DSP BINDER
Revised Direction

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Semiconductor Industry Service
Digital Signal Processing

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Digital Signal Processing Table of Contents

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Digital Signal Processing
Table of Contents

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How to Use the Table of Contents

The Digital Signal Processing (DSP) notebook is arranged in a series of major sections defined by blue primary tabs with labels in all capital letters. These major topic areas may be further divided by white subtabs whose labels begin with initial capital letters. In most cases, the documents following either of these tabs will repeat in their running headlines the wording of the primary subject tab and/or that particular subtab.

To assist in locating a particular document, a table of contents has been provided. This table lists the primary tabs, the subtabs, and the running headline of each document contained in the notebook. The following is an annotated example of the format of the DSP table of contents:

SAMPLE TABLE OF CONTENTS

DSP OVERVIEW*

Executive Summary**

DSP Executive Summary#

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DSP Forecast Summary

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PACKAGING

Worldwide IC Packaging Update##

*Entries shown in this manner are primary subject tabs (blue).
**Entries shown in this manner are subtabs (white).
#Entries shown in this manner are document titles.
##A primary subject tab may, in some cases, have no subtabs and will be followed directly by documents.

INTRODUCTION

Introduction to Digital Signal Processing

SEMICONDUCTOR INDUSTRY SERVICE

Dataquest's Semiconductor Industry Service (SIS) is a comprehensive information service covering the worldwide semiconductor industry. It provides a product-oriented, executive-level perspective intended to assist key executives and product managers with their strategic decisions. In recognition of the fact that some semiconductor organizations focus on specific product areas within the industry, Dataquest offers various service options. These product-focused options provide detailed analysis in specific product areas while omitting information about irrelevant product areas.

This research notebook focuses on the product, market, and technology issues influencing the digital signal processing (DSP) market.

INTRODUCTION

The subject of digital signal processing (DSP) encompasses a broad range of exciting technology, market, and semiconductor product categories. As a base technology, advances in digital signal processing algorithms and architectures are important to all industry participants because of the promise for new ways to solve problems that in the past were either technologically impractical or prohibitively expensive. Simultaneously with the maturing of the base technology, important market opportunities have emerged that require digital signal processing techniques. This situation, in turn, presents new opportunities for semiconductor manufacturers, systems companies, and software houses to provide new products and services that will ultimately benefit all industry participants. Illustrative of this fact, DSP technology today provides the basis for a wide range of applications, such as advanced military radar systems, medical ultrasonic imaging, personal computer modems, and interactive talking toys.

DIGITAL SIGNAL PROCESSING NOTEBOOK

Undertaking the task of providing a comprehensive research notebook on the digital signal processing marketplace presents some interesting challenges. First, digital signal processing is really a technology, not simply a product category like the more mature areas of memories or microprocessors. Hence, a significant number of different types of products, each with its own unique characteristics, market niches, and development tools, combine to form the complete semiconductor DSP product categories. Dataquest partitions these products into the following four categories:

- DSP microprocessors (DSMPUs)
- Microprogrammable DSP (MPDSP)
- Special-function DSP integrated circuits (SFDSP)
- Application-specific DSP integrated circuits (ASDSP)

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A second challenge is that the market for DSP products is still relatively young. It is difficult to adequately project future growth rates for products in this market without fully understanding where digital signal processing can (and cannot) be effectively used in the end applications. It is also important to understand the growth rates of the end markets themselves. For these reasons, Dataquest has included a section on markets and applications in this research notebook that is independent of the previously listed DSP product categories. This section identifies where DSP can contribute to the end applications and also presents forecast market growth rates for the next five years.

DSP Overview Section

The notebook opens with an overview of the DSP market. All of the remaining sections of the notebook are summarized in this section. This section quickly provides the reader with an understanding of the DSP market and products by summarizing the information presented in each of the sections, as follows:

- Executive Summary—Identifies the pertinent issues influencing this market in easy-to-read bullet form
- Forecast Summary—Combines the individual product forecasts contained in the product sections into a total market forecast by product category and end-use market
- Market Dynamics—Discusses the global issues affecting the DSP market, applications, and the players involved
- Family Tree—Provides a definition of the product categories used in this analysis and how one relates to another

Markets and Applications

This section analyzes the end DSP markets and applications. These markets and applications are analyzed using a number of criteria, including technical issues, performance requirements, DSP content within a system, and forecasts. Dataquest broadly partitions semiconductor applications markets into the following six categories:

- Military
- Industrial
- Communications
- Data processing (computer)
- Consumer
- Transportation

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Introduction to Digital Signal Processing

Product Sections

Each product section is designed to provide the reader with in-depth, detailed information on the structure and makeup of the market segments that these products represent. Topics discussed may include:

- Executive summary—Provides the reader with a bulleted overview of the factors affecting this product area
- Forecast—Summarizes Dataquest's five-year forecast for this product segment
- Product analysis—Compares market share, product features, pricing, life cycles, and design wins on a product-type or family basis
- Competitive analysis—Discusses the configuration of the market based on market share, product positioning, applications support issues, and number of suppliers
- Emerging technology and trends—Identifies emerging trends in the marketplace, including product or technology developments
- Applications and user issues—Addresses the appropriate applications areas for each product category as a function of technical, performance, and user requirements
- Historical shipment data—Records the shipment history of the various products in this category by manufacturer

DSP Technical Overview

This section provides an overview of the technical aspects of digital signal processing. It begins with a discussion of the domain encompassed by digital signal processing, discusses the concepts of sampled systems, and introduces some of the common DSP functions, such as filtering and Fast Fourier Transforms. A glossary is provided at the end of this section to define DSP terminology.

Company Profiles

The major semiconductor companies manufacturing DSP products are profiled, with an emphasis on their strengths, weaknesses, and market presence.

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NEWSLETTERS

In addition to general executive-issue newsletters, the subscriber will receive newsletters focused specifically on topics in digital signal processing. These newsletters provide information such as:

- Analyses of emerging markets and applications
- New product and technology trends
- Analyses of DSP-related products
- Summaries of key industry events
- Changes or updates to the reference material in this notebook
- Other dynamic business or product issues that are of interest to industry participants

INQUIRY PRIVILEGE

To support the unique information needs of each of our subscribers, Dataquest provides the registered subscriber and one designated alternate the privilege of direct access to our semiconductor staff. Two forms of this service are available:

- Access to the semiconductor inquiry center—The inquiry center provides assistance in finding or interpreting material in the data base notebooks or other Dataquest published material. It is manned full-time by a staff that is dedicated to providing immediate response to the needs of our subscribers.

- Access to the semiconductor research staff—Clients may seek additional commentary on or clarification of the published material from the semiconductor research staff. Using this feature, clients may interact with industry experts on a one-on-one basis to discuss attitudes and opinions about topics covered in the service.

RESEARCH METHODOLOGY

The methodology used by Dataquest in support of this research has a number of unique features. The primary research staff has extensive industry experience in the market area covered by this research. Adding to this base knowledge, Dataquest has significant numbers of contacts within both the semiconductor manufacturer and end-user communities to contribute a balanced perspective to this work. Additional insight is provided from other research groups at Dataquest studying technology areas related to digital signal processing, such as the Telecommunications Industry Service and Technical Computer Systems Industry Service. A financial outlook provided through Dataquest's extensive business contacts complements this research. Figure 1 summarizes the perspectives that contribute to this work.

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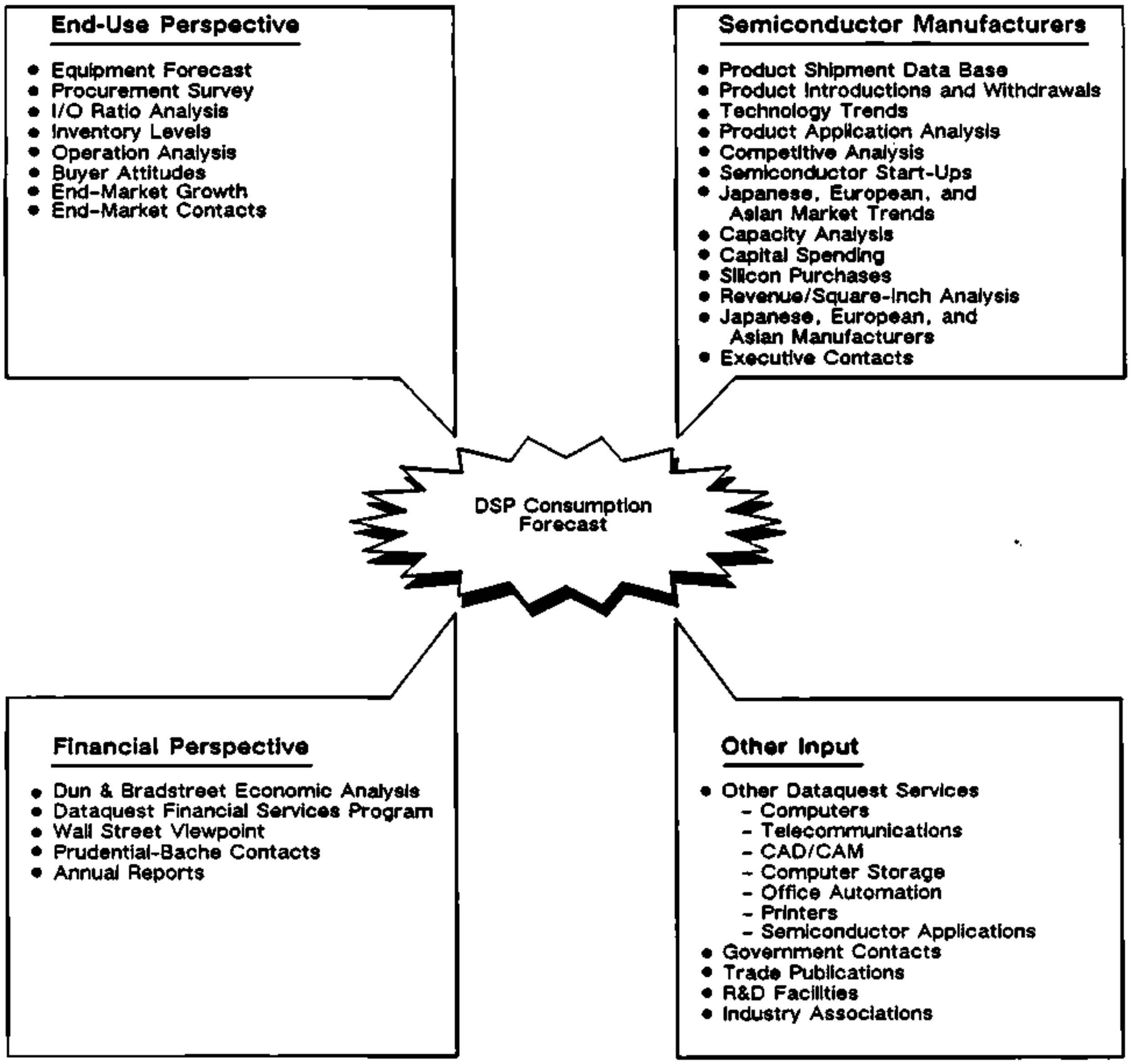
Figure 1

Worldwide Input to Dataquest Semiconductor Forecasts



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Manufacturing Perspective

Dataquest's Semiconductor Information Group comprises seven different semiconductor information services. The combined worldwide research network of these services provides input to the forecasts based on all relevant aspects of the industry. Dataquest uses its extensive product shipment data base and information about new and obsolete products when compiling the annual consumption forecasts.

Executive level input from almost all semiconductor manufacturers in the free world provides insight into the industry environment, current business levels, and major competitors. Information regarding technology trends, capital spending, capacity utilization, and product acceptance is analyzed by Dataquest's industry experts in formulating the forecasts.

Other considerations are analyses of wafer starts, wafer consumption, and revenue per wafer. Our worldwide research offices and contacts in Western Europe, Japan, and Asia provide primary input as well as checks and balances for each forecast cycle.

End-Use Perspective

Research about trends in the application and procurement of semiconductors is another cornerstone of our forecasts. The Semiconductor Application Markets service contributes this end-use analysis through equipment forecasts, procurement surveys, and I/O ratio analysis. The Semiconductor User Information Service studies buyer attitudes, changes in operation methods, inventory analysis, and short-term pricing trends.

Financial Perspective

Dataquest's general economic outlook and financial viewpoint is based on business surveys and financial analyses from Dataquest's parent company, Dun & Bradstreet. In addition, Dataquest's Financial Services Program provides close contact with venture capitalists, fund managers, and financial institutions. Through our exclusive relationship with Prudential-Bache, Dataquest has access to Wall Street's attitudes about all areas of technology. These sources, combined with Dataquest's own research on financial and economic trends, provide one of the cornerstones of our forecasts.

Other Input

Close association with other Dataquest information services provides additional input to the forecast accuracy and quality. This includes analysis of key industries that consume semiconductors such as technical, business, and personal computers. In addition, input is solicited from services that analyze CAD/CAM, telecommunications, computer storage, printers, office automation, and graphics terminal industries. Dataquest analysts also attend industry trade shows and technical symposiums to monitor the latest product introductions and technology trends. Other input comes from government contracts and publications, industry associations, and trade publications.

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DSP Executive Summary

EXECUTIVE SUMMARY

Broadly, the digital signal processing (DSP) marketplace consists of a tremendous variety of different semiconductor product offerings targeted at a tremendous variety of end applications. The need for different DSP semiconductor products is driven by the performance requirements of DSP systems, where sample rates range from hundreds of hertz at the low-performance end to hundreds of megahertz at the high-performance end. Historically, this has allowed plenty of room for manufacturers to search for unique market niches in which to target their business.

Currently, the products serving the end DSP marketplace are undergoing some fundamental changes. It is important for semiconductor manufacturers to understand and react effectively to these changes, or risk disastrous business consequences. Highlights of these changes are presented in this section.

The semiconductor DSP marketplace is characterized by four different product categories, each addressing a different portion of the user market. Currently, each of these product categories is roughly the same size in revenue. However, the growth rates of these markets are not the same. There are nearly 50 semiconductor companies supplying products to different portions of this market. Very few of these companies have product offerings in all of the product categories; many offer products only in niches within one of the categories.

At this time, the largest market for DSP semiconductors is communications, followed closely by the military. In 1987, these two market areas together accounted for an astounding 77 percent of total DSP revenue. However, market applications for DSP semiconductors are all-pervasive. DSP semiconductors are being designed into applications ranging from simple toys to high-performance military radar systems. Driven by both price declines and technology advances, Dataquest expects that by 1992 the largest application market for DSP semiconductors will be consumer products.

DSP Technical Introduction

Digital signal processing is a technique for manipulating (processing) signals digitally. A simple block diagram of a DSP system is shown in Figure 1. Because the world we live in is analog (continuous time, continuous sight, continuous smell, etc.), Figure 1 shows the requisite analog-to-digital and digital-to-analog converters. These converters change the analog world into a digital representation upon which a DSP system can operate. Usually at least one (sometimes both) of these converters is present in a DSP system.

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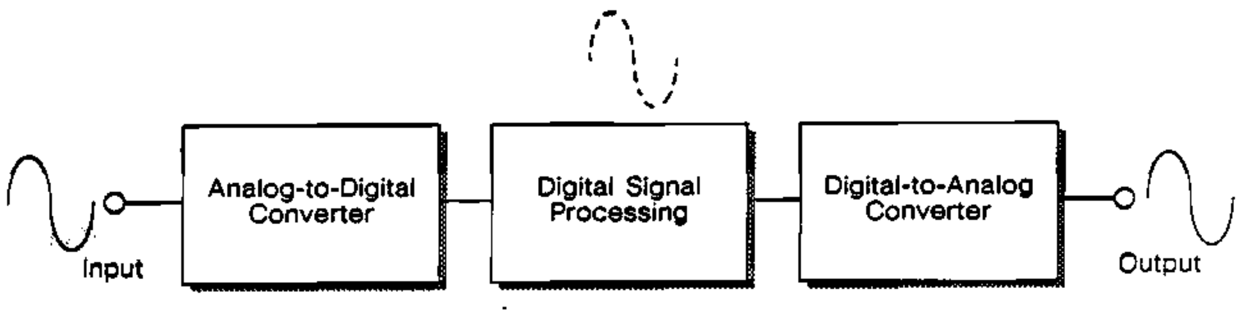
Figure 1

Block Diagram of a Generic DSP System



Source: Dataquest September 1988

DIGITAL SIGNAL PROCESSING MARKET FORECAST

The Dataquest market forecast for DSP semiconductors is shown graphically in Figure 2. It includes breakouts of the four product subcategories that combine to form the cumulative forecast. Highlights of this forecast include the following:

- We forecast the worldwide DSP revenue for 1988 to be $586 million, an increase of 30.8 percent over 1987.
- Worldwide DSP revenue will grow to more than $1 billion in 1990, representing a compound annual growth rate (CAGR) of nearly 34 percent over 1987 revenue.
- All product categories except MPDSP are growing at impressive CAGRs of greater than 30 percent; MPDSP through 1992 will likely experience a CAGR of less than 2 percent.

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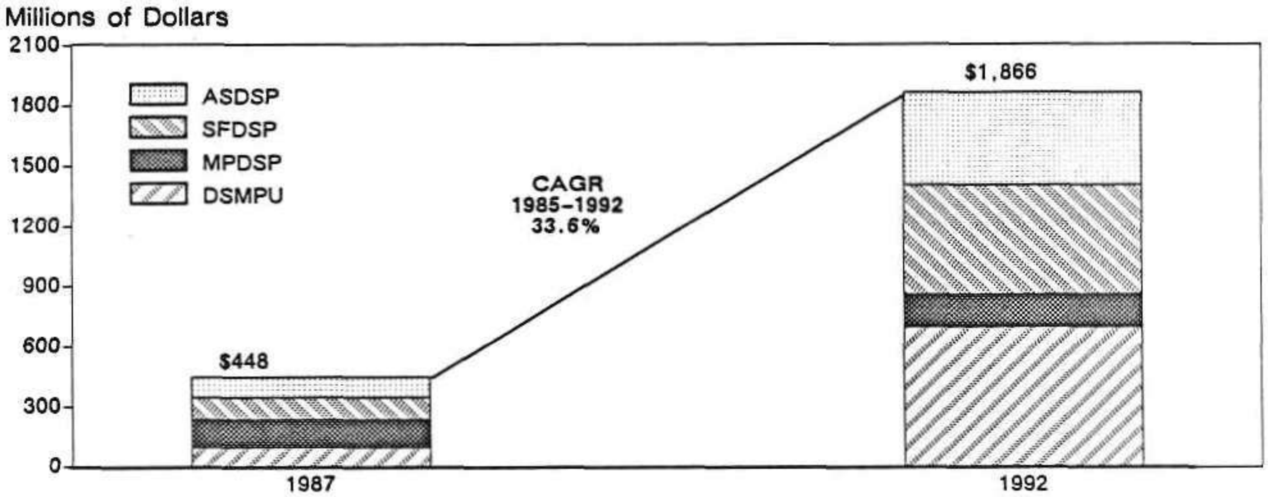
Figure 2

Worldwide DSP Revenue Forecast



Source: Dataquest
September 1988

Product Categories/Revenue Estimates

Dataquest partitions DSP semiconductor products into four different categories. These categories, including 1987 and 1988 revenue estimates, are shown in Table 1.

Table 1

DSP Product Category Revenue Estimates
(Millions of Dollars)

Product Category	Abbreviation	Revenue Estimates 1987	1988
DSP Microprocessors	(DSMPU)	$ 98	$147
Microprogrammable DSP	(MPDSP)	$139	$150
Special-Function DSP	(SFDSP)	$113	$158
Application-Specific DSP	(ASDSP)	$ 98	$131

Source: Dataquest
September 1988

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DSP Executive Summary

Factors Influencing DSP Revenue Growth

A number of factors are contributing to the continued growth of revenue for DSP products:

- DSP design expertise, which had existed primarily in the military sector, has recently spread into the commercial sector.
- Entirely new applications, which were not practical prior to maturing DSP techniques, have developed. An example is the talking "Julie" doll introduced by Worlds of Wonder.
- Tremendous price declines of DSP products (some close to 40 percent per year) have brought previously sophisticated, high-priced technology to low-cost, mass-market items like toys and personal computer modems.
- Conversion of older analog products to newer, more reliable designs with more features using digital signal processing is taking place. An example is the migration from analog oscilloscopes to newer digital scopes.
- Availability of powerful hardware and software development tools has aided the system designer in incorporating digital signal processing into end products.

DIGITAL SIGNAL PROCESSING PRODUCTS

This section highlights some of the key issues affecting each of the specific product categories. Included are a category description, reasons for future revenue growth, major suppliers, trends, and competitive issues.

DSP Microprocessors (DSMPU)

- DSMPU products are general-purpose, programmable digital signal processors. They are similar to microprocessor architectures containing hardware multipliers and other architectural optimizations that address specifically the needs of the DSP marketplace.
- The DSMPU market can expect significant revenue growth through 1992, achieving annual revenue of nearly $700 million at a CAGR of nearly 48 percent.
- The three leading DSMPU manufacturers continue to be Texas Instruments, NEC, and Fujitsu, in that order. Combined, they contribute more than 70 percent of DSMPU revenue.

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- Analog Devices, AT&T, and Motorola form the core group of "second-tier" DSMPU manufacturers. While the revenue for each of them is less than $10 million, they have each adopted strategies designed to secure their long-term commitment to this market.

- Dataquest expects the new generation of floating-point DSMPUs to gain a nearly 40 percent share of the market by 1992.

- For applications where DSMPUs are sufficiently fast, they will dominate over MPDSPs and ASDSPs on system cost alone.

- There are currently 13 manufacturers of different DSMPU architectures available to designers of DSP systems.

- Dataquest expects a shakeout in the number of suppliers to this market segment over the next three years, similar to the shakeout that occurred in the microprocessor market in the late 1970s and early 1980s. Ultimately we expect no more than three major suppliers and two minor suppliers to the general-purpose DSMPU market.

- U.S. manufacturers are currently better positioned than Japanese manufacturers to win the bulk of the DSMPU design slots available for the foreseeable future.

Microprogrammable DSP (MPDSP)

- In the past, MPDSP components have been labeled by the industry as "bit-slice" processors. However, the term "bit slice" is somewhat archaic and does not adequately describe the newer 32- and 64-bit processors available today. The primary components which form this category are:

  - Microprogrammable Arithmetic Units (MAUs)

  - Multipliers and Multiplier-Accumulators (MACs)

- The MPDSP category is heavily populated with IC manufacturers. Sixteen manufacturers supply products to this segment of the market. The leading suppliers are AMD, Analog Devices, IDT, Texas Instruments, TRW, and Weitek.

- Annual revenue in this product category is expected to peak at $177 million in 1990, then to decline gradually.

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- While overall growth in this market is expected to be relatively flat, a subportion of this market, made up of floating-point multipliers and MAUs, should continue to experience growth of approximately 20 percent through 1990 before beginning to flatten out.

- Competitive pressure from products in both the DSMPU and SFDSP categories are the major contributors to the revenue slowdown in the MPDSP market.

Special Functions DSP (SFDSP)

- Products in this category have dedicated (usually not general-purpose) DSP features. They include modems, codecs, speech processors, digital television/circuits, filters, and Fast Fourier Transform (FFT) functions. Some of these functions have been traditionally implemented using analog techniques. This category includes only those devices which implement the functions using DSP architectures.

- Revenue in this product category is expected to continue growing at a CAGR of about 36 percent through 1992, achieving annual revenue of about $550 million.

- Historically, DSP modem chip sets have fueled the growth of this market, achieving 1987 revenue of about $100 million.

- Digital chip television sets are expected to provide impressive growth to this segment over the next few years, achieving annual revenue of $270 million by 1992.

Application Specific DSP (ASPSP)

- Products in this category are generally not standard products sold on the open market. Instead, they are usually custom architectures designed using standard cell or gate array techniques for a specific application and user.

- Revenue growth in this category is expected to be strong through 1992 with a CAGR of 37 percent, achieving annual revenue of $461 million.

- There are over 30 manufacturers able to supply ASDSP solutions to their customers.

- Many DSMPU manufacturers are in the process of migrating their early DSMPU architectures into standard cells.

- Many of the applications now using MPDSP will shift to ASICs constructed from ALUs, MACs, and registers currently in cell libraries.

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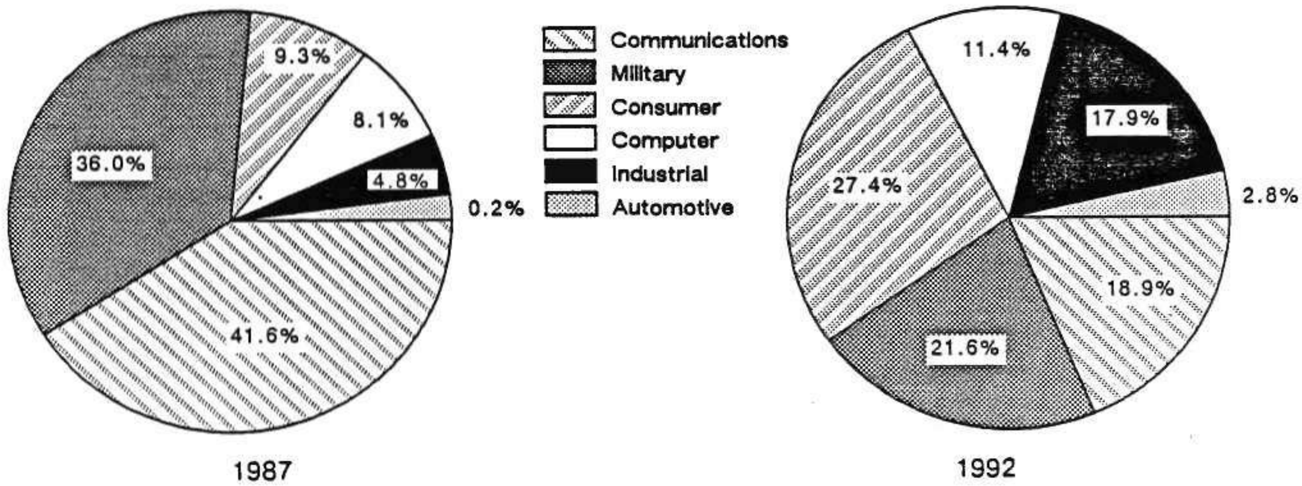
APPLICATION TRENDS

Dataquest segments the semiconductor application markets into six primary segments. A snapshot of the percentage of total DSP revenue distributed across these markets both now and in 1992 is shown in Figure 3.

- Currently military and communication applications account for about 77 percent of all DSP revenue.
- As observed in Figure 3, Dataquest expects consumer application areas, led by digital television, to become the largest DSP application segment by 1992.

Figure 3

Percentage of DSP Revenue Across the Six Applications Markets



Source: Dataquest
September 1988

GENERAL ISSUES AND TRENDS

- DSP devices are "design win" products, much like microprocessors. Manufacturers must work with and support end users in order to secure design slots.
- As device architectures become more sophisticated, product support and application assistance become important issues to end users; in some cases, more important than the details of architectural differences between suppliers.

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DSP Executive Summary

- In all four product categories, prices have been dropping dramatically, at rates exceeding 30 percent per year. The significance of this is underscored by observing revenue growth projections: greater than 33 percent per year through 1992.

- Across all four DSP product categories, CMOS is the dominant process technology. Alternate technologies such as ECL or GaAs may achieve penetration in small performance niches, but none are expected to displace CMOS in the foreseeable future.

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DSP Forecast Summary

HISTORICAL ECONOMIC FACTORS

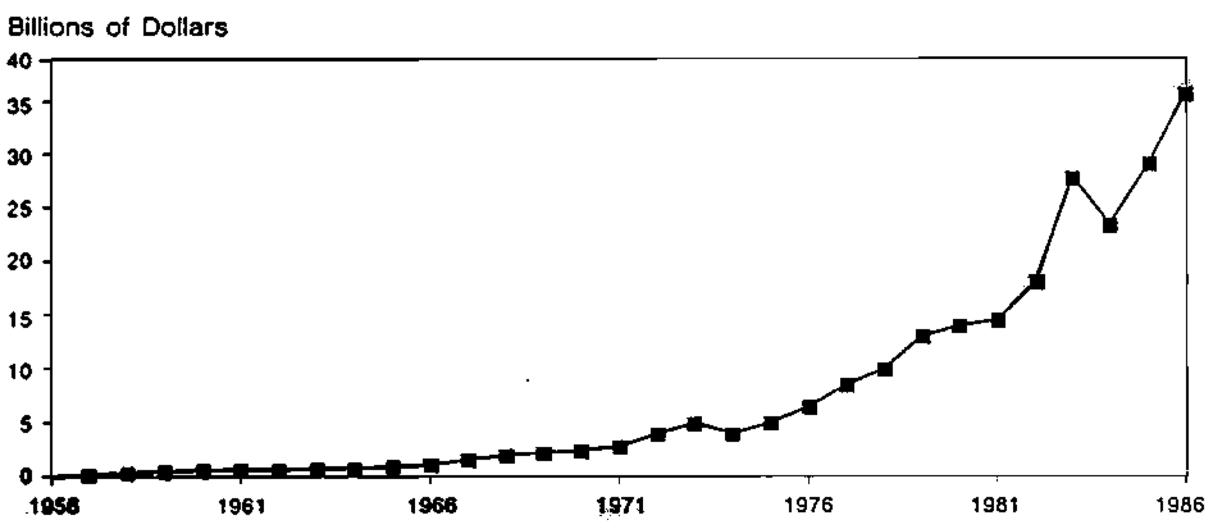
The worldwide semiconductor industry experienced a much-needed recovery during 1987. For the North American semiconductor market, 1987 turned out to be a better year than even Dataquest had predicted. Although our original 1987 forecast for North American consumption projected 12 percent growth over the preceding year, the actual growth of the U.S. market was 19 percent.

The fundamental optimism that this recovery would continue in 1988 was shaken somewhat by events on Wall Street in the final quarter of 1987. Nevertheless, Dataquest believes that the industry will maintain its momentum in 1988. Dataquest forecasts more than 30 percent growth in worldwide semiconductor shipments in 1988 over 1987. This translates into a worldwide semiconductor market that will reach nearly $50 billion by the end of this year, with the highest overall growth rate in the area of MOS (metal oxide semiconductor) products. Through 1992, Dataquest expects a worldwide semiconductor compound annual growth rate (CAGR) of 15.5 percent, achieving revenue of $75 billion.

Figure 1 establishes that although some analysts speak of the semiconductor business as a maturing industry, its most meteoric growth has really been during the last five years. In fact, in the last five years, annual consumption has grown by $18 billion, surpassing an annual level that took more than 25 years to attain.

Figure 1

Historical Worldwide Semiconductor Consumption
1956–1987



Source: Dataquest
October 1988

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DSP Forecast Summary

Digital Signal Processing Revenue Forecast

Digital signal processing (DSP) is still a relatively new technology that should outgrow the worldwide semiconductor industry over the next few years. While Dataquest estimates that revenue for worldwide semiconductor shipments will grow at a CAGR of 15.5 percent through 1992, DSP product revenue during this same period is forecast to grow at a significantly higher CAGR of 33.6 percent. Table 1 and Figure 2 illustrate both historical and estimated worldwide DSP revenue growth through 1992.

Table 1

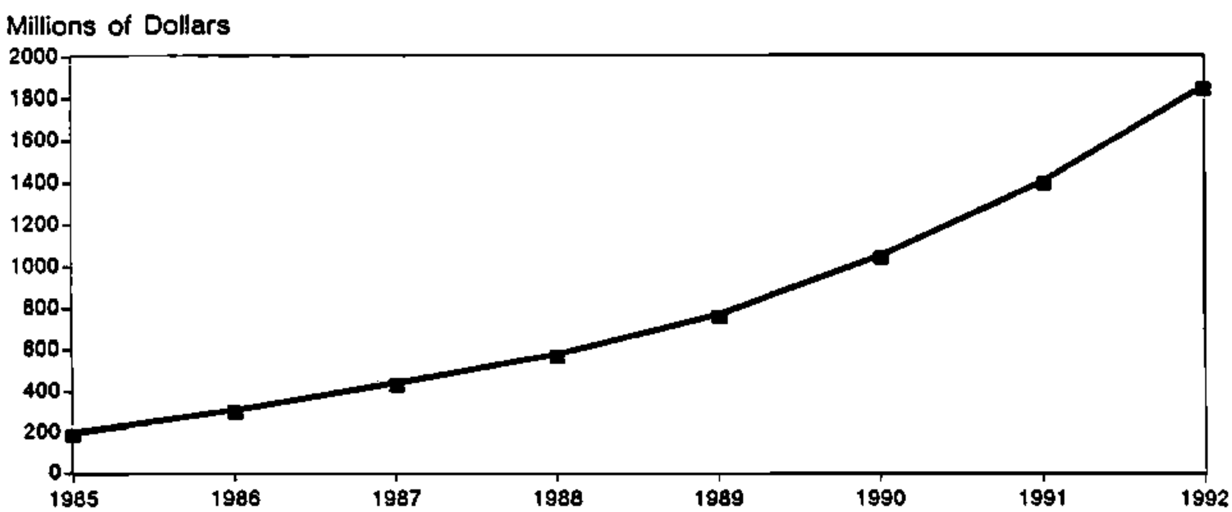
Worldwide DSP Revenue Forecast
(Millions of Dollars)

	Actual			Forecast					CAGR	CAGR
	1985	1986	1987	1988	1989	1990	1991	1992	1985-1987	1988-1992
Total DSP Revenue	$208	$316	$448	$586	$778	$1,057	$1,410	$1,866	46.8%	33.6%

Source: Dataquest
October 1988

Figure 2

Worldwide DSP Revenue Forecast



Source: Dataquest
October 1988

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Product Segmentation

Dataquest segments DSP products into four distinct categories, as shown below:

- DSP microprocessors (DSMPUs)
- DSP building blocks (MPDSPs)
- Special-function DSP ICs (SFDSPs)
- ASIC DSP ICs (ASDSPs)

A full description of the products in each category is given in the section entitled "DSP Family Tree."

Estimated worldwide revenue growth segmented by DSP product category for 1985 through 1992 is shown in Table 2 and Figure 3. Of particular significance is the DSMPU category, which is expected to grow faster than other product categories, with a projected CAGR of 47.5 percent through 1992. Contributing to continued DSMPU growth is a maturing of DSP as a technology and the simultaneous maturing of these high-performance, flexible, and programmable devices. The market potential for DSMPUs used for real-time signal processing applications is analogous to the market impact of general-purpose microprocessors to data processing applications in the 1980s.

Table 2

Worldwide DSP Revenue Forecast by Product Category
(Millions of Dollars)

	Actual			Forecast					CAGR	CAGR
	1985	1986	1987	1988	1989	1990	1991	1992	1985-1987	1988-1992
DSMPU	$ 34	$ 62	$ 98	$147	$221	$ 320	$ 485	$ 695	69.8%	47.5%
MPDSP	97	111	139	150	161	177	170	160	19.7%	1.6%
SFDSP	34	75	113	158	215	310	415	550	82.3%	36.6%
ASDSP	43	68	98	131	181	250	340	461	51.0%	37.0%
Total DSP Revenue	$208	$316	$448	$586	$778	$1,057	$1,410	$1,866	46.8%	33.6%

Source: Dataquest
October 1988

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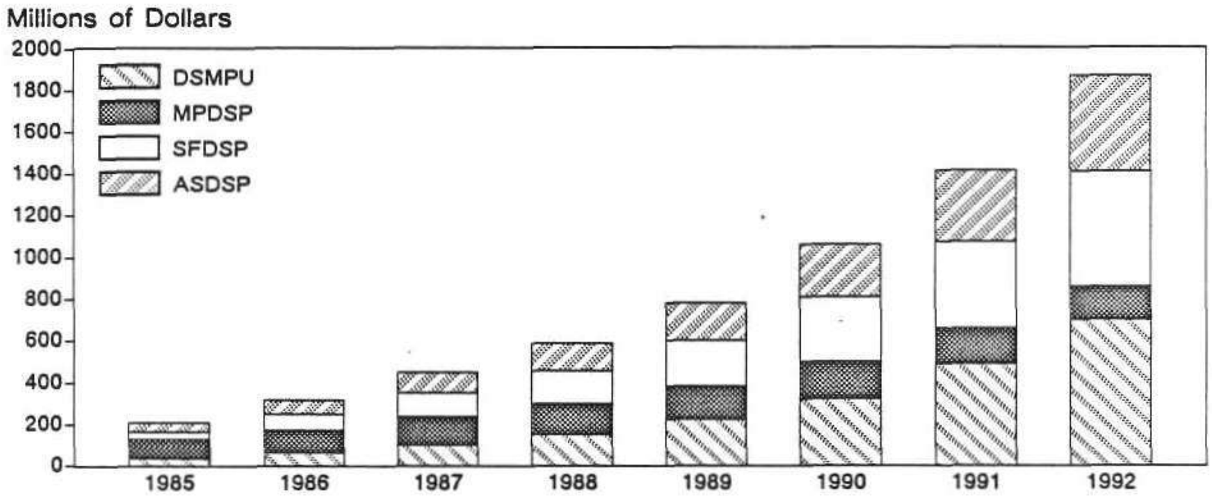
Figure 3

Worldwide DSP Revenue Forecast by Product Category



Source: Dataquest
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ASICs and SFICs that perform DSP functions are also expected to experience rapid growth. These devices are generally used in systems requiring optimized architectures to solve high-performance signal processing problems. Interestingly, these devices are generally not directly competitive with DSMPU products, as their more optimized and less general-purpose architectures usually allow performance that exceeds that of the DSMPU.

The market growth for the MPDSP market is also of interest, but not because of expected high growth rates. MPDSP products should experience sluggish growth through the early 1990s because of competitive products in three different areas:

- Very fast and flexible DSMPUs
- Incorporation of MPDSP cells into standard cell libraries, allowing customization of architectures in silicon instead of on a board
- Emergence of RISC microprocessors that will displace many MPDSP products in high-performance control applications

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DSP Forecast Summary

Market Segmentation

Dataquest segments semiconductor applications into six primary markets as shown below:

- Military
- Communications
- Industrial
- Computer
- Automotive
- Consumer

A description of the uses of DSP within these applications markets is provided in the section on Markets and Applications. Table 3 summarizes the usage of DSP within these six markets.

Table 3

Worldwide DSP Revenue Forecast by Application (Millions of Dollars)

	Actual			Forecast					CAGR	CAGR
	1985	1986	1987	1988	1989	1990	1991	1992	1985-1987	1988-1992
Military	$ 88	$121	$161	$201	$242	$ 289	$ 344	$ 403	35.8%	19.0%
Communi-cations	94	136	187	196	230	272	323	352	40.7%	15.8%
Industrial	1	16	22	51	80	143	217	335	435.4%	60.3%
Computer	21	26	37	46	59	88	135	212	30.9%	47.0%
Consumer	4	16	41	92	163	254	366	511	207.5%	53.7%
Automotive	0	0	0.1	1.3	3.8	13	25	53	N/C	154.6%
Total DSP Product Revenue	$208	$315	$448	$587	$778	$1,059	$1,410	$1,866	46.6%	33.6%

N/C = Not Computed

Source: Dataquest
October 1988

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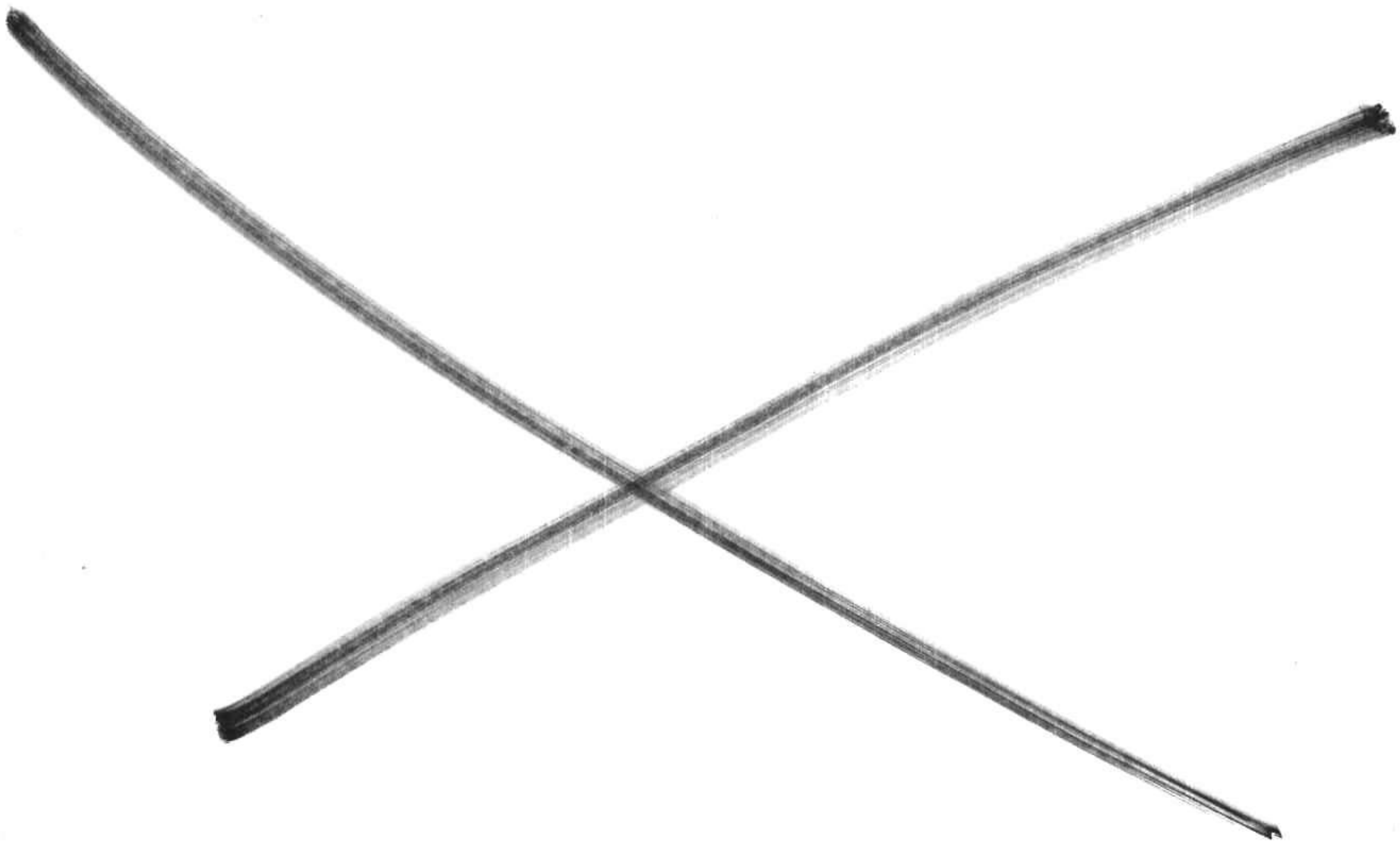

DSP Markets and Applications

INTRODUCTION

Understanding the growth prospects for DSP products requires a deep understanding of the size, growth rates, and trends of the end markets served by the products. It further requires an understanding of where this technology called digital signal processing (DSP) fits into the end applications that comprise the market.

While other sections in this report focus on DSP products, this section focuses on end DSP markets and applications independent of the specific products. Perspective is provided toward understanding the various applications and market forces that influence the growth of semiconductor DSP products. Three global market trends are compounding the rapid growth of DSP products:

- Growth prospects for existing markets already served by DSP technology
- Identification of emerging market opportunities that benefit from DSP technology
- Transitioning from older analog signal processing technology to digital signal processing technology

END MARKET DEFINITION

As shown in Table 1, Dataquest divides semiconductor applications into six major market areas: communications, industrial, military, computer, consumer, and automotive. Under the six major categories are subdivisions that are (or will be) well served by DSP products.

