses				to PDP-7	[DW15] to PDP-9
TRANSDUCERS					
Papertape reader	std. 400c/s	std.300c/s	std. 300c/s	std.300c/s	std.300c/s
Papertape punch	std. 63c/s	[75] 63c/s	[75] 63c/s	[PC09] 50c/s	[PC15] 50c/s
Typewriter	std. 10 c/s	[65] 28KSR,	[643] 33KSR	33 KSR, ASR	33,35,ASR,KSR

~~The DEC-assigned option number is given in square brackets, e.g., [177].~~

Table 5 - OPTIONS FOR DEC's 18-BIT COMPUTERS*

	1	4	7	9	15
		10 c/s			
CRTs.					
point plotting	[30] 16"1Kx1K 5" 4Kx4K 21" Color	[30D]	[30D] [340] vector plot	[30D] [340C],	[VP15]
storage	[34]Tektronix storage	[34]	[34]	[34H]	
DMA				[339]P.display with 340	[VT15]
precision	[31] 5" 4Kx4K				
alphanumeric					[VT05]
Card reader	[421]200c/m	[41]200c/m	[421]200 or 800c/m	[CR01E] 100 or 200c/m	[CR033] 200c/m
Card punch	[40]100c/m	[40]100c/m	[410]100c/m	-	
Line printer	[64]300l/m	[64]300l/m	[64]300l/m	[647]300 or 600l/m	[647]300 or 1000 l/m
Plotter			[350] to Calcomp	[350]	[350],[x415]

~~*The DEC-assigned option number is given in square brackets, e.g., [177].~~

fix

Table 5 - OPTIONS FOR DEC's 18-BIT COMPUTERS*

	1	4	7	9	15
Relays	[140]18ch	[140] 18ch	[140]18ch	[DR09A]	DR09A
A/D converter	[138/139]64ch	[138/139]	[138/139]	64 ch	[AF02] 64ch
				1000 ch	[AF04] 1000ch
D/A converter					AFC 15-analog
					UDC 15-digital

The DEC-assigned option number is given in square brackets, e.g., [177].