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Table 1

Six Semiconductor Applications Markets with Subcategories Served by DSP Technology

Communications	Industrial	Military
Modems	Test equipment	Radar
DTMF receivers	Medical equipment	Sonar
Transmultiplexers	Office automation	Navigation
Speech synthesis	Inspection equipment	Fuses
Speech recognition	Remote monitors	Communication
Speech compression	Robot systems	Reconnaissance
Mobile communications	Global pos satellites	
Video teleconferencing	Motor control	
Computer	**Consumer**	**Transportation**
Arithmetic accelerators	Compact disc players	Antilock brakes
Array processors	Digital video	Distance sensors
Image processing	Electronic cameras	Lane sensors
Graphics	Toys	
Geophysical processing		

Source: Dataquest
September 1988

Table 2 shows Dataquest's revenue forecast for DSP products in the six major market categories. Notice that in the mid-1980s, military and communication applications were by far the largest consumers of DSP semiconductors. While these two segments of the market will remain important over time, Dataquest expects that consumer applications will be the largest users of DSP products by 1992. This rapid growth will be fueled by entertainment applications such as digital television and digital audio.

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DSP Markets and Applications

Table 2

Worldwide DSP Revenue Forecast by Application (Millions of Dollars)

	Actual 1985	Actual 1986	Actual 1987	Forecast 1988	Forecast 1989	Forecast 1990	Forecast 1991	Forecast 1992	CAGR 1985-1987	CAGR 1988-1992
Military	$ 88	$121	$161	$201	$242	$ 289	$ 344	$ 403	35.8%	19.0%
Communications	94	136	187	196	230	272	323	352	40.7%	15.8%
Industrial	1	16	22	51	80	143	217	335	435.4%	60.3%
Computer	21	26	37	46	59	88	135	212	30.9%	47.0%
Consumer	4	16	41	92	163	254	366	511	207.5%	53.7%
Automotive	0	0	0.1	1.3	3.8	13	25	53	N/C	154.6%
Total DSP Product Revenue	$208	$315	$448	$587	$778	$1,059	$1,410	$1,866	46.6%	33.6%

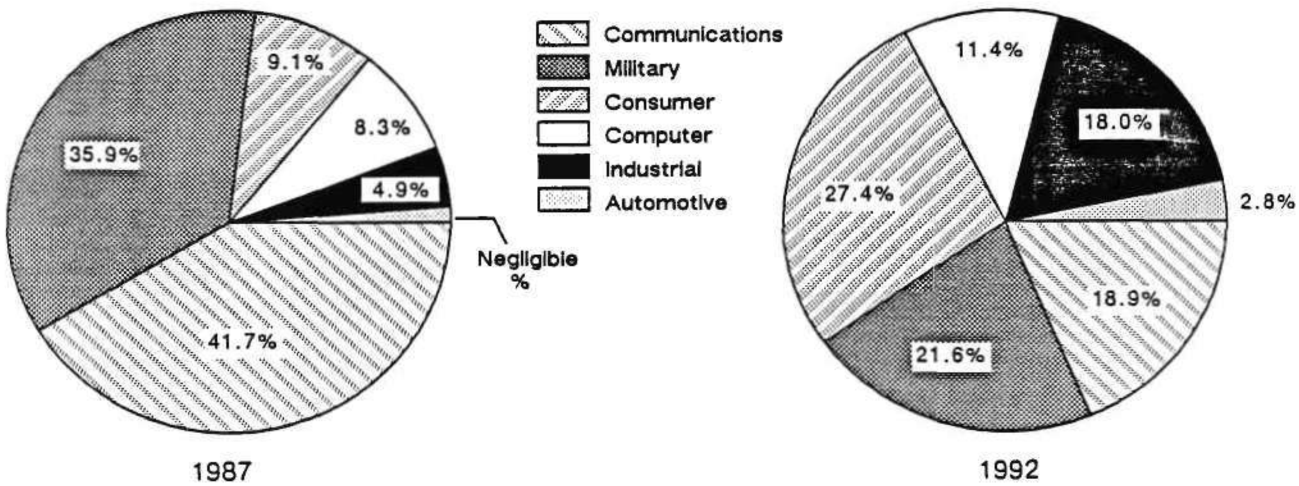
N/C = Not Computed
Note: Columns may not add to totals shown because of rounding.

Source: Dataquest
September 1988

Figure 1 provides a snapshot look at the same revenue data for the years 1987 and 1992, expressed as a percentage of total DSP revenue. This perspective illustrates the growing importance of DSP technology, especially to the industrial and consumer markets.

Figure 1

Revenue for DSP Products in Six Major Semiconductor Application Markets



Source: Dataquest
September 1988

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DSP Markets and Applications

MARKET ANALYSIS

Introduction

The market for DSP products was essentially created in 1977 by TRW with the introduction of the first monolithic multiplier, originally targeted for internal TRW use. Soon thereafter, the first monolithic video-speed flash converter was also introduced by TRW, and the combination of the two made high-performance, real-time DSP operations a reality. The military market quickly embraced these new products, and still remains one of the largest (and most sophisticated) users of DSP technology.

The early 1980s saw the introduction of single-chip DSPs such as TI's TMS32010, AMI's 28211, and NEC's 7720. These processors found tremendous success initially in the communications market for applications in modems, DTMF receivers, and speech applications.

Today, the military and communications markets are still the two largest users of DSP semiconductor products. However, DSP techniques are being used in a plethora of new ways, spurring growth in the industrial, computer, consumer, and automotive markets.

Military

As shown in Table 3, Dataquest expects revenue growth for military applications to increase at a compound annual growth rate (CAGR) of 19 percent through 1992. Military expenditures for DSP products should total the second largest of the six markets in 1992 (see Table 2). However, the percentage of military DSP revenue drops from 42.3 percent in 1985 to 21.7 percent in 1992, compared with total DSP revenue. This is attributable to the much higher DSP growth rates expected in the commercial marketplace.

The most important applications using DSP technology in the military market include the following:

- Radar
- Sonar
- Navigation
- Fuses
- Communications
- Reconnaissance

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Table 3

DSP Revenue Forecast for the Military Market
(Millions of Dollars)

Product Category	Actual 1985	Actual 1986	Actual 1987	Forecast 1988	Forecast 1989	Forecast 1990	Forecast 1991	Forecast 1992	CAGR 1985-1987	CAGR 1988-1992
DSMPUs	$16	$ 26	$ 35	$ 49	$ 64	$ 84	$110	$139	48.0%	29.8%
MPDSP	43	55	65	73	81	87	92	96	23.0%	7.1%
ASDSP	20	28	44	58	72	88	106	128	48.4%	21.9%
SFDSP	9	12	17	21	25	30	36	42	37.7%	19.0%
Total Military DSP Revenue	$88	$121	$161	$201	$242	$289	$344	$405	35.8%	19.0%
Military as Percent of Total DSP Revenue	42.3%	38.3%	35.9%	34.3%	31.1%	27.3%	24.4%	21.7%		

Source: Dataquest
September 1988

As in other market segments, DSMPU products will experience the largest part of the market growth; nearly 30 percent through 1992.

Microprogrammable products enjoy their largest market penetration in military applications. In 1985, 44 percent of microprogrammable revenue was funded by military applications. In 1992, Dataquest expects that 60 percent of MPDSP revenue will be funded by military applications. This growth is caused by two primary factors:

- Because of shorter design cycles in the commercial market, MPDSP usage is being displaced by the other three DSP product categories, slowing total MPDSP revenue growth.

- Many military projects take from three to seven years to enter production; hence, products designed using MPDSP components a number of years ago are only now beginning to enter production.

Communications

Usage of digital signal processing components in the communications market experienced significant growth in the early 1980s. As shown in Table 4, this was spurred by two primary applications: modems and DTMF receivers. These two applications have historically used both first-generation DSMPU and special-function devices almost exclusively. Very few applications in the communications market use MPDSP components.

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Table 4

DSP Revenue Forecast for the Communications Market (Millions of Dollars)

Application Category	Actual 1985	1986	1987	Forecast 1988	1989	1990	1991	1992	CAGR 1985-1987	CAGR 1988-1992
Modems	$45.0	$ 70.0	$101.0	$106.0	$127.0	$151.0	$171.0	$161.0	49.7%	11.1%
DTMF Rxr	25.0	30.0	35.0	31.0	27.0	23.0	20.0	18.0	18.3%	(12.5%)
Speech Synth.	2.0	4.0	6.0	8.0	11.0	16.0	26.0	40.0	73.2%	49.5%
Speech Recog.	0.7	0.9	1.0	1.6	2.6	4.4	7.0	10.0	19.5%	58.1%
Speech Compres.	1.0	2.0	3.4	5.7	9.6	14.0	18.0	25.0	84.4%	44.7%
Mobile Commun.	0.3	0.5	1.0	2.0	4.0	6.0	12.0	20.0	82.6%	77.8%
Video Telecon	1.4	1.7	2.0	2.4	3.0	3.8	5.0	7.0	19.5%	30.7%
Other	19.0	27.0	37.0	39.0	46.0	54.0	65.0	70.0	40.7%	15.8%
Total Communications DSP Revenue	$94.3	$136.3	$186.6	$195.9	$229.8	$272.0	$323.4	$351.9	40.7%	15.8%
Communications as Percent of Total DSP Revenue	45.3%	43.1%	41.7%	33.4%	29.5%	25.7%	22.9%	18.9%		

Note: Columns may not add to totals shown because of rounding.

Source: Dataquest
September 1988

To add perspective to the revenue significance of modems and DTMF receivers, in 1985 these two applications accounted for more than 33 percent of all DSP revenue. Partly because of both price erosion and proliferation of DSP technology into other areas, the percentage of DSP revenue accounted for by both of these applications in 1988 should be down to 23 percent.

Modems will continue to contribute significantly to total communications revenue through 1992. This is attributed in part to new generations of modems defined by the Consultive Committee for International Telephony and Telegraphy (CCITT) such as the CCITT V.22bis (2400 bps full duplex) and CCITT V.32 (9600 bps full duplex). These modems use more sophisticated signal processing algorithms (such as adaptive equalizers) than previous generations of slower-speed modems. In the case of the V.32, echo cancellation algorithms are also required. Both adaptive equalizers and echo cancellers require DSP algorithms for implementation. In addition, these modems are beginning to use second-generation DSMPUs, which also command higher prices than first-generation processors.

Revenue for DTMF receiver applications is expected to decline at a CAGR of about 12.5 percent through 1992, due mainly to price declines for the first-generation DSMPUs that normally implement this function. This is in contrast to a positive CAGR of 4.1 percent in the number of installed central office and PBX lines through 1992.

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Dataquest expects remaining communications applications using DSP technology to begin experiencing impressive revenue gains through 1992 as shown in Table 4. Voice messaging applications using speech synthesis and speech compression algorithms will help drive this revenue growth. Mobile communications is another large growth area with enormous potential for DSP.

Industrial

Dataquest expects the industrial market to turn in impressive DSP revenue gains as shown in Table 5, with 1992 revenue at nearly $335 million, more than six times the 1988 revenue. This number is even more impressive given the small revenue number attributed to this market in 1985.

As shown in Table 5, the test equipment category of the industrial market consists of applications such as the following:

- Digital oscilloscopes
- Spectrum analyzers
- Vibration analysis
- Recording instruments
- Automatic test equipment

In general, test equipment applications tend to use DSMPU and SFDSP products for operations such as fast Fourier transforms (FFTs) and digital filters. Digital oscilloscopes and spectrum analyzers account for about 70 percent of the test equipment revenue in 1988. In 1992, this percentage should decline to about 60 percent, as the other equipment applications incorporate larger amounts of DSP.

As shown in Table 5, the medical equipment category of the industrial market consists of applications such as the following:

- Computed tomography (CT) scanners
- Magnetic-resonance imaging
- Doppler ultrasound
- Hearing aids
- Vision aids

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Table 5

DSP Revenue Forecast for the Industrial Market (Millions of Dollars)

Application Category	Actual 1985	Actual 1986	Actual 1987	Forecast 1988	Forecast 1989	Forecast 1990	Forecast 1991	Forecast 1992	CAGR 1985-1987	CAGR 1988-1992
Test Equipment	N/C	$ 9.4	$ 9.1	$13.0	$15.0	$ 17.0	$ 20.0	$ 23.0	N/C	15.3%
Oscilloscope	N/A	3.4	3.8	4.4	5.2	6.0	7.0	8.2	N/C	16.8%
Spec Analysis	N/A	4.0	2.4	4.7	4.8	5.0	5.2	5.6	N/C	4.5%
Vib Analysis	N/A	0.4	0.6	0.8	1.0	1.2	1.4	1.6	N/C	18.9%
Record Instr.	N/A	0.4	0.6	0.8	1.0	1.2	1.4	1.6	N/C	18.9%
ATE	N/A	0.2	0.3	0.4	0.5	0.7	0.8	1.0	N/C	25.7%
Other	N/A	1.0	1.4	1.8	2.4	3.0	3.8	4.8	N/C	27.8%
Medical	N/C	1.8	3.2	5.0	7.8	12.0	17.0	24.0	N/C	47.9%
CT Scanners	N/A	0.9	1.2	1.5	1.8	2.1	2.3	2.5	N/C	13.6%
MRI	N/A	0.5	1.2	2.0	2.8	4.2	6.0	8.0	N/C	41.4%
Doppler Ultr	N/A	0.4	0.6	0.9	1.2	1.6	2.0	2.4	N/C	27.8%
Hearing Aids	N/A	0	0.2	0.6	2.0	4.0	7.0	11.0	N/C	106.9%
Office	0	0.2	0.4	5.5	13.0	33.0	51.0	85.0	N/C	98.3%
Image Compr	0	0.1	0.2	1.0	2.0	5.0	10.0	20.0	N/C	111.5%
Copiers	0	0	0	0.5	1.5	3.0	5.0	10.0	N/C	111.5%
Laser Print	0	0.1	0.2	4.0	9.0	25.0	36.0	55.0	N/C	92.6%
Inspection	0.1	0.1	0.2	0.6	2.0	6.0	10.0	16.0	41.4%	127.0%
Remote Monitor	0.3	0.6	1.3	2.5	5.0	10.0	20.0	40.0	108.2%	100.0%
GPS	0.1	0.5	1.0	4.0	6.0	10.0	16.0	24.0	216.2%	56.5%
Motor Control	0.1	0.5	2.0	10.0	16.0	26.0	40.0	56.0	347.2%	53.8%
Other	0.2	3.3	4.3	10.0	16.0	29.0	44.0	67.0	435.4%	60.3%
Total Industrial DSP Revenue	$0.8	$16.4	$21.5	$50.6	$80.3	$143.0	$217.0	$335.0	435.4%	60.3%
Industrial as Percent of Total DSP Revenue	0.3%	5.2%	4.8%	8.6%	10.3%	13.5%	15.4%	18.0%		

N/C = Not Computed
N/A = Not Available
Note: Columns may not add to totals shown because of rounding.

Source: Dataquest
September 1988

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Dataquest expects much of the revenue growth in the medical market through 1992 to come from a dramatic increase in the number of hearing aids. By 1992, 46 percent of medical revenue could come from hearing aids. This compares with less than 7 percent in 1988.

According to the Ear Research Institute in Southern California, there are two million people in the United States who are either totally deaf or lack the ability to detect speech without some form of external aid. Techniques in the form of either electrical stimulation of the cochlea by implanted electrodes or tactile cutaneous stimulation are often used in order to simulate hearing for the deaf. There exist another 12 million hearing impaired individuals who suffer from serious hearing loss, often treated using conventional analog hearing aids. A number of different digital signal processing techniques are being developed to aid both groups of people, providing a level of hearing quality not achievable today using analog technology.

As shown in Table 5, the office equipment category of the industrial market consists of applications such as the following:

- Image compression
- Copiers
- Laser printers

Dataquest expects the office category of the industrial market to achieve the most significant revenue growth of any category in the industrial market. We expect revenue to reach nearly $85 million by 1992, from essentially no revenue in 1985. Furthermore, there is additional upside potential in this category, as all of the applications are currently growing at impressive rates.

Image compression techniques will be used to compress both gray-scale and color images for storage and transmission requirements. Examples include transmission of images over telephone lines using group IV facsimile and storage of high-quality images on computer hard discs. A number of different DSP-based compression techniques currently exist, including:

- Discrete (or fast) cosine transform
- Adaptive differential pulse-code modulation (ADPCM)
- Vector quantization

Laser printers are beginning to incorporate DSP components for generating fonts and graphics. This is important, particularly for page-description languages (PDLs) such as Adobe Systems' "PostScript." PDLs such as this allow integration of both texts—with a wide range of different font types and sizes—and graphics for desktop publishing applications. Digital copiers are also beginning to appear on the market using DSP operations such as digital filters.

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An interesting application area that deserves some discussion is global positioning satellites (GPS). GPS is a three-dimensional coordinate system using triangulation techniques from satellites orbiting the earth. The GPS system has both military and commercial uses. Military uses include:

- Replacement of terrain maps for cruise missiles with GPS location-finding electronics
- Soldier, transportation, and equipment location and placement on battlefields

Commercial applications include:

- Surveying equipment
- Aircraft and boat location
- Navigation
- Terrain maps for transportation, including automobiles

Computer

As shown in Table 6, DSP revenue in the computer market as a percentage of total DSP revenue is expected to remain relatively stable at about 10 percent through 1992. As can be seen in Table 6, applications that serve the computer market include:

- Arithmetic accelerators
- Array processors
- Graphics
- Image processing
- Geophysical processing

Applications within this market are slightly different from DSP applications within other markets. Many of the applications in the computer market require general-purpose arithmetic (numerical processing) in addition to more classical digital signal processing functions. Historically, hardware implementations have relied principally upon MPDSP products because of the higher speed and inherent architecture flexibility allowed by these products. This market is now beginning to migrate toward usage of second- and third-generation DSMPU products because of the higher integration and lower cost of implementation.

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Table 6

DSP Revenue Forecast for the Computer Market
(Millions of Dollars)

Application Category	Actual 1985	1986	1987	Forecast 1988	1989	1990	1991	1992	CAGR 1985-1987	CAGR 1988-1992
Arith. Accel.	0	0	0	$ 0.5	$ 2.0	$10.0	$ 30.0	$ 70.0	N/C	244.0%
Array Proc.	$ 5.0	$ 7.0	$10.0	12.0	15.0	18.0	22.0	26.0	41.4%	21.3%
Image Proc.	3.0	4.0	6.0	8.4	12.0	20.0	30.0	44.0	41.4%	51.3%
Graphics	9.0	10.0	13.0	15.0	18.0	21.0	25.0	29.0	21.1%	16.9%
Geo Process	0.1	0.1	0.1	0.2	0.5	0.7	1.0	1.3	0	59.7%
Other	4.3	5.3	7.3	9.1	12.0	18.0	27.0	43.0	30.9%	47.0%
Total Computer DSP Revenue	$21.4	$26.4	$36.6	$45.5	$59.1	$87.6	$135.0	$212.0	30.9%	47.0%
Computer as Percent of Total DSP Revenue	10.3%	8.4%	8.2%	7.8%	7.6%	8.3%	9.6%	11.4%		

N/C = Not Computed
Note: Columns may not add to totals shown because of rounding.

Source: Dataquest
September 1988

It is important to also understand that the applications shown above for this market are not entirely orthogonal. In other words, arithmetic accelerators and array processors are often used as OEM products within image processing or geophysical processing stations. Dataquest has taken care to reduce the risk of double counting these products.

Certain parts of this market, primarily image processing and graphics, also use both SFDSP and ASDSP devices because of the very high processing rates required. This trend is expected to continue.

Consumer

As shown in Table 7, Dataquest expects the consumer market to be the single largest market for DSP products by 1992. DSP technology is currently being developed for inclusion in applications such as the following:

- Audio compact disc players
- Digital television
- Electronic cameras
- Toys

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Table 7

DSP Revenue Forecast for the Consumer Market
(Millions of Dollars)

Application Category	Actual 1985	1986	1987	Forecast 1988	1989	1990	1991	1992	CAGR 1985-1987	CAGR 1988-1992
CD Players	$3.0	$10.0	$20.0	$30.0	$ 45.0	$ 64.0	$ 86.0	$110.0	158.2%	38.4%
Digital Vid	0	2.0	10.0	40.0	80.0	130.0	190.0	270.0	N/C	61.2%
Elec Cameras	0	0	0.1	0.3	1.0	4.0	10.0	20.0	N/C	185.7%
Toys	0.5	1.0	3.0	3.0	4.0	5.0	7.0	9.0	144.9%	31.6%
Other	0.9	3.3	8.3	18.0	33.0	51.0	73.0	102.0	207.5%	53.7%
Total Consumer DSP Revenue	$4.4	$16.3	$41.4	$91.6	$163.0	$253.0	$366.0	$511.0	207.5%	53.7%
Consumer as Percent of Total DSP Revenue	2.1%	5.2%	9.2%	15.6%	21.0%	24.0%	26.0%	27.4%		

NC = Not Computed

Source: Dataquest
September 1988

Digital-audio applications such as audio compact disc (CD) players provide an example of the huge volume potential of DSP technology. Dataquest estimates that nearly 10 million audio CD players will be shipped in 1988, with nearly half of them using DSP technology. DSP is used for implementing digital interpolation filters in all CD players that "oversample." Because of the high volume of this application, SFDSP devices are used to optimize the architecture and reduce costs as much as possible. Dataquest estimates that nearly $30 million worth of digital filters will be shipped in audio CD players in 1988.

A similar growth scenario holds true for digital television sets, which hold the promise for improved video quality. DSP technology will be important in digital television regardless of the direction of standards for future high definition (HDTV), extended definition (EDTV), or improved definition (IDTV) television. As in audio CD players, DSP-based digital TV chip sets will be designed as SFDSP products.

A third consumer growth area is for digital cameras which hold the promise of "filmless" cameras for the future. A picture will be taken by a user in the same fashion as today, but the image will be stored electronically in the camera. The photographer will have the options of connecting the camera directly to his VCR for viewing, or having a "hard copy" (photograph) generated with quality equivalent to that achievable using today's cameras with film. Experimental cameras are available for newspaper photographers today, although the technology is still a few years away for widespread commercial use.

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Sophisticated toys will also provide a ready application area for DSP technology. In fact, Dataquest believes the "Julie" doll introduced by Worlds of Wonder, represents the single largest order ever received for a DSMPU product.

Automotive

As shown in Table 8, the automotive market has historically been the smallest user of DSP technology. This trend is expected to continue through 1992. However, there are a number of automotive applications in which DSP will begin to appear, including:

- Antilock brakes
- Distance sensors
- Lane sensors

Table 8

DSP Revenue Forecast for the Automotive Market (Millions of Dollars)

Application Category	Actual 1985	1986	1987	Forecast 1988	1989	1990	1991	1992	CAGR 1985-1987	CAGR 1988-1992
Antilock Brakes	0	0	$0.1	$1.0	$3.0	$10.0	$20.0	$40.0	N/C	151.5%
Distance Sens	0	0	0	0	0	0	0	1.0	N/C	N/C
Lane Sensors	0	0	0	0	0	0	0	1.0	N/C	N/C
Other	0	0	0	0.3	0.8	2.5	5.0	10.5	N/C	154.6%
Total Automotive DSP Revenue	0	0	$0.1	$1.3	$3.8	$12.5	$25.0	$52.5	N/C	154.6%
Automotive as Percent of Total DSP Revenue	0	0	0	0.2%	0.5%	1.2%	1.8%	2.8%		

NC = Not Computed

Source: Dataquest
September 1988

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Antilock brakes are becoming a standard feature on many cars today. Many of the hardware implementations use DSMPUs. This application continues to represent a significant growth opportunity.

The car that can drive itself has been dreamed about for many years now. DSP technology promises to allow some of those features to be incorporated within the next decade. Technology to implement distance sensors to detect moving objects (other cars) and stationary objects (like telephone poles) is relatively straightforward, using simple radar techniques. Lane sensors that track visual lines on the highway or some other form of reference can also be built using existing DSP technology.

Certainly the technology to allow a car to drive itself down long, lonely stretches of highway is here today. Adapting that technology to cars that can drive themselves within an urban environment will require additional technology that is probably further in the future. Certainly other DSP-intensive applications that have been discussed previously will ultimately be important in cars of the future, such as navigation using global positioning satellites and communications using cellular telephones.

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DSP Market Strategies

FACTORS WORKING FOR DSP

The digital signal processing (DSP) market is reaping the benefits of the long-term conversion from a purely mechanical world to a digital world--a process that started in the early 1950s with the development of the first digital computers. One by one over the years, as semiconductor technology has improved, applications that previously could be implemented only in analog circuitry have been converted to digital.

Analog first gave way to digital in non-real-time applications such as accounting. Real-time applications required a speed and performance level not available initially. Advances in semiconductor design and fabrication are only just now making some of these real-time applications feasible through technologies such as DSP.

Already, most low-frequency industrial control applications can be totally implemented digitally. Inroads are also being made into the audio frequency realm in areas such as telecommunications. Eventually, DSP products will replace most, if not all, analog circuitry in this frequency range. Even some of the simpler video frequency applications, such as non-real-time enhancement of pictures from spacecraft, are being implemented using DSP techniques. DSP implementations of more difficult applications, such as real-time programmable image processing, are just around the corner as a new generation of DSP processors comes off the drawing board. These new DSPs are expected to be in production by the early 1990s.

Other factors are coming into play to enhance growth in the DSP market. One of the major factors is the reduced cost of DSP products, particularly digital signal microprocessors (DSMPUs). The price of DSP technology is no longer prohibitive compared to the performance enhancements DSPs provide. The new availability of DSMPUs will also contribute to the growth of the DSP market as engineers become more familiar with DSP technology. DSMPUs actually make new products possible, like low-cost, high-bit-rate dial-up modems.

Perhaps the single largest factor working in favor of the DSP market is the conversion of the worldwide telephone system from analog to digital (ISDN). This is a massive market. By 1990, Dataquest expects the U.S. telecommunications market alone to consume approximately $45 billion of equipment. Of this amount, $301 million is expected to be spent on the purchase of DSP integrated circuits.

Furthermore, the military requirements for DSP technology will continue to increase, as the quest for military superiority demands the development of more "intelligent" weapons.

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DSP Market Strategies

FACTORS WORKING AGAINST DSP

Several factors are expected to slow the growth of the DSP market over the next five years. These include a lack of DSP engineers, a lack of adequate development tools, and competing signal processing techniques.

Digital signal processing is new to the vast majority of analog engineers who are used to operational amplifiers, capacitors, inductors, transformers, diodes, and electrically induced noise and cross talk. They have solved signal-processing problems by the same methods for years and are comfortable with analog analysis techniques.

The new DSP techniques are very complicated, and understanding the algorithms requires a degree of mathematical expertise that is not widespread in the industry. Universities are just now creating DSP courses. Professors who have had experience using DSP circuits are rare, and there are only a few textbooks on the subject. It could be as long as four years before enough engineers have graduated and are employed designing commercial products to have any impact on the industry.

The lack of adequate development tools, particularly in-circuit emulators and inexpensive design software, may severely hamper the growth of this new industry. Today, the starting package cost to begin a DSP design is in the range of $5,000 to $10,000. This provides an engineer with an evaluation board, a simulator, an assembler, and an in-circuit emulator. The engineer is expected to provide the personal computer. These support tools are also somewhat primitive. Dataquest expects a retrenchment period in DSP market growth as support tools come up to speed.

A third reason for slow acceptance of DSP is the development progress of competing technologies. Advances in analog circuit technology, switched capacitors, surface acoustic wave filters, and optical filtering are impeding the transition from traditional signal processing to digital signal processing. Switched capacitors, although difficult to design and lacking the precision and programmability of DSMPUs, are still more familiar and cost-effective than DSP circuits and will continue to steal high-volume applications in the audio spectrum.

DSP MARKET STRATEGIES

The DSP market is in a rapid transition phase, and the relative positions of suppliers to this market are highly volatile. Early DSP microprocessors such as Intel's 2920 and AMI's 28S211, have disappeared. TRW, which used to dominate the multiplier market, has lost most of its market share to an oligarchy of CMOS vendors.

DSP Market Strategies

New entrants are announcing products every day, and the market is undergoing rapid technological change both in architecture and in device speed. Customers are still willing to buy a new manufacturer's DSP if its specifications look good, rather than seeking the safety of a brand name. Suppliers can quickly establish themselves as major market participants with just one revolutionary product. In addition, few defined second-sourcing relationships exist today. This leaves open the possibility of powerful market alliances that could radically change the face of the DSP market. Such turmoil presents fertile ground for clever strategic planners.

Foreign Alliances

Some of the most advanced DSP parts are coming from Europe and Japan. Europe is particularly strong in telecommunications, and Japan is strong in video technology, machine vision, and pattern recognition. Given that the television industry exists almost exclusively in the Far East, it is likely that Japan will continue to lead the world in video technology.

These advanced video and telecom chips are needed by the U.S. military for new weapon systems, and military applications represent 30 to 40 percent of the total DSP market in the United States. Foreign producers cannot effectively sell into this market, however, as the military cannot rely on parts that may not be procurable during conflict or during times of trade restrictions. Therefore, the potential exists for alliances between U.S. semiconductor manufacturers and foreign manufacturers to effectively tap this very lucrative market.

The Fast Microprocessor

Because of the speed they offer, DSP microprocessors are used in many applications besides signal processing. Speed is exactly the same reason engineers have been using bit slices for the past 10 years. DSMPUs are now being designed into some of the same applications previously implemented with bit slices, but this may be overkill. The bulk of these applications using DSMPUs for speed could probably do without the multiplier. A stripped-down version of a Harvard-architecture DSMPU would offer an attractive alternative for these types of applications.

The market potential for a fast microcomputer that uses the architectural tricks of a DSMPU is huge. Dataquest estimates that the total microcomputer market will be about $4 billion in 1990. If only 10 percent of this market chooses a Harvard-architecture pipelined reduced instruction set computing (RISC) machine, this would present a $400 million opportunity.

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DSP Market Strategies

Product Families

No I/O standard currently exists for DSP microprocessors and filters. In most cases, glue chips are required for interfacing with the real world. These glue chips can be as simple as SSI packages between a DSMPU and its host microprocessor, or they can range from filters and amplifiers for A/D conversion to expensive dual-port memories.

No families of parts in today's DSP market have uniform part numbers and interfaces. A typical design combines some parts from a microprocessor supplier, some from an analog supplier, and some from a memory supplier. There is no one-stop shopping.

A standard DSP product family has yet to emerge. Any company that tries to set the standard needs to display a commitment to a line of parts, to provide information to customers on the next generation planned, and to be able to convince the engineering community that its interface architecture will endure. Texas Instruments is the company that is coming the closest to this goal.

The DSP Solution Company

DSP applications, because of the need for high speed, are more economical on one chip than spread over many chips. The DSP microprocessor offers a one-chip solution, but it is limited because application customization may only be done via software algorithms.

Hardware solutions can significantly outperform software mappings. Custom silicon hardware takes longer from product conception to market, however, and hardware limits the functional complexity. For the past 10 years, engineers have been using a combination of bit slices and software mappings. When more processing power was needed, additional bit-slice components were added. Control of both the hardware architecture and the software architecture is invaluable to the designer for the best trade-off between flexibility and cost.

Equivalent bit-slice circuits are now available as standard cells in semicustom implementations. One possible strategy using these cells would be to target the DSP market specifically with DSP functional building blocks plus DSP simulation and analysis software. This may prove to be a good niche in the crowded field of ASIC suppliers.

The revenue from gate arrays and standard cells used strictly for DSP applications will be about $200 million in 1990. An ASIC supplier with DSP standard cells and DSP software support would gain a sizable share of this niche.

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DSP Market Strategies

Preprogrammed DSP Microprocessors

DSP microprocessors are difficult and expensive to program. First, there is the initial $10,000 price tag for software, evaluation boards, and emulators. Then, there is the cost of programming time. Programming a DSMPU costs $10 to $30 per byte, fully supported. At 3,000 source code lines per year, 2 bytes per source code line on the average, costs could run as high as $180,000 a year.

Some customers will choose to buy a preprogrammed chip instead of making the investment required to program their own. We expect this to be the case especially with applications using proprietary algorithms that would ordinarily involve considerable software design and development time. Consequently, we believe that there will be a large market for preprogrammed chips. The functions of these chips will mirror the DSP market. For instance, these chips might involve speech-recognition algorithms and high-speed modem standards.

Dataquest estimates that 15 percent of the forecasted DSMPU revenue will be from preprogrammed products, representing approximately $40 million in revenue in 1990. The development of these chips can be done most successfully by companies that are experts in a particular vertical market. Any company focused on a vertical market is best in command of the proprietary algorithms, specifications, and key features required by that market.

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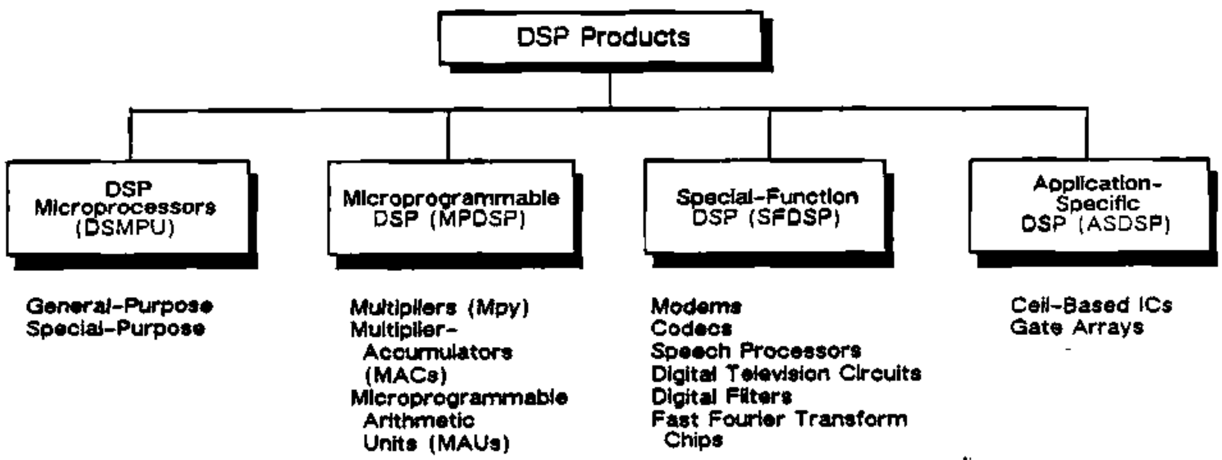
DSP Family Tree

OVERVIEW

The digital signal processing (DSP) semiconductor market is characterized by a variety of different products which address a diverse set of markets and applications. Dataquest partitions DSP products into four categories, as shown in Figure 1. Each product category is quite distinct from the others in terms of functionality, performance, and end application.

Figure 1

Segmentation of DSP Products



Source: Dataquest
September 1988

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DSP Family Tree

DSP MICROPROCESSORS

DSP microprocessors (DSMPUs) are general-purpose, programmable devices similar in many ways to conventional microprocessors. Their distinction is characterized by clever architectural modifications which make them efficient for implementing the repetitive multiplications and additions required by DSP algorithms. DSMPUs are available as standard catalog products from manufacturers.

In some cases, manufacturers will mask-program a general-purpose device and resell it as a function-specific device such as a modem. In this case, the product will not be counted as a DSP microprocessor, but instead as a special-function (i.e., modem) DSP device. The reasons behind this are:

- Often the end user is unaware that the device is really a DSP microprocessor because it is sometimes put into a different package with a different pin configuration.

- When the product is resold it fits the definition of a special-function device. It is useful to group all special-function devices into the same category regardless of whether a general-purpose or custom architecture was designed to implement the function.

- An analysis is also provided to obtain the importance of DSMPU architectures to the special-function DSP market.

MICROPROGRAMMABLE DSPs

The category of microprogrammable DSP (MPDSP) products encompasses the traditional "bit-slice" or "building-block" components, such as multipliers, multiplier-accumulators (MACs), and arithmetic-logic units (ALUs). These products are designed to allow high-performance, modular DSP architectures to be designed using standard off-the-shelf components. Dataquest uses the term "microprogrammable" to describe these products instead of "bit-slice" or "building block". These latter terms are misleading and are not truly descriptive of the applications for these devices.

Dataquest believes that it is important to analyze the microprogrammable market separately from the mainstream DSP market. Many of the products in this category are used in applications such as graphics and controllers, which do not specifically fit the definition of digital signal processing. In order to keep this category distinct, only products traditionally considered as arithmetic building blocks are included in the revenue forecasts. These range from older 4-bit ALUs and 8-bit multipliers to the newer 32- and 64-bit multipliers and ALUs.

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DSP Family Tree

Systems designed using MPDSP products also require additional support circuitry such as sequencers, FIFOs, registers, and static memories. These peripheral products are not specifically DSP products, and will not be counted in the DSP revenue forecasts. Additionally, they are generally counted in other semiconductor services within Dataquest. However, because of their applicability to DSP systems, forecasts will be provided for these products in cooperation with the other appropriate Dataquest semiconductor service sections.

SPECIAL-FUNCTION DSPs

Special-function DSPs (SFDSPs) include products that are built using DSP techniques and architectures, but which are designed for specific functions. Examples of these include modems, codecs, speech processors, digital television circuits, digital filters, and fast Fourier transform chips. DSP technology is inherent to all of these devices, but they are not designed to be general-purpose in nature. Generally these devices cannot be programmed by users to perform operations other than their defined functions; i.e., a DSP modem cannot be programmed to do fast Fourier transforms.

Occasionally, conflicts may arise regarding the category into which some products fit. SFDSP products retain the following characteristics:

- They are designed to implement specific functions.
- Their architecture implementation uses DSP techniques.
- The product is not reprogrammable by the user to implement functions other than those intended.
- They are available as standard catalog items.

APPLICATION-SPECIFIC DSPs

Products in the application-specific DSP (ASDSP) category are custom devices designed using primarily gate-array or cell-based IC techniques. In order to avoid confusion with some products which may be considered SFDSP, ASDSP products retain the following characteristics:

- All products are targeted at DSP applications.
- Products are not available as standard catalog items, but are instead proprietary to the user. If the products do become available as standard catalog items, they will be moved to the most appropriate of the other DSP product categories.
- Full-custom devices are also included in the ASDSP category as long as they meet the above two criteria.

DSP Definitions

A/D (analog to digital). A circuit that transforms a linear (analog) signal to a digital representation. The digital representation is usually in the binary format of 1s and 0s.

analog. A circuit or system in which the output signals bear a continuous relationship to the input signals, as opposed to a digital circuit.

ASIC (application-specific integrated circuit). An integrated circuit designed or adapted for a specific application.

ASP (average selling price).

bit slice. A section or slice of an ALU, typically 4 bits wide.

CAGR (compound annual growth rate).

CBIC (cell-based integrated circuit). ASIC design technique utilizing nonfixed width or height megacells.

CODEC (coder/decoder circuit). An integrated circuit that codes a voice signal into a binary waveform or decodes a binary waveform into a voice signal. Such circuits are now used in digital communications applications.

D/A (digital to analog). A circuit that transforms a digital representation of a waveform to a linear (analog) waveform.

digital. A circuit or system whose values or levels are binary.

digital signal processing (DSP). The manipulation of the digital representation of an analog waveform, the digital data being obtained by sampling the analog waveform often and converting the sampled data to digital via an A/D converter.

DSMPU (digital signal microprocessing unit). A single-chip microprocessor that performs the special vector and array manipulations necessary for digital signal processing.

DSP building blocks. High-speed arithmetic "pieces," such as bit slices, multipliers, multiplier-accumulators, and registers, which can be combined to form a high-speed computing system capable of performing the special vector and array manipulations necessary for digital signal processing.

FACT. A Fairchild Semiconductor trademark denoting Fairchild Advanced CMOS Technology.

FAST. A Fairchild Semiconductor trademark denoting Fairchild Advanced Schottky TTL.

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DSP Definitions

FFT (fast Fourier transform).

mflops (million floating-point operations per second).

GaAs (gallium arsenide).

gate array. An IC consisting of a structured pattern of logic devices that are customized to meet each customer's requirements.

IC (integrated circuit).

linear. A semiconductor circuit whose output varies directly with the input. (See **analog.**)

SFIC (special function DSP integrated circuit). A category of DSP chips performing a specific function (i.e., not general-purpose DSMPUs) such as speech synthesis.

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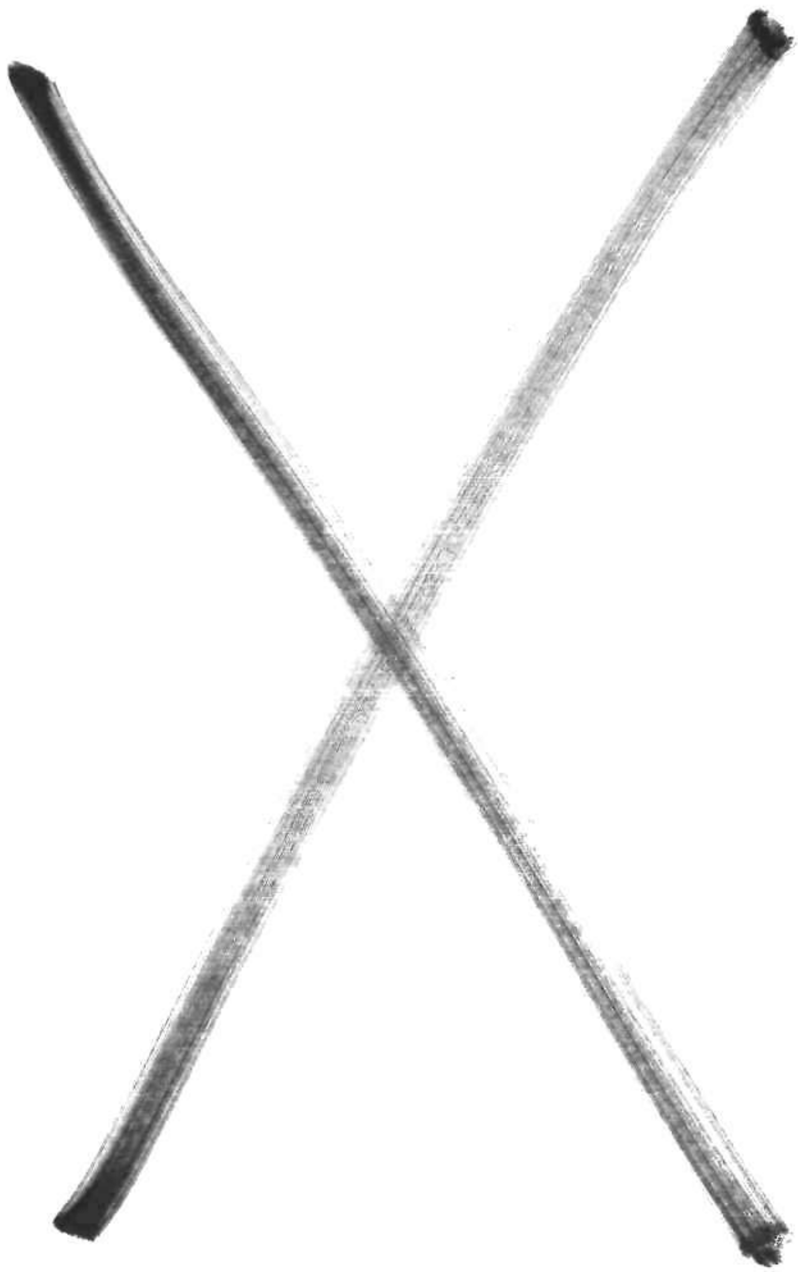

DSMPU--Executive Summary

SUMMARY

The general-purpose digital signal processing microprocessor (DSMPU) is the fastest growing of the four categories of DSP products. Fueled by new applications, replacement of older analog technology, and the simplicity of reprogrammability, revenue for DSMPU products should continue to grow significantly over the next five years. To date, most DSMPU revenue comes from the more established base of 16-bit integer processors. However, Dataquest sees a significant trend towards 32-bit floating-point processors for next generation designs.

DSMPU REVENUE FORECASTS

The following should be noted about the size of the DSMPU market:

- DSMPU revenue was $98 million in 1987, a 58 percent increase over 1986. This number is on target with Dataquest's projection made in June 1987.
- Worldwide DSMPU revenue is forecasted to be $147 million in 1988, up 50 percent over 1987.
- CAGR should continue through 1992 at nearly 48 percent, reaching annual revenue of $695 million.
- DSMPU products in 1987 represented 22 percent of total DSP revenue. By 1992, Dataquest expects DSMPU products to represent over 37 percent of total DSP revenue.

DSMPU APPLICATIONS

The following are key points regarding applications:

- Communication applications currently represent the largest market for DSMPU products, accounting for nearly 70 percent of all DSMPU revenue.
- The two largest-volume DSMPU applications are currently modems and DTMF receivers. Of the $98 million in 1987 DSMPU revenue, about $60 million went into these two applications.
- The military and industrial markets represent the largest growth opportunities for DSMPU products through 1992.

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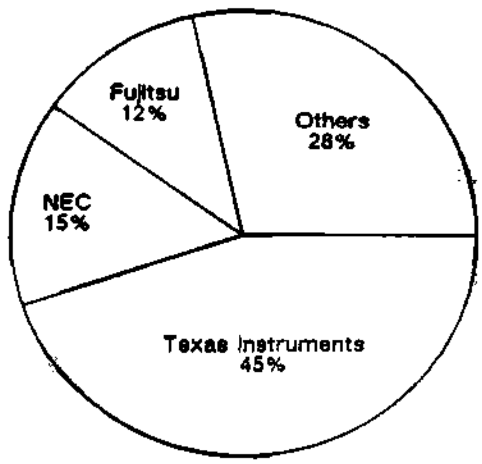
DSMPU COMPETITIVE ENVIRONMENT

The following are key points regarding the competitive environment of the DSMPU market:

- There are currently 14 different manufacturers of DSMPU products.
- The three leading DSMPU manufacturers (worldwide) continue to be Texas Instruments, NEC, and Fujitsu, respectively, totalling 72 percent of DSMPU revenue. Individual market share estimates for these three manufacturers are shown in Figure 1

Figure 1

Worldwide Market Share Estimates— Three Largest DSMPU Manufacturers



Total = $98 Million

Source: Dataquest
September 1988

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DSMPU—Executive Summary

- Dataquest expects a DSMPU vendor shakeout over the next several years, similar to the shakeout that occurred in the microprocessor marketplace (for similar reasons) in the late 1970s and early 1980s. National Semiconductor made a visible exit from the DSMPU business in 1987.

- DSP system design issues, such as availability of development tools and application support from IC manufacturers, are becoming as important to the DSMPU selection process as which architecture is "optimal" for the application.

- Because of the large investment and time required to develop and support new DSMPU architectures, coupled with the expected shakeout in the next few years, Dataquest expects that it will be difficult for new manufacturers to enter this market successfully.

DSMPU TRENDS

Products

The following are key points regarding products:

- DSMPU products were essentially the first RISC processors, characterized predominantly by single-cycle instructions. Most of the devices have at least some elements of Harvard architectures, allowing simultaneous instruction and data fetch, overlapped with instruction execution. This trend continues to evolve with new-generation designs.

- Sixteen-bit integer DSMPU products currently represent more than 90 percent of DSMPU revenue in comparison with other arithmetic formats.

- Dataquest expects floating-point DSMPUs to begin winning significant numbers of design slots across portions of the military, industrial, computer, and communication markets. We expect floating-point DSMPUs to achieve nearly a 35 percent share of the market by 1992.

Technology

The following are key points regarding technology:

- A trend is beginning to evolve whereby DSMPU manufacturers are migrating the architectural "cores" of existing first- and second-generation DSMPU products into cell libraries.

- Dataquest believes that CMOS will continue to be the dominant process technology for DSMPU designs.

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DSMPU--Executive Summary

Pricing

The following are key points regarding pricing:

- First-generation DSMPUs in the class of the TMS32010 (Texas Instruments), 7720 (NEC), and 8764 (Fujitsu) are currently selling in volume from $5 to $10. Dataquest does not expect these prices to decrease significantly below $5.

- Second-generation products such as the TMS320C25 (Texas Instruments), MC56000 (Motorola), and ADSP-2100 (Analog Devices) were introduced with low-quantity prices of $200 to $500.

  - Volume prices on second-generation processors are now below $50.

  - Dataquest expects these prices to be in the $10 to $25 range within two years.

- Third-generation floating-point DSMPUs are being introduced at sample prices of $500 to $1000.

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DSMPU—Forecast

INTRODUCTION

Digital Signal Processing (DSP) microprocessors (DSMPUs) are without question the fastest-growing category of all DSP products. Other sections within this report will deal specifically with the issues of why DSMPUs are growing so rapidly. This section will concentrate specifically on the DSMPU unit and revenue forecasts and the assumptions that were used in creating the forecasts.

DSMPU PRODUCT SEGMENTATION

Dataquest segments DSMPU products into three different categories as defined below. While it is difficult to create categories that all products fit into perfectly, general characteristics for the processors are defined in each section.

First-Generation DSMPU Products

Characteristics of first-generation DSMPU products are:

- Generally 16-bit integer processors
- Instruction execution times of greater than or equal to 200 nsec
- Single instruction, single data (SISD) von Neumann architectures
- Original products designed in NMOS technology (some have since been redesigned in CMOS)
- Volume prices generally \$5-\$15
- Representative products:
  - TMS3201X (Texas Instruments)
  - uPD7720 (NEC)

Second-Generation DSMPU Products

Characteristics of second-generation DSMPU products are:

- Generally 16-bit integer processors; some other arithmetic formats also exist such as block floating-point, 24-bit integer, 22-, 24-, and 32-bit floating point
- Instruction execution times of 80-200 nsec

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DSMPU--Forecast

- Adoption of (modified) Harvard and/or RISC architecture characteristics
- More efficient architectures for interfacing with external memory
- Volume prices generally $15–$40
- Representative products:
  - TMS320C25 (Texas Instruments)
  - ADSP–2100 (Analog Devices)
  - DSP56000 (Motorola)
  - WE DSP–16/32 (AT&T)

Third–Generation DSMPU Products

Characteristics of third–generation DSMPU products are:

- Generally 32–bit floating–point processors
- Instruction execution times of 50–100 nsec
- Harvard and/or RISC architecture characteristics
- Large (greater than 24–bit) external data address space
- Efficient subroutine and looping architectures
- Sample prices generally $500–$1300 (no production yet)
- Representative products:
  - TMS320C30 (Texas Instruments)
  - DSP96000 (Motorola)
  - WE DSP–32C (AT&T)
  - ZR34325 (Zoran)

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DSMPU--Forecast

REVENUE AND UNIT FORECAST

Revenue

Table 1 and Figure 1 show Dataquest's forecast for the DSMPU market through 1992. The following bullets summarize highlights of the figures from the table:

- All segments of the market should experience revenue growth rates exceeding 30 percent through 1992.
- Revenue for the entire DSMPU market through 1992 should experience a CAGR of nearly 50 percent.
- DSMPU products as a percentage of total DSP revenue should reach over 37 percent in 1992, up from about 16 percent in 1985.

Of special significance is the expected revenue increase for 3rd-generation DSMPUs. This market is expected to grow at an enormous CAGR of about 285 percent through 1992, at which point revenue is expected to be larger than that of 1st-generation DSMPUs. As can be observed in later tables, this is partly attributable to the much higher average selling prices (ASPs) expected for these devices, compared with 1st-generation DSMPUs.

Table 2 shows Dataquest's forecast for DSMPU unit shipments through 1992. The following bullets summarize highlights of the figures from the table:

- Dataquest expects total DSMPU unit shipments to increase at an impressive CAGR of over 77 percent per year through 1992.
- Unit shipments for both 2nd- and 3rd-generation DSMPUs are expected to grow at rates significantly above that of the rate for the aggregate DSMPU market.
- Unit volume for 2nd-generation DSMPUs will probably not exceed volume for 1st-generation DSMPUs until 1992, even though revenue for 2nd-generation products should be higher in 1988.

Notice from both Tables 1 and 2 that the CAGR for unit shipments through 1992 (76.8%) is much higher than the CAGR for revenue growth through the same period (47.5%). This is attributable to the significant decrease in ASPs for all DSMPU products as shown in Table 3. Third-generation DSMPUs are expected to have much higher ASPs, but will not be able to keep overall DSMPU ASPs high in the near term because of the relatively small unit penetration of these devices in their first few years of production.

Figure 2 shows the percentage of market penetration by all three generations of devices.

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DSMPU--Forecast

Table 1

Worldwide DSMPU Revenue Forecast (Millions of Dollars)

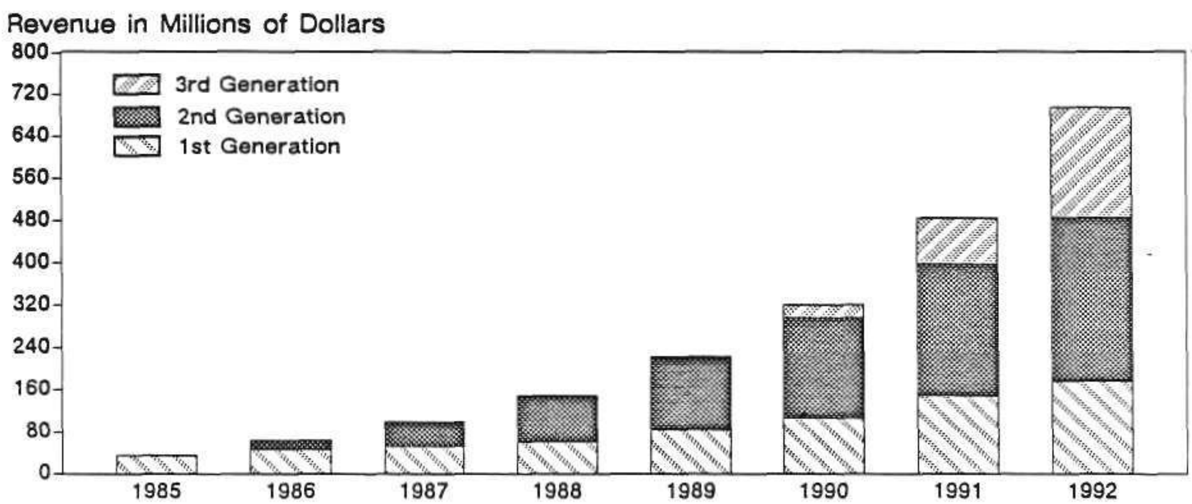
	Actual 1985	1986	1987	Forecast 1988	1989	1990	1991	1992	CAGR 1985-1987	CAGR 1988-1992
1st-Generation	$ 34	$ 45	$ 51	$ 60	$ 83	$ 105	$ 148	$ 176	22.0%	30.8%
2nd-Generation	0	17	47	86	135	191	250	310	N/C	37.8%
3rd-Generation	0	0	0	1	3	24	87	209	N/C	285.1%
Total DSMPU Revenue	$ 34	$ 62	$ 98	$147	$221	$ 320	$ 485	$ 695	69.8%	47.5%
Total DSP Products Revenue	$208	$316	$448	$586	$778	$1,057	$1,410	$1,866	46.8%	33.6%
DSMPU as Percent (%) of Total DSP Revenue	16.3%	19.7%	21.9%	25.1%	28.4%	30.3%	34.4%	37.2%		

N/C = Not Computed

Source: Dataquest
September 1988

Figure 1

Revenue Growth for DSMPU Products



Source: Dataquest
September 1988

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Table 2

Estimated DSMPU Unit Shipments (Millions of Units)

	Actual			Forecast					CAGR	CAGR
	1985	1986	1987	1988	1989	1990	1991	1992	1985-1987	1988-1992
1st-Generation	0.6	1.3	3.2	5.5	9.2	15.0	24.7	35.2	136.2%	59.4%
2nd-Generation	0	0.1	0.8	2.5	6.1	11.9	22.7	38.7	N/C	99.3%
3rd-Generation	0	0	0	0.002	0.01	0.14	0.87	3.48	N/C	584.8%
Total DSMPU Units	0.6	1.4	4.0	7.9	15.4	27.1	48.3	77.4	164.1%	76.8%

Note: Columns may not add to totals shown because of rounding.
N/C = Not Computed

Source: Dataquest
September 1988

Table 3

Estimated DSMPU Average Selling Price (Dollars)

	Actual			Forecast					CAGR	CAGR
	1985	1986	1987	1988	1989	1990	1991	1992	1985-1987	1988-1992
1st-Generation	$60	$ 35	$16	$ 11	$ 9	$ 7	$ 6	$ 5	(48.4%)	(17.9%)
2nd-Generation	0	$150	$60	$ 35	$ 22	$ 16	$ 11	$ 8	N/C	(30.9%)
3rd-Generation	0	0	0	$600	$300	$180	$100	$60	N/C	(43.8%)
ASP	$60	$ 44	$25	$ 19	$ 14	$ 12	$ 10	$ 9	(35.7%)	(16.6%)

N/C = Not Computed

Source: Dataquest
September 1988

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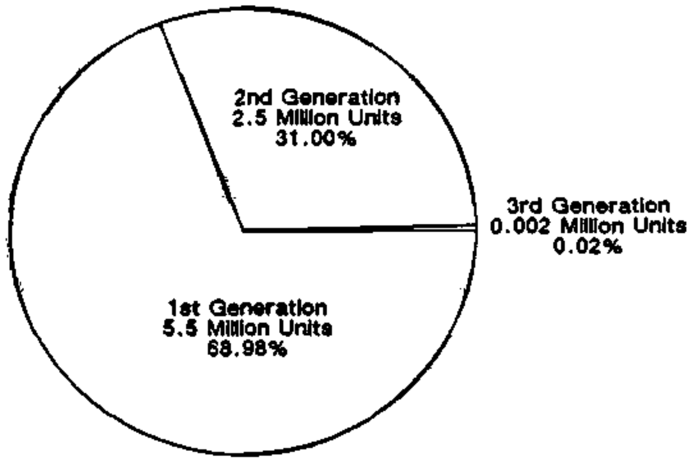
Figure 2

Percentage Penetration of 1st–, 2nd–, and 3rd–Generation DSMPUs to Total DSMPU Market

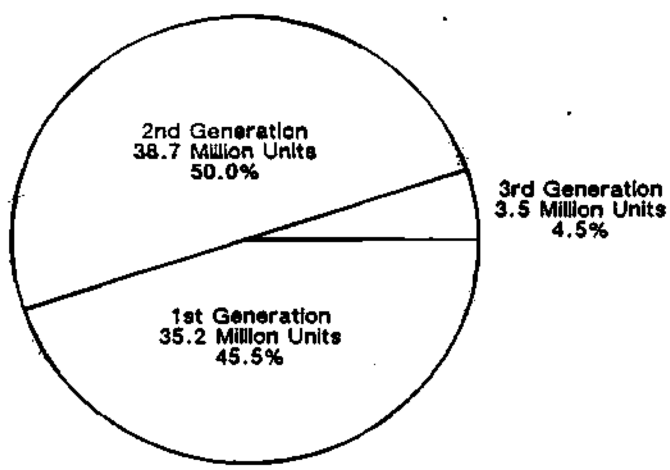
1988



Total DSMPU Units = 8 Million

Source: Dataquest
September 1988

1992



Total DSMPU Units = 77.4 Million

Source: Dataquest
September 1988

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DSMPU--Product Comparison

ARCHITECTURES

A digital signal processing microprocessor (DSMPU) is a single-chip microcomputer designed for fast execution of signal processing algorithms. The DSMPU contains its own arithmetic and logic units, multiplier, local data storage registers, instruction sequencer, and instruction decoder.

There are three styles of DSMPUs being used today:

- General-purpose DSP microprocessor
- Parallel-array microprocessor
- Data-flow microprocessor

General-Purpose DSMPUs

Most current DSMPU designs use a variation of the Harvard architecture. A Harvard architecture differs from the classical von Neumann architecture in that the program and data memories lie in two separate spaces, permitting full overlap of the instruction fetch and execution. The von Neumann model, used in standard microprocessors, relies on a step-by-step sequence of fetch and execute cycles. The Harvard modification allows data and program accesses to execute in parallel, rather than simultaneously. Despite the implied parallelism, the Harvard design is still considered a single- instruction, single-data-path (SISD) device. Figure 1 illustrates a typical Harvard architecture used in DSMPUs.

The Harvard architectural differences have one purpose—speed. A typical Harvard architecture DSMPU can calculate complex vector and matrix mathematical functions approximately 10 times faster than a standard microprocessor.

These DSMPUs are harder to program than the standard microprocessors, however. Although their instruction sets are very similar to those of standard microprocessors, the implied parallelism of these DSMPUs substantially increases the burden placed on the programmer.

Parallel-Array Microprocessors

Another type of DSMPU architecture is the parallel-array microprocessor. Parallel processor architectures fall into two categories:

- Single Instruction Multiple Data (SIMD)
- Multiple Instruction Multiple Data (MIMD)

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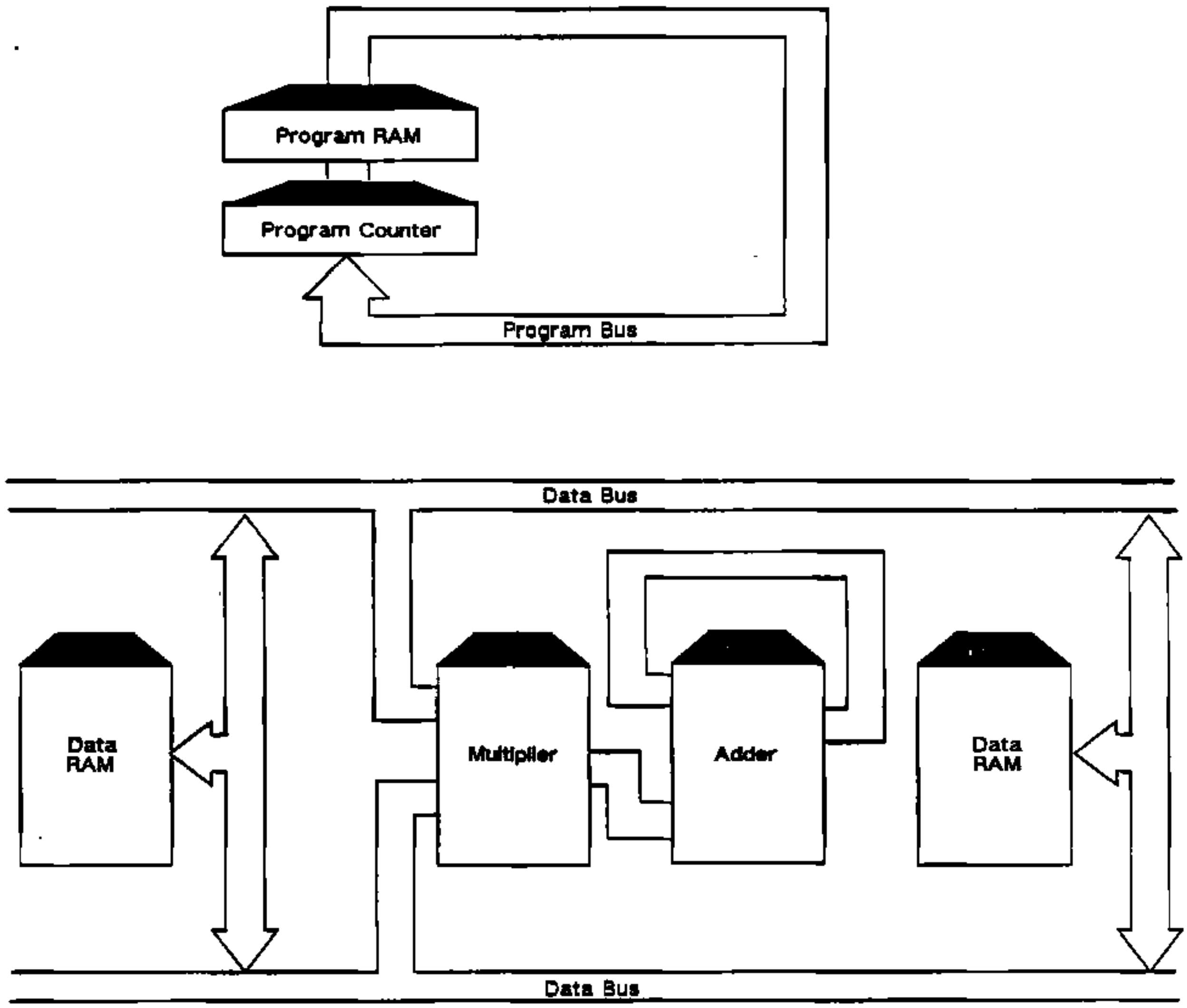
Figure 1

Typical Harvard Architecture



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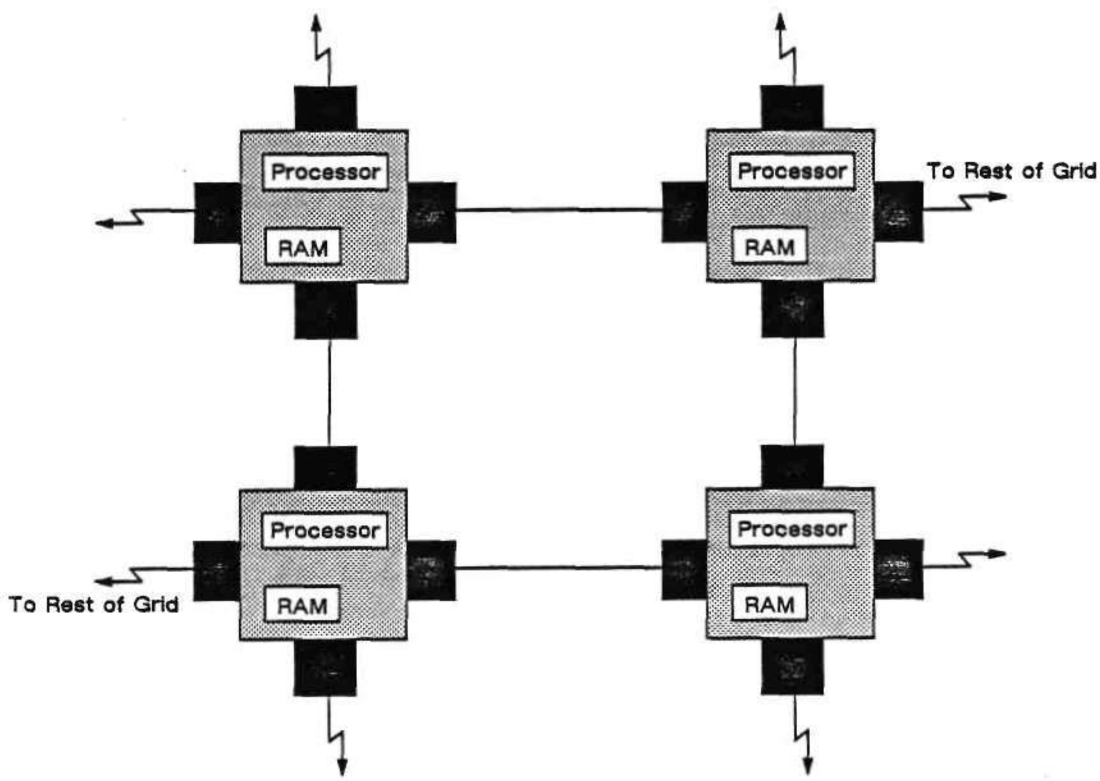
The systolic-array microprocessor, shown in Figure 2, is an example of an SIMD machine. A systolic-array microprocessor is a matrix of processors, each with its own local memory and communication links to neighboring processors. Each processor calculates its data in parallel with the others. The advantage of this architecture is the amount of parallel processing that is achieved. If there are N processors, then the number of instructions being executed is N times that of a single processor.

Figure 2

Systolic-Array Microprocessor



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NCR introduced the first commercial systolic chip, known as the geometric arithmetic parallel processor (GAPP), in 1984. The GAPP consists of a 6 x 12 arrangement of bit serial processor cells, with each processor connected to its four nearest neighbors.

The second systolic chip, the MSM6956, known as an adaptive-array processor, was introduced by Oki Semiconductor earlier this year. The array grid comprises 8 x 8 single-bit processing elements, each communicating with its eight neighbors. This chip has a hierarchical bypassing scheme that allows data to skip rows in the matrix if no operation is to be performed. Both the MSM6956 and GAPP arrays may be expanded to handle larger processing problems by linking identical processors together.

Another type of parallel processor to consider is the Transputer from Inmos. The Transputer is a 32-bit microcomputer with its own local memory and with links to connect one transputer to another in a multiprocessor (MIMD) mode. The transputer is supported by its own communication language known as Occam.

Transputers may be linked together to form networks of programmable components in any topology desired, from as simple as a binary tree to as complex as a hypercube.

Data-Flow Microprocessors

The last major type of DSMPU is the data-flow microprocessor. Currently, the only example of this type of architecture is the NEC uPD7281, known as an image-pipelined processor. The uPD7281 employs a token-based data flow and pipelined architecture to achieve a very high throughput rate. Although it is tailored for image processing, the uPD7281 is considered a general-purpose DSP.

The token-based data-flow architecture used by the uPD7281 is very similar to that used by token-based communication systems. Specially formatted input tokens are downloaded from the host processor to the link and function tables of the uPD7281. The contents of the link and function tables are closely related to a computational graph.

The computational process may be represented graphically by a directed data-flow graph. In this type of graph, entries into the link table are represented by the arcs, and entries into the function table are represented by the nodes. The arc between two nodes has a data value and is known as a token. Each node signifies an operation.

A real-world analogy would be the automobile assembly line, with the assembly line representing the data-flow path and the individual assembly stations being the functional nodes. Identifying information (in the form of tokens) travels with each vehicle as it moves down the line. This information details what type of equipment is to be installed at each location. At each station, these "travelers" are consulted, the necessary operation is performed, and the automobile is sent on down the line. This type of flow enables automobiles to be produced at the rate of one per minute.

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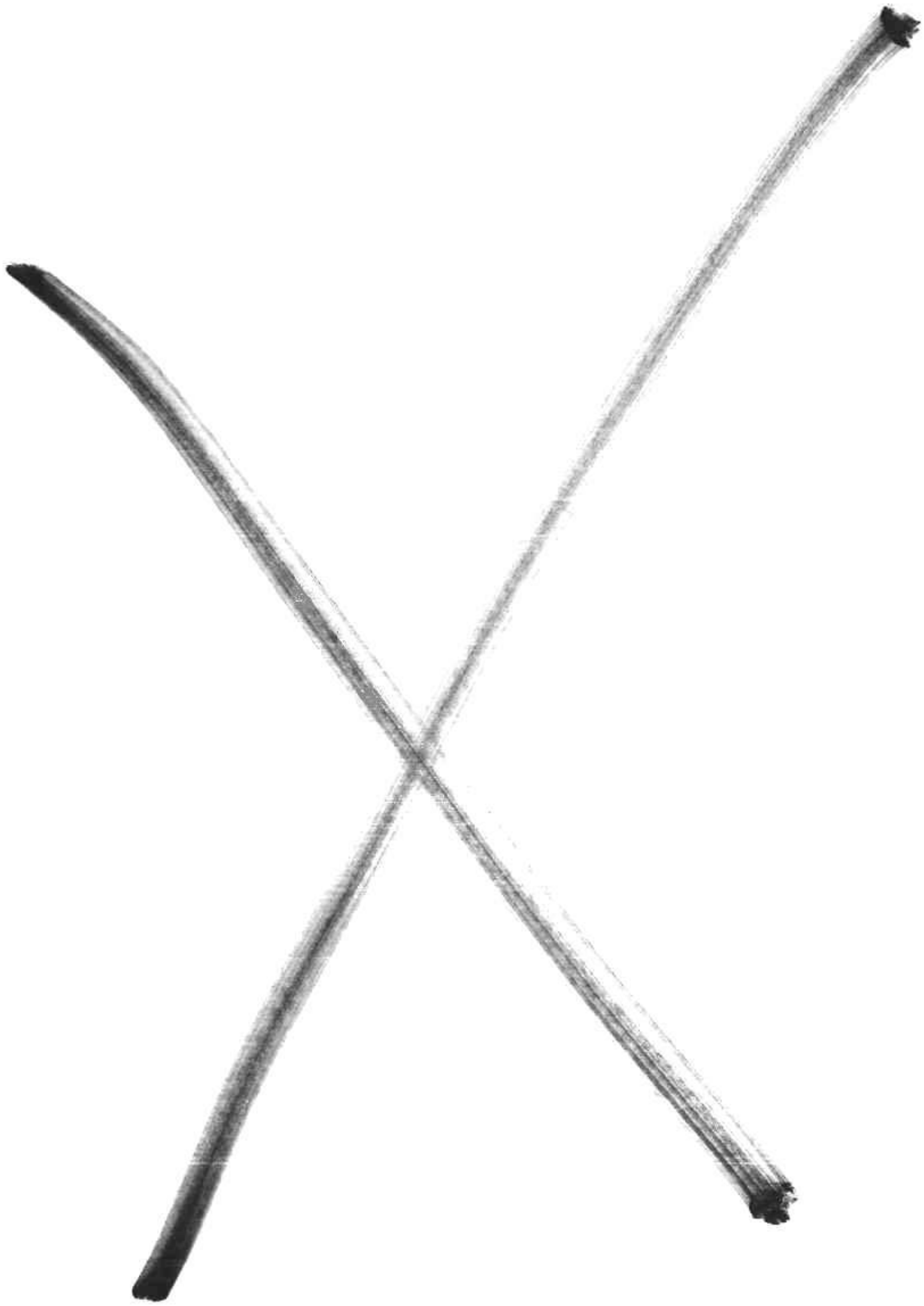

DSMPU--Emerging Technology and Trends

This section describes the major technical issues of today's digital signal processing microprocessor (DSMPU) architectures. In it, we discuss the different approaches chip makers are employing to solve digital signal processing (DSP) problems and offer pros and cons for each.

INSTRUCTION SETS

General-Purpose versus Special-Purpose

A typical DSP system combines very high speed signal processing with low-speed control functions. For example, in a modem, the low-speed functions include scanning of the front panel buttons, checking for carrier presence, making decisions on whether to retransmit a block of data, and dialing a telephone number. The program loops for these functions execute from 10 to 1,000 times per second. DSP loops, on the other hand, occur at rates of 25,000 to 1 million instruction executions per second. There is a wide discrepancy between the processing power needed for low-speed "housekeeping" functions and that needed for high-speed signal processing functions.

To perform housekeeping functions, a processor must have timers, interrupts, and an easy-to-use instruction set, all of which impede fast DSP algorithms. Consequently, many designs employ two processors—a DSMPU to handle the fast signal processing algorithms and a general-purpose microcontroller for the housekeeping functions. Separation of the housekeeping functions and the signal processing functions into separate processors minimizes their interaction, consequently reducing system design time and improving system reliability.

Dataquest believes that the two-processor solution will be the predominant system design for the next 5 to 10 years. DSMPU users tend to favor a specific microcontroller, the one for which they have development systems and programming experience. In addition, because prices of the most popular microcontrollers—including the 8051, the TMS7000, and the 6801—are approximately 20 percent of the price of a DSMPU, there is no pressure to eliminate the general-purpose microcontroller.

Instruction Word Width

There are two major approaches to handling instruction word width. In the first, the DSMPU architecture provides a wide program instruction width. For instance, the Philips PCB5010 has a 40-bit instruction word. This wide instruction word is similar to the microcoded instruction sets found in minicomputers. The instruction has multiple fields, and each field controls a portion of the chip, such as the arithmetic logic unit (ALU). One instruction executes a number of parallel operations, such as gating data onto buses, setting up the ALU, multiplying, and conditionally branching to the next instruction.

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When using a wide instruction word, the programmer must refer to a block diagram of the chip. Using the diagram, the programmer will decide which data items gate onto the buses and which counters increment. While this process affords the most flexibility, it also creates a very difficult programming task. The programmer must keep track of a number of operations occurring in parallel while being aware of pipelining delays.

Some manufacturers, such as Texas Instruments, take a different approach to instruction word width. They are using small instructions, typically 16 bits wide. The chip designer preselects a number of the possible operations and makes these into instructions. Each 16-bit instruction fans out through a decoder into the individual control signals for the buses and the adders. This approach is considerably easier to program. An assembly language programmer has no trouble learning to use this type of DSP instruction set.

Data Word Width

A data path 16 bits wide, with its 96dB dynamic range, has proven to be adequate for most audio and telecommunications applications. Approximately 70 percent of all commercial DSMPUs have 16-bit data paths. ALUs, however, must be larger than 16 bits.

Mathematical operations induce noise in the signal being processed. To minimize this noise, more bits are used. Toshiba engineers, for example, found that they needed a 32-bit machine to do a fast Fourier transform (FFT) on 16-bit input data. When a 16-bit machine was used, round-off and truncation errors in the FFT built up and destroyed the significance of the output. By using a 32-bit ALU, the Toshiba engineers were able to keep 16 bits of significant data.

Approximately 25 percent of all DSMPU offerings have 32-bit word lengths. Most of these chips are also floating-point machines. Dataquest believes that there will be a long-term trend toward 32-bit floating-point DSMPUs. Until 1995, however, the workhorse will continue to be the 16-bit fixed-point DSMPU.

INPUT/OUTPUT

DSMPU communication paths typically resemble the application problem. For instance, the Inmos transputer has four serial channels for communication between adjacent chips. As a result, it can be put into a two-dimensional topology in which there is another transputer to the north, south, east, and west. Image-processing problems are two-dimensional problems. Therefore, a typical application for the transputer is image enhancement, where a two-dimensional picture is sliced into rectangles and each transputer operates on one piece of the picture. In a system with 16 transputers, each transputer would process one-sixteenth of the image.

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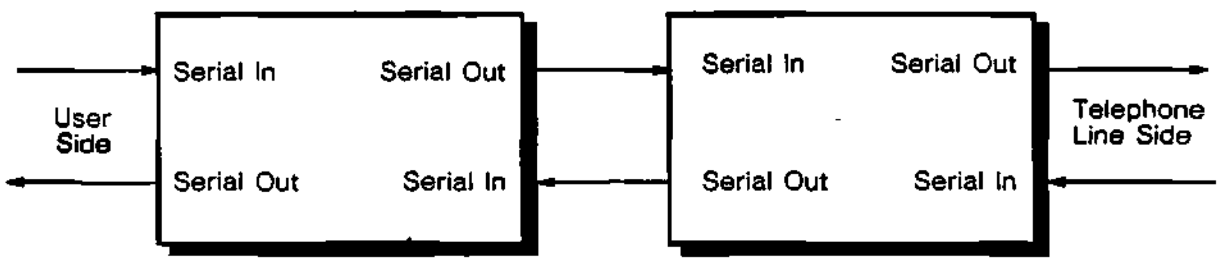
Telecommunication problems, on the other hand, are linear. There are two communication paths—one going in and one going out. A linear string of DSMPUs is, therefore, the most typical configuration. A good example of a telecom-oriented DSMPU is the Philips PCB5010. It has two full-duplex serial ports that facilitate stringing the processors along the signal path, as shown in Figure 1.

Figure 1

Serially Connected DSMPUs in a Telecom Application



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NUMBER OF INTERNAL BUSES

The Harvard architecture is the most widely used structure for DSMPUs. It has at least two buses, one for instructions and one for data. An example of a two-bus DSMPU is Texas Instruments' TMS320C25.

Because of the nature of DSP operations, two buses can limit the data transfer rate. During the "multiply-accumulate" instruction, the instruction sequencer fetches two data operands. One operand is the signal value, and the other is a filter coefficient. Because the instruction and each data operand requires a bus, a two-bus DSMPU is insufficient.

The solution in a two-bus DSMPU is to repeat the multiply-accumulate instruction. During the instruction repeat, both buses transfer data. The instruction needs to be fetched only once, after which it is held in a register while a counter counts the repetitions. In this way, the buses are freed from multiple instruction fetches during a repetitious operation.

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The other solution, used in approximately half of all DSMPUs, is to separate the instruction path from the data buses. An example is the Philips PCB5010. Because instruction fetches do not interfere with data transfers, this type of DSMPU can fetch a new instruction while simultaneously fetching two data operands.

Both of these solutions work well. At present, the number of buses may be pointed out in the marketing literature of these products, but ultimately this is an unimportant feature critical only to the chip designers themselves.

ARITHMETIC

Floating-Point versus Fixed-Point

In highly iterative algorithms, the round-off error problem can be reduced by using floating-point arithmetic. At present, Dataquest estimates that only 5 percent of all applications use floating-point arithmetic. Dataquest forecasts that this percentage will rise to 25 percent by 1990 and to 50 percent by 1995 because of floating-point arithmetic's ability to increase dynamic range, simplify DSP algorithms, and shorten time to market.

Figure 2 contrasts the signal-to-noise ratio of a 22-bit floating-point multiplier with a 22-bit fixed-point multiplier. A 22-bit fixed-point format guarantees a 96dB signal-to-noise ratio over the range of 96dB to 132dB. A 22-bit floating-point format does not reach as high a maximum signal-to-noise ratio. It does, however, maintain a 96dB signal-to-noise ratio from 96dB to 380dB. When the 36dB fixed-point dynamic range is contrasted with the 284dB floating-point dynamic range, the difference is substantial.

The greater dynamic range of floating-point arithmetic is an advantage in radar signal processing. The strength of incoming radar signals may vary from a signal that saturates the A/D converter to a signal that barely registers. Using a floating-point format, the signal power level differences can be easily handled without losing the signal to arithmetic overflows.

Not only does floating-point arithmetic have a greater dynamic range than fixed-point, but it is also easier to use to implement filters. In DSP filter algorithms, fixed coefficients are multiplied against the signal. These coefficients are often very close to one or to zero. This is analogous to a high Q resonator in the analog world being very close to oscillation. While a fixed-point coefficient has many ones or zeros after the decimal point, the number of significant digits huddled over to the right is small. The lower the number of significant digits used in a multiplication, the less significant the result. Maintenance of significance using fixed-point arithmetic requires the use of scaling tricks and careful selection of coefficients.

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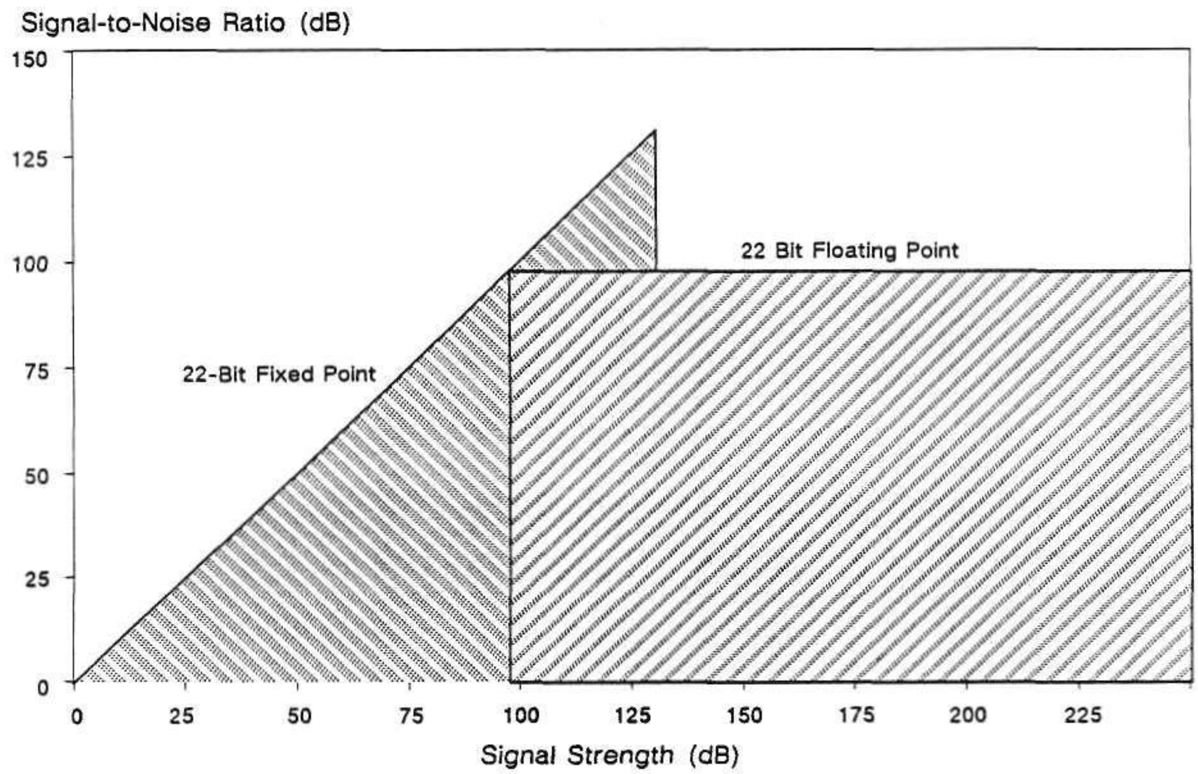
Figure 2

Effect of Fixed-Point versus Floating-Point Arithmetic on Signal-to-Nosie Ratio



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Typically, multidimensional adaptive filters require floating-point arithmetic. In this type of computation, numbers may occasionally become very large or very small on the way to a final value. Fixed-point arithmetic would overflow during computation unless scaling of the data is done before arithmetic calculations are attempted.

Floating-Point Performance Trade-Offs

Floating-point units present some performance trade-offs in speed and in size to the user who selects them to take advantage of the wide dynamic range already discussed. Floating-point units are more complex and, consequently, larger than their fixed-point counterparts. As shown in Figure 3, a floating-point multiplier requires an additional adder and extra registers.

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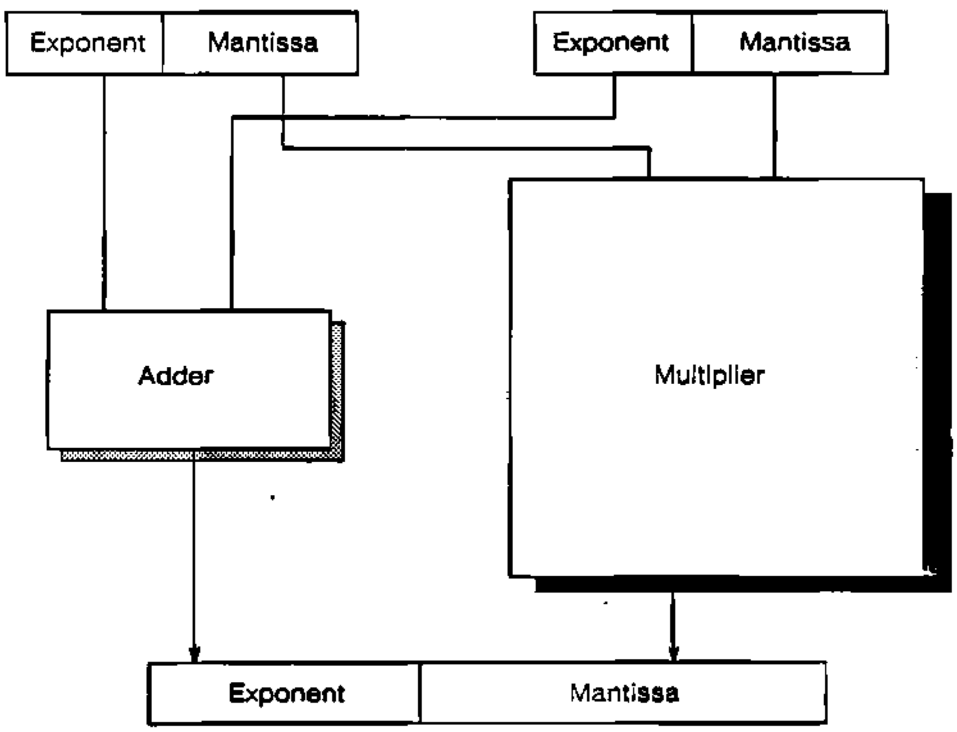
Floating-point units use more chip area. Floating-point processors have a larger die size because of the additional circuit elements required to implement their superior data-processing capabilities. The extra functional blocks shown in Figure 3 actually have a less substantial impact on overall chip size than the space taken up by the additional RAM required to process the greater data load of floating-point operations.

Figure 3

Block Diagram of a Floating-Point Multiplier



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Floating-point chips are approximately 50 percent slower than fixed-point chips for two reasons. The first reason is that extra operations are needed. A floating-point "multiply" operation consists of a "multiply" followed by an additional "add" to process the exponent. Similarly, a floating-point "add" operation requires an extra "shift" operation followed by an extra "add." A second reason that floating-point chips are slower is that they usually have longer data word lengths than their fixed-point counterparts. A 32-bit "add" in a floating-point chip is going to take more time than a 16-bit fixed-point "add."

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Additionally, in spite of its many advantages, floating-point arithmetic can be inexact. The amount of noise added during arithmetic operations is not an absolute percentage of the maximum input signal level. Instead, the noise added during floating-point operations varies, depending on the values being added or multiplied. Since the amount of noise being added varies from operation to operation, it is difficult to mathematically predict the performance of a floating-point algorithm. In 16- and 22-bit formats, floating-point arithmetic requires as much care as fixed-point arithmetic.

Smaller-size floating-point formats, such as the Hitachi format, can cause signal-to-noise problems just like those caused by small fixed-point formats. Using small word lengths requires detailed analysis, but floating-point arithmetic is more complex than fixed-point arithmetic and, consequently, harder to analyze. Therefore, most floating-point DSMPUs have at least a 32-bit data path. With the longer word length, the noise added in each operation is small and its effect on the algorithm can be neglected. Basically, applications needing 16 to 32 bits of precision can use fixed-point DSMPUs; those needing 32 to 64 bits of precision must use floating-point DSPMUs.

Normalization

When floating-point numbers are normalized, they retain their significance. The normalization operation shifts the data bits to eliminate zeros after the decimal point. The result is a word in which all the bits are significant. Because floating-point arithmetic automatically performs normalization, the resulting data are nicely packed with significant data. The programmer is not required to check the magnitude of the data and then scale it in order to pack the most significance into each word, as is necessary in fixed-point arithmetic.

A floating-point DSMPU can lighten a programmer's burden by automatically normalizing after each mathematical operation. However, this raises an architectural issue as to whether the DSMPU should, in fact, do this postoperation normalization or leave it up to the programmer. The main argument against automatic postoperation normalization is the time added to each operation.

The NEC 77230 DSMPU does not do postoperation normalization. As a result, it is faster than other floating-point DSMPUs that do normalize after each "multiply." Because a filter calculation normally requires only one normalization, the NEC 77230 can eliminate automatic postoperation normalization by having an expanded 55-bit ALU to accumulate the intermediate results. The wider format eliminates round-off and truncation errors. A single "normalize" instruction is sufficient to return the data to a 32-bit floating-point format after as many as 32 filter taps.

Dataquest expects fixed-point DSMPUs to maintain their majority share of DSMPU sales through 1995. Their faster speed and lower cost will facilitate design-ins into high-volume applications, such as consumer electronics. Dataquest anticipates the inherent advantages of floating-point DSMPUs to open up new market opportunities, such as complex modulation communication techniques in telecommunications.

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Standards for Floating-Point Formats

Floating-point formats have been a controversial issue since the early mainframe days and the minicomputer days. The initial controversy stemmed from the fact that each manufacturer used its own format, the result being that data could not be interchanged easily between computers. The controversy over floating-point format continues into the DSP arena today. Standardization of formats is perhaps more important for DSMPUs than it was for large computers. With DSMPUs, data must be transferable from chip to chip without intervening translators that would increase cost and slow operation.

There are several floating-point formats competing to become the standard. NEC has a 32-bit two's-complement format. TRW has offered products with a 22-bit floating-point format, and Hitachi introduced a 16-bit format in the HD61810. Analog Devices and AT&T are using the IEEE 32-bit format.

The main argument against using the IEEE 32-bit format is that it is difficult to implement. The IEEE format contains features to please everyone. Signal processing does not need some of the features intended primarily for scientific data processing, such as "-" infinity, "+" infinity, and seminormalized data formats. These extra features add cost and slow down operations. Since the main design goals of DSMPUs are high speed and low cost, many companies are choosing to eliminate unneeded features and use simpler floating-point formats for DSP.

For computational efficiency, NEC chose a two's-complement 32-bit floating-point format for its 77230. NEC acknowledged the IEEE format for data interchange, however, by including one instruction to convert between their two's-complement format and the IEEE 32-bit standard. As a result, data computed by the 77230 can be prepared for output with a single instruction.

TRW is championing a 22-bit format in its DSP building block product line. TRW's format has its advantages: It has a lower cost than the IEEE format, and it operates at a higher speed. It is TRW's contention that 22 bits is more than sufficient to satisfy the signal-to-noise requirements of typical applications, such as radar processing.

The difference in chip area between 22 bits and 32 bits is approximately one-third, which amounts to nearly a factor of 2 in die cost. Packaging is also less costly with a 22-bit format. It is conceivable that IC cost in a 22-bit system might be as low as one-half that of a 32-bit system.

Dataquest forecasts that both the 22-bit TRW format and the 32-bit IEEE format will succeed in the marketplace. Worldwide DSMPU shipments are forecast to grow at a 42.3 percent compound annual growth rate (CAGR) from $62 million in 1986 to $254 million in 1990. DSMPUs will gradually replace analog devices at higher and higher bandwidths, as they are now replacing analog devices in the audio spectrum. It is only a short time before DSP moves into an intermediate frequency spectrum below 1-MHz bandwidth. As DSP grows, there will be a greater opportunity for floating-point formats that are sufficiently differentiated from one another to provide unique features for specific applications.

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Bit-Serial Arithmetic

An internal implementation issue for DSP chips is whether to use parallel or bit-serial arithmetic. In parallel arithmetic, which is used by every DSMPU except the NCR GAPP processor, the entire word is added or multiplied at one time; consequently, throughput is very fast. An add or multiply operation typically takes 100ns, which is a rate of 10 MHz. In bit-serial arithmetic, each bit is processed sequentially, a relatively slow process. For example, adding two 16-bit numbers serially would take 16 clocks, one clock for each bit. If the clock frequency is 10 MHz, the total operation would require 1.6 microseconds, which is equivalent to a rate of 600 kHz.

Even though bit-serial arithmetic may be slower than the parallel arithmetic, it can be used successfully in a fixed algorithm. Examples of fixed algorithms are those used in hi-fi graphic analyzers and nonadaptive telephone line filters. In these applications, a number of simplifications can be made to the algorithms, such as left-shifting a data word to do a multiply-by-two operation. The left-shift and the multiply operations are equivalent mathematically, but a shift takes much less circuitry than a multiplier.

By simplifying the algorithm to conform to operations that can be implemented effectively by bit-serial hardware, it is possible to drastically reduce the amount of chip area used. For instance, a hi-fi graphic equalizer implemented in bit-serial arithmetic would be approximately 20 percent of the chip size of a parallel arithmetic version.

Historically, bit-serial machines have not fared well. Before the 8-bit microprocessor was available, many people made bit-serial processors out of standard TTL. The popularity of 4-, 8-, and 16-bit parallel microprocessors attests to the fact that bit-serial arithmetic is not seriously considered for standard microprocessor designs.

Dataquest does not expect bit-serial DSMPUs to be offered. Bit-serial algorithms are difficult to change and, for substantial chip-area savings, multiplication coefficients must be powers of two. These restrictions make bit-serial arithmetic unsuitable for general-purpose DSMPUs. For special-function DSP circuits (SFICS), however, bit-serial arithmetic may be a viable approach. If the algorithm can be transformed into a bit-serial implementation and if the sampling rate bandwidth is low enough, then a bit-serial architecture is worth considering. The potential 80 percent reduction in chip area more than outweighs the difficulties.

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DSP BUILDING BLOCKS

DSP Building Blocks—Product Comparison

OVERVIEW

Bit slices, multipliers, multiplier-accumulators, and filters are types of DSP building blocks. They are an integration level below the DSP microprocessor (DSMPU) and are used where performance or speed is needed. When using the building block approach, the designer creates his own DSP processor. This is a very flexible approach because the hardware can be selected to fit the processing task. For higher-performance applications, a number of arithmetic units can be cascaded together. For lower-performance applications, cost can be saved by multiplexing the use of one arithmetic unit.

Additionally, building blocks are often available in faster technologies, such as gallium arsenide (GaAs) or bipolar emitter coupled logic (ECL), than DSP microprocessors. Thus, to achieve ECL speeds, the engineer is constrained to using building blocks. However, as DSMPUs become available in a technology, they displace building blocks, despite the higher performance available in building blocks.

DSP BUILDING BLOCKS

Bit Slices

Bit slices consist of an arithmetic logic unit (ALU), microsequencers, and miscellaneous components, such as register sets. Since its introduction, the bit slice approach has developed into a major segment of the building block IC market. There are three major bit slice product lines: AMD's 2901, the Texas Instruments 74AS88 series, and Fairchild's FAST line. Of these, AMD has the predominant share. AMD's original 2901 design is widely sourced, with several vendors having converted it into standard cells.

The bit slice approach is midway between DSP microprocessors and custom designs in flexibility and performance. Bit slices give the designer the ability to manipulate the hardware topology of the algorithm as well as the microcode. But, with DSP microprocessors increasing in speed and CAD tools making custom designs easier, is there a place for bit slices?

Dataquest believes that 4-bit ALU slices will continue to evolve toward wider microprogrammable products that are sliced on a functional level rather than the bit level. These products, although noncascadable, offer more complex internal functions and faster system speeds. Total hardware flexibility may be sacrificed, but perhaps better software tools will be gained.

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Semicustom vendors offering high-speed microprogrammable cells will also gradually erode the 4-bit ALU slice customer base by offering the desired hardware flexibility combined with the speed advantages of a single piece of silicon, not to mention the board space savings.

Multipliers

The DSP IC industry was born with the invention of the high-speed multiplier. In the early 1970s, TRW's bipolar high-speed parallel multipliers were the clear standard. Pin-compatible circuits abounded. However, TRW was not fast enough in switching to CMOS, with its inherent power savings and cost advantages. Consequently, several small companies with CMOS technologies were able to enter the market. There are now more than 16 suppliers of multipliers, with CMOS products offered by companies such as Analog Devices, IDT, Logic Devices, and Weitek.

The multiplier industry structure is quite flat and characterized by many suppliers, small market shares, a lack of a dominant supplier, low margins, and low prices. There have been many market entrants, and the market is currently oversupplied. Eventually, multipliers should become identified with a major bit slice product line and will be supplied as part of a chip set. An industry fallout should result in a readjustment of market shares.

Multiplier-Accumulators

Since most DSP algorithms require a multiply followed by an ADD, another DSP building block is the multiplier-accumulator. The block diagram of a multiplier-accumulator is shown in Figure 1.

The fastest multiplier-accumulators are bipolar ECL devices, such as those offered by Bipolar Integrated Technology. A 16 by 16 multiply can be performed by CMOS multiplier-accumulators in 60 nanoseconds, by CMOS/SOS in 30 nanoseconds, by TTL bipolar in 25 nanoseconds, and by ECL bipolar in 8 nanoseconds.

The current multiplier-accumulator market is crowded; the number of participants is large, at approximately 18, and market shares are low. No dominant supplier presently exists.

Filters

The integration of the multiplier will continue to drive digital signal processing products. For instance, the infant DSP filter industry was created by the ability to put several multipliers on one chip. All high-quality filter applications are expected to convert to digital, giving this market segment the highest compound annual growth rate of any of the building block areas.

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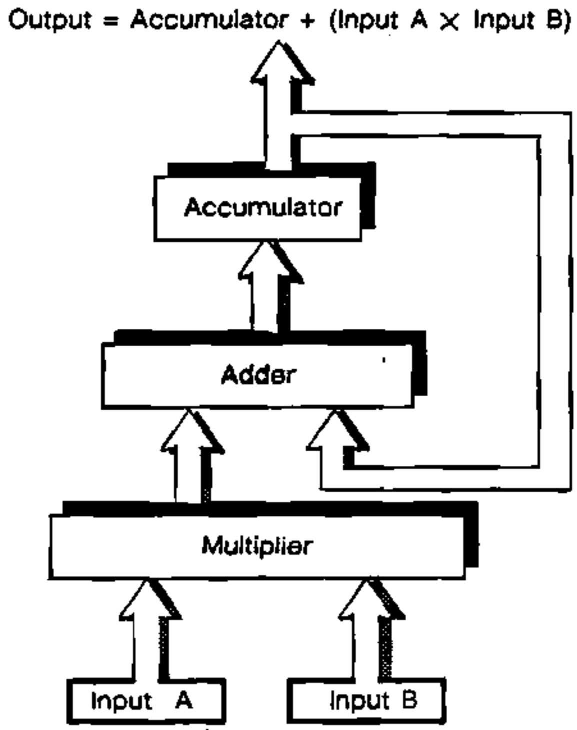
Figure 1

Multiplier-Accumulator Block Diagram



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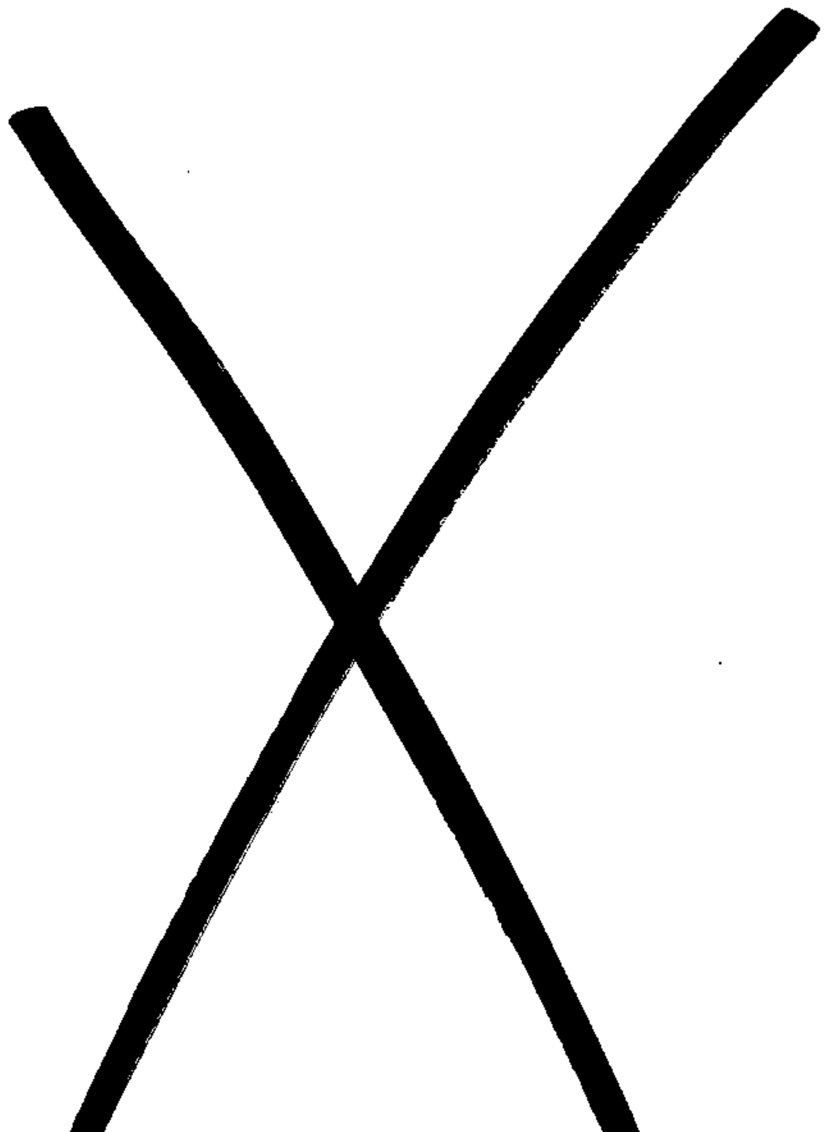

Microprogrammable DSP Building Blocks— Executive Summary

Building blocks are no longer the largest segment of the DSP IC market. Total revenue is expected to decline modestly because of competing alternate solutions. Although product lines are broad and the industry has many suppliers, product and supplier successes are becoming increasingly rare.

To understand this unusual and dynamic situation, Dataquest has outlined three primary objectives for use with the material accompanying these market estimates and forecasts. The first objective is to establish clear product and market distinctions. Building blocks are basic and serve broad markets, but now are more accurately seen as specific products with narrow and only sometimes overlapping user markets. The second objective is to understand the key product trends weighted by their market importance. Numerous product directions currently exist, but some important user market trends may eclipse these directives. The third objective is to clarify the real business opportunity. The building block market is an easy-to-enter and highly visible market. Many companies have to enter this market and their relative lack of success is not widely understood.

FORECAST SUMMARY

Market Size

- Actual DSP building block revenue in 1988 was $150 million.
- The largest product revenue category in 1988, $85 million, was fixed-point data path elements, but it is declining.
- The largest market use in 1988 ($70 million) was in data processing accelerators and coprocessors.

Market Forecast

- Expected building block revenue in 1993 is $149 million, representing a small net decline.
- In 1993 the largest product revenue category is expected to be floating-point data path elements at $101 million, but it should experience slow growth.
- The largest market use in 1993 will continue to be data processing coprocessors and accelerators, at $100 million, but it is expected to experience declining revenue.

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Microprogrammable DSP Building Blocks—Executive Summary

PRODUCT ANALYSIS SUMMARY

- DSP building blocks can be clearly distinguished from processors and special-function devices, even though the products exist in both processor families and functional product lines.
- A large overlap exists in the use of DSP and data processing building blocks.
- The major product distinctions are in function, data format, and process and interface technology.
- Major building block processor family suppliers are AMD, Analog Devices, TI, and Weitek.
- Significant building block functional product line suppliers are BIT, IDT, Logic Devices, and TRW.
- Software development is a major problem for microcoded building block processors, because only primitive tools can be supplied for general use.

MARKET ANALYSIS SUMMARY

- Building blocks are used for architectural flexibility in meeting high-performance needs not met by other standard products.
- Single usage is at low to moderate levels, otherwise an ASIC investment would be justified.
- In general-purpose data processing, the major uses in order of size are coprocessors, controllers, and central processing units (CPUs).
- The largest use of coprocessors is for PCs and high-performance workstations.
- In DSP, the largest user market is for special-purpose processors for radar, sonar, imaging, and graphics.

PRODUCT, MARKET, AND BUSINESS TRENDS SUMMARY

The following conclusions are drawn from looking at how products and market uses change over time:

- The most important product and user market trend is the existence of attractive alternate solutions: i.e., DSP processors (DSMPUs), special-function DSPs (SFDSPs), and application-specific DSPs (ASDSPs).

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Microprogrammable DSP Building Blocks—Executive Summary

- The most important technology trend is that high integration levels make block partitioning unnecessary, and because of interface delays and software support, undesirable.

- The most important business trend is that because of easy market entry, many have entered this market but few have been successful.

- Building block opportunities will continue to exist at the edges of technology and for immature functions.

- The reasons for the creation of the building block market have largely disappeared.

- The building block skill set in the future will reside in application-specific functional libraries.

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DSP Building Blocks--Executive Summary

EXECUTIVE SUMMARY

The digital signal processing (DSP) building blocks category currently enjoys the largest share of the DSP market. This category is also the most populous in terms of products and competitors. Nevertheless, Dataquest is forecasting a slowing in the growth rate of the DSP building block segment as DSP microprocessors and application-specific DSPs take a bite out of this market.

DSP BUILDING BLOCK MARKET

Market Size

The following should be noted about the size of the DSP building block market:

- DSP building block revenue was $131 million in 1986.
- DSP building block unit shipments were 9.3 million in 1986.

Market Forecast

The Dataquest DSP building block market forecast is as follows:

- Worldwide DSP building block revenue is forecast to be $139 million in 1987.
- Worldwide DSP building block revenue is forecast to be $177 million in 1990.

Competitive Environment

The following are key points regarding the competitive environment of the DSP building block market:

- The leading suppliers of microprogrammable arithmetic units, which include bit slices, are AMD, Texas Instruments, and Fairchild, respectively.

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- Leading suppliers of multipliers and multiplier-accumulators include TRW, Weitek, IDT, AMD, Texas Instruments, and Analog Devices, respectively.

- Interesting new programmable digital filters are being offered by Gould, Fairchild, Inmos, Motorola, NCR, RCA, TRW, and Zoran.

DSP BUILDING BLOCK TRENDS

Product Trends

DSP building block product trends include the following:

- Dataquest expects the DSP building block market to increase at a modest compound annual growth rate (CAGR) of 7.8 percent through 1990, giving way to DSMPUs and ASICs.

- Many applications currently using bit slices will shift to ASICs constructed from ALUs, MACs, and registers currently in cell libraries.

- At least eight ASIC manufacturers are offering 2901 equivalent bit slice cells.

- New fast 16- and 32-bit ALUs are providing the designer with an alternative to the traditional 4-bit slice.

Technology Trends

DSP building block technology trends include the following:

- The bulk of all DSP building block products are still TTL bipolar.

- ECL bipolar products offered by companies such as Bipolar Integrated Technology and gallium arsenide products offered by companies such as Vitesse will begin to take a bite out of the very high speed end of this market.

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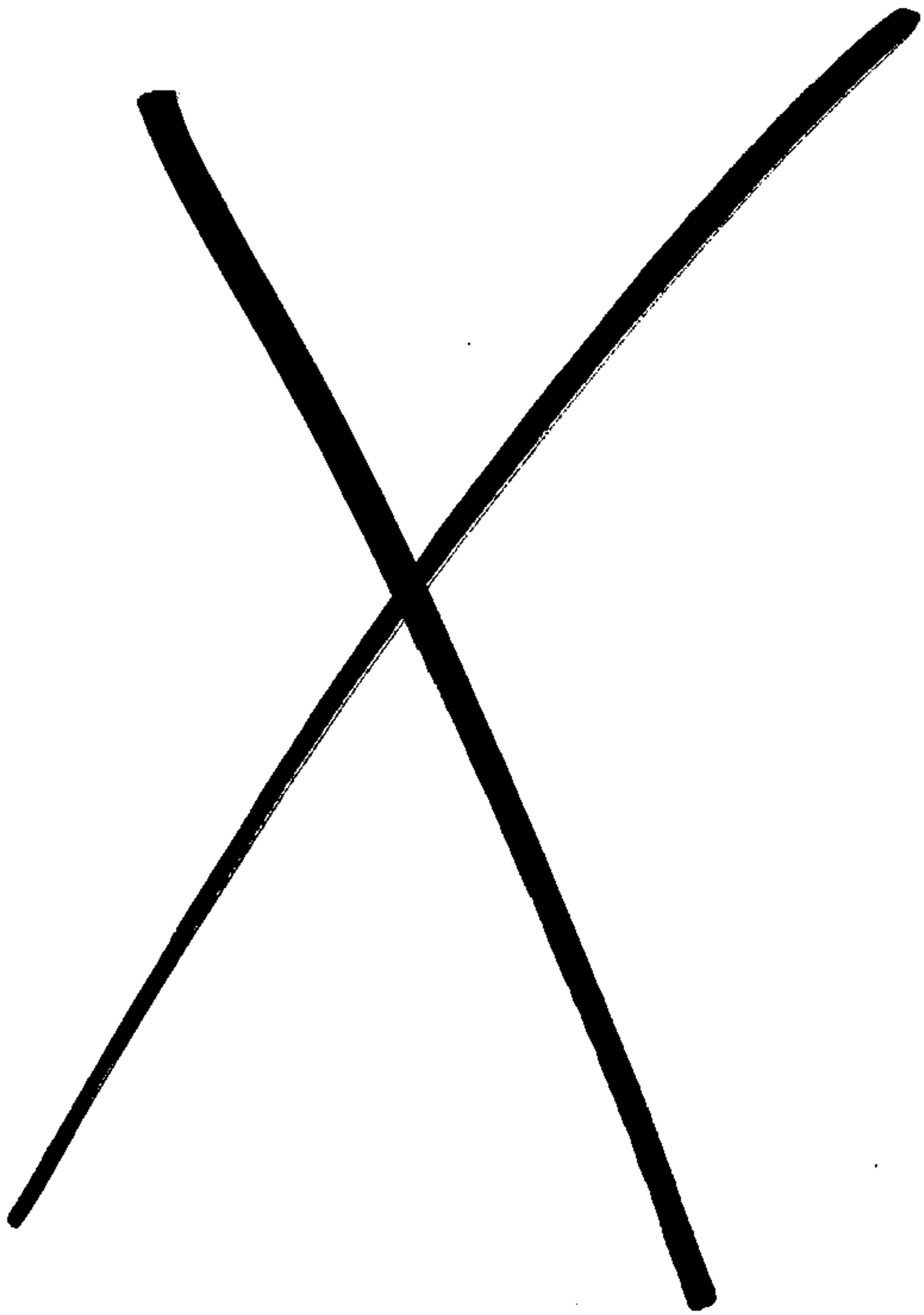

Microprogrammable DSP Building Blocks—Forecast

INTRODUCTION

Component products can be defined either by their inherent function (product distinction) or their end use (market distinction). Each is forecast separately in this document. The difference is important because natural groupings of products by function do not necessarily equal natural market groupings. This is particularly true with digital signal processing (DSP) building blocks, as the following analysis sections describe. Likewise, the term DSP, as opposed to general-purpose data processing, must be looked at in both product and market domains. Figure 1 schematically illustrates these and other distinctions used in this section.

Figure 1

Building Block Product and Market Distinctions

Building Block Product and Market Distinctions

Product (Function) Domain	Marketing (Use) Domain
Separate-Function Product Lines	General-Purpose Systems
General-Purpose	Controllers
DSP	Coproducers
	CPUs
Processor Family Product Lines	DSP Systems
General-Purpose	Array processors
DSP	Special-purpose

0004604-1

Source: Dataquest
August 1989

PRODUCT DEFINITIONS

For forecast purposes, the building block processor families and separate-function product lines are combined and broken into five segments, as follows:

- Fixed-point data path elements—Fixed-point data path elements include all shifters, ALUs, multipliers, and multiplier-accumulators with fixed-point only formats. They also include bit-slice forms.

- Floating-point data path elements—Floating-point data path elements include all of the above functions that use floating-point formats. Fixed-point formats also may be present, as well as register files.

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- Microcontrollers and address generators--Microcontrollers are microsequencers and special-purpose sequencers such as coprocessor controllers. Address generators are used for data memories and include memory management units as well as memory controllers.

- Special memories--Special memories include multiported register files, pipeline registers, and special DSP shift registers. FIFOs are not included.

- Special-purpose elements—Special-purpose elements include filter, convolver, correlator, and template-matching DSP building blocks.

MARKET DEFINITIONS

For forecast purposes, the DSP building block markets are divided into five segments, as follows:

- General-purpose data processing systems
  - Controllers—Controllers are any non-data-path processor used in a system for any control purpose. The definition includes all peripheral controllers except coprocessors or data path accelerators.
  - Coprocessors—Coprocessors are data processors that operate under control of a CPU such as floating-point coprocessors, vector processors, and graphics accelerators in a general-purpose system.
  - Central processing units (CPUs)—Central processing units are used for general-purpose data processing.
- Digital signal processing systems
  - Array processors--Array processors are programmable CPUs or peripheral processors designed for digital signal processing in its broad form.
  - Special-purpose--Special-purpose digital processing systems are used for a narrow range of signal processing functions or problems and often are not programmable.

FORECAST

Dataquest expects attractive alternative solutions to reduce the total DSP building block revenue of $161 million forecast for 1989 to $149 million in 1993. This negative 2 percent compound annual growth rate (CAGR) compares with a positive 16 percent growth during the previous four years (1985-1988). We believe that the largest revenue

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growth by product type will continue to be achieved by the floating-point data path elements, as shown in Table 1. The largest revenue growth by market use will be for data processing coprocessors as Table 2 shows.

Table 1

Worldwide DSP Building Block Revenue Forecast by Product Type
(Millions of Dollars)

	Actual				Forecast					CAGR	
Product Type	1985	1986	1987	1988	1989	1990	1991	1992	1993	1985-1988	1989-1993
Data path elements											
Fixed-point	$83	$ 86	$ 85	$ 85	$ 81	$ 77	$ 62	$ 43	$ 26	1%	(25%)
Floating-point	4	12	37	45	60	81	89	96	101	124%	14%
Microcontrollers & address generators	2	2	3	6	6	6	6	7	7	44%	4%
Special memories	4	6	8	8	7	5	4	4	3	26%	(19%)
Special-purpose	4	5	6	6	7	8	9	10	12	15%	14%
Total revenue	$97	$111	$139	$150	$161	$177	$170	$160	$149	15.6%	(1.9%)

Source: Dataquest
August 1989

Table 2

Worldwide DSP Building Block Revenue Forecast by Market Use
(Millions of Dollars)

	Actual				Forecast					CAGR	
Market Use	1985	1986	1987	1988	1989	1990	1991	1992	1993	1985-1988	1989-1993
Data processing systems											
Controller	$39	$ 37	$ 34	$ 29	$ 27	$ 25	$ 20	$ 17	$ 15	(9%)	(14%)
Coprocessor	14	28	58	70	80	94	101	105	100	71%	6%
CPU	11	9	6	5	5	4	4	3	3	(23%)	(12%)
DSP systems											
Array processor	5	6	7	8	9	10	11	12	13	17%	10%
Special-purpose	28	31	34	38	40	44	34	23	18	11%	(18%)
Total revenue	$97	$111	$139	$150	$161	$177	$170	$160	$149	15.6%	(1.9%)

Source: Dataquest
August 1989

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DSP Building Blocks—Forecast

MARKET DEFINITION

Dataquest breaks the DSP building block market segment into four subsegments, as follows:

- Microprogrammable arithmetic units (MAUs)
- Multipliers and multiplier-accumulators (MACs)
- Digital filters
- Other miscellaneous building blocks

The MAU category includes bit slices, arithmetic logic units (ALU), and special arithmetic support chips. The MAC category consists of independent multipliers and accumulators as well as multiplier-accumulators. The digital filter category is self-explanatory.

All other building blocks, such as sequencers, register files, and barrel shifters, are combined into the miscellaneous building block (Other) category.

FORECAST

Dataquest expects the continuing development of both integrated DSP microprocessors (DSMPUs) and high-speed general-purpose microprocessors to slow revenue growth of the DSP building block market segment. Table 1 shows building block revenue growing from $131 million in 1986 to $177 million in 1990, which is equivalent to a compound annual growth rate (CAGR) of 7.8 percent.

Figure 1 compares the revenue growth for each of the four categories of building blocks. The only category showing any significant growth is digital filters, which are expected to grow from $9 million in 1986 to $28 million in 1990 at a CAGR of 32.8 percent.

Vigorous competition among building block manufacturers is expected to drive price reductions in all building block categories. Dramatic reductions in average selling prices (ASPs) as a result of increased competition and the conversion from bipolar products to CMOS products will have the greatest negative effect on revenue growth for the period.

As shown in Table 2, healthy growth in unit shipments is expected through 1990. Dataquest forecasts DSP building block unit shipments to grow at a CAGR of 24.2 percent, from 9.3 million units in 1986 to 22.1 million units in 1990.

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DSP Building Blocks--Forecast

Table 1

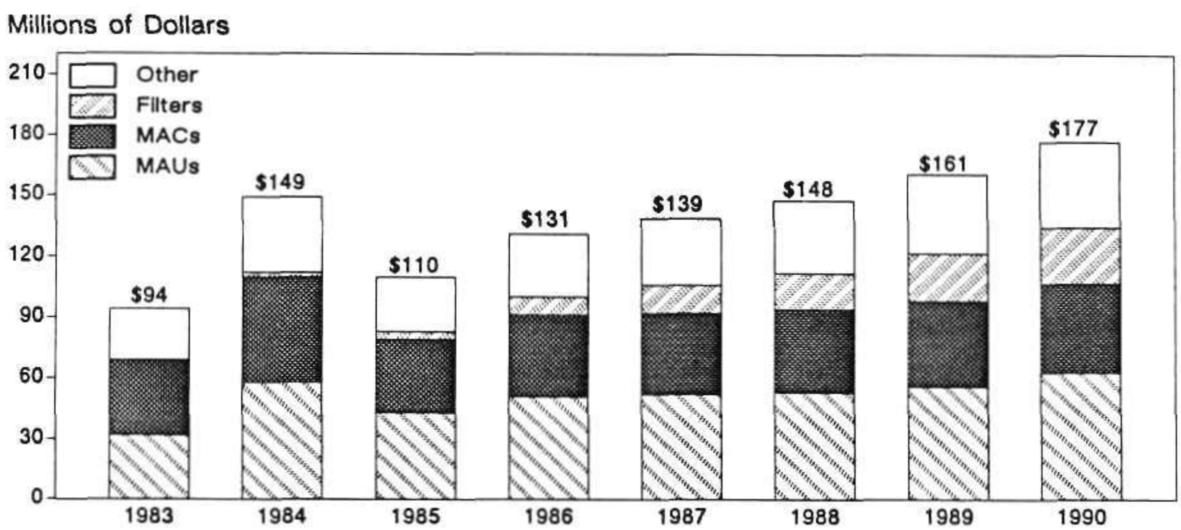
WORLDWIDE DSP BUILDING BLOCK REVENUE FORECAST
(Millions of Dollars)

	Actual				Forecast				CAGR	CAGR
	1983	1984	1985	1986	1987	1988	1989	1990	83-86	86-90
MAUs	$32	$ 58	$ 43	$ 51	$ 52	$ 53	$ 56	$ 63	16.8%	5.4%
MACs	37	52	36	40	40	41	42	44	2.6%	2.4%
Filters	0	2	4	9	14	18	24	28	348.1%	32.8%
Other	25	37	27	31	33	36	39	42	7.4%	7.9%
Total Bldg. Block Revenue	$94	$149	$110	$131	$139	$148	$161	$177	11.7%	7.8%

Source: Dataquest
May 1987

Figure 1

WORLDWIDE BUILDING BLOCK REVENUE GROWTH BY PRODUCT CATEGORY



Source: Dataquest
May 1987

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DSP Building Blocks--Forecast

Table 2

WORLDWIDE DSP BUILDING BLOCK SHIPMENT FORECAST
(Millions of Units)

	Actual				Forecast				CAGR	CAGR
	1983	1984	1985	1986	1987	1988	1989	1990	83-86	86-90
MAUs	2.1	4.3	3.8	4.1	5.1	6.3	8.1	9.8	25.0%	24.3%
MACs	1.1	1.6	2.1	2.4	2.8	3.6	4.5	5.0	29.7%	20.1%
Filters	0	0.1	0.2	0.3	0.5	0.9	1.4	1.9	210.7%	58.6%
Other	1.6	2.4	2.4	2.5	3.2	4.0	4.8	5.4	16.4%	21.2%
Total Bldg. Block Shipments	4.8	8.4	8.5	9.3	11.6	14.8	18.8	22.1	24.7%	24.2%

Source: Dataquest
May 1987

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Microprogrammable DSP Building Blocks—Product Analysis

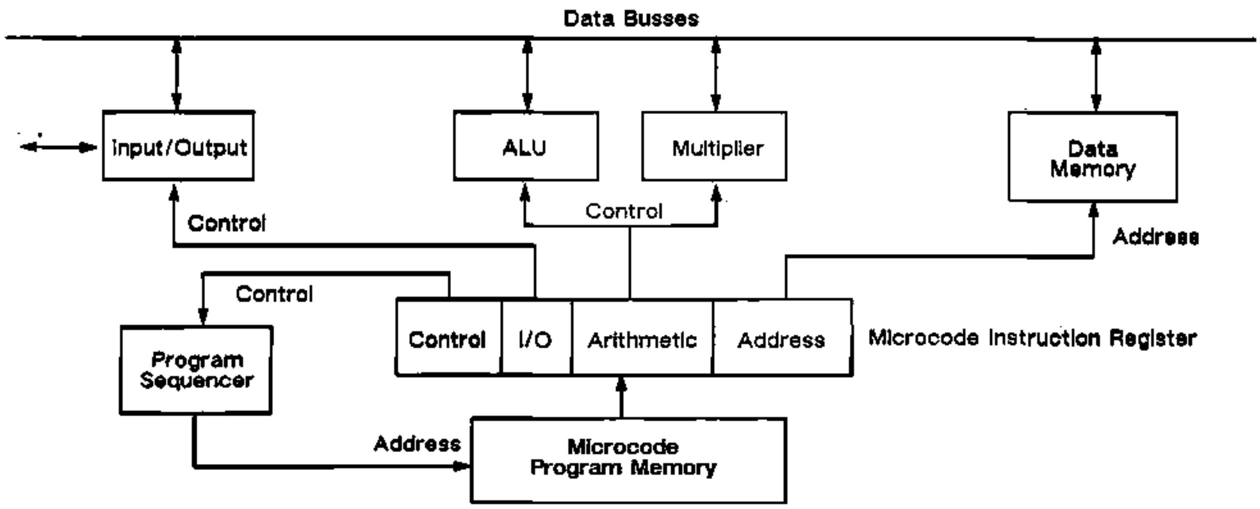
PRODUCT DISTINCTIONS

Processor Family versus Separate Function Product Lines

Historically, building blocks have been derived from a natural grouping of gates into some function such as an adder or arithmetic logic unit (ALU). Product lines are formed around blocks that fit together to form a processor, while other product lines are formed around a particular function such as multiplication. Dataquest looks at them as two different types of product lines; separate function or processor families, as shown in Figure 1.

Figure 1

Building Block Product and Market Distinctions



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Source: Dataquest August 1989

Building Blocks versus Processors

As functional densities have increased, the definition of the term "building blocks" may have blurred. Generally, however, if such products continue to have control lines that must be sequenced externally at a basic clock rate, they are considered to be building blocks. If a product operates on its own after loading control registers, then it is considered to be a processor; even if multiple products fit together in block style, the result is not considered a building block. Digital filters still illustrate the distinction: filters may be designed using multiplier-accumulator array building blocks, which must have data and controls sequenced to them (e.g., Zoran ZR33881) or standalone

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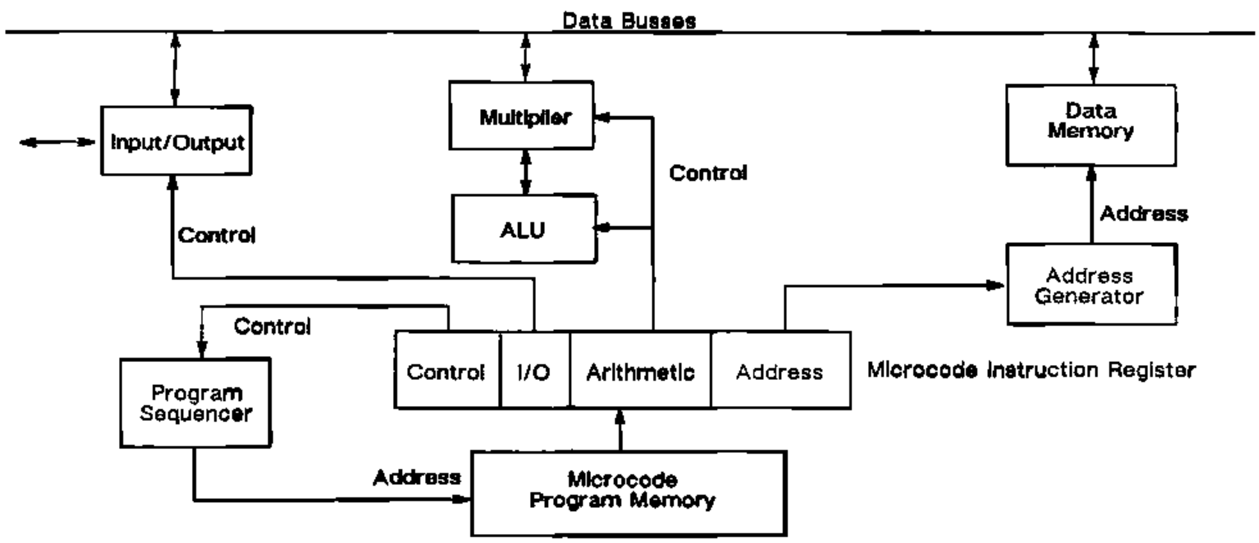
special-function digital signal processors (SFDSPs), which need only a data stream and clock. The Motorola DSP 56200 and the Inmos IMS A110, for example, are SFDSPs, not building blocks.

Digital Signal Processing (DSP) versus General-Purpose Data Processing

Figure 2 shows the functional breakdown of a general-purpose data processor. These functions are the basis for the partitioning of most building block processor product lines today. Figure 3 is the same diagram modified to represent a typical digital signal processor. More complex data memory address generation and the multiply-accumulate data path element are the only significant differences.

Figure 2

Building Block Elements of a General-Purpose Data Processor



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Source: Dataquest August 1989

Figure 3

Building Block Elements of a Digital Signal Processor

Building Block Product and Market Distinctions

Product (Function) Domain	Marketing (Use) Domain
Separate Function Product Lines	General-Purpose Systems
General-Purpose	Controllers
DSP	Coproducers
	CPUs
Processor Family Product Lines	DSP Systems
General-Purpose	Array processors
DSP	Special-purpose

0004603-3

Source: Dataquest
August 1989

Forecast Distinctions

With this major overlap in usage, no distinction is made between general-purpose and DSP building blocks for the processor product line market estimates and forecasts. Separate functional blocks outside of the processor families, however, are included only if they are DSP related. For example, correlators are considered functional DSP building blocks, while FIFOs are not part of a processor family, are not uniquely DSP, and so are not considered DSP building blocks. A/D and D/A converters, likewise, are not uniquely DSP and therefore are not included.

SEPARATE-FUNCTION PRODUCT LINES

Functional product lines have grown up because suppliers are able to master enabling technology and/or thoroughly understand the market requirements for that function. For example, multipliers became a mainstay product line for TRW because the highly regular design uses TRW's high-density bipolar process to advantage. Knowledge of the market it created allowed TRW to broaden that market successfully for many years by introducing many variations of multipliers. TRW never defined a complete processor product line. Weitek engineers were experts in floating-point computations, and they used those skills to develop a broad product line that only recently became a processor family.

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Microprogrammable DSP Building Blocks—Product Analysis

Different product lines are distinctive in function, precision or data format, and implementation technology. Dataquest only briefly examines these major distinctions because market forces may make a careful understanding of product differences and trends of little value. Major functional and precision distinctions and example products are summarized in Tables 1 and 2.

Table 1

Examples of Building Blocks in Processor Families from Major Suppliers

Building Blocks	AMD	AD	TI	Weitek
Data Path Elements				
Shifter				
16-Bit	29130	-		-
32-Bit	-	-	8838	-
Floating Point	-	-	8833	-
Exchange	-	-	8839	-
ALU				
4-Bit	2901	-	-	-
8-Bit	29501	-	888	-
16-Bit	29116	-	-	-
32-Bit	29332	-	8832	-
Floating Point	-	3221		2265
MPY				
8-Bit	-	1080	-	-
12-Bit	-	1012	-	-
16-Bit	29516	1016	1616	2516
32-Bit	-	-	-	-
Floating Point	-	3211	-	2264
MAC				
8-Bit	29509	1008	-	-
16-Bit	29510	1110	9510	2010
32-Bit	29323	-	8836	-
Floating Point	29325	-	-	-
ALU-MPY				
16-Bit	-	1101	-	-
32-Bit	-	-	-	-
Floating Point	-	-	8847	-
ALU-MPY-RF				
16-Bit	-	-		
32-Bit	-	-	-	8137
Floating Point	29327	3264	-	3364

(Continued)

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Table 1 (Continued)

Examples of Building Blocks in Processor Families from Major Suppliers

Building Blocks	AMD	AD	TI	Weitek
Control				
Program Sequencer	29331	1402	8818	8136
Crossbar	-	-	8841	-
Controller	29141	-	-	-
Address Generation				
General	-	1410	-	-
FFT	29540	-	897	-
Memory				
Register File	29334	3128	8834	1066
Pipeline Register	29525	-	-	-

Source: Dataquest
August 1989

Table 2

Examples of Special-Function Building Blocks

Company	Product	Precision (Bits)	Multiplier-Accumulators
FIR Filters			
TRW	TDC1028	4x4	8
	TMC2243	10x10	3
Zoran	ZR33481	8x8	4
	ZR33881	8x8	8
	ZR33891	9x9	8
NEC	NCR45CF8	8x9	4
LDi	LMS12	12x12	1
GE/RCA	TA13073A	8x8	20
Correlators			
TRW	TMC2023	64x1	64
	TMC2220	32x4	128
	TMC2221	128x1	128

Source: Dataquest
August 1989

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Functional Distinctions

Figure 3 shows the functional blocks of a DSP processor; these correspond generally with the functional product lines. This is a result of the building consisting of all elements that lack internal control or sequencing, and the processors being defined from their horizontal microcode control method.

Data path operations have the high functional complexity that makes building blocks attractive. The basic adder function was enhanced with shifters and other logical operations to be a full ALU. Only the multiplier had to be separate. The multipliers combined to form an adder for the DSP multiply-accumulate function; then the full ALU and multiplier were merged.

Simple register sets grew into multiported register files that supplied data to the arithmetic functions. These register files then merged with the combined arithmetic functions. Some blocks configured the memory and several multiplier-accumulators to do filtering and correlation operations. Examples of these special DSP functions are shown in Table 2.

The relatively simple program counter with branch capability grew into a stack-and-interrupt controller for the time-critical task of generating program memory addresses. Address generation for the data memory has received less attention over the years and were left to the standard ALUs, although they were poorly suited. Only the fast Fourier transform (FFT) address sequence received special attention.

Data Format Distinctions

As process density increased, data widths expanded from the initial artificially narrow 4-bit "slice" to 8-, 12- and 16-bit complete words, which is the full precision that many applications need. The 8-bit words were, and largely remain, the precision of choice for radar, image, and video processing. Higher-resolution systems in these applications now call for 12 bits in line with what is attainable from high-speed A/D and D/A converters.

The highest-speed devices are often building blocks, and, at the highest speeds, precision often is limited. The 16-bit word widths are natural for DSP at less than the highest bandwidth signals, as well as in general data processing, so they now are the most common. Fixed-point formats greater than 16-bit have had limited applications. Two's-complements representation of negative numbers is almost universal in addition to unsigned mode.

The addition of floating-point was a natural enhancement with the higher densities of NMOS circuits, and the building-block format allowed it to be used most widely. Because of the complex arithmetic and the operation sequence necessary, pipelined operation was used to increase throughput. Initial products were 32-bit, but multiple precisions are handled with repeated use of the basic internal arithmetic elements, with a correspondingly longer processing time.

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Microprogrammable DSP Building Blocks— Product Analysis

Building blocks, like microprocessor coprocessors, have largely avoided the floating-point format wars. The first products were compiled with the IEEE standard 754, and largely because of the PC revolution, this is all that has been required. The Digital, IBM, and military 1750 formats all have been added to some building blocks, but additional floating-point formats have not been important in determining the success of these products. Complete IEEE exception handling and function coverage, however, has been very important.

Technology Distinctions

Because of the simple design and the standard function, the first products in a faster, denser, or better technology often are building blocks. Generally, the progression mirrors the rest of the semiconductor industry in absorbing new technologies, but older ones die more slowly because of their more basic functions and adaptability to special needs. NMOS and CMOS displaced bipolar slowly, although power and speed improvement were great. BiCMOS is expected to replace CMOS as I/O speeds become more important in overall speed performance.

GaAs still has a high cost and limited density, but it is used for its high speeds, particularly where it can reduce the basic microcode sequencer microcycle time. The TTL I/O interface and Am 2900 series functions have been maintained.

As device geometries shrink, the on-chip delays get shorter, but off-chip I/O times remain the same and become relatively larger in the complete system. BiCMOS can provide faster bipolar I/O with a high-density CMOS core, which will reduce this problem. The interface preferred still is 5V TTL but the superior speed and noise properties of ECL I/O make it a new option. Many products with bipolar technology are available with either TTL or ECL interfaces.

Bipolar processes continue to increase in density and to rival CMOS. Although BiCMOS has lower power, these high-density bipolar processes are at little disadvantage when used with ECL interfaces.

Examples of Separate-Function Product Lines

TRW's LSI Products Division originated building block circuits for DSP. For more than 12 years, TRW has remained functional only. Starting with multipliers, multiplier-accumulators, and memory products, TRW has increased speed and lowered power requirements through many generations of process enhancement, both bipolar and CMOS. Functionality increased slowly, and every precision need was met, generally setting the industry standard for function and pinout.

Integrated Device Technology (IDT) used a higher-performance CMOS process and aggressive pricing to become a significant supplier. Initial products were simply higher-speed versions of industry-standard products. But IDT now is introducing new products with improved functions as well.

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Logic Devices became a broad supplier by offering low prices and low-cost packages on industry-standard parts. Product improvements on new proprietary parts have expanded the line.

Bipolar Integrated Technology (BIT) used its bipolar process to make the fastest parts commercially available. BIT was first with ECL interfaces as well as the standard TTL.

PROCESSOR FAMILY PRODUCT LINES

Only four companies have produced product families with interlocked functional blocks, making a consistent and, in a sense, complete processor. The latest and/or highest-performing members of these families are shown in Figure 4. Of these, only Analog Devices and Weitek concentrated on DSP in determining the initial functions.

Advanced Micro Devices

The whole building block concept started in earnest with the Am2900 bit-slice series from AMD. The initial bipolar 4-bit slice has expanded to 16-bit words with the 29100 series and to 32-bit words with the CMOS 29300 series. Special functions for DSP, such as multipliers, complex arithmetic ALUs, MACs, and FFT addressers were added in the 29500 series. The 29400 series are future ECL versions of the 29300 series. The 2900 and 29100 were the industry standards that made second-sourcing and enhancements to individual products possible without producing a whole new product line. This AMD processor family's steady growth in precision, performance, and technology has defined building blocks' status. All other products are viewed in relation to their framework.

Texas Instruments

The current 32-bit CMOS TI 88XX family is an outgrowth of the 8-bit bipolar 88X family. Bipolar product availability often was late and was not leading edge in any sense, so it never became a standard that others followed. The 88XX series is more aggressive and has set the price/performance standard in single-chip floating-point functions. The rest of the series faces the same uncertainties as all 32-bit building blocks at this time.

Analog Devices Incorporated

The ADSP-1000 series started as a CMOS product line with 16-bit precision. It was directly targeted for DSP and, as a result, paid attention to real-time control issues and fast concurrent address generation. Its use of other modern computer science concepts made it attractive for data processing in general. Major enhancements have been made in the address generator and microsequencer, but the most rapid change has been in the

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floating-point data path blocks driven by the accelerator market. A general strategy has been to maximize the function per chip rather than carefully selecting functions for the lowest price and minimum package size.

Weitek

The 8XXX series started as an improved family of loosely coupled processor building blocks but has become an array processor chip set with three different arithmetic precisions. The change resulted from trying to solve the microcode problem. By limiting the configurations to three with fixed instruction sets, higher-level languages could be supported and microcode libraries could be developed. This strategy put Weitek in competition with potential customers—board array processor suppliers—but more accurately, this product family may have been the first of the high-performance RISC processors with a fast floating-point vector coprocessor. In any case, Weitek has progressed out of the traditional building block market.

SOFTWARE SUPPORT

Microcode's flexibility is inherent in building block processor families, but this flexibility translates into complexity in writing and maintaining the microcode. These tasks generally are underestimated and constitute building block use's largest disadvantage. The flexibility limits all but the most basic meta assembler from being a useful software tool for many different processor designs. The two most widely used assemblers today are ones provided by microprogram ROM simulator suppliers Step Engineering and HiLevel Technology.

As building block complexity has grown, functional simulation models have become necessary, particularly for floating-point data path elements. The IEEE floating-point standard has elaborate exception handling that increases demands on the microcode routines as well as improving arithmetic correctness. Because time to market is so important, a functional simulator often is required before working silicon on new building block products. Logic Automation has become the dominant supplier of these functional models.

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Microprogrammable DSP Building Blocks— Emerging Technology and Trends

PRODUCT AND MARKET TRENDS

The most important market trend is that product alternates to building blocks are now available to current users for new designs. Technology limits may also impact the use of building blocks.

Alternate Solutions

The single-chip DSP microprocessor (DSMPU) is now a serious alternative to building block processor families in many applications. The on-chip performance of DSPMUs has long been nearly equal to building block performance. However, DSMPUs now offer much greater I/O and support of external memory, so that total system performance is now equal or greater. Benefits include lower cost and far easier software development with a fixed instruction set and full hardware and software support systems. New multiprocessor configurations promise an even greater performance/price ratio in the future.

Special-function processors (SFDSPs) now exist for many of the tasks that before could only be done efficiently with a special microcoded architecture. The complete digital filter, FFT, and image-processing chips now available often provide higher performance than building blocks as well as providing much easier use.

The microcoded building block solution has always offered architectural flexibility. This flexibility now is available in a practical form in application-specific processor (ASDSP) methodologies. The semicustom cells are often used like building blocks. Functional simulation tools in this design environment already exceed what is available for standalone building blocks.

The rapid increase in performance of general-purpose microprocessors also provides competitive solutions. Not only have raw speeds approached that of DSP building blocks but functionality has expanded to make general-purpose processors more suitable for DSP applications. Vector processing and floating-point capability additions to microprocessors have been the last large market for building blocks. These functions are increasingly being added on-chip to the main processor. The wide markets for these general-purpose microprocessors ensures that they will always have attractive, low-cost, and widely available support systems and personnel.

Technology Limits

Building blocks have always been a way of partitioning functions to take advantage of chip density while separating the control function to allow flexibility. With the densities achievable today, fewer functions demand a full chip that cannot also accommodate the control function. In addition, as on-chip speeds increase, keeping the control function separate can reduce system speeds substantially as well as unnecessarily increasing power consumption and packaging costs. I/O speed and power penalities are increasingly high and unnecessary.

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For new process technologies that offer unusual performance and that alter these limits, building blocks still make sense. GaAs does not appear to alter these limits, but rather confirms the interface problem. Its high speed is lost getting on and off the chip and yet density is still low, so that functions must be partitioned into blocks.

For new functions in which system integration is immature and for very complex functions, building blocks also may still be appropriate. But product planners should see this as a near-term necessity rather than part of a positive strategy of a growing building block product concept.

BUSINESS TRENDS

Market Entry

Becoming a producer of building blocks is relatively easy. There are established functions, pin-outs, and simulation support so that if a company has an improved process, industry standard building blocks are a natural vehicle for displaying its lower power or higher speed. No costly software support is needed. Likewise, improved process density allows the chip count within an accepted functional framework be reduced. An increase in precision is a natural and often-used improvement.

Initially, the high profit margins were incentive to enter this market. And with the low cost of entry, many suppliers entered the market. Building blocks became commodity parts, and only the lowest-cost producers got any significant market share. This situation remains current today and the cost of entry for building blocks in the future also should remain low. As a result, regardless of other factors that are mostly unattractive, building blocks should always attract competitors because of easy market entry.

Business Success

Business success is the result of having profitable, producible products that meet a market need. There can be little question that AMD, Analog Devices, IDT, Texas Instruments, TRW, and Weitek have had the right products in healthy markets for periods long enough to recover their investments. But such success is becoming less common, and now the only successful efforts are for products that move into more complete processors. The following experiences support those conclusions:

- TRW, having stuck to function-only products, has suffered losses and maintained business volume only by doing custom designs.
- AMD did not recover investment costs on its last expansion to 32-bits with the Am29300 series. AMD's new thrust is the Am29000, a complete RISC processor.

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Microprogrammable DSP Building Blocks—Emerging Technology and Trends

- Weitek's profitability and volume growth has come from floating-point coprocessors for personal computers and workstations. Special-purpose controllers, like the XL-8200 laser printer controller, are the new company thrust.

- Analog Devices is putting new development efforts into DSMPUs, after it lost out in most of the floating-point coprocessor wars.

- Texas Instruments has one notable success in its 32-bit CMOS building block line: the floating-point block used in coprocessors. This product is also part of its SPARC RISC commitment.

- IDT, a price and technology leader with a function-only DSP building block product line, is making no future investments in building blocks.

The functional reasons for building blocks seem to be going away. Building blocks were a transitional product in the increasing density curve of integrated circuits. The business success of the suppliers now reflects this when looked at carefully. It will become even more apparent in the future.

New Business Opportunities

As separate functions, building blocks will continue to offer opportunities, particularly where other processor family building blocks are not required. Generally, new building blocks must implement some new function that does not have a natural connection with some existing microprocessor or else must use some new technology that is not mature enough to have a natural connection into existing processing systems. Even these opportunities are best viewed as transient. Building blocks are best viewed as part of a larger cell-based ASIC design system product plan.

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DSP Building Blocks— Emerging Technology and Trends

GALLIUM ARSENIDE TRENDS IN DSP

Product development activity is accelerating in the gallium arsenide (GaAs) industry. In the area of DSP building blocks, several companies are already offering GaAs versions of the 2901 4-bit ALU slice.

Vitesse

Vitesse introduced the first commercially available LSI GaAs digital IC set, an ECL 100K-compatible 4-bit-slice family. The product family consists of the VE29G01 4-bit microprocessor slice, the VE29G02 look-ahead carry generator, and the VE29G10 microsequencer. The VE29GXX family is expected to permit customers to achieve a factor of 3x speed improvement over a CPU implementation using the AMD2901C, which is a bipolar device. Interestingly, Vitesse has employed leaded chip carrier (LCC) packaging to preserve the device speed advantage at the system level as much as practical.

Gigabit Logic Inc.

Gigabit Logic (GBL) is also offering a family of 4-bit ALU slice products. They are the 10G181 4-bit microprocessor slice, the 10G100 4-bit adder, and the 10G101 carry look-ahead unit. GBL's goal is to become the leader in the commercial GaAs IC market. Currently, the company is focusing on the computer, instrumentation, defense, and communications markets.

Adams Russell

Adams Russell offers a family of more than 50 analog standard cells for custom and semicustom applications. The parent company manufactures airborne antenna and cable assemblies, microwave and RF components and subsystems, and special-purpose high-speed DSP systems.

Sony Corporation

In 1983, Sony reported results of R&D and successful testing of a GaAs JFET chip containing 511 DCFL gates organized as a 4x4 multiplier, 10-bit accumulator, and 8-bit shift register.

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Microprogrammable DSP Building Blocks—Application and User Issues

MARKET DISTINCTIONS

Initially, the uses of building blocks were as broad as the TTL market itself because the primary benefit simply was higher density. As processor families began to form, then programmable processors of all types, special-purpose or general data processing became more popular. As microprocessors flourished and gate arrays became larger, building blocks have been used increasingly only for special-purpose tasks involving coprocessors, controllers, or digital signal processing (DSP), where the highest speeds are necessary or the processing architecture is unusual. Yearly unit volume in these applications generally is low or moderate; otherwise, an ASIC design would be justified. The majority of building blocks still are used to build programmable processors, but the trend is toward hardwired fixed-function or state machine designs.

GENERAL-PURPOSE DATA PROCESSING SYSTEMS

The naturally wide instruction sets of the building block families generally have not aligned with the instruction sets of major central processing unit (CPU) suppliers. Initially, however, microcode allowed designers to emulate existing minicomputer instruction sets. In addition, microcoded systems could be enhanced readily as the instruction set grew. Compared with the original complex-instruction-set computers (CISC) and slow-core main memories, multiple-chip building block designs suffered no speed penalty.

As fast, inexpensive semiconductor memories became available, the speed penalty was noticeable unless the processor operated in its native microcode. Within general data processing, native microcode operation was possible only in special attached controllers or coprocessors. Typically, coprocessors were designed for floating-point arithmetic, vector processing, simulation kernels, or graphics.

In minicomputer and mainframe systems, high-speed microcoded peripheral controllers became the main use for building blocks because every system had multiple disk and I/O channel controllers. The floating-point coprocessor often used the same technology as the CPU as the coprocessor became more of a standard part of the system. Also, non-IEEE formats had to be supported.

New superminicomputer and parallel processor systems adopted the vector and general-purpose array processor requirement for simulation and graphics. The IEEE floating-point format is the usual choice, so superminicomputers are making wide use of the floating-point arithmetic building blocks, sequenced by a controller, and usually designed in gate arrays.

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Microprogrammable DSP Building Blocks—Application and User Issues

In PC and microcomputer systems, simulation and graphics created a large market for faster vector and floating-point calculations. The need for faster vector and floating-point calculations was met in two ways, both of which used floating-point building blocks:

- Add-in accelerator boards
- Higher-speed replacements for existing floating-point coprocessors such as the 80X87 family

The high-performance engineering workstation is the complete answer to simulation and graphics needs. As with microcomputers, special controllers are used rather than others of the building block processor family. Today, this represents the largest single use of building blocks, generally for floating-point ALUs, multipliers, and register files in various combinations.

DIGITAL SIGNAL PROCESSING SYSTEMS

The array processor is the general-purpose computer for DSP. Array processors always have been microcoded for speed and flexibility and thus were quick to use DSP building blocks. Large array processors now are in decline as they are replaced by superminicomputers. But the density of new building blocks has allowed moving a function onto a single board for use in PCs, workstations, or VME bus microcomputer systems. The end applications cover all digital signal processing applications in some form. Most processors are broadly applicable, but image and graphics requirements are different enough to require that special architectures be used. These array processors are the purest application of the DSP building block processor families and are highly visible, but they are not a large-volume market.

Many signal processing tasks are highly repetitive and do not need the flexibility of programming. In addition, maximum speed is needed, so a hardwired special-purpose processor is used. Data path building blocks and special-function blocks often can be used directly, although some sequencing circuits may be required. Large-end applications include radar, sonar, medical and military imaging, graphics, and high-performance real-time simulation. Collectively, these represent the largest market for DSP building blocks.

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ASICs/SFICs Executive Summary

EXECUTIVE SUMMARY

The combined potential of application-specific DSP integrated circuits (ICs) and special-function DSP ICs is tremendous. Dataquest believes that application-specific ICs (ASICs) and special-function ICs (SFICs) will account for 44 percent of all DSP revenue by 1990.

ASIC/SFIC MARKET

Market Size

The following should be noted about the size of the ASIC/SFIC market:

- Application-specific DSP IC revenue was $68 million in 1986.
- Application-specific DSP IC unit shipments were 9.8 million in 1986.
- Special-function DSP IC revenue was $50 million in 1986.
- Special-function DSP IC unit shipments were 3.8 million in 1986.

Market Forecast

The Dataquest ASIC/SFIC market forecast is as follows:

- Worldwide application-specific DSP IC revenue is forecast to be $98 million in 1987.
- Worldwide application-specific DSP IC revenue is forecast to be $192 million in 1990.
- Worldwide special-function DSP IC revenue is forecast to be $73 million in 1987.
- Worldwide special-function DSP IC revenue is forecast to be $146 million in 1990.

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ASICs/SFICs Executive Summary

Competitive Environment

The following are key points regarding the competitive environment of the ASIC/SFIC market:

- The ASIC marketplace is crowded, to say the very least. A minimum of eight vendors offer 2901 bit-slice cells in their ASIC libraries. Many more vendors are capable of duplicating the function in bipolar gate arrays--even in ECL bipolar gate arrays.

- The SFIC market is diverse by definition, with pockets of heavy competition in certain areas such as 300-baud modems.

ASIC/SFIC TRENDS

Product Trends

ASIC/SFIC product trends include the following:

- Dataquest expects the application-specific DSP market segment to increase at a compound annual growth rate (CAGR) of 29.6 percent through 1990 as discrete DSP building block designs convert to ASIC.

- We expect the special-function DSP segment to grow at a CAGR of 30.7 percent, fueled by the growing digital-telecommunications and graphics-generation markets.

Technology Trends

The availability of high-speed, low-power CMOS standard cells is expected to have a significant impact on the ASIC DSP market.

Application Trends

ASIC/SFIC application trends include the following:

- Special-function DSP ICs are expected to play an increasingly important role in graphics generation.

- Certain general signal processing applications in telecommunications, such as modems, will also evolve from general-purpose DSP microprocessors to special-function DSP ICs.

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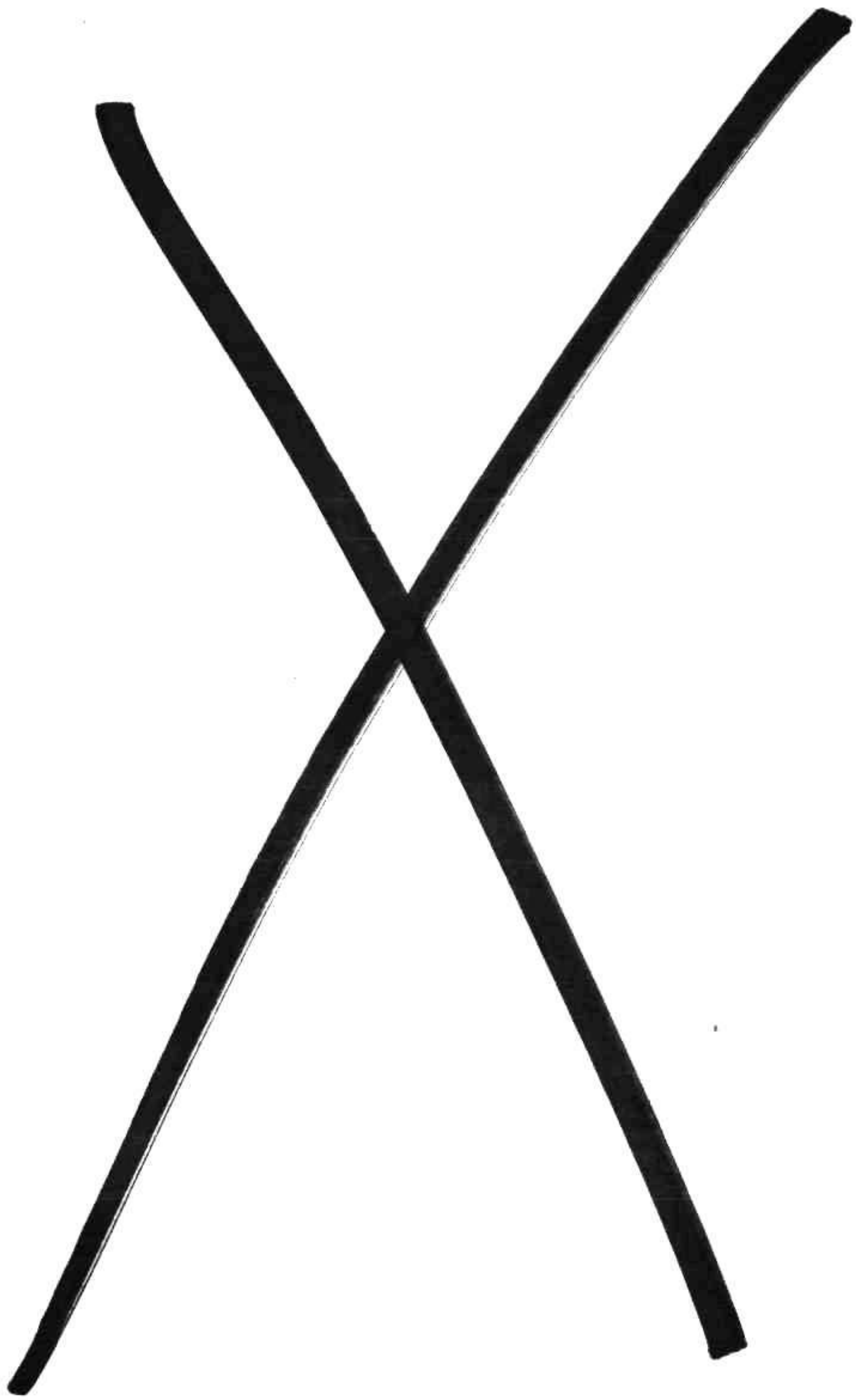


ASICs/SFICs—Forecast

DSP APPLICATION-SPECIFIC INTEGRATED CIRCUITS (ASICs)

Market Definition

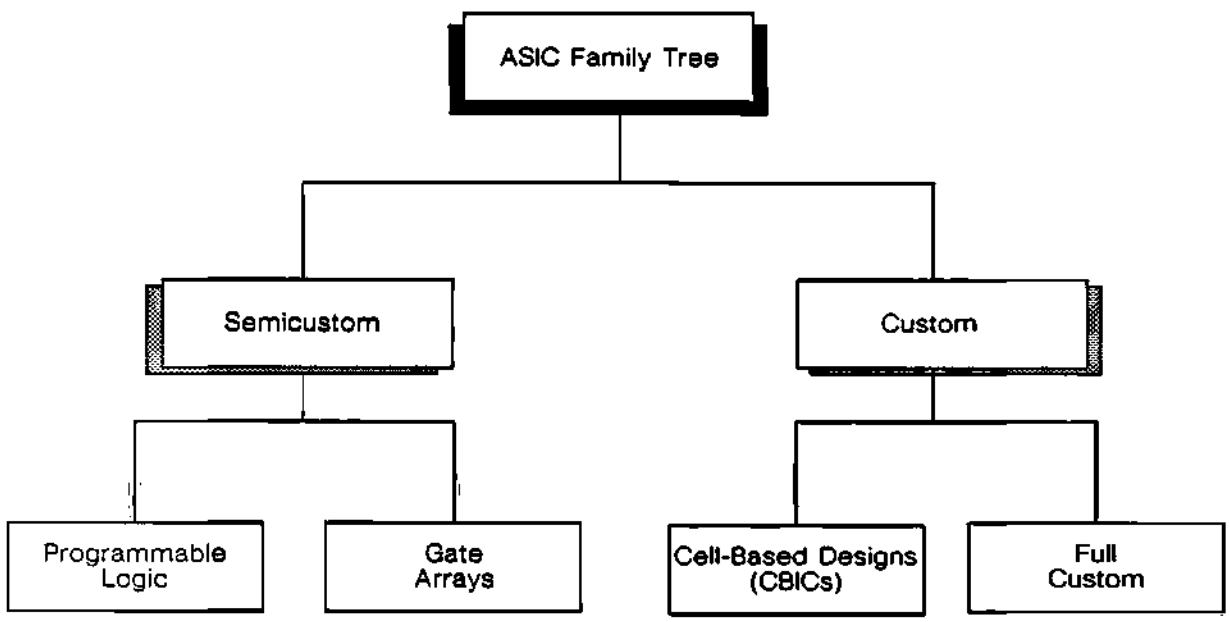
Dataquest recognizes four types of products as belonging to the application-specific integrated circuit (ASIC) product category, as follows:

- Programmable logic devices (PLDs)
- Gate arrays
- Cell-based integrated circuits (CBICs)
- Full-custom logic designs

Figure 1 shows the entire ASIC family tree segmented as either semicustom or custom devices.

Figure 1

ASIC FAMILY TREE



Source: Dataquest
June 1987

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ASICs/SFICs--Forecast

ASICs are used in many digital signal processing (DSP) applications to replace a combination of small-scale integration (SSI) devices, medium-scale integration (MSI) devices, and DSP building blocks. Signals from one component to another frequently require slight modification. SSI and MSI are the glue that cements the building blocks together. The number of gates required to glue building blocks together is usually small. SSI and MSI have only a few gates per chip; therefore, the number of individual SSI and MSI chips needed is large, typically accounting for 50 percent of the printed circuit board area. By using an ASIC design that incorporates many of the glue-chip functions, the total chip count of a DSP design can be significantly decreased. The reduction in chip count results in a cost advantage that, at high production quantities, outweighs the higher development cost of ASICs.

It should be pointed out that there is no one best design technique. ASICs, building blocks, and DSMPUs all excel in certain areas. ASICs generally are preferred for very high volume applications.

Forecast

Dataquest estimates that gate arrays and cell-based ASIC designs used in DSP applications will grow at a 29.6 percent compound annual growth rate (CAGR), from $68 million in 1986 to $192 million in 1990. Table 1 illustrates the relative growth of DSP ASIC revenue by end-use market. We believe that the use of ASICs will grow most rapidly in high-volume communications and consumer applications. Military use of ASICs will remain quite strong, with a CAGR of 28.0 percent through 1990.

Because of size and performance benefits, as well as ease of implementation, DSP ASIC customers will increasingly turn to cell-based integrated circuit (CBIC) designs. Dataquest expects that 90 percent of ASIC DSP designs will be cell based by 1990.

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Table 1

WORLDWIDE DSP ASIC REVENUE BY END-USE MARKET
(Millions of Dollars)

	Actual				Forecast				CAGR	CAGR
	1983	1984	1985	1986	1987	1988	1989	1990	83-86	86-90
Data Processing	$ 3	$ 5	$ 7	$ 9	$12	$ 15	$ 18	$ 21	44.2%	23.6%
Communications	12	20	17	28	40	55	71	84	32.6%	31.6%
Industrial	1	2	3	4	6	8	9	11	58.7%	28.8%
Consumer	1	1	2	2	3	4	5	7	26.0%	36.8%
Military	13	23	18	25	36	45	56	67	24.4%	28.0%
Transportation	0	0	0	0	1	1	1	2	0	111.5%
Total DSP ASIC Revenue	$30	$51	$47	$68	$98	$128	$160	$192	31.4%	29.6%

Source: Dataquest
June 1987

DSP SPECIAL-FUNCTION INTEGRATED CIRCUITS (SFICs)

Market Definition

Dataquest defines special-function DSP integrated circuits (SFICs) as commercially available, standard semiconductor products that are designed to perform a specific function and employ digital signal processing. DSP capability is not the exclusive function of these products; rather, DSP is primarily an implementation technique allowing the circuit to perform its targeted function.

These dedicated or specialized chips typically originate as a custom design for a specific customer or group of customers. As the particular end market grows, demand for these and other specialized chips to serve the application also grows. Eventually, merchant semiconductor companies will offer standard semiconductor products to fill these needs.

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ASICs/SFICs--Forecast

Special-function circuits employing DSP will replace general-purpose DSP designs as the size of each particular market warrants it. Examples of SFICs include the following:

- Modems
- CODECs
- Music-synthesizer chips
- Speech-synthesizer chips
- Speech-recognition chips

Forecast

SFICs have applications in a wide variety of end equipment markets including the telecommunications, consumer, and military markets. Dataquest forecasts that the consumption of DSP SFICs will grow at a 30.7 percent CAGR from $50 million in 1986 to $146 million in 1990. As shown in Table 2, we believe that rapid growth will occur in the communications, industrial, and military segments.

Table 2

WORLDWIDE DSP SFIC REVENUE BY END-USE MARKET
(Millions of Dollars)

	Actual				Forecast				CAGR	CAGR
	1983	1984	1985	1986	1987	1988	1989	1990	83-86	86-90
Data Processing	$ 1	$ 3	$ 5	$ 7	$ 9	$11	$ 15	$ 16	91.3%	23.0%
Communications	9	14	13	20	31	41	56	64	30.5%	33.8%
Industrial	1	2	2	3	4	6	7	9	44.2%	31.6%
Consumer	0	1	1	2	2	3	4	5	171.4%	25.7%
Military	10	15	13	18	26	35	44	50	21.6%	29.1%
Transportation	0	0	0	0	1	1	2	2	0.0%	111.5%
Total DSP SFIC Revenue	$21	$35	$34	$50	$73	$97	$128	$146	33.5%	30.7%

Source: Dataquest
June 1987

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ASICs/SFICs--Suppliers

APPLICATION-SPECIFIC DSP INTEGRATED CIRCUITS (ASICs)

ASICs offer a designer the opportunity to fully integrate a building-block system onto a single piece of silicon. Several ASIC vendors now offer cell equivalents of AMD's 2900 microprogrammable family. Table 1 highlights some of these vendors. Table 2 gives a more complete list of worldwide ASIC suppliers by region, by technology, and by type of product offered.

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ASICs/SFICs--Suppliers

Table 1

REPRESENTATIVE ASICs SUPPORTING
MICROPROGRAMMABLE COMPONENTS

MANUFACTURER	ASIC PART NUMBER	MICROPROGRAMMABLE ELEMENTS SUPPORTED IN LIBRARY (SEE NOTE 1)	IC PROCESS	2901 A,B-TO-Y DELAY (nSEC)	NRE CHARGES	PART COST
CALIFORNIA DEVICES	CHA3200	2901, 2910	CMOS	51	$18k TO $24k	$7 (10,000) IN AN 84-LEAD PLCC
GOULD INC	MEGACELL	2901, 2902, 2904, 2909, 2910, 2911	HCMOS	72	(SEE NOTE 2)	(SEE NOTE 2)
INTEGRATED LOGIC SYSTEMS	CA2000	2901, 2902, 2904 2910	CMOS	67	$25k TO $55k	$22.77 (5000) FOR A CA2110 IN AN 84-LEAD PLCC
LSI LOGIC	LSA2005	2901, 2902, 2903, 29203, 2904, 2909, 2910, 2910A, 16-BIT 2910, 2911, 29116, 29117, 29501	HCMOS	56	$40k TO $80k	$50 TO $150 COMMERCIAL, BASED ON PACKAGE AND VOLUME
	LSA2006	SAME AS LSA2005	HCMOS	66.1	SAME AS LSA2005	SAME AS LSA2005
	LSA2011	SAME AS LSA2005	HCMOS	58	SAME AS LSA2005	SAME AS LSA2005
NATIONAL SEMICONDUCTOR	SCX6200	2901, 2909, 2911	CMOS	29	$15k TO $70k	(SEE NOTE 3)
	SCL	2901, 2909, 2911	CMOS	29	$30k TO $70k	(SEE NOTE 4)
UNICORN	COMPILE	29C01, 29C03, 29C10, 29C14	CMOS	10 (TYP)	FROM $50k	(SEE NOTE 5)
VTC	VL2000	2901, 2902	CML	3.25	$40k TO $50k	(SEE NOTE 6)
WAFERSCALE	MODULAR-CELL	8-, 16-, 32-BIT 2901s, 2910A	CMOS	30 (4-BIT)	$80k TO $125k	(SEE NOTE 7)

NOTES:

1 KEY TO 2901 FAMILY:

2901	4-BIT ALU SLICE
2902	LOOKAHEAD-CARRY GENERATOR
2903, 29C03	4-BIT EXPANDED-FUNCTION ALU SLICE
29203	4-BIT ALU SLICE WITH BCD ARITHMETIC
2904	STATUS AND SHIFT-CONTROL UNIT
2909	4-BIT MICROSEQUENCER SLICE
2910, 29C10, 2910A	12-BIT MICROSEQUENCER
2911	4-BIT MICROSEQUENCER SLICE
29116	16-BIT ALU
29117	2-PORT, 16-BIT ALU
29501	MULTIPORT, PIPELINED, 8-BIT ALU SLICE

2 HYPOTHETICAL GOULD MEGACELL ASIC:

FUNCTION				% AREA CHIP USAGE
MICROCODE ENGINE COMPONENTS:	QUANTITY	DEVICE		
	1	2910 MICROSEQUENCER		
	4	2901 4-BIT SLICE ALU		
	1	2902 LOOKAHEAD CARRY		
	—	REGISTERS, MUXES (1000-GATE EQUIVALENT)	SUBTOTAL	29%
MICROCODE STORAGE:		1k-WORD×60-BIT ROM		22%
AUXILIARY STORAGE:		1k-WORD×16-BIT ROM 512-WORD×16-BIT RAM	SUBTOTAL	24%
PROPRIETARY DIGITAL COMPONENTS:		2000-GATE EQUIVALENT RANDOM LOGIC		15%
ANALOG INTERFACE CIRCUITS:		FILTER, SAMPLE AND HOLD, ANALOG SWITCHES, COMPARATOR, VOLTAGE DOUBLER, CLOCK CIRCUITS	SUBTOTAL	10%
			TOTAL	100%

USER PROVIDES GOULD WITH A SEMIVALIDATED NET LIST USING GOULD LIBRARIES. NRE COST: LESS THAN $50,000; PART COST: LESS THAN $30 (10,000/YEAR) IN 68-LEAD PLCC.

3 A NATIONAL SEMICONDUCTOR SCX6287 GATE ARRAY WITH A 16-BIT ALU REPRESENTING APPROXIMATELY 25% OF THE DIE AREA, PACKAGED IN AN 84-LEAD PLCC, WOULD COST APPROXIMATELY $39.

4 A NATIONAL SEMICONDUCTOR SCL SEMICUSTOM ASIC WITH A 16-BIT ALU REPRESENTING APPROXIMATELY 25% OF THE DIE AREA, PACKAGED IN AN 84-LEAD PLCC, WOULD COST APPROXIMATELY $32

5. A UNICORN ASIC GENERATED FROM THE COMPILE LIBRARY WITH A 16-BIT ALU REPRESENTING APPROXIMATELY 25% OF THE DIE AREA, PACKAGED IN A 68-PIN PLCC, WOULD COST APPROXIMATELY $14 (50,000).

6. A VTC VL2000 SEMICUSTOM ASIC WITH A 16-BIT ALU REPRESENTING APPROXIMATELY 25% OF THE DIE AREA, PACKAGED IN AN 84-LEAD PLCC, WOULD COST APPROXIMATELY $50 (5000/YEAR)

7. A WAFERSCALE MODULAR-CELL ASIC WITH A 32-BIT ALU, A 1k-WORD×64-BIT EPROM, A 6k-BIT RAM, AND A 5910 MICROSEQUENCER IN A 132-PIN PLASTIC PGA COSTS APPROXIMATELY $200 (5000/YEAR).

Source: EDN

Table 2

WORLDWIDE ASIC SUPPLIERS

Companies by Region	PLDs		Gate Arrays		CBICs	
	MOS	Bipolar	MOS	Bipolar	MOS	Bipolar
Worldwide Total	16	7	83	42	80	13
North American Companies	15	7	51	28	55	10
AT&T Technologies	0	0	0	0	1	0
Acumos	0	0	1	0	0	0
Advanced Micro Devices	1	1	0	1	0	0
Altera	1	0	0	0	0	0
Applied Micro Circuits Corp.	0	0	1	1	1	1
Atmel	1	0	0	0	0	0
Barvon Research	0	0	1	1	1	0
California Device Inc.	0	0	1	0	1	0
California Micro Devices	0	0	1	0	1	0
Calmos Systems	0	0	1	0	0	0
Cherry Semiconductor	0	0	0	1	0	0
Circuit Technology Inc.	0	0	1	0	1	0
Cirrus Logic	0	0	0	0	1	0
Commodore Semiconductor	0	0	1	0	1	0
Custom Arrays	0	0	0	1	0	0
Custom Integrated Circuits (CIC)	0	0	0	1	1	0
Custom Silicon	0	0	1	1	1	0
Cypress Semiconductor	1	0	0	0	0	0
Data Linear	0	0	0	1	0	1
Exar Integrated Systems	0	0	1	1	1	0
Exel Microelectronics	1	0	0	0	0	0
Fairchild Semiconductor	0	1	1	1	1	0
Ferranti Interdesign	0	0	1	1	1	1
GTE Microcircuits	0	0	1	0	1	0
General Instruments	0	0	1	0	1	0
Gould Semiconductors	1	0	1	0	1	0
Harris Semiconductor	1	1	1	1	1	0
Holt Integrated Circuits	0	0	0	0	1	0
Honeywell	0	0	1	1	1	0
Hughes Solid State	0	0	1	0	1	0

(Continued)

Table 2 (Continued)

WORLDWIDE ASIC SUPPLIERS

Companies by Region	PLDs		Gate Arrays		CBICs	
	MOS	Bipolar	MOS	Bipolar	MOS	Bipolar
ICI Array Technology	0	0	1	0	1	0
ITT VLSI	0	0	1	0	1	0
Integrated Circuits Systems	0	0	1	0	1	0
Integrated Logic Systems (ILSI)	0	0	1	0	0	0
Integrated Microcircuits	0	0	1	0	0	0
Intel	1	0	1	0	1	0
Intercept Microelectronics	0	0	1	0	0	0
Interconics	0	0	1	1	0	0
International CMOS Technology	1	0	0	0	0	0
International Microcircuits Inc. (IMI)	0	0	1	0	1	0
International Microelect. Products (IMP)	0	0	0	0	1	0
LSI Logic	0	0	1	0	1	0
Laseroath	0	0	1	0	0	0
Lattice Semiconductor	1	0	0	0	0	0
Linear Technology Inc.	0	0	0	1	0	1
MCE Semiconductor	0	0	1	1	1	0
Matra Design Semiconductor	0	0	1	0	1	0
McDonnell Douglas Corporation	0	0	0	0	1	0
Micro Linear	0	0	1	1	1	1
Micro Power Systems	0	0	0	0	1	1
Micro-Rel	0	0	0	0	1	1
Microcircuits Technology	0	0	1	0	0	0
Mitel	0	0	1	0	1	0
Mitron	0	0	1	0	0	0
Monolithic Memories	1	1	0	0	0	0
Motorola	0	0	1	1	1	0
NCM	0	0	1	1	1	0
NCR	0	0	1	0	1	0
National Semiconductor	0	1	1	0	1	0
Pacific Microcircuits Ltd.	0	0	1	0	1	0

(Continued)

Table 2 (Continued)

WORLDWIDE ASIC SUPPLIERS

Companies by Region	PLDs MOS	PLDs Bipolar	Gate Arrays MOS	Gate Arrays Bipolar	CBICs MOS	CBICs Bipolar
Panasonic	0	0	1	0	1	0
Polycore Electronics	0	0	0	1	0	0
RCA	0	0	1	0	1	0
Raytheon	0	0	1	1	0	0
S-MOS Systems (Seiko)	0	0	1	0	1	0
Sierra Semiconductor	0	0	0	0	1	0
Signetics	1	1	0	1	1	0
Silicon Systems	0	0	0	1	1	0
Siliconix	0	0	1	0	0	0
Siltronics	0	0	0	0	1	1
Soraque Solid State	0	0	0	0	1	0
Standard Microsystems Corp.	0	0	0	0	1	0
Supertex	0	0	0	0	1	1
Tektronix	0	0	0	1	0	0
Texas Instruments	1	1	1	1	1	0
United Microelectronics Corp.	0	0	1	0	0	0
United Technologies	0	0	1	0	0	0
VLSI Technology Inc.	1	0	1	0	1	0
VTC	0	0	1	1	1	1
Vatic	0	0	0	1	0	0
WaferScale Integration	0	0	0	0	1	0
Western Digital	0	0	1	1	1	0
Xilinx	1	0	0	0	0	0
Zymos	0	0	0	0	1	0
Japanese Companies	1	0	11	5	11	0
Asahi	0	0	1	0	0	0
Fujitsu	0	0	1	1	1	0
Hitachi	0	0	1	1	0	0
Matsushita Electronics	0	0	1	0	1	0
Mitsubishi Electronics	0	0	1	1	1	0

(Continued)

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Table 2 (Continued)

WORLDWIDE ASIC SUPPLIERS

Companies by Region	PLDs MOS	PLDs Bipolar	Gate Arrays MOS	Gate Arrays Bipolar	CBICs MOS	CBICs Bipolar
NEC	0	0	1	1	1	0
Oki	0	0	1	1	1	0
Ricoh-Panatech	1	0	1	0	1	0
Sanyo	0	0	0	0	1	0
Seiko Epson	0	0	1	0	1	0
Sharp	0	0	1	0	1	0
Toshiba	0	0	1	0	1	0
Yamaha	0	0	0	0	1	0
European Companies	0	0	18	8	14	3
ASEA HAFO Inc.	0	0	0	0	1	0
Austria Microsystems (Gould)	0	0	1	0	1	0
Electronic Technology Corp. (ETC)	0	0	1	1	1	0
European Silicon Structure	0	0	0	0	1	0
Eurosil GMBH	0	0	1	0	0	0
Ferranti Electronics	0	0	1	1	1	1
HMT Microelectronics Ltd.	0	0	1	0	0	0
Heuer Microtechnology (HMT)	0	0	1	0	0	0
Marconi Electronic Devices	0	0	1	0	1	0
Matra-Harris Semiconductors	0	0	1	0	0	0
Micro Circuits Engineering (MCE)	0	0	1	0	1	0
Mietec	0	0	0	0	1	0
Newmarket Microsystems	0	0	1	1	0	0
Philips	0	0	1	0	0	0
Plessey	0	0	1	1	1	1
R.T.C. La Radiotechnique-Compelec	0	0	0	1	0	0
Recal Electronics Ltd.	0	0	1	0	0	0
SGS Semiconductor	0	0	1	0	1	1
Siemens	0	0	1	1	1	0
Silicon Microsystems LTD. (SMS)	0	0	1	1	1	0

(Continued)

Table 2 (Continued)

WORLDWIDE ASIC SUPPLIERS

Companies by Region	PLDs MOS	PLDs Bipolar	Gate Arrays MOS	Gate Arrays Bipolar	CBICs MOS	CBICs Bipolar
Smiths	0	0	1	0	0	0
Swindon Silicon Systems Ltd.	0	0	0	0	1	0
Thomsen Semiconductor (inc. Mostek)	0	0	1	1	1	0
ROW Companies	0	0	3	1	0	0
AWA Microelectronics	0	0	1	1	0	0
Gold Star Semiconductor	0	0	1	0	0	0
Micro Electronic Ltd.	0	0	1	0	0	0

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DSP—Technical Overview

DEFINITION

Digital Signal Processing (DSP) is a circuit technique whereby a digital representation of an analog waveform is manipulated using computer techniques. Digital processing allows operations upon signals that are difficult and complex (or sometimes, impossible) with conventional analog methods.

DIGITAL SIGNAL PROCESSING ADVANTAGES

The advantages of digital signal processing techniques affect system performance, engineering design, manufacturing, and maintenance. Cost reductions may occur, but that will depend upon the complexity of the final system.

Performance Advantages

Precision and Accuracy

Wider word lengths improve the signal-to-noise ratio. It is neither limited nor changed by the noise of its individual transistors. This allows flexibility in choosing the best word length for each application.

With sufficient processing speed, a DSP system will reproduce exact filter characteristics. Also, it is easy to design a phase linear filter (using a finite impulse response filter). This is difficult in analog circuits.

Temperature Insensitivity

The properties of a DSP processor do not drift with changes in the temperature of its environment. This is a frequent reason for performance shortcomings in analog circuits. Compensating for temperature drift in circuits is a difficult engineering task and is more of an art than a science.

Vibration Insensitivity

Physical vibrations cause an effect called microphonics in circuits that use inductors and capacitors. Microphonics causes undesirable changes in performance during high G-force situations and periods of vibration, such as in military applications. DSP components do not change when shaken; thus, vibrations do not affect the circuit output.

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DSP--Technical Overview

Design Advantages

A DSP program (called an algorithm) usually consists of addition and multiplication operations that are performed on binary words that have up to 32 bits of accuracy. With DSP techniques, designers have the flexibility to choose the word length and computational speed to fit each application.

Programmability

In analog circuits, changing the filter characteristics can require changing the component values. In digital signal processing only the coefficients in the equations need to be changed. Thus a filter can adapt to signal line conditions. Similarly, a DSP processor can be completely reprogrammed to perform a different set of functions.

Quick Implementation

Since software determines the characteristics of the DSP designs, circuits can be quickly prototyped, changed, and upgraded. DSP software is, however, more difficult than non-real-time microcomputer programming.

Integration

Capacitors and inductors necessary for analog processing are difficult to integrate on silicon. For instance, when IC features are smaller than 5 microns, capacitors become nonlinear. This causes implementation problems for conventional analog techniques such as switched capacitor filters.

DSP circuits, on the other hand, using basic on-off circuitry, are amenable to shrinking. In fact, 0.5-micron parts are now working in engineering laboratories. Shrinking the chip does not change the circuit function, only its speed and size. Thus DSP has a clear future as transistors get smaller and faster.

Pinouts

Analog integrated circuits require pins to attach the capacitors, resistors, and inductors that are not part of the chip. Even with technologies such as switched capacitors, which eliminate much of the need for external components, there are always pins for components that alter and customize the characteristics of the part (slew rate, band pass, etc.). Future DSP chips could have a single pin to allow bit serial programming from a microcomputer. Additionally, DSP circuits for audio frequencies can also use bit serial signal paths. As silicon dice continue to shrink, packaging costs and board space are ultimately the determining factors in system costs. Therefore DSP will eventually be cheaper than analog just based on pinouts.

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DSP—Technical Overview

Manufacturing Advantages

Repeatability

Each DSP system coming off the assembly line can have the same algorithm as any other. Analog components, however, are manufactured with a tolerance on the parameter values. Because of the cumulative effects of these tolerances, circuit designs that use many analog components require individual adjustments on every circuit to meet critical performance specifications.

Device-to-device conformity is desirable in communication systems where optimum information transfer depends on the matching of transmitter and receiver characteristics.

Maintenance Advantages

Stability

Since the DSP algorithm does not change with temperature or age, once it is fixed into read only memory, it stays fixed. There are fewer capacitors, inductors, or resistors to drift out of alignment on equipment using digital signal processing ICs. Consequently, the systems need less routine maintenance to adjust and recalibrate the circuits. Since the performance-critical features of the circuit are embodied in software, routine maintenance can be performed by less-skilled laborers.

Cost

Cost saving is dependent upon the complexity of the final system. In simple systems with modest performance requirements, the costs of DSP components are unacceptable at the present state of the art. When designing a single filter, for example, it is usually cheaper to use operational amplifiers instead of a signal processor.

With high-performance applications, however, the cost advantages are clear. In fact, some systems have performance requirements that are very difficult to achieve without using DSP techniques. For example, one DSP chip can replace an entire board of audio frequency analog circuits. A DSP processor can implement 100 filters by multiplexing the use of a single multiplier and adder. An analog implementation, by comparison, would need 100 individual sets of hardware. In a DSP circuit, each signal requires only a memory location, while an analog implementation requires an actual line for each signal.

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Life costs are lower since the DSP algorithm does not change as devices age. This helps to minimize "downtime" required for routine maintenance because the DSP circuits do not need frequent realignment. In many military and telecommunications projects maintenance and total life costs are primary decision criteria.

DIGITAL SIGNAL PROCESSING DISADVANTAGES

Lack of Knowledge

The slow acceptance of DSP is in part due to the need for education. Digital signal processing is a new technique compared to conventional analog methods. Consequently, fewer engineers are skilled in DSP compared to those who understand alternative techniques such as operational amplifiers. Furthermore, many of the design engineers experienced with DSP work on sensitive or classified military projects. For security reasons they are unable to publish as frequently or in as much detail as their industrial counterparts. This means that detailed application knowledge as well as the clever ideas and tricks-of-the-trade will take longer to diffuse throughout the industry.

Retraining

Test and assembly technicians will require retraining in the digital signal processing technology. This involves considerable expense and time in a large manufacturing organization. Technicians who have accumulated years of intuitive know-how will find a portion of their skill obsolete with the conversion to DSP technology.

Instrumentation

Manufacturing operations will have to retrofit test and assembly stations with some new equipment and other instruments will become obsolete. This also applies to field repair depots.

Obsolescence

New parts in this rapidly changing technology are being introduced every month. But standards have not yet emerged. As IC manufacturers learn more about application requirements, they will continue to upgrade their component offerings. The result will be early obsolescence of first-generation parts. The risk is greater for equipment manufacturers because the semiconductor industry has not developed second sources for the new DSP chips.

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National Defense Issues

Military applications have been the driving force behind development of digital signal processing methods. Many of the components available today are critical in defense systems. From time to time this nation expresses concern about the export of such advanced technology. We know of no activity at present to limit the export of these devices. However, such actions could be considered in response to concerns about the supremacy of the United States' global military position. Such action would affect the international marketing strategy of U.S. semiconductor manufacturers.

A SIMPLE DSP CIRCUIT

A block diagram of a simple digital signal processing system is shown in Figure 1. This circuit is too simple to perform a useful function but will serve to illustrate some digital signal processing fundamentals. The basic elements are an analog-to-digital convertor (A/D), a digital section that performs operations using computer techniques, and a digital-to-analog convertor (D/A). The digital section is usually more complex than the simple register shown here. At each clock pulse, the A/D samples the input waveform and converts that voltage to a binary number. At the end of each clock period the number from the A/D is stored in the register. The output of the register is converted back to an analog signal that has different characteristics from the original input signal.

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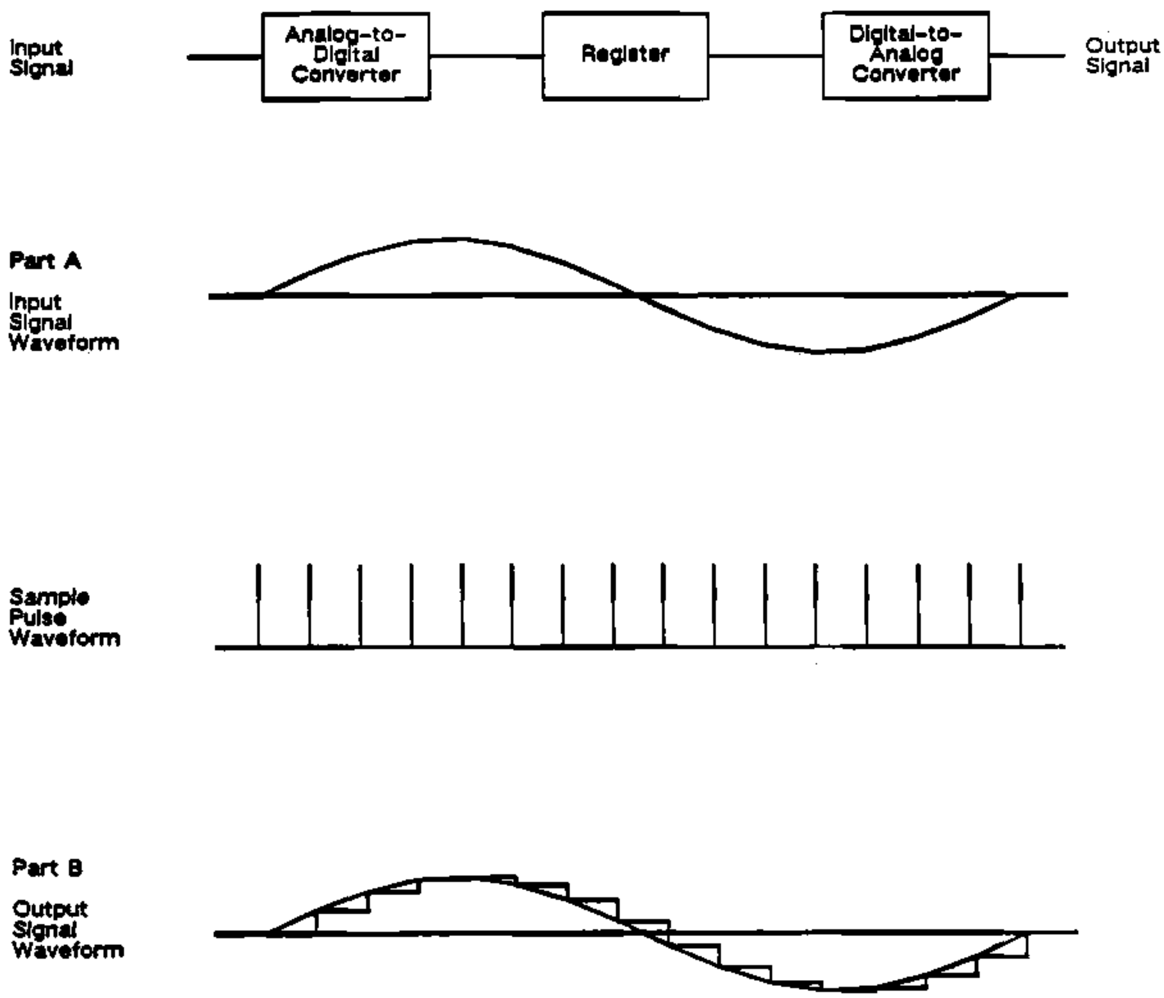
Figure 1

Block Diagram of a Simple DSP System



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DSP--Technical Overview

Sampling Rate

Note that although the input signal, as shown in part A of Figure 1, is a smooth continuous signal, the output signal, as illustrated in Part B of Figure 1, looks more like a set of stairs. With a faster sampling rate, the output signal will more closely approximate the input. This points out the importance of the sampling rate on the performance of the circuit. In general, a faster sampling rate is more desirable. There are, however, both theoretical and practical constraints upon the sampling rate.

The rate at which samples are taken is called the sampling frequency, usually expressed in megasamples per second (MSPS). From a theoretical basis, waveform sampling must occur at least twice as fast as the highest frequency component in order for the system to capture the information contained in that waveform. This is known as the Nyquist criterion. A sampling rate that is too low will create unwanted frequency components. A second consideration is the amount of time required for the various circuit elements to perform their part of the operation. This places a restriction on the maximum sample rate. A new sample cannot be taken, for example, until the A/D convertor finishes with the previous sample.

Word Length

At each tick of the sample clock, the circuit converts the analog input signal to a digital number. The number of bits in this number is the word length. This is important in determining how well the output represents the desired signal. Analog signals are continuous and have an infinite number of values, but digital signals only have a discrete and finite number of values. The apparent stair-step effect introduces noise in the output signal. The noise is called the quantization error. Therefore the finer the stair-step, the lower the noise component of the output signal.

Generally there is a 6dB of signal-to-noise ratio per bit. An 8-bit word will provide 48db of signal-to-noise ratio, which is telephone-line quality. A 16-bit word will provide 96db signal-to-noise ratio, which is superb high-fidelity quality. Processing speed is dependent upon the word length. A longer word length will require more time to perform the signal conversions and calculations. Consequently, each digital system designer must weigh the trade-off between speed and word length.

Distortion

There are two main reasons for unwanted signal components to be present in the output. First, if the input contains frequencies that are faster than the Nyquist rate, then false signals (called alias signals) will be present in the output. The solution is to increase the sampling rate or to eliminate the undesirable component from the input signal. Second, the stair-step-like output signal contains an infinite set of harmonics.

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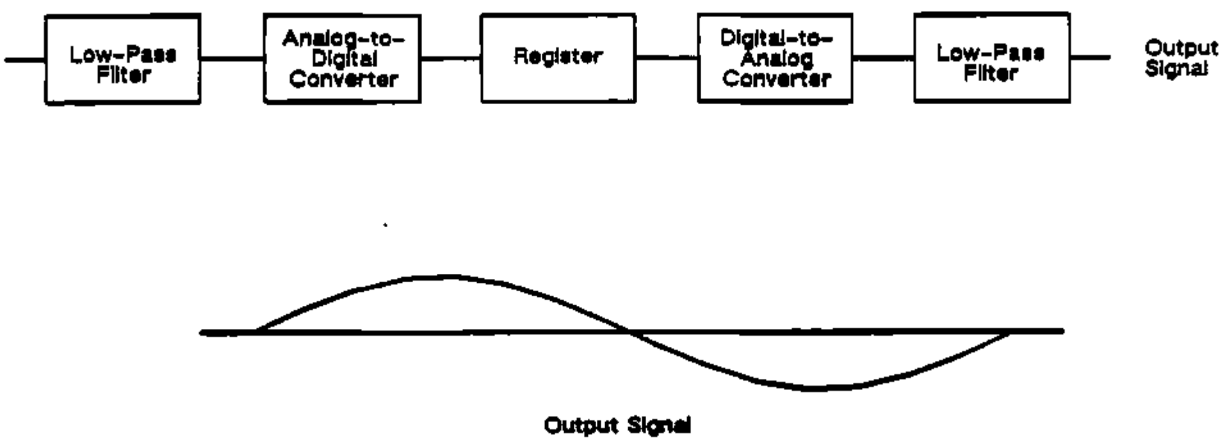
Low-pass filters, as shown in Figure 2, are used to eliminate these unwanted distortions. A low-pass filter placed in front of the A/D converter will eliminate the aliasing effect. This input filter is called an anti-aliasing filter. Another low-pass filter after the D/A converter will eliminate the quantization error. The addition of these two filters eliminates the unwanted distortion from the output signal.

Figure 2

A Simple DSP System with Anti-Aliasing Filters



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Where it might take 10 transistors and some coils and capacitors to design an analog filter, with DSP it might take 10,000 transistors. Thus it appears at first glance that DSP is an unwarranted luxury. However, DSP has a number of advantages, and in a world where transistors are free, DSP is steadily replacing analog.

A LOW-PASS FILTER: A PRACTICAL EXAMPLE

A block diagram for a simple DSP low-pass filter is shown in Figure 3. An input register takes the sample word from the A/D converter at each sample clock. A second register, the result register, feeds the D/A converter with the output signal. This hardware implements a simple equation that computes an output number as a combination of the input number and the previously computed number.

This implementation is the equivalent of a simple resistor, capacitor low-pass filter shown in Figure 4. The output register of the DSP low-pass filter acts like the capacitor, storing an average of all the previous samples. The constants, .3 and .7, determine the time constants.

Figure 3

Block Diagram for a Low-Pass Filter

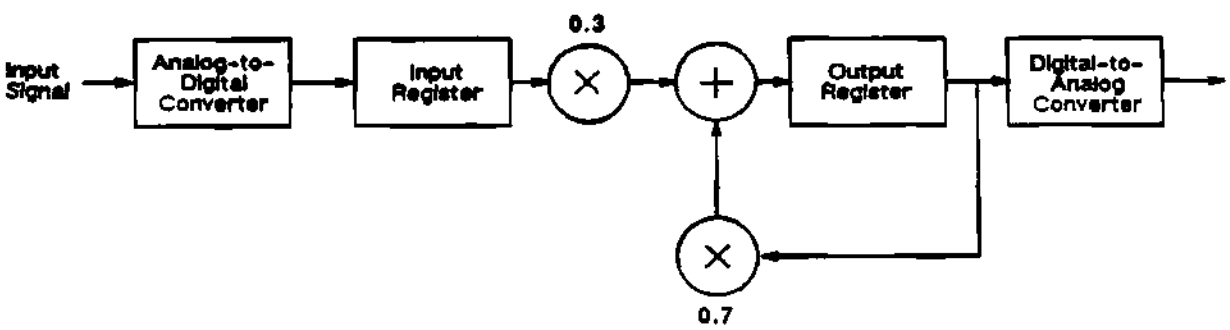

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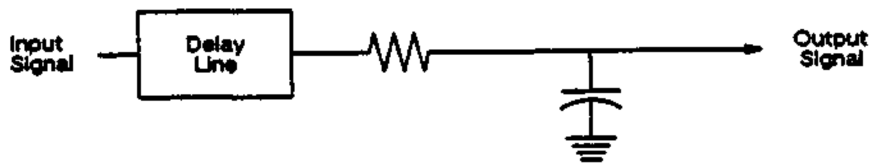
Figure 4

Analog Implementation of a Low-Pass Filter



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The input register is tied to a multiplier that calculates the product 0.3 times the value of the input signal and has this number available at its output at all times. For instance, if the input register contained the number 10, then the multiplier would have the number 3 at its output.

The result register is similarly tied to a multiplier that calculates the product 0.7 times the value in the result register and has this number available at its output. An adder sums the two multiplier outputs and provides a new input for the result register, thus completing the calculation for the current sample.

At each clock period the value in the input register is multiplied by 0.3 and is added to the value in the result register multiplied by 0.7. The result of this operation is stored in the result register, replacing the previous number. The final value in the result register at the end of the clock period is 0.3 x input + 0.7 x result. The content of the result register is then converted back to an analog value by the D/A converter.

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One common way to characterize the operation of a filter is to instantaneously change the input signal from zero to a constant value and observe the behavior of the output. Such an input is called a step function. The intermediate calculations and the final response to this step function are shown in Figure 5. This low-pass filter circuit smooths the waveform by averaging the input register and the result register. The sequences of numbers illustrate this averaging process by showing the values in the input and result registers at each sample period.

The first time period begins with the input signal equal to zero. After the A/D conversion process, the circuit stores the resulting binary 0 in the input register. The initial values of the registers are shown in the row labeled sample period 0. Before the next sample period, the input changes to 100 volts. At the next sample clock, the A/D converter puts the number 100 in the input register. During this period, the circuit computes the value 100 x 0.3 plus 0 x 0.7 and transfers the answer to the result register. As this process continues, the circuit generates a new output for each new value of the input signal.

When the input register equals 100, the output register approaches 100 exponentially. Likewise, when the input register equals zero, the output register approaches zero exponentially.

Note, however, that the output register approaches but never reaches the value 100. It appears to stop at 97 because of rounding error. Since this circuit uses integer arithmetic, the remainder of each multiplication operation is discarded. For instance, .3 x 100 + .7 x 97 = 97.9. The integer value of 97 is kept while the decimal part of 0.9 is dropped. In some applications this will cause unacceptable errors, so more complex floating point operations are employed.

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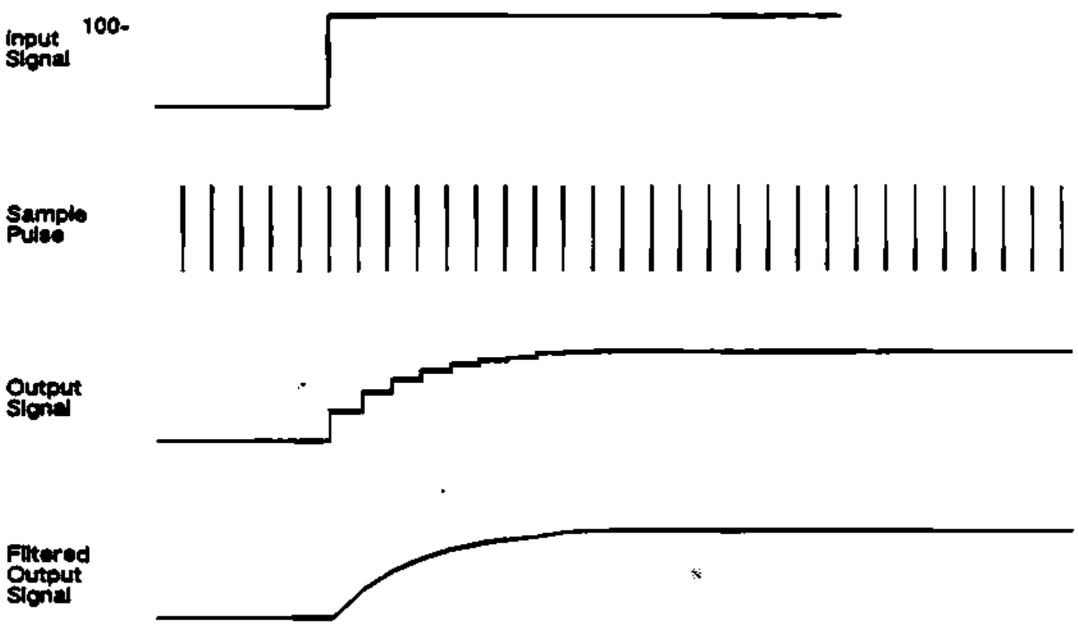
Figure 5

Step Function Response of a Digital Low-Pass Filter



Clock Period	Input Register	Result Register	Output Register
0	.3 x 0	.7 x 0	0
1	.3 x 100	.7 x 0	30
2	.3 x 100	.7 x 30	51
3	.3 x 100	.7 x 51	65
4	.3 x 100	.7 x 65	75
5	.3 x 100	.7 x 75	82
6	.3 x 100	.7 x 82	87
7	.3 x 100	.7 x 87	90
8	.3 x 100	.7 x 90	93
9	.3 x 100	.7 x 93	95
10	.3 x 100	.7 x 95	96
11	.3 x 100	.7 x 96	97
12	.3 x 100	.7 x 97	97

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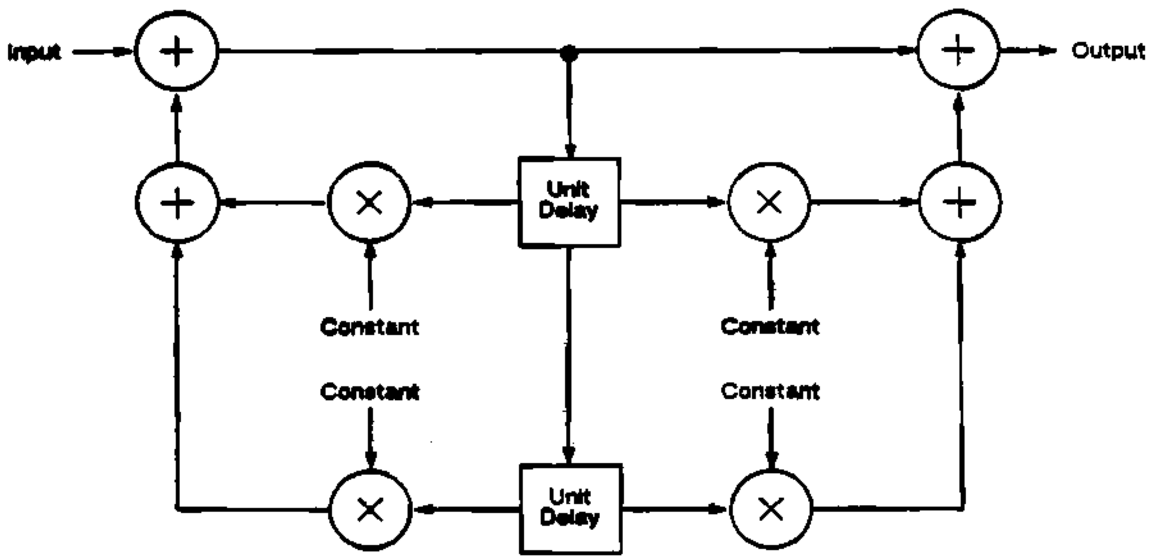
More complicated filters are possible with digital signal processing techniques. Common filter applications include the Biquad filter, the Finite Impulse Response filter, and many nonlinear filters.

The block diagram of a DSP implementation of a Biquad filter is shown in Figure 6. It is like an analog filter with capacitors, inductors, operational amplifiers, and feedback. The Biquad has both poles and zeros and can oscillate.

Figure 6

DSP Implementation of a Biquad Filter



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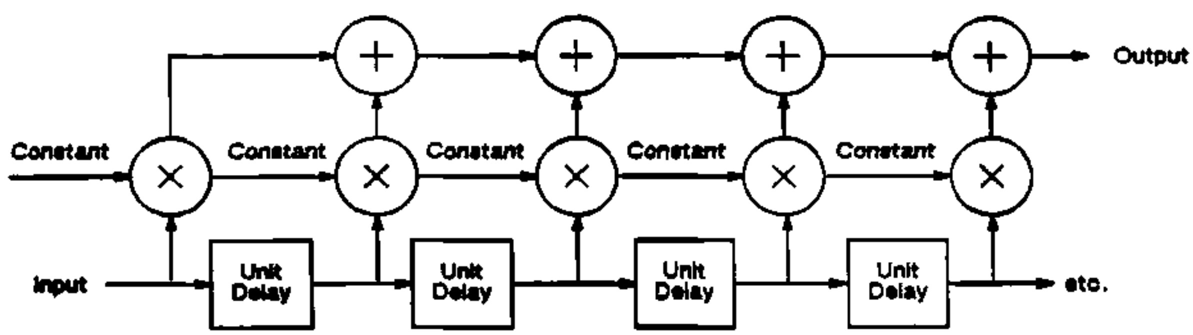
An important DSP filter is the Finite Impulse Response (FIR) filter shown in Figure 7. One of its nice features is its stability—there is no feedback. It is ideal for designing phase linear filters. A phase linear filter changes the amplitude of the frequency spectrum of a signal but does not affect its phase spectrum.

The FIR filter is especially important in communications and television. For instance, in television the phase of the subcarrier signal contains information about the picture color. Changes in the phase relationship will distort the picture color. By using the FIR, the composite television signal can be filtered without changing the color.

DSP can do other things that are difficult to do in the analog world. Decision algorithms such as pitch extraction, data compression, and speech compression are not simple filtering; they resemble computer programs with flowcharts and decision points. A DSP processor can do more than filtering; it can act like a computer by performing logical decisions.

Figure 7

Finite Impulse Response Filter



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Morristown, NJ 07960

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DND Teletronics, Inc.
235 Elizabeth Street
Utica, NY 13501

Dacon Electronics, Inc.
7 Industrial Avenue
Upper Saddle River, NJ 07458

Digital Transmission, Inc.
315 Eisenhower Lane South
Lombard, IL 60148

Fujitsu Systems of America, Inc.
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San Diego, CA 92130

GTE Switching & Telephone Products
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Stamford, CT 06904

Isotek Communications, Inc.
6 Thorndal Circle
Darien, CN 06820

Ring Communications
35 Pinelawn Road
Melville, NY 11747

Rockwell International
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Dallas, TX 75207

ROLM Corporation
4900 Old Ironsides Drive
Santa Clara, CA 95050

Solid-State Systems
1990 Delk Industrial Blvd.
Marietta, GA 30067

Teknekron/Infoswitch
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Richardson, TX 75081

Telcom Technologies
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Ontario, CA 91764

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CADLINC, Inc.
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Elk Grove, IL 60007

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Boulder, CO 80301

Calay Systems, Inc.
Irvine, CA

Calma Company
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Automation Company
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Prime Park
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Gloucestershire, England
GL20 8HE

Scientific Calculations, Inc.
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Fishers, NY 14453

Silvar-Lisco
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Synercom
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Sugarland, TX 77478

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New York, NY 10022

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Garden Grove, CA 92641

GTE Communications Systems
2800 Utopia Road
Phoenix, AZ 85027

International Telephone
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Network Systems Division
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Raleigh, NC 27604

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Reno, NV 89520

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Radio & Transmission Division
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Northern Telecom, Inc.
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Stone Mountain, GA 30083

Pulsecom
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Herndon, VA 22071

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Downers Grove, IL 60515

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Transmission Systems Division
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Irvine, CA 92718

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Tulsa, OK 74102

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4951 Indiana Avneue
Lisle, IL 60532

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South Corinth, MI 38834

E.F. Johnson Company
299 Johnson Avenue
Waseca, MN 56093

Ericsson Radio Systems
730 International Parkway
Richardson, TX 75081

Fujitsu America, Inc.
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New York, NY 10022

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Dept. 582/A6
400 North Wolf Road
Northlake, IL 60164

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Mountain View Road
Lynchburg, VA 24502

Glenayre Electronics
12 Pacific Highway
Blaine, WA 98230

Harris Corp.
RF Communications Group
1680 University Avenue
Rochester, NY 14610

Hitachi America, Ltd.
2990 Gateway Dr., Suite 1000
Norcross/Atlanta, GA 30071

ITT Telecon
3100 Highwoods Blvd.
Raleigh, NC 27604

Kokusai Electronic Company Ltd.
America
363 Coral Circle
El Segundo, CA 90245

Mitsubishi International
Corporation
879 Systems Drive
Bewsenville, IL 60106

Northern Telecom, Inc.
1201 East Arapaho Road
Richardson, TX 75081

NovAtel Communications
2820 Peterson Place
Norcross, GA 30071

OKI Advanced Communications
1 University Plaza
Hackensack, NJ 07601

Panasonic Industrial Company
Telecommunications Division
1 Panasonic Way
Secaucus, NJ 07094

Quintron Corporation
1 Quintron Way
P.O. Box 3726
Quincy, IL 62305

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Reston, VA 22091

GTE Communications Systems
2500 W. Utopia Rd.
Phoenix, AZ 85027

ITT Telecom
Network Systems Division
3100 Highwoods Blvd.
Raleigh, NC 27604

Northern Telecom, Inc.
4001 E. Chapel Hill-Nelson Hwy.
Research Triangle Park, NC 27709

Stromberg-Carlson
400 Rinehart Rd.
Lake Mary, FL 32746

NEC America, Inc.
1525 Walnut Hill Lane
Irving, TX 75062

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ADC
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Minneapolis, MN 55435

Advanced Data Support Systems
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Bakersfield, CA 93307

Amdahl
2200 N. Greenville
Richardson, TX 75081

Anritsu
128 Bauer
Oakland, NJ 07436

AstroCom Corporation
120 W. Plato
St. Paul, MN 55107

AT&T Communications
202/206 North
Bedminster, NJ 07921

AT&T Information Systems
One Exchange Plaza
New York, NY 10006

Atlantic Research
7401 Boston Blvd.
Springfield, VA 22153

Avant-Garde Computing
8000 Commerce Parkway
Mount Laurel, NJ 08054

Bytex Corporation
120 Turnpike Rd.
Southborough, MA 01776

C-Cor Electronics
1400 N.W. Compton Dr.
Beaverton, OR 97006

Case Communications
2120 Industrial Parkway
Silver Spring, MD 20904

Codex Corporation
20 Cabot Blvd.
Mansfield, MA 02048

Connections Telecommunications
130 Steamboat Rd.
Great Neck, NY 11024

Dataswitch Corporation
444 Westport Ave.
Norwalk, CT 06851

Datacom Northwest
3303 112th St.
Everett, WA 98204

Datacomm Management Sciences
25 Van Zant St.
East Norwalk, CT 06855-1790

Datagram
11 Main St.
East Greenwich, RI 02818

Datatel
81 N. Oak Lane
Cherry Hill, NJ 08003

Digilog Inc.
1370 Welsh Rd.
Montgomeryville, PA 18936

Digitech Industries
66 Grove St.
Ridgefield, CT 06877

DMW Group
2070 Hogback Rd.
Ann Arbor, MI 48104

Domain Systems
241 Central Avenue
East Farmingdale, NY 11735

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Directory of Potential Users
Data Network Control Systems

COMPANY DIRECTORY (Continued)

Dynatech Data Systems
7644 Dynatech Ct.
Springfield, VA 22153

Electrodata, Inc.
23070 Miles Rd.
Bedford Heights, OH 44128

Emcom Corporation
101 E. Park Blvd.
Plano, TX 75074

Foremark Technologies
550 Old Country Rd.
Hicksville, NY 11801

General Datacomm
Route 63
Middlebury, CT 06762-1298

Giltronix
3780 Fabian Way
Palo Alto, CA 94303

Hard Engineering, Inc.
2804 B Memorial Parkway
Huntsville, NY 35801

Hekimian Labs
9298 Gaither Rd.
Gaithersburg, MD 70877

Hewlett-Packard
P.O. Box 7050
Colorado Springs, CO 80933

Halcyon
2121 Zanker Rd.
San Jose, CA 95131

IBM Corporation
1133 Westchester Ave.
White Plains, NY 10604

Idacom Electronics
Research Center One
9411-20th Ave.
Edmonton, Alberta, Canada T6W 1E5

Infinet
6 Shattuck Rd.
Andover, MA 01810

Infotron Systems Corporation
Cherry Hill Industrial Center
9 N. Olay Ave.
Cherry Hill, NJ 08003

LPCom
21020 Homestead Rd.
Cupertino, CA 95014

Navtel
3331 N.W. 55th St.
Ft. Lauderdale, FL 33309

NCC
9600 W. 76th St.
Minneapolis, MN 55344

NEC America
110 Rio Robles
San Jose, CA 95134

Northern Telecom
Spectron Division
8000 Lincoln Dr.
Marlton, NJ 08053

NU Data
32 Fairview Ave.
Little Silver, NJ 07739

Ocean Data Systems
6000 Executive Blvd.
Rockville, MD 20852

Paradyne Corporation
8550 Ulmerton Rd.
Largo, FL 33541

Penril Datacomm
207 Perry Parkway
Gaithersberg, MD 20877-2197

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COMPANY DIRECTORY (Continued)

Plantronics Wilcom
P.O. Box 508
Laconia, NH 03247

Questronics
3570 South W. Temple
Salt Lake City, UT 84115

Racal-Milgo
1601 N. Harrison Parkway
Sunrise, FL 33323

Symplex
2002 Hogback Road
Ann Arbor, MI 48107

T-Bar, Inc.
141 Danbury Rd.
Wilton, CT 06847

Tekelec, Inc.
26540 Agoura Rd.
Calabazas, CA 91302

Tektronix
1800 S.W. Merlord
Beaverton, OR 97075

Telecommunications Technologies
444 N. Fredrick Ave.
Gaithersburg, MD 20877

Telenex
502 Pleasant Valley Ave.
Moorestown, NJ 08057

Teleprocessing Products
4565 E. Industrial St.
Simi Valley, CA 93036

Tymnet
2710 Orchard Parkway
San Jose, CA 95014

VIR
2255 Pioneer Rd.
Hatboro, PA 19040

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Directory of Potential Users
Data PBX

COMPANY DIRECTORY

ATT Network Systems
475 South Street
Morristown, NJ 07960

Bridge Communications
2081 Stierlin Road
Mountain View, CA 94043

CASE Communications
8310 Guilford Road
Columbia, MD 21046

Codex Corporation
20 Cabot Boulevard
Mansfield, MA 02048

ComDesign Inc.
751 S. Kellogg Avenue
Goleta, CA 93117

Commtex Inc.
24511 Crofton Lane
Crofton, MD 21114

Develcon Electronics
744 Nina Way
Warminister, PA 18974

Equinox Systems, Inc.
12041 S.W. 144th Street
Miami, FL 33186-6108

Gandalf Data, Inc.
1019 S. Noel Avenue
Wheeling, IL 60090

Infotron Systems Corporation
Cherry Hill Industrial Center
Cherry Hill, NJ 08003

Intelligent Business Communications
80 Oser Avenue
Hauppauge, NY 11787

M/A-COM Linkabit, Inc.
3033 Science Park Road
San Diego, CA 92121

METAPATH, Inc.
727 Lincoln Center Drive
Foster City, CA 94404

Micom Systems, Inc.
20151 Nordhoff Street
Chatsworth, CA 91311

Network Products
Research Triangle Park, NC 27709

Sequal Data
975 Walnut Street
Cary, NC 27511

TELLABS, Inc.
4951 Indiana Avenue
Lisle, IL 60532

Western Telematic Inc.
2435 S. Anne Street
Santa Ana, CA 92704

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Directory of Potential Users
Digital Radiography

COMPANY DIRECTORY

ADAC Laboratories
Sunnyvale, CA

Andersen Group, Inc.
Bloomfield, CT

Diasonics, Inc.
Milpitas, CA

Picker International
Highland Heights, OH

Philips Medical Systems, Inc.
Shelton, CT

Raytheon Medical Systems
Lexington, MA

Siemens
Iselin, NJ

Squibb Corporation
Princeton, NJ

Technicare Corporation
Solon, OH

Toshiba Medical Systems
Tustin, CA

Xonics
Des Plaines, IL

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Directory of Potential Users
Facsimile Equipment

COMPANY DIRECTORY

Adler-Royal Business
 Machines, Inc.
1600 Route 22
P.O. Box 1597
Union, NJ 07083

Alden Electronics, Inc.
Washington Street
Westborough, MA 01581

Amacom
5115 Calvert Road
College Park, MD 20740

AT&T Information Systems
One Speedwell Avenue
Morristown, NJ 07960

Fujitsu Imaging Systems of
 America, Inc.
Corporate Drive, Commerce Park
Danbury, CT 06810

Canon U.S.A., Inc.
One Canon Plaza
Lake Success, NY 11042

Hitachi America Ltd.
2990 Gateway Drive
Suite 1000
Norcross, GA 30071

Minolta Corporation
101 Williams Drive
Ramsey, NJ 07446

Mitsubishi Electric Sales
 of America, Inc.
5757 Plaza Drive
Cypress, CA 90630

Muirhead Inc.
1101 Bristol Road
Mountainside, NJ 07092

Murata Business Systems
4801 Spring Valley Road
Suite 108B
Dallas, TX 75240

NEC America, Inc.
8 Old Sod Farm Road
Melville, NY 11747

Panafax Corporation
10 Melville Park Road
Melville, NY 11747

Pitney Bowes
1515 Summer Street
Stamford, CT 06926

Ricoh Corporation
7 Kingsbridge Road
Fairfield, NY 07006

Sanyo Business Systems
 Corporation
51 Joseph Street
Moonachie, NJ 07074

Sharp Electronics Corporation
10 Sharp Plaza
Paramus, NJ 07652

Teleautograph Corporation
8700 Bellanca Avenue
Los Angeles, CA 90045

Harris/3M Business Products, Inc.
2300 Parklake Drive, N.E.
Atlanta, GA 30345

Toshiba America
2441 Michelle Drive
Tustin, CA 92680

Xerox Corporation
Information Products Division
1341 West Mockingbird Lane
Dallas, TX 75247

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Directory of Potential Users
Front-End Processors

COMPANY DIRECTORY

Amdahl Corporation
1250 E. Arques Avenue
P.O. Box 3470
Sunnyvale, CA 94088

Burroughs Corporation
Burroughs Place
Detroit, MI 48232

CHI Corporation
26055 Emery Road
Cleveland, OH 44128

Computer Communications, Inc.
2610 Columbia Street
Torrance, CA 90503

Control Data Corporation
8100 34th Avenue, South
Minneapolis, MN 55440

Honeywell Information
 Systems, Inc.
Honeywell Plaza
Minneapolis, MN 55408

IBM Corporation
P.O. Box 12195
Research Triangle Park, NC 27709

Lemcon Systems, Inc.
2104 W. Peoria
Phoenix, AZ 85029

NCR Comten, Inc.
1700 S. Patterson Blvd.
Dayton, OH 45479

Periphonics
4000 Veterans Memorial Hwy.
Bohemia, NY 11716

Sperry Corporation
Computer Systems Operations
P.O. Box 500
Blue Bell, PA 19424

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Directory of Potential Users
Graphics Systems

COMPANY DIRECTORY

Adage, Inc.
One Fortune Drive
Billerica, MA 01821

CIE Terminals, Inc.
2505 McCabe Way
Irvine, CA 97214

Digital Equipment Corporation
146 Main Street
Maynard, MA 01754

Hewlett-Packard Company
3000 Hanover Street
Palo Alto, CA 94304

Intecolor Corporation
225 Technology Park/Atlanta
Norcross, GA 30092

ITT Qume Corporation
2350 Qume Drive
San Jose, CA 95131

Tectronix, Inc.
P. O. Box 1700
Beaverton, OR 97075

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Directory of Potential Users
Integrated Voice/Data Workstations

COMPANY DIRECTORY

AMBI Corporation
1033 Washington Blvd.
Stamford, CT 06901

AT&T Information Systems
1766 on The Green
Room 48-5A38
Morristown, NJ 07960

Basic Telecommunications Corp.
4414 East Harmony Road
Fort Collins, CO 80525

Cygnet Technologies
12 Lawrence Station Road
Sunnyvale, CA 94089

DAVOX Corporation
4 Federal Street
Billerica, MA 01821

GEC Information Systems, Ltd.
P.O. Box 6
Coventry CV1 5PU
England

Liberty Electronics
625 Third Street
San Francisco, CA 94107

Matra Communications, Inc.
1202 Charleston Road
Mountain View, CA 94043

Mitel Corporation
5400 Broken Sound Blvd.
Boca Raton, FL 33431

Northern Telecom, Inc.
9705 Data Park
Minnetonka, MN 55440

ROLM Corporation
2420 Ridgeport Drive
Austin, TX 78754

Sydis, Inc.
4340 Stevens Creek Blvd.
San Jose, CA 95129

Telerad Telecommunications and
Electronic Industries, Ltd.
P.O. Box 50
Lod, Israel 71100

Thomson CSF
2 Gannett Drive
White Plains, NY 10604

Zaisan
13910 Champion Forest Drive
Houston, TX 77069

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Directory of Potential Users
Key Telephone Systems

COMPANY DIRECTORY

ADAX
6961 Peachtree Industrial Blvd.
Norcross, GA 30071

AEL Microtel, Ltd.
100 Strowger Blvd.
Brockville, Ontario K6V 5WB
Canada

AT&T Technologies, Inc.
222 Broadway
New York, NY 10017

Astrocom Division, QCT, Ltd.
1702 South Del Mar Ave.
San Gabriel, CA 91776

ASUZI, Inc.
310 Frontage Road
Greer, SC 29651

Code-a-Phone
P.O. Box 5656
Portland, OR 97228

Comdial Telephone Systems, Inc.
1180 Seminole Trail
Charlottesville, VA 22906

Crest Industries, Inc.
6922 North Meridian
Puyallup, WA 98371

DBA Communication Systems, Inc.
339 West 2nd Street
N. Vancouver, B.C. V7M 1E2
Canada

DEKA, Inc.
16555 Shannon Road
Los Gatos, CA 95030

Eagle Telephonics, Inc.
375 Oser Avenue
Hauppauge, NY 11788

Emulex Corporation
3545 Harbor Blvd.
Costa Mesa, CA 92626

Ericsson
P.O. Box 3110
Greenwich, CT 06832

EXTROM Communications
137 Express Street
Plainview, NY 11803

Fujitsu Business Communications, Inc.
3190 Mira Loma Avenue
Anaheim, CA 92806

GAI-Tronics
P.O. Box 31
Reading, PA 19603

GTE Business Communications Systems, Inc.
8301 Greensboro Drive
McLean, VA 22102

Goldstar Telecommunications, Inc.
One Madison Street
East Rutherford, NJ 07073

Harris/Lanier
1700 Chantilly Drive N.E.
Atlanta, GA 30324

Hitachi America
2696 Peachtree Square
Doraville, GA 30360

ITT Telecom
3100 Highwoods Blvd.
Raleigh, NC 27604

In Electronic Inc.
667 Madison Ave., Suite 800
New York, NY 10021

Information Dynamics
1251 Exchange Drive
Richardson, TX 75081

Integrated Telecomputing Systems
1153 Bordeaux Dr., Ste. 107
Sunnyvale, CA 94086

COMPANY DIRECTORY (Continued)

Inter-Tel Equipment, Inc.
3232 West Virginia Ave.
Phoenix, AZ 85009

Interconnect Planning Corp.
One Lafayette Place
Greenwich, CT 06830

Isoetec
6 Thorndal Circle
Darien, CT 06970

Iwatsu America, Inc.
430 Commerce Blvd.
Carlstadt, NJ 07072

Jackson Associates
505 North Lake Shore Drive
Chicago, IL 60611

Kanda Telecom, Inc.
11130 Metric Blvd.
Austin, TX 78758

Kanda Tsushin Kogyo
611 West 6th Street
Los Angeles, CA 90017

Ma Best Telephone Products
P.O. Box 4522
North Hollywood, CA 91607

Melco Labs
14408 N.E. 20th
Bellevue, WA 98007

Micro-Z
900 South Magnolia Avenue
Monrovia, CA 91016

Mitel
5400 Broken Sound Blvd.
Boca Raton, FL 33431

Model Rectifier Corp.
2500 Woodbridge Ave.
Edison, NJ 08817

Multitel
505 North Lake Shore Drive
Chicago, IL 60611

NEC Telephones, Inc.
8 Old Sod Farm Road
Melville, NY 11747

Nicho
8660 Troy Twp. Rd. #4 RR9
Mansfield, OH 44904

Northcom
600 Industrial Parkway
Industrial Airport, KS 66031

Northern Telecom, Ltd.
Business Products Division
2916 5th Ave., N.E.
Calgary, Alberta T2A 6K4
Canada

Oki Electronics of America
4031 N.E. 12th Terrace
Fort Lauderdale, FL 33308

PKS Communications
46 Quirk Road
Milford, CT 06460

Panasonic
One Panasonic Way, Box 1503
Secaucus, NJ 07094

Philips Communications
89 Marcus Blvd.
Hauppauge, NY 11788

Philips KBX Systems
85 McKee Road
Mahwah, NJ 07430

Plant Equipment Inc.
28075 Diaz Rd.
Temecula, CA 92390

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COMPANY DIRECTORY (Continued)

Plessey Communications
235 Yorkland Blvd.
Willowdale, Ontario
Canada

Proctor & Associates
15050 Northeast 36th Street
Redmond, WA 98052

R-TEC Systems
2100 Reliance Parkway
Bedford, TX 76021

SAN/BAR Corp.
Telephone Systems Division
2405 South Shiloh Road
Garland, TX 75041

Sanyo Business Systems
51 Joseph Street
Moonachie, NJ 07074

Scott Technologies Corp.
Foot of Broad Street
Stratford, CT 06497

Solid State Systems
1990 Delk Industrial Blvd.
Marietta, GA 30067

TIE/Communications, Inc.
5 Research Drive
Shelton, CT 06484

TT Systems Corp.
9 East 37th Street
New York, NY 10016

Tadiran Electronic Industries
10901 Endeavour Way, Ste. A
Largo, FL 33543

Technicom International
23 Old Kings Highway South
Darien, CT 06820

Tecom
8134 Zionville Road
Indianapolis, IN 46268

Telefony and Electronics
of America, Inc.
8675 N.W. 56th St.
Miami, FL 33166

Tel-Path Industries
3361 Melrose Ave.
Roanoke, VA 24017

TelRad
42-15 Crescent Street
Long Island City, NY 11101

TELEDEX
4051 Burton Drive
Santa Clara, CA 95050

Telephonic Equipment
17401 Armstrong Avenue
Irvine, CA 92714

Teletec Systems
1380 Old Freeport Road
Pittsburgh, PA 15238

Teltone Corp.
10801-120th Avenue, N.E.
Kirkland, WA 98033

Teltrend Inc.
P.O. Box 400, Dept. 101A
West Chicago, IL 60185

Thomson-CSF
Two Gannet Drive
White Plains, NY 10604

Tone Commander Systems
4320 150th Avenue N.E.
Redmond, WA 98052

Toshiba America
2441 Michelle Drive
Tustin, CA 92680

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COMPANY DIRECTORY (Continued)

Touch Com
253 North Grand Avenue
Poughkeepsie, NY 12603

Trillium Telephone Systems
603 March Road
Kanata
Canada K2K 1X3

Turret Equipment Corp. (TEC)
880 3rd Avenue
New York, NY 10022

Tymetek
770 Church Road
Elmshurst, IL 60126

V Band Systems
345 Hudson Street
New York, NY 10014

Valcom
1111 Production Street
Roanoke, VA 24013

Viking Electronics
P.O. Box 4522
North Hollywood, CA 91607

Vodavi
8300 E. Raintree Drive
Scottsdale, AZ 85260

Walker Communications Corp.
200 Oser Avenue
Hauppauge, NY 11788

WEBCOR Electronics
28 South Terminal Drive
Plainview, NY 11803

Wren Company c/o Nicho
880 Reynard Street
Cincinnati, OH 45231

XTEL
1301 Cornell Parkway
Oklahoma City, OK 73108

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Directory of Potential Users
Local Area Network Equipment

COMPANY DIRECTORY

Acorn Computers
Fulbourn Road
Cherry Hinton
Cambridge CB1 4JN
England

Advanced Computer Communications
720 Santa Barbara Street
Santa Barbara, CA 93101

Allen-Bradley Co., Inc.
555 Briarwood Circle
Ann Arbor, MI 48104

Allied Data Communications Group
5375 Oakbrook Parkway
Norcross, GA 30093

American Photonics
71 Commerce Drive
Brookfield Center, CT 06805

AMP Incorporated
P.O. Box 3608
Harrisburg, PA 17105

Apollo Computer, Inc.
330 Billerica Road
Chelmsford, MA 01824

Apple Computer, Inc.
20525 Mariani Avenue
Cupertino, CA 95014

Applied Knowledge Groups
1095 E. Duane Street, Suite 203
Sunnyvale, CA 94086

Applitek Corporation
107 Audubon Road
Wakefield, MA 01880

Artel Communications Corporation
P.O. Box 100, West Side Station
Worchester, MA 01602

Astra Communications, Inc.
329 North Bernardo
Mountain View, CA 94043

AST Research
2121 Alton Avenue
Irvine, CA 92714

AT&T Information Systems
Crawford Corner Road
Holmdel, NJ 07737

Avatar Technologies, Inc.
99 South Street
Hopkinton, MA 01748

Banyan Systems, Inc.
135 Flanders Road
Westboro, MA 01581

BICC Data Networks
1800 West Park Drive
Westborough, MA 01581

Bridge Communications, Inc.
2081 Stierlin Road
Mountain View, CA 94043

Cabletron
2514 Seaboard Avenue
San Jose, CA 95131

Chipcom Corporation
195 Bear Hill Road
Waltham, MA 02154

Codenoll Technology
1086 N. Broadway
Yonkers, NY 10701

Codex (a subdivision of Motorola)
20 Cabot Boulevard
Mansfield, MA 02048

COMPANY DIRECTORY (Continued)

ComDesign, Inc.
751 South Kellog Avenue
Goleta, CA 93117

Communication Machinery Corporation
1421 State Street
Santa Barbara, CA 93101

Complexx Systems, Inc.
4930 Research Drive
Huntsville, AL 35805

Computer Pathways
19102 North Creek Parkway
Bothell, WA 98011

Concord Communications, Inc.
397 Williams Street
Marlborough, MA 01752

Contel Business Networks
4330 East-West Highway
Bethesda, MD 20814

Control Data Corporation
8100 34th Avenue South
Minneapolis, MN 55440

Convergent Technologies, Inc.
2700 N. First Street
San Jose, CA 95150

Corvus Systems, Inc.
2100 Corvus Drive
San Jose, CA 95124

Data General Corporation
4400 Computer Drive
Westboro, MA 01580

Datapoint
9725 Datapoint Drive
San Antonio, TX 78284

DAVID Systems, Inc.
701 East Evelyn Avenue
Sunnyvale, CA 94086

The Destek Group
830 East Evelyn Avenue
Sunnyvale, CA 94086

Digital Communications Assoc.
1000 Alderman Drive
Alpharetta, GA 30201

Digital Equipment Corporation
1925 Andover Street
Tewksbury, MA 01876

Digital Products, Inc.
108 Water Street
Watertown, MA 02172

Excelan, Inc.
2180 Fortune Drive
San Jose, CA 95131

Fairchild Data Corporation
350 N. Hayden Road
Scottsdale, AZ 85257

Fast Feedback Technologies
1505 Aviation Boulevard
Redondo Beach, CA 90278

FiberCom, Inc.
3353 Orange Avenue, N.E.
Roanoke, VA 24012

FiberLAN
P.O. Box 12726
Research Triangle Park, NC 27709

Fibronics
325 Stevens Street
Hyannis, MA 02601

COMPANY DIRECTORY (Continued)

Fox Research
7005 Corporate Way
Dayton, OH 45459

Gandalf Data, Inc.
1019 South Noel Avenue
Wheeling, IL 60090

Gateway Communications, Inc.
2941 Alton Avenue
Irvine, CA 92714

Hewlett-Packard Company
5725 West Las Positas
Pleasanton, CA 94566

Honeywell, Inc.
P.O. Box 8000
Phoenix, AZ 85066

IBM Corporation
Research Traingle Park, NC 27709

IBM Entry Systems Division
1000 NW 51st Street
Boca Raton, FL 33432

IdeAssociates, Inc.
29 Dunham Road
Billercia, MA 01821

Infotron Systems
Cherry Hill Industrial Center
Cherry Hill, NJ 08003

Intel Corporation
3065 Bowers Avenue
Santa Clara, CA 95051

Intel Corporation
5000 West Chandler Boulevard
Chandler, AZ 85226

ITT Information Systems
2350 Qume Drive
San Jose, CA 95131

Kee Incorporated
10727 Tucker Street
Beltsville, MD 20705

Kimtron
1709 Junction Court, Bldg. 380
San Jose, CA 95112-1090

KMW-Auscom
8307 Highway 71 West
Austin, TX 78735

Lancore Technologies, Inc.
31324 Via Colinas, #110
Westlake Village, CA 91362

LanTel Corporation
3100 Northwoods Place, Suite A
Norcross, GA 30071

Metapath
222 Lincoln Center Drive
Foster City, CA 94404

Micom/Interlan
155 Swanson Road
Boxborough, MA 01719

Microsoft
16011 N.E. 36th Way
Redmond, WA 98073

Motorola/Four-Phase Systems
10700 N. De Anza Boulevard
Cupertino, CA 95014

National Semiconductor
2900 Semiconductor Drive
Santa Clara, CA 95051

COMPANY DIRECTORY (Continued)

NCR Corporation
1700 So. Patterson Boulevard
Dayton, OH 45479

Nestar Systems, Inc.
1345 Shorebird Way
Mountain View, CA 94043

Netlink
3214 Spring Forest Road
Raleigh, NC 27604

Netronix
1372 North McDowell Boulevard
Petaluma, CA 94952

Network General Corporation
1296B Lawrence Station Road
Sunnyvale, CA 94089

Network Research Corporation
2380 North Rose Avenue
Oxnard, CA 93030

Network Systems Corporation
7600 Boone Avenue North
Brooklyn Park, MN 55428

Novell, Inc.
748 North 1340 West
Orem, UT 84057

Orchid Technology, Inc.
47790 Westinghouse Drive
Fremont, CA 94539

Paradyne Corporation
8550 Ulmerton Road
Largo, FL 33541

Phoenix Digital
2315 North 35th Avenue
Phoenix, AZ 85009

Phoenix Technology Inc.
2803 Bunker Hill Drive
Santa Clara, CA 95054

Prime Computer Inc.
Prime Park
Natick, MA 01760

Proteon
Two Technology Drive
Westborough, MA 01581-5008

Quadram Corporation
4355 International Boulevard
Norcross, GA 30093

Racal-Milgo
8600 N.W. 41st Street
Miami, FL 33166

Retix
1547 Ninth Street
Santa Monica, CA 90401

Santa Cruz Operation
400 Encinal Street
Santa Cruz, CA 95061

Server Technology Inc.
1095 E. Duane Street, Suite 103
Sunnyvale, CA 94086

Siecor Corporation
P.O. Box 13625
Research Triangle Park, NC 27709

Siemens Information Systems Group
5500 Broken Sound Boulevard
Boca Raton, FL 33431

The Software Link, Inc.
8601 Dunwoody Place, Suite 632
Atlanta, GA 30338

Standard Microsystems Corporation
35 Marcus Boulevard
Hauppauge, NY 11788

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COMPANY DIRECTORY (Continued)

Sterling Communications Corporation
10320 Little Patuxent Parkway
Suite 808
Columbia, MD 21044

Sun Microsystems
2550 Garcia Avenue
Mountain View, CA 94043

Sytek
1225 Charleston Road
Mountain View, CA 94043

Tandem Computers, Inc.
19333 Vallco Parkway
Cupertino, CA 95014

Texas Instruments, Inc.
Data Systems Group
Dallas, TX 75380

Tiara Computer Systems, Inc.
2685 Marine Way
Mountain View, CA 94043

Torus
495 Seaport Court, Suite 105
Redwood City, CA 94063

TRW Information Networks Division
23800 Hawthorne Boulevard
Torrance, CA 90505

Ungermann-Bass, Inc.
3990 Freedom Circle
Santa Clara, CA 95052

Univation, Inc.
1231 California Circle
Milpitas, CA 94035

Vitalink
1350 Charleston Road
Mountain View, CA 94043

Wang Laboratories, Inc.
One Industrial Way
Lowell, MA 01851

Waterloo MicroSystems, Inc.
175 Columbia Street West
Waterloo, Ontario
Canada

Western Digital Corporation
2445 McCabe Way
Irvine, CA 92714

The Wollongong Group
1129 San Antonio Road
Palo Alto, CA 94303

Xerox Corporation
Xerox Square 006
Rochester, NY 14644

Xyplex, Inc.
100 Domino Drive
Concord, MA 01742

Zenith Electronics Corporation
699 Wheeling Road
Mt. Prospect, IL 60056

Zeta Laboratories
3265 Scott Boulevard
Santa Clara, CA 95054

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Directory of Potential Users Medical NMR Equipment

COMPANY DIRECTORY

Diasonics, Inc.
Milpitas, CA

Fonar Corporation
Melville, NY

General Electric Medical Systems
Milwaukee, WI

Philips Medical Systems, Inc.
Shelton, CT

Picker International
Highland Heights, OH

Siemens
Iselin, NJ

Technicare Corporation
Solon, OH

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Directory of Potential Users
Microwave Radio Equipment

COMPANY DIRECTORY

AT&T Technologies
222 Broadway
New York, NY 10038

Avantek Inc.
481 Cottonwood Dr.
Milpitas, CA 95035

Aydin Microwave
75 East Trimble Dr.
San Jose, CA 95131

California Microwave
990 Almanor Ave.
Sunnyvale, CA 94086

Cardion Electronics
Long Island Expressway
Woodbury, NY 11797

Digital Microwave Corp.
2363 Calle del Mundo
Santa Clara, CA 95054

Ericsson Information Systems
301 Route 17 North
Rutherford, NJ 07070

Fujitsu America
680 Fifth Ave.
New York, NY 10019

General Electric Co.
316 E. Ninth St.
Owensboro, KY 42301

GTE Communications Company
2500 West Utopia Rd.
Phoenix, AZ 85027

Granger Associates
3101 Scott Blvd.
Santa Clara, CA 95051

Harris/Farinon
1691 Bayport Ave.
San Carlos, CA 94070

Hughes Microwave
P.O. Box 92426
Los Angeles, CA 90009

ITT
2912 Wake Forest Rd.
Raleigh, NC 27611

Loral TerraCom
9020 Balboa Ave.
San Diego, CA 92123

M/A Com, Inc.
7 New England Road
Burlingame, MA 01803

Magnum Microwave Corp.
365 Ravendale Dr.
Mountain View, CA 94043

Motorola
3103 E. Algonquin Rd.
Schaumburg, IL 60190

NEC America
2990 Telstar Ct.
Falls Church, VA 22042

Northern Telecom
2300 Park Lake Dr.
Atlanta, GA 30348

Oki Electronics of America, Inc.
4031 N.E. 12th Terrace
Fort Lauderdale, FL 33308

Raytheon Co.
1415 Boston-Providence Turnpike
Northwood, MA 02062

Rockwell/Collins
1200 N. Alma Rd.
Richardson, TX 75081

San/Bar
17422 Pullman St.
Santa Ana, CA 92711

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Directory of Potential Users
Modems

COMPANY DIRECTORY

Anderson Jacobson, Inc.
521 Charcot Avenue
San Jose, CA 95131

Astrocom Corporation
120 West Plato Boulevard
St. Paul, MN 55107

AT&T Technologies Inc.
222 Broadway
New York, NY 10035

Avanti Communications Corp.
Aquidneck Industrial Park
Newport, RI 02840

Bizcomp Corporation
532 Weddell Drive
Sunnyvale, CA 94089

CASE/Rixon
2120 Industrial Parkway
Silver Spring, MD 20904

Cermetek Microelectronics Inc.
1308 Borregas Avenue
Sunnyvale, CA 94086

Codex Corporation
20 Cabot Boulevard
Mansfield, MA 02048

Concord Data Systems, Inc.
442 Marrett Road
Lexington, MA 02173

Data Race, Inc.
5839 Sebastian Drive
San Antonio, TX 78249

Digital Communications
 Association
303 Research Drive
Atlanta, GA 30092

Gandalf Data Incorporated
1019 South Noel
Wheeling, IL 60090

General DataComm Industries, Inc.
Route 63
Middlebury, CT 06762

Hayes Microcomputer Products, Inc.
5835 Peachtree Corners East
Norcross, GA 30092

IBM Data Processing Division
1133 Westchester Avenue
White Plains, NY 10604

Intertel, Incorporated
6 Shattuck Road
Andover, MA 01810

Micom Systems Inc.
4150 Los Angeles Avenue
Simi Valley, CA 93063

Microcom, Inc.
1400A Providence Highway
Norwood, MA 02062

Multi-Tech Systems, Incorporated
82 Second Avenue S.E.
New Brighton, MN 55112

Novation
18664 Oxnard Street
Tarzana, CA 91356

Omnitech Data Corporation
2405 South 20th Street
Phoenix, AZ 85034

Paradyne Corporation
8550 Ulmerton Road
Largo, FL 33541

Penril Corp. Data Comm. Div.
3204 Monroe Street
Rockville, MD 20852

Prentice Corporation
266 Caspian Drive
Sunnyvale, CA 94086

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COMPANY DIRECTORY (Continued)

Racal-Milgo, Inc.
8600 N.W. 41st Street
Miami, FL 33166

Racal-Vadic, Incorporated
222 Caspian Drive
Sunnyvale, CA 94086

Rixon, Incorporated
2120 Industrial Parkway
Silver Spring, MD 20904

Rockwell International
4311 Jamboree Road
Newport Beach, CA 92660

Telebit Corporation
10440 Bubb Road
Cupertino, CA 95014

Universal Data Systems (UDS)
5000 Bradford Drive
Huntsville, AL 35805

Ven-Tel, Incorporated
2342 Walsh Avenue
Santa Clara, CA 95051

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Directory of Potential Users
Multiplex Equipment

COMPANY DIRECTORY

AT&T Technologies
222 Broadway
New York, NY 10038

Fujitsu America
680 Fifth Avenue
New York, NY 10019

GTE/Lenkurt
250 West Utopia Road
Phoenix, AZ 85027

Granger Associates
3101 Scott Boulevard
Santa Clara, CA 95051

Harris/Farinon
1691 Bayport Avenue
San Carlos, CA 94080

ITT Telecommunications
2912 Wake Forest Road
Raleigh NC 27611

Karkar
245 11th Street
San Francisco, CA 94103

L. M. Ericsson Telecommunications
7465 Lampson
Garden Grove, CA 92641

Motorola
3103 E. Algonquin Road
Schaumburg, IL 60190

NEC America
2990 Telestar Court
Falls Church, VA 22042

Northern Telecom, Inc.
1555 Roadhaven Drive
Stone Mountain, GA 30083

Rockwell International
1200 N. Alma Road
Richardson, TX 75080

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Directory of Potential Users
PBX and Centrex Telephone Systems

COMPANY DIRECTORY

AT&T Information Systems
100 Southgate Parkway
Morristown, NJ 07960

Anderson Jacobson, Inc.
521 Charcot Avenue
San Jose, CA 95131

CXC Corporation
2852 Alton Avenue
Irvine, CA 92714

Candella Electronics
550 Del Rey Avenue
Sunnyvale, CA 94088

Cyber Digital Inc.
175 Commerce Drive
Hauppauge, NY 11788-3901

DTI
315 Eisenhower Lane South
Lombard, IL 60463
(markets the Rockwell Wescom PBX line)

Executone Ltd.
Two Jericho Plaza
Jericho, NY 11753

GTE Communications Systems
2500 West Utopia Road
Phoenix, AZ 85027

Harris Digital Telephone Systems
One Digital Drive
Novato, CA 94947

Hitachi America
2990 Gateway Drive
Norcross, GA 30071

Honeywell Inc.
Honeywell Plaza
Minneapolis, MN 55408

IPC Communications
One Lafayette Place
Greenwich, CT 06830

ITT Telecom
3100 Highwoods Blvd.
Raleigh, NC 27604

Information Dynamics
1251 Exchange Drive
Richardson, TX 75081

InteCom Corporation
601 InteCom Drive
Allen, TX 75002

Jistel
76 Ferry Blvd.
Stratford, CT 06497

Matsushita
1072 East Meadow Circle
Palo Alto, CA 94303

Melco Labs
14408 Northeast 20th Street
Bellevue, WA 98007

Mitel Corporation
5400 Broken Sound Blvd. N.W.
Boca Raton, FL 33431

NEC Telephones
532 Broad Hollow Road
Melville, NY 11747

Northern Telecom
1001 East Arapaho Road
Richardson, TX 75081

Oki Electronics of America
Palisades Area
5901-B Peachtree Dunwoody Road
Atlanta, GA 30328

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COMPANY DIRECTORY (Continued)

Philips DVS
85 McKee Drive
Mahwah, NJ 07430

Redcom Labs
750 Fairport Park
Fairport, NY 14450

ROLM Corporation
4900 Old Ironsides Drive
Santa Clara, CA 95050

SRX
15926 Midway Rd.
Dallas, TX 75234

Siemens Corporation
5500 Broken Sound Blvd.
Boca Raton, FL 33431

Solid State Systems
1990 Delk Industrial Blvd.
Marietta, GA 30067

Stromberg-Carlson BCS
2301 Maitland Center Parkway
Maitland, FL 32751

TIE/Communications
5 Research Drive
Shelton, CT 06484

Tadiran
10801 Endeavor Way
Largo, FL 33543

Telenova
102-B Cooper Court
Los Gatos, CA 95030

Tele-Path Industries
3361 Melrose Avenue N.W.
Roanoke, VA 24017
(markets the hotel/motel PBX
Model 87 to the lodging industry)

Tele/Resources
Northway 10, Executive Park
Bellston Lake, NY 12019

Telrad Telecommunications
Electronic Industrial Ltd.
510 Broad Hollow Road
Melville, NY 11747

Telex Computer Products
Telexecom Division
31829 La Tienda Dr.
Westlake Village, CA 95362

Teltone Corporation
P.O. Box 657
Kirkland, WA 98033

Thomson CSF Communications
2 Garnett Drive
White Plains, NY 10604

Tone Commander Systems
4320 150th Avenue N.E.
Redmond, WA 98052

Toshiba Telecom
2441 Michelle Drive
Tustin, CA 92680

Z-Tel
181 Ballardale Street
Wilmington, MA 01887

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Directory of Potential Users
Private Packet Data Networks

COMPANY DIRECTORY

PADs

Amdahl Communications Systems
2200 N. Greenville
Richardson, TX 75081

Amnet, Inc.
101 Morse Street
Watertown, MA 02172

Atlantic Research
5390 Cherokee Avenue
Alexandria, VA 22312

AT&T Network Systems
P.O. Box 1278R
Morristown, NJ 07960

Auscom
2007 Kramer Lane
Austin, TX 78758

BBN Communications
70 Fawcett Street
Cambridge, MA 02238

Cableshare, Inc.
20 Enterprise Drive
London, Ontario N6A4L6
Canada

Case Communications
7200 Riverwood Drive
Columbia, MD 21046-1199

ComDesign
751 S. Kellogg
Goleta, CA 93117

Databit, Inc.
110 Ricefield Lane
Hauppauge, NY 11788

Datagram Corp.
11 Main Street
E. Greenich, RI 02818

Digital Communications Assoc.
1000 Alderman Drive
Alvaretta, GA 30201

Dynatech Packet Technology
6464 General Green Way
Alexandria, VA 22312

Ericsson
1810 N. Glenville, Suite 116
Richardson, TX 75081

Gandalf Data
1019 S. Noel
Wheeling, IL 60090

General Datacom
Middlebury, CT 06762-1299

GTE Telenet
12490 Sunrise Valley Drive
Reston, VA 22096

Hewlett-Packard Company
19055 Pruneridge
Cupertino, CA 95014

IBC
80 Oser Avenue
Hauppauge, NY 11787

ICOT
830 Maude Avenue
Mountain View, CA 94039

Infotron Systems Corporation
N. Olney Avenue
Cherry Hill, NJ 08003

ITT
320 Park Avenue
New York, NY 10022

COMPANY DIRECTORY (Continued)

PADs (Continued)

M/A-COM DCC
11717 Exploration Lane
Germantown, MD 20874

Memotec
3320 Holcomb Bridge Road
Norcross, GA 30092

Micom
20151 Nordhoff Street
Chatsworth, CA 91311

NEC America
1525 Walnut Hill Lane
Irving, TX 75062

Northern Telecom
1001 E. Arapaho Road
Richardson, TX 75081

Paradyne
8550 Ulmerton Road
Largo, FL 33540

Protocol Computers, Inc.
26630 Agoura Road
Calabasas, CA 91302-1988

Protocom Devices
190 Willow Avenue
Bronx, NY 10454

Siemens (Databit)
110 Ricefield Lane
Hauppauge, NY 11788

Telematics
1415 NW 62nd Street
Fort Lauderdale, FL 33309

Timeplex, Inc.
400 Chestnut Ridge Road
Woodcliff Lake, NJ 07675

Tymnet
2710 Orchard Parkway
San Jose, CA 95131

Uninet
10957 Lakeview Avenue
Lenexa, KS 66219

Wolfdata
187 Billerica Road
Chelmsford, MA 01824

XMIT AG
Widen Switzerland CH 8967

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COMPANY DIRECTORY (Continued)

Nodes/Engines

Amdahl Communications Systems
2200 N. Greenville
Richardson, TX 75081

AT&T Network Systems
P.O. Box 1278R
Morristown, NJ 07960

Amnet, Inc.
101 Morse Street
Watertown, MA 02172

BBN Communications
70 Fawcett Street
Cambridge, MA 02238

Dynatech (Dynapac) Packet Technology
6464 General Green Way
Alexandria, VA 22312

Ericsson
1810 N. Glenville, Suite 116
Richardson, TX 75081

GTE Telenet
12490 Sunrise Valley
Reston, VA 22096

Harris Corporation
1025 W. Nasa Boulevard
Melbourne, FL 32419

ITT
320 Park Avenue
New York, NY 10022

M/A-COM DCC
11717 Exploration Lane
Germantown, MD 20874

NEC America
1525 Walnut Hill Lane
Irving, TX 75062

Northern Telecom
1001 E. Arapaho Road
Richardson, TX 75081

Paradyne (SESA)
8550 Ulmeiton Road
Largo, FL 33540

Siemens (Databit)
110 Ricefield Lane
Hauppauge, NY 11788

Telematics
1415 N.W. 62nd Street
Fort Lauderdale, FL 33309

Tymnet
2710 Orchard Parkway
San Jose, CA 95131

Uninet
10957 Lakeview Avenue
Lenexa, KS 60219

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COMPANY DIRECTORY (Continued)

Switch/Concentrators

Amdahl Communications Systems
2200 N. Greenville
Richardson, TX 75081

Dynatech Packet Technology
6464 General Green Way
Alexandria, VA 22312

Memotech
3320 Halcomb Bridge Road
Norcross, GA 30092

Micom
20151 Nordhoff Street
Chatsworth, CA 91311

Northern Telecom
1001 E. Arapaho Road
Richardson, TX 75081

Protocom Devices
190 Willow Road
Bronx, NY 10454

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Directory of Potential Users
Satellite Earth Station Equipment

COMPANY DIRECTORY

Satellite Carriers and Systems Operates

Alascom, Inc.
210 E. Bluff Road, Box 6607
Anchorage, AK 99502

American Satellite Company
1801 Research Blvd.
Rockville, MD 20850

AT&T Communications Satellite Systems
Route 202/206, Room 2A235
Bedminster, NJ 07921

Communications Satellite Corporation
950 L'Enfant Plaza SW
Washington, DC 20024

COMSAT General Corporation
950 L'Enfant Plaza SW
Washington, DC 20024

Ford Aerospace Satellite Services Corporation
1140 Connecticut Ave. NW
Suite 708
Washington, DC 20036

Geostar Corporation
101 Carnegie Center
Suite 302
Princeton, NJ 08540

GTE Satellite Corporation
One Stamford Forum
Stamford, CT 06904

GTE Spacenet Corporation
1700 Old Meadow Road
McLean, VA 22102

Hughes Communications Galaxy, Inc.
Worldway Postal Center
P.O. Box 92424
Los Angeles, CA 90009

International Maritime Satellite Organization-INMARSAT
40 Melton Street
London NW1 ZE0
England

International Satellite, Inc.
1331 Pennsylvania Ave. NW
Washington, DC 20004

International Telecommunications Satellite Organization-INTESAT
5400 Inernational Drive
Washington, DC 20028

MCI-Space Resources Division
8283 Greensboro Drive
McLean, VA 22102

Orion Satellite Corporation
1835 K Street NW
Suite 201
Washington, DC 20036

Pan American Satellite Corporation
460 W. 42nd Street
New York, NY 10036

Rainbow Satellite Communications
P.O. Box 395
Leesburg, FL 32749

RCA American Communications, Inc.
Four Research Way
Princeton, NJ 08540

Telesat Canada
333 River Road
Ottawa, Ontario K1L 8B9
Canada

Western Union Telegraph Company
One Lake Street
Upper Saddle River, NJ 07458

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COMPANY DIRECTORY (Continued)

Earth Station Equipment Manufacturers

Avantek, Inc.
48761 Kato Road
Fremont, CA 94538

Aydin Systems Division
30 Great Oaks Blvd.
San Jose, CA 95119

COMSAT Telesystems
27621 Prosperity Avenue
Fairfax, VA 22031

COMTEL
2811 Airpark Drive
Santa Maria, CA 93455

Equatorial Communications
189 N. Bernardo Avenue
Mountain View, CA 94046

Fairchild Communications and
Electronics Company
20301 Century Blvd.
Germantown, MD 20874-1182

Harris Corporation
Satellite Communication Division
P.O. Box 1700
Melourne, FL 32901

Hughes Aircraft Company
P.O. Box 9219
Los Angeles, CA 90009

M/A-COM DCC, Inc.
11717 Exploration Lane
Cermantown, MD 20874

Multipoint Communication
Corporation
1284 Geneva Drive
Sunnyvale, CA 94089

Satellite Transmission
Systems, Inc.
Subsidiary of California
Microwave, Inc.
125 Kennedy Drive
Hauppauge, NY 11788

Scientific Atlanta
One Technology Parkway
P.O. Box 105600
Atlanta, GA 30348

Telecom General Corporation
2730 Junction Avenue
San Jose, CA 95134

Vitalink Communications
Corporation
1350 Charleston Road
Mountain View, CA 94043

Varian Associates
Microwave Equipment Division
3200 Patrick Henry Drive
Santa Clara, CA 95054

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Directory of Potential Users
Statistical Multiplexers

COMPANY DIRECTORY

AT&T Information Systems
One Speedwell Avenue
Morristown, NJ 07960

Anderson Jacobson
521 Charcot Avenue
San Jose, CA 95131

Astrocom Corp.
120 W. Plato
St. Paul, MN 55107

Backus Data Systems
1440 Knoll Circle
San Jose, CA 95112

Bit 3 Computer Corporation
8210 Penn Ave.
Minneapolis, MN 55431

Black Box
P.O. Box 12800
Pittsburgh, PA 15421

Canoga Data Systems
21218 Vanowen Street
Canoga Park, CA 91303

CASE Communications
2120 Industrial Parkway
Silver Spring, MD 20904

Codex Corporation
20 Cabot Blvd.
Mansfield, MA 02048

Coherent Communications
60 Commerce Dr.
Hauppauge, NY 11788

ComDesign, Inc.
751 South Kellog Avenue
Goleta, CA 93117

Complexx Systems
4939 Research Dr.
Huntsville, AL 35805

Datagram Corporation
11 Main Street
East Greenwich, RI 02818

Datatel, Inc.
Pin Oak Avenue
Cherry Hill, NJ 08003

Develcon Electronics
744 Nina Way
Warminister, PA 18974

Digital Communications
Association
303 Technology Park
Norcross, GA 30092

Digital Equipment Corporation
146 Main Street
Maynard, MA 01754

Doelz Networks, Inc.
18581 Teller Avenue
Irvine, CA 92715

Emulex Corporation
3545 Harbor Blvd.
Costa Mesa, CA 92676

Fiberonics International, Inc.
218 West Main Street
Hyannis, MA 02601

Fujitsu America, Inc.
1945 Gallows Road
Vienna, VA 22180

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Directory of Potential Users
Statistical Multiplexers

COMPANY DIRECTORY (Continued)

Gandalf Data, Inc.
1019 South Noel Avenue
Wheeling, IL 60090

General Datacom
One Kennedy Avenue
Danbury, CT 06810

Halcyon Communications
2121 Zanker Road
San Jose, CA 95131

Infinet, Inc.
6 Shattuck Rd.
Andover, MA 01810

Infotron Systems Corporation
9 North Olny Avenue
Cherry Hill, NJ 08033

Interactive Systems/3M
3M Center
Saint Paul, MN 55144

Honeywell
830 E. Arapaho Rd.
Richardson, TX 75081

M/A-COM DCC
11717 Exploration Lane
Germantown, MD 20874

Micom Systems, Inc.
20151 Nordhoff Street
Chatsworth, CA 91311

Minntronics Corporation
2599 White Bear Ave.
St. Paul, MN 55109

Network Products, Inc.
Progress Center
Research Triangle Park, NC 27709

Nixdorf Computer
300 Third Ave.
Waltham, MA 02154

Paradyne Corporation
8550 Ulmerton Road
Largo, FL 33540

Penril
207 Perry Parkway
Gaithersburg, MD 20877

Prentice Corporation
266 Caspian Drive
Sunnyvale, CA 94088

Racal-Milgo
8600 NW 41st Street
Miami, FL 33166

Racal-Vadic
1525 McCarthy Blvd.
Milpitas, CA 95035

Scitec Corporation
850 Aquidneck
Middletown, RI 02840

Sequal Data Comm
P.O. Box 4069
Carey, NC 27511

Solana Electronics
249 S. Hwy. 101
Solana Beach, CA 92075

Symplex Communications Corp.
2002 Hogback Road
Ann Arbor, MI 48104

TeleProcessing Products, Inc.
4565 E. Industrial St.
Simi Valley, CA 93063

Tellabs, Inc.
4951 Indiana Avenue
Lisle, IL 60532

Teltone Corporation
10801 120th Avenue, N.E.
Kirkland, WA 98033

COMPANY DIRECTORY (Continued)

Timeplex, Inc.
400 Chestnut Ridge Road
Woodcliff Lake, NJ 07675

Tri-Data
505 East Middlefield Road
Mountain View, CA 94039

Western Datacom
5083 Market Street
Youngstown, OH 44512

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Directory of Potential Users
T-1 Multiplexers

COMPANY DIRECTORY

Amdahl Corporation
2500 Walnut Avenue
Marina Del Rey, CA 90291

AT&T Information Systems
One Speedwell Avenue
Morristown, NJ 07960

Avanti Communications Corp.
Aquidneck Industrial Park
Newport, RI 02840

Aydin Microwave
75 E. Trimble Road
San Jose, CA 95131

Aydin Monitor
502 Office Center Drive
Fort Washington, PA 19034

Bayly Engineering
167 Hunt Street
Ajax, Ontario, Canada L1S 1P6

CASE Communications
8310 Guilford Road
Columbia, MD 21046

Coastcom
2312 Stanwell Drive
Concord, CA 94520

Codex
20 Cabot Blvd.
Mansfield, MA 02048

Cohesive Network
1680 Dell Avenue
Campbell, CA 95008

Comtech Communications
6150 Lookout Road
Boulder, CO 80301

Data Communications Associates
3030 Research Drive
Norcross, GA 30092

DATATEL, Inc.
Cherry Ind. Ctr.
Cherry Hill, NJ 08003

Digi-Voice Corp.
565 Fifth Avenue
New York, NY 10017

Ericsson Communications
7465 Campson
Garden Grove, CA 92642

Fujitsu America
3055 Orchard Drive
San Jose, CA 95134

Galdalf Data
1019 S. Noel
Wheeling, IL 60090

General Datacomm Industries
One Kennedy Avenue
Danbury, CT 06810

Granger Associates
3101 Scott Blvd.
Santa Clara, CA 95054-3394

GTE-Lenkurt
501 Sycamore Drive
Milpitas, CA 95035

Halcyon Communications
2121 Zanker Road
San Jose, CA 95131

IDS
7 Wellington Road
Lincoln, RI 02865

Infotron Systems Corporation
9 North Olney
Cherry Hill, NJ 08003

Integrated Telecom Corporation
9216 Markville
Dallas, TX 75243

COMPANY DIRECTORY (Continued)

ITT
3100 Highwoods Blvd.
Releigh, NC 27604

Loral-Terracom
9020 Balboa Avenue
San Diego, CA 92123

Lynch Communications
204 Edison Way
Reno, NV 89520

M/A-Comm Linkabit
3033 Science Park Road
San Diego, CA 92121

Micom Systems
20151 Nordhoff Street
Chatsworth, CA 91311

NEC
2741 Prosperity Avenue
Fairfax, VA 22039

Network Equipment Technology
400 Penobscot Drive
Redwood City, CA 94063

Network Switching Systems
3 Dundee Park
Andover, MA 01810

Northern Telecom
1555 Roadhaven Drive
Stone Mountain, GA 30083

Paradyne Corporation
8550 Umberton Road
Largo, FL 33540

Racal-Milgo
8600 NW 41st Street
Miami, FL 33166

San/Bar
9999 Muirlands Blvd.
Irvine, CA 92714

Scitec Corporation
811 Aquidneck Avenue
Middletown, RI 02840

Seiscor Technologies
5311 S. 122nd E. Avenue
Tulsa, OK 74147

Stratcom
10341 Bubb Road
Cupertino, CA 95014

Tau-Tron
27 Industrial Avenue
Chelmsford, MA 01824

Tellabs
4951 Indiana Avenue
Lisle, IL 60532

Teltone Corporation
1080 120th Avenue
Kirkland, WA 98033

Timplex, Inc.
400 Chestnut Ridge Road
Woodcliff Lake, NJ 07675

Wescom, Inc.
8245 S. Lamont Road
Downers Grove, IL 60515

Directory of Potential Users
Telephone Equipment

COMPANY DIRECTORY

American Telecom, Inc.
3190 East Miraloma Avenue
Anaheim, CA 92806

American Telephone & Telegraph
P.O. Box 49209
Atlanta, GA 30359

Buckeye Telephone and Supply Co.
1800 Arlingate Lane
Columbus, OH 43228

Centel Supply Co.
16215 Marquardt
Cerritos, CA 90701

Comdial Telephone Systems
1180 Seminole Trail
Charlottesville, VA 22906

Crest Industries, Inc.
6922 North Meridian
Puyallup, WA 98371

Electra
300 East County Line Road
Cumberland, IN 46229

Famous Telephone Supply Co.
110 North Union
P.O. Box 2172
Akron, OH 44309

General Electric Company
316 East Ninth Street
Owensboro, KY 42301

GTE Business Communications
Systems, Inc.
Consumer Products Department
P.O. Box 4148
Huntsville, AL 35803

GEC Telecommunications Limited
P.O. Box 53
Coventry CV3 1HJ
England

Goldstar Telecommunications, Inc.
One Madison Street
East Rutherford, NJ 07073

Graybar Electric Company
900 Commerce Drive
Oak Brook, IL 60521

ITT Business Communications Corp.
300 East Park Drive
Harrisburg, PA 17111

Iwatsu America, Inc.
230 Lincoln Centre Drive
Foster City, CA 94404

Melco Labs, Inc.
Rte. 1, Box 96X
Union Springs, AL 36089

Motorola Communications and
Electronics, Inc.
2700 Augustine Drive
Santa Clara, CA 95051

North Supply Company
600 Industrial Parkway
Industrial Airport, KS 66031

Northern Telecom
1001 E. Arapaho Road
Richardson, TX 75081

Telenova, Inc.
102-B Cooper Court
Los Gatos, CA 95030

Telicom, Inc.
11411 Addison Street
Franklin Park, IL 60131

Webcor Electronics
28 South Terminal Drive
Plainview, NY 11788

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Directory of Potential Users Ultrasound Equipment

COMPANY DIRECTORY

Advanced Tech Labs
Bellevue, WA

American Hospital Supply Company
Evanston, IL

Andersen Group, Inc.
Bloomfield, CT

Cooper Labs
Palo Alto, CA

Diasonics, Inc.
Milpitas, CA

General Electric Medical Systems
Milwaukee, WI

Picker International
Highland Heights, OH

Hewlett-Packard Company
Palo Alto, CA

Honeywell
Minneapolis, MN

Philips Ultrasound
Santa Ana, CA

Siemens
Iselin, NJ

Squibb Corporation
Princeton, NJ

Technicare Corporation
Solon, OH

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Directory of Potential Users
Video Teleconferencing Systems

COMPANY DIRECTORY

American Satellite Corp.
1801 Research Boulevard
Rockville, MD 20850

American Telephone & Telegraph Co.
195 Broadway Ave.
New York, NY 10007

Avalex
310 Bonifant Rd.
Silver Springs, MD 20904

Colorado Video
P.O. Box 928
Boulder, CO 80306

Conferex Corporation
1848 E. Carnegie Ave.
Santa Ana, CA 92705

Compression Labs, Inc.
2305 Bering Drive
San Jose, CA 95131

Concept Industries Co.
1116 Summer Street
Stamford, CT 06905

Decisions and Designs, Inc.
8400 Westpark Drive, Suite 600
McLean, VA 22101

GEC McMichael
Sefton Park
Stoke Poges, Slough, SL2 4HD
England

Image Data Corporation
7986 Mainland Dr.
San Antonio, TX 78250

Interand Corp.
3200 West Peterson Ave.
Chicago, IL 60659

ISACOM
1815 Century Boulevard
Suite 500
Atlanta, GA 30345

Luma Telecom
3350 Scott Boulevard
Building 49
Santa Clara, CA 95054

NEC America, Inc.
Radio and Transmission Division
2740 Prosperity Ave.
Fairfax, VA 22031

PicTel
One Intercontinental Way
Peabody, MA 01960

Pierce-Phelps, Inc.
2000 N. 59th Street
Philadelphia, PA 19131

Robot Research
7591 Convoy Court
San Diego, CA 92111

Satellite Business Systems
8283 Greensboro Drive
McLean, VA 22102

Shure Brothers
222 Hartrey Avenue
Evanston, IL 60204

Vidicom Video Communications
Division of L.D. Bevan Co., Inc.
742 Hampshire Road, Suite D
Westlake Village, CA 91361

Vitalink Communications Corp.
1350 Charleston Road
Mountain View, CA 94043

Widcom
1500 Hamilton Ave.
Campbell, CA 95008

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Directory of Potential Users
Voice Messaging Systems

COMPANY DIRECTORY

AT&E, Inc.
1400 NW Compton Drive
Suite 300
Beaverton, OR 97006-1922

AT&T Information Systems
One Speedwell Avenue
Headquarters Plaza West Tower
Morristown, NJ 07060

American Telesystems
Six Piedmont Center
Suite 608
Atlanta, GA 30305

Applied Voice Technologies
2445 140th Avenue N.E.
Suite 201
Bellevue, WA 98005

BBL Industries, Inc.
P.O. Box 48488
Atlanta, GA 30362

Centigram Corporation
1362 Borregas Avenue
Sunnyvale, CA 94089

Commterm, Inc.
The Third Avenue
Burlingame, MA 01532

Digital Equipment Corporation
10 Forbes Road
Northboro, MA 01532

Digital Pathways
1060 East Meadow Circle
Palo Alto, CA 94303

Digital Sound
2030 Alameda
Padre Serra, CA 93103

Genesis Electronics Corporation
Lake Forest Technical Center
103 Woodmere Road
Folsom, CA 95630

IBM Corporation
1133 Westchester Avenue
White Plains, NY 10604

NEC America, Inc.
532 Broad Hollow Road
Melville, NY 11747

Natural MicroSystems Corporation
6 Mercer Road
Natick, MA 01760

Northern Telecom, Inc.
Business Communications Systems
2305 Mission College Blvd.
Santa Clara, CA 95050

Octel Communications Corporation
1841 Zanker Road
San Jose, CA 95131

ROLM Corporation
4900 Old Ironsides Drive
Santa Clara, CA 95050

Solid State Systems, Inc.
1900 Delk Industrial Blvd.
Marietta, GA 30067

Sperry Corporation
P.O. Box 500
Blue Bell, PA 19424

Sudbury Systems
31 Union Avenue
Sudbury, MA 01776

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COMPANY DIRECTORY (Continued)

VMX, Inc.
1241 Columbia Drive
Richardson, TX 75081

Voice Computer Technologies Corporation
5730 Oakbrook Parkway
Suite 175
Norcross, GA 30093-1888

Voicemail International, Inc.
2225 Martin Avenue
Santa Clara, CA 95050

Voicetek Corporation
61 Chapel Street
Newton, MA 02195

Votan
4487 Technology Drive
Fremont, CA 94538

Votrax, Inc.
1394 Rankin
Troy, MI 48083

Wang Laboratories
One Industrial Avenue
Lowell, MA 01851

Zaiaz Communications, Inc.
207 Lakin Drive
Huntsville, AL 35801

Zymacom
2 Lyberty Way
Westford, CT 01886

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PACKAGING

Worldwide IC Packaging Update

OVERVIEW

The normal state of affairs in the semiconductor industry is to be in a "state of transition" or to have "reached a milestone." Or, something has occurred that will "revolutionize" the industry. Packaging of semiconductors is no exception.

Significant achievements in VLSI fabrication and design technologies have reached the point where concurrent improvements in die-level interconnection technologies are necessary for continued system performance. Of all the packaging and interconnection technology issues discussed, one issue readily agreed upon is that both users and suppliers of semiconductors are going through a demanding transitional phase of component packaging decisions--decisions that will have to be dealt with in the near future, as the industry approaches submicron geometries.

One very clear trend that we are seeing is that equipment manufacturers are using more and more VLSI devices. There is a sweeping desire to reduce space and cost through more condensed packaging and to automate as much as possible. To accomplish this, packaging technology must approach chip technology.

PACKAGE CONSUMPTION

Figure 1 shows the estimated worldwide integrated circuit (IC) package consumption for 1986. The estimates are based on Dataquest's worldwide IC consumption data and therefore show consumption by all packaged ICs. Japan captured 40 percent of packaged ICs in 1986, while U.S. market share dropped to approximately 33 percent and Europe came in at 17 percent. The remaining 10 percent not shown went to ROW.

We expect that the Japanese will maintain their lead in the 1988 market using 44 percent of packaged ICs, with the United States holding approximately 38 percent, and Europe with 18 percent. By 1991, we anticipate that Japan will strengthen its lead to 45 percent, by virtue of its majority share of the consumer business, concerted efforts in the industrial sector, and its lead in automated assembly. At this point, U.S. market share will drop to 34 percent, and Europe's share will climb to 21 percent. While Europe is obviously not defeating its American and Asian competitors, we do expect it to modestly regain market share. At this time, we believe that European users are changing to surface-mount technology more readily than the American and Japanese users. Telecommunications and IC smart card applications, focusing on small-outline (SO) and tape-automated bonding (TAB) will provide Europe with the biggest growth opportunities for the next 10 years.

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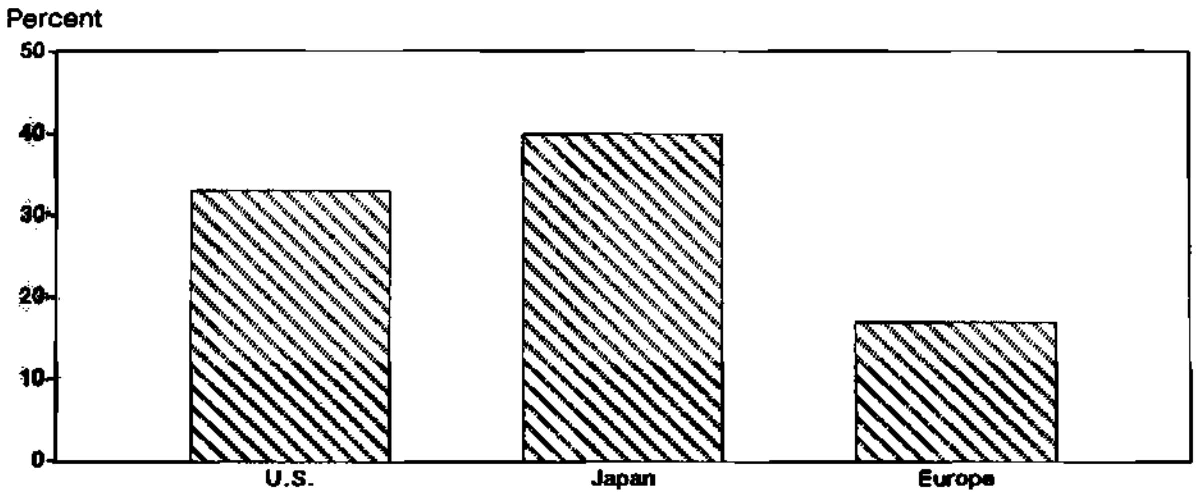
Figure 1

ESTIMATED 1986 WORLDWIDE PACKAGING TRENDS
(Units)



Source: Dataquest
May 1987

THE MEMORY ROLE

Over the last few years, memory devices have been on the leading edge of packaging technology due to density requirements. We have forecast that approximately 55 million 1-Mbit DRAMs will be shipped worldwide in 1987. As shown in Figure 2, 70 percent of those units will be shipped in either plastic or ceramic dual in-line packages (DIPs). By 1988, DIP package usage for DRAMs will shrink to 65 percent, while zig-zag in-line package (ZIP) and small-outline J-lead (SOJ) usage will grow. As we move into the 1990s, the SOJ package is expected to grow to 32 percent. High-density device architectures, led by smaller geometries and line widths, coupled with the desire to bring down costs while maintaining price competitiveness and building better and faster machines, will require the increased use of surface-mount technology (SMT).

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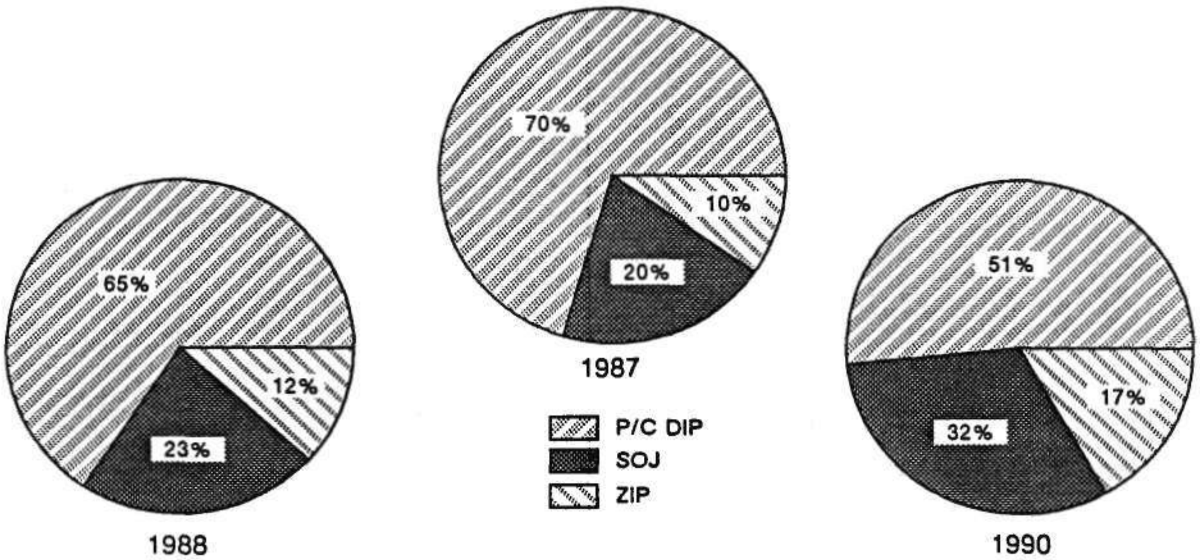
Figure 2

ESTIMATED 1Mb DRAM PACKAGES



Source: Dataquest
May 1987

SMT ISSUES

Despite the many advantages, implementation of surface-mount (SM) packages into systems manufacturing is taking longer than anticipated. Surface-mount technology is still immature and as such the manufacturing infrastructure is not fully developed. Preferring the tested reliability of through-hole (TH) packages, users continue to mix SM/TH designs. Reliability of SM devices has not yet been proven and solder joint inspection is difficult. However, as shown on Table 1, concentrated use of SM devices is occurring in applications where small size and weight are the primary issues. As shown on Table 2, computers were the leading end-use segment for SMDs in the United States, in 1986. While cost reduction was the driving force, reliability continues to play a major role in acceptance of SMT. Europe led the United States in acceptance and usage of SMT in telecom applications; and by virtue of its command over the consumer market, Japan led the market with 10 percent of ICs packaged in SMT. As a comparison, Japan's Printed Circuit Association (JPCA) estimated that SM consumption in Japan reached 13 percent for ICs, and that over the next five years, ICs in SMT will grow to 33.9 percent in Japan.

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Table 1

SURFACE-MOUNT TECHNOLOGY

Where?

- Consumer
- Automotive
- Disk storage
- Avionics, missiles, and space
- High-density memories
- Power supplies

Table 2

SURFACE-MOUNT TECHNOLOGY
END-USE SEGMENTS
1986

	Japan	Europe	United States
End Use	Consumer	Telecommunications	Computers
Driving Force	Small size	Reliability	Cost reduction/ reliability
Percent of ICs Consumed Worldwide	40%	17.7%	32.8%
Percent of ICs in SMT	10%	8.0%	4.0%
Dominant SMT Approach	TAB/QUAD/SO	SO	SO/CC/TAB

Source: Dataquest
June 1987

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Worldwide IC Packaging Update

SUMMARY

At the present time, we believe that there is no single solution to future VLSI packaging problems. For the 1990s and beyond, we expect that package designs will continue to proliferate. Advanced multichip product designs will incorporate ASICs, use advanced circuit design techniques, and use advanced board assembly methods incorporating TAB and other multichip packages. While plastic packaging has its hermetic limitations, its high-volume, low-cost, high-performance, 40 pin-and-below characteristics will make it the dominant package by 1990.

Automated assembly will change the way that ICs and other components are packaged. TAB or some variation of this method of construction is the most likely packaging style for ICs in the 1990s. Chip-on-board (COB) has also made its way up the automated assembly ladder in consumer applications. From early single-chip digital watch applications, it is now being used in multi-chip applications such as copiers, facsimile, and IC cards.

REGIONAL ANALYSIS

If we use the premise that memory devices have been on the leading edge of packaging technology due to density requirements, then we can assume that Japan has a two-year lead on the industry and will gain overall leadership in packaging technology before the 1990s. With its vertically integrated structure, Japan can maintain closer technical and strategic cooperation among members of its packaging chain. Their command over the consumer market and surface-mount approach has given them a lead in packaging technology. There are already major efforts among equipment suppliers in Japan to develop automated assembly processes.

Despite major engineering efforts dedicated to designs, substrate and component materials, and assembly equipment, cooperation lags among members of the packaging chain in the United States. At times, cooperation seems better between U.S./Japanese partners than between U.S./U.S. alliances. The strong financial/technical megacorporate links of Japan are nonexistent in the United States. Outside of Texas Instruments and a few systems groups, everyone else has transported assembly offshore. Unlike Europe and Japan, there is very little academic research and cooperation. There is some hope in U.S. research consortiums, but cooperative efforts in packaging are weak. Finally, except for a few systems houses, the fear of capital investments in automated assembly technology has paralyzed many companies from making the decision to automate, a decision that could prevent them from staying on the competitive edge.

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Surface-Mount Technology Overview

SURFACE-MOUNT TECHNOLOGY

What Is It?

Surface-mount technology (SMT) was first used in the United States in the early 1960s by the military because it met their requirements for space savings and high reliability. SMT became available for commercial use in the United States in the 1970s. Today, SMT is used most often in the automotive, computer, and consumer electronics industries as well as aerospace.

Dataquest defines SMT CAD as the laying out of printed circuit boards (PCBs) with chips mounted to the surface of the board. The differences between through-hole technology and SMT that affect CAD systems include device footprints, packaging, and access to internal layers of the board.

How Is It Different?

When designers lay out printed circuit boards (PCBs) with through-hole technology (THT) devices, footprints (the graphic shape of a device) for components consist of round pads that go through all layers of the board. In SMT, footprints are made up of rectangular pads that reside on the external layers of the board only (please refer to Figure 1).

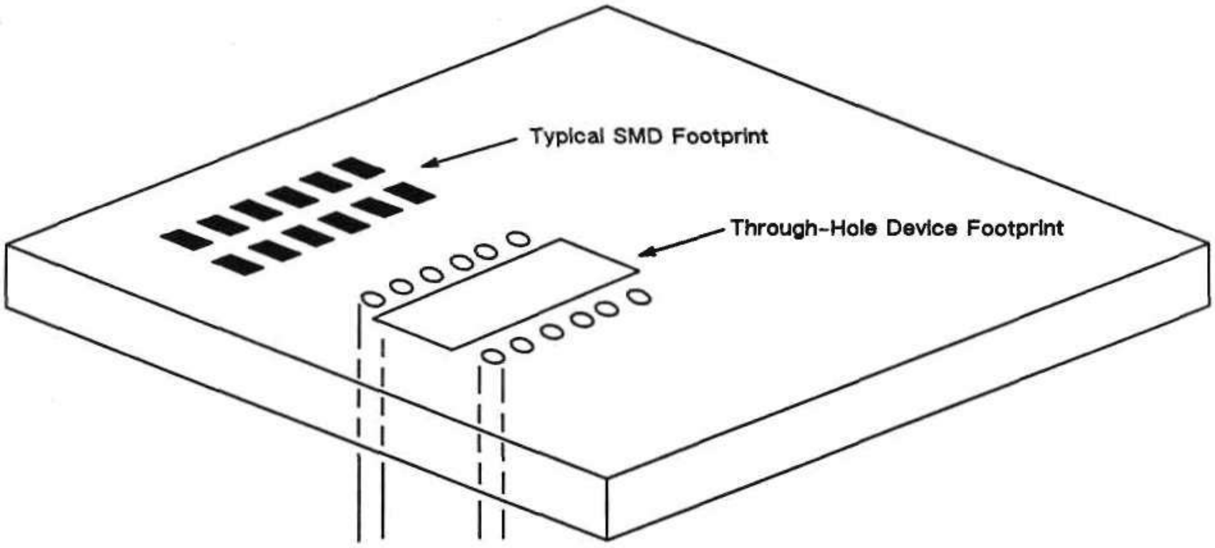
Looking further into the differences among THT and SMT devices, there are standards for through-hole device packages (i.e., the same-shaped device is available from a variety of vendors), while there are no such standards for SMT devices. Although there are several organizational efforts to standardize SMT device packages, today's users contend with the confusion caused by the same technology or device being available in too many packages.

The variation in packages causes designers confusion because they must create the footprints and physical library for each SMT device. Before they begin the physical layout, users need to know which manufacturer's components will be used so that the footprint graphic will match the actual device.

Another difference between these technologies is that through-hole devices use vias that go through all layers of the board, whereas in surface mounting, designers use blind and/or buried vias to access the internal layers of the board (see Figure 2).

Figure 1

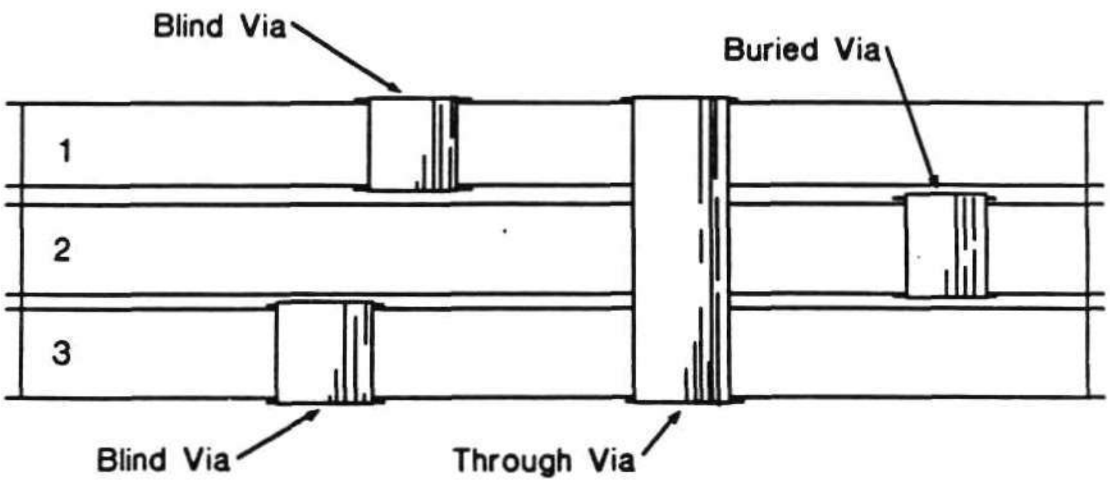
DEVICE FOOTPRINTS



Source: Nugrafix Group
Design Guideline Book

Figure 2

VIAS



Source: Nugrafix Group
Design Guideline Book

Surface-Mount Technology Overview

THE SMT SURVEY

Demographics

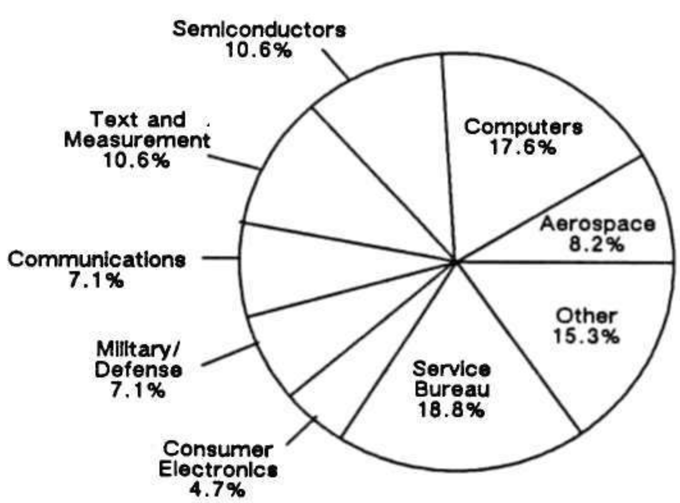
Dataquest recently completed a survey focusing specifically on the needs of end users implementing SMT on CAD systems. The survey sample consisted of 100 PCB CAD end users. Our selection criterion was based on whether the users were using their CAD systems for PCB layout rather than whether they were using SMT or not.

Among the responses, 19 percent came from service bureaus and another 18 percent came from computer companies. Please refer to Figure 3 for further details on the industries of the respondents.

One-third (33 percent) of the respondents indicated that they have been using SMT for one year or less. However, the bulk of the respondents (47 percent) responded that they have been using surface-mount technology for two to three years. Approximately 20 percent have been using SMT for more than three years. Less than 1 percent indicated that they do not use SMT and have no plans to do so in 1987.

Figure 3

RESPONDENTS BY END-USER INDUSTRY



Source: Dataquest June 1987

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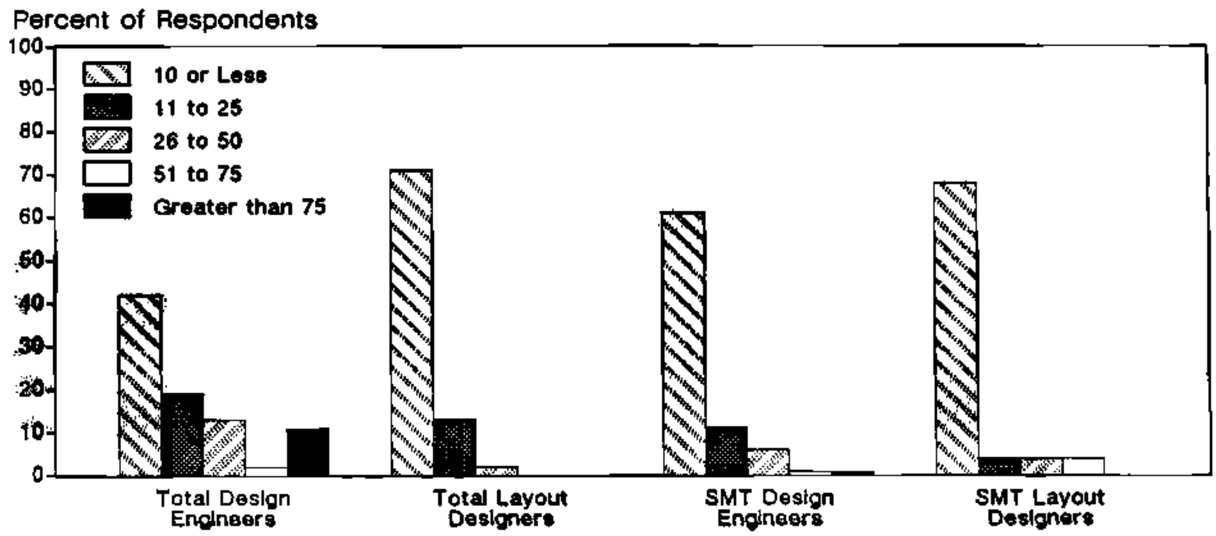
Most responding organizations had a total design engineering staff of 10 people or less. Furthermore, 61 percent of these organizations responded that their engineers are doing surface-mount design. Similarly, total layout designers numbered 10 or less for the majority of respondents, with 68 percent indicating that 1 to 10 designers are designing with surface-mount technology (please see Figure 4).

Figure 4

NUMBER OF ENGINEERS AND DESIGNERS



Source: Dataquest June 1987

How Is SMT Being Used?

In examining the prevalence of SMT design in proportion to traditional through-hole technology (THT), we looked at this issue from several angles: Total annual design starts (see Figure 5), which of those use SMT (see Figure 6), how SMT is implemented (see Figure 7), the number of components, and the number of layers per design (see Figures 8 and 9).

Results indicate that implementation of surface-mount technology on CAD systems is still relatively new and definitely not widespread. Why are users converting to SMT? Figure 10 shows the top five reasons respondents have chosen to use surface-mount technology over through-hole design methods.

In spite of the sparsity of SMT usage, there is a perception, particularly among responding service bureaus, that users must support SMT to stay in business because their customers demand it and their competition supports it.

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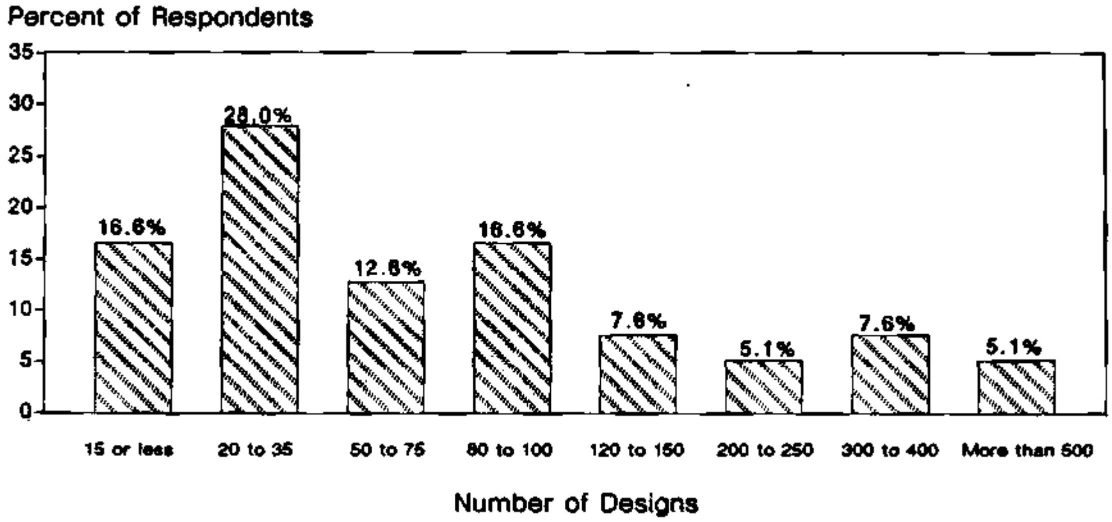
Figure 11 shows the layout phase of the design cycle as a percent of the total design time, comparing through-hole technology to SMT. In our focus research, end users indicated that one of the benefits of using SMT was that they could get their products designed and manufactured faster. Yet, the results of our survey show that there is little or no time saved by choosing surface-mount technology instead of THT. In researching this issue further, we learned that the time savings involved in SMT comes from the manufacturing process, where SMDs are more suited to automated manufacturing processes.

Figure 5

TOTAL ANNUAL PCB DESIGN STARTS



Source: Dataquest
June 1987

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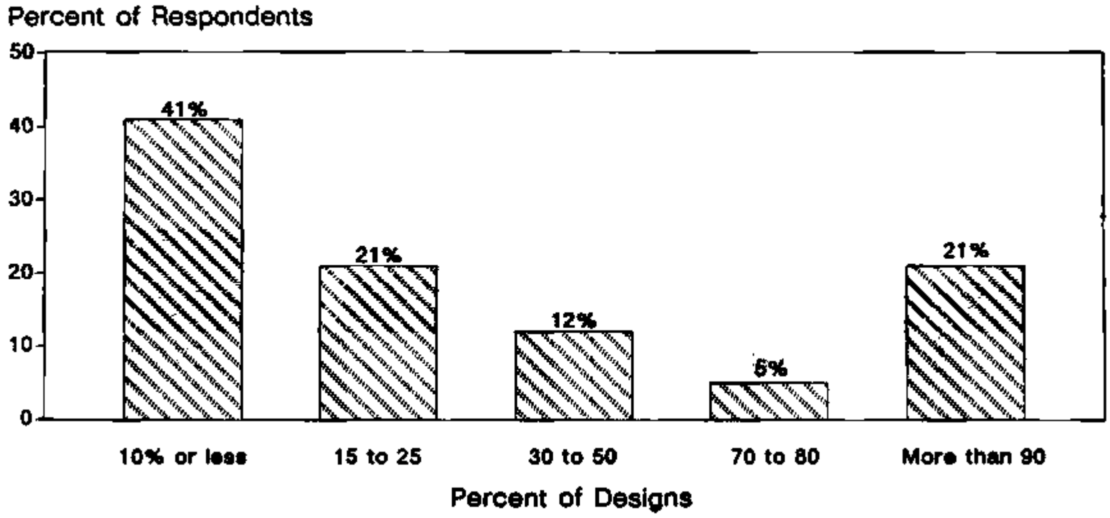
Figure 6

DESIGNS WITH SMT



Source: Dataquest
June 1987

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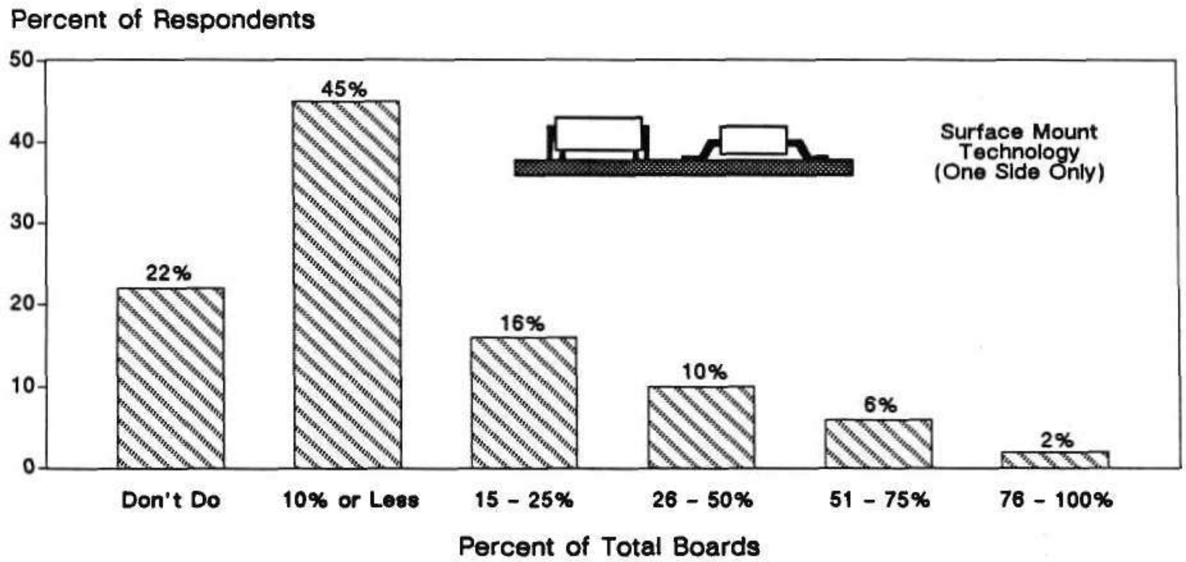
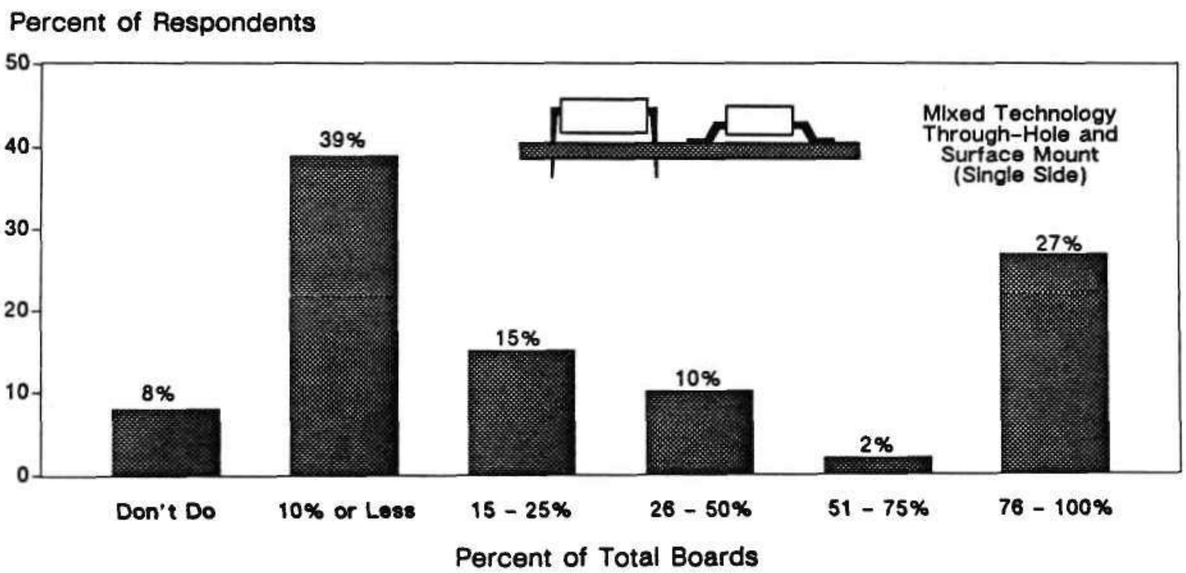
Figure 7

DISTRIBUTION OF DESIGNS
BY TECHNOLOGY IMPLEMENTATION





Continued

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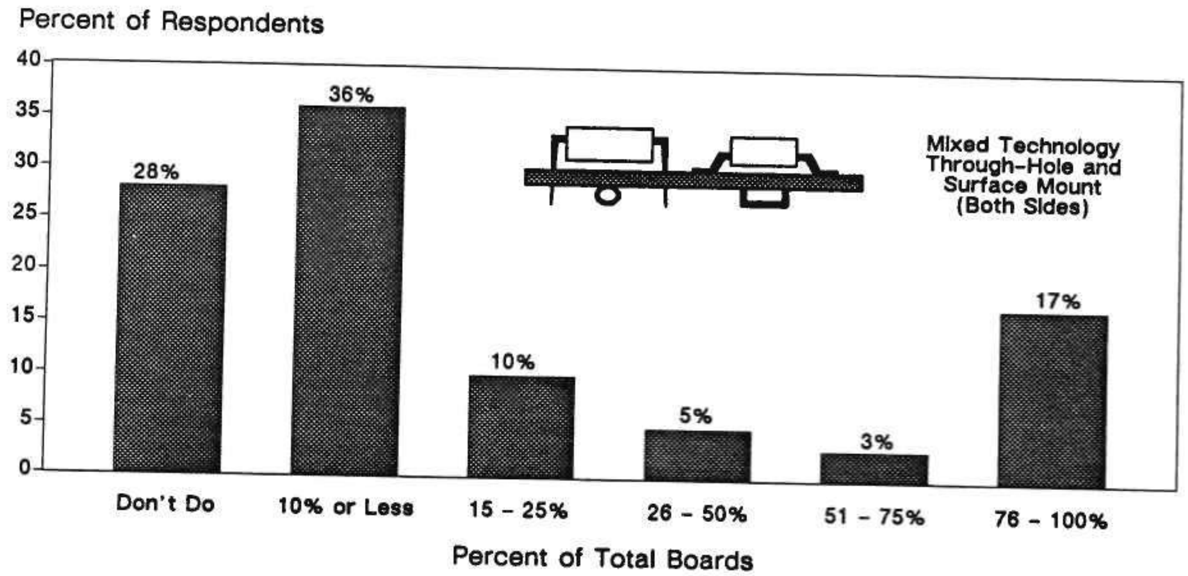
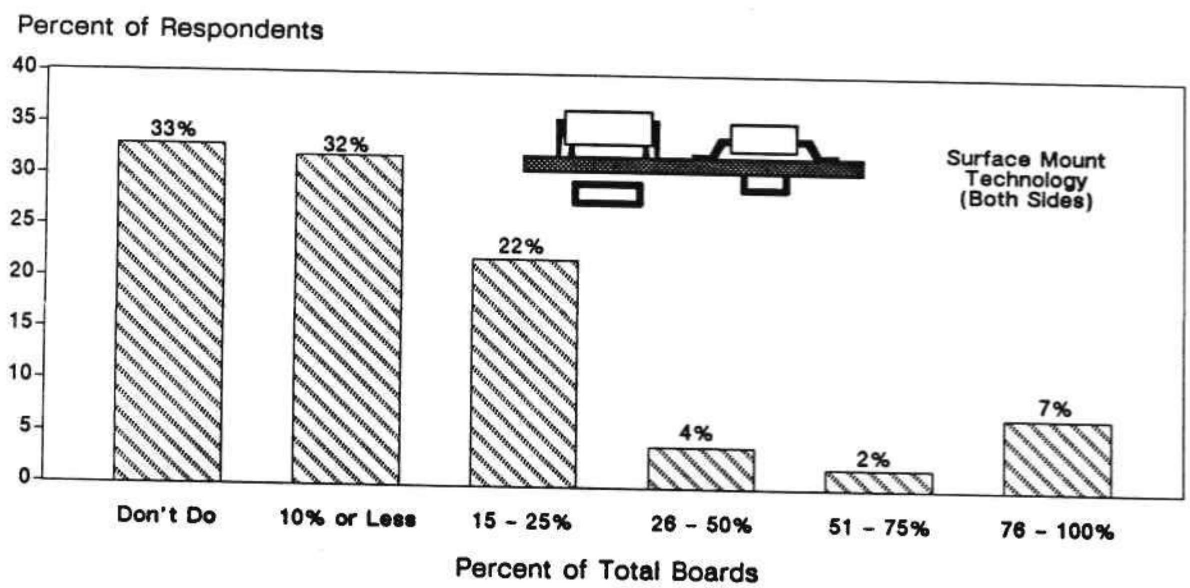
Figure 7 (Continued)

DISTRIBUTION OF DESIGNS
BY TECHNOLOGY IMPLEMENTATION





Source: Dataquest
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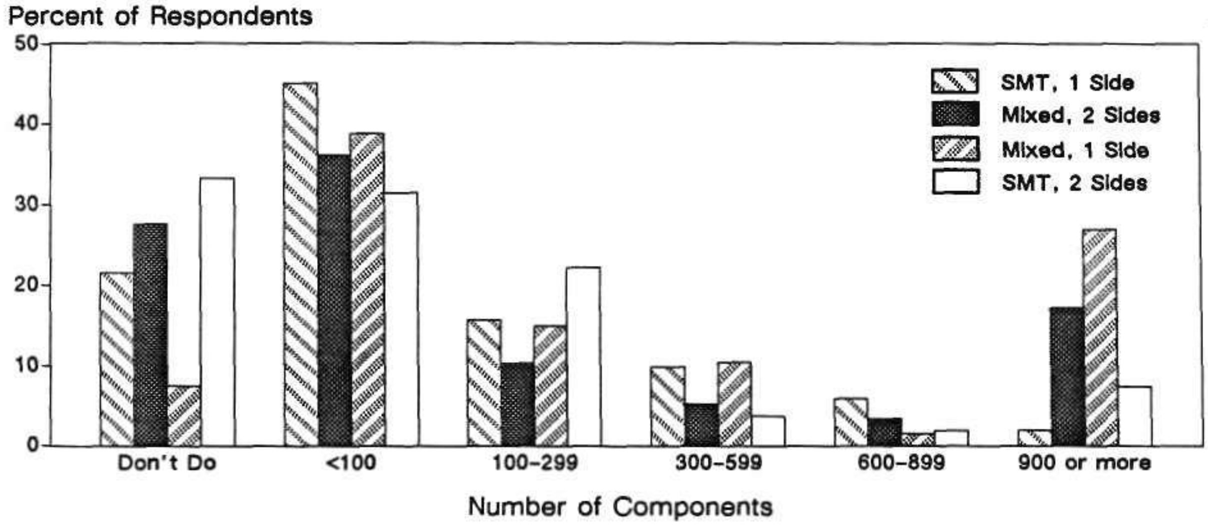
Figure 8

AVERAGE NUMBER OF COMPONENTS
BY BOARD TYPE



Source: Dataquest
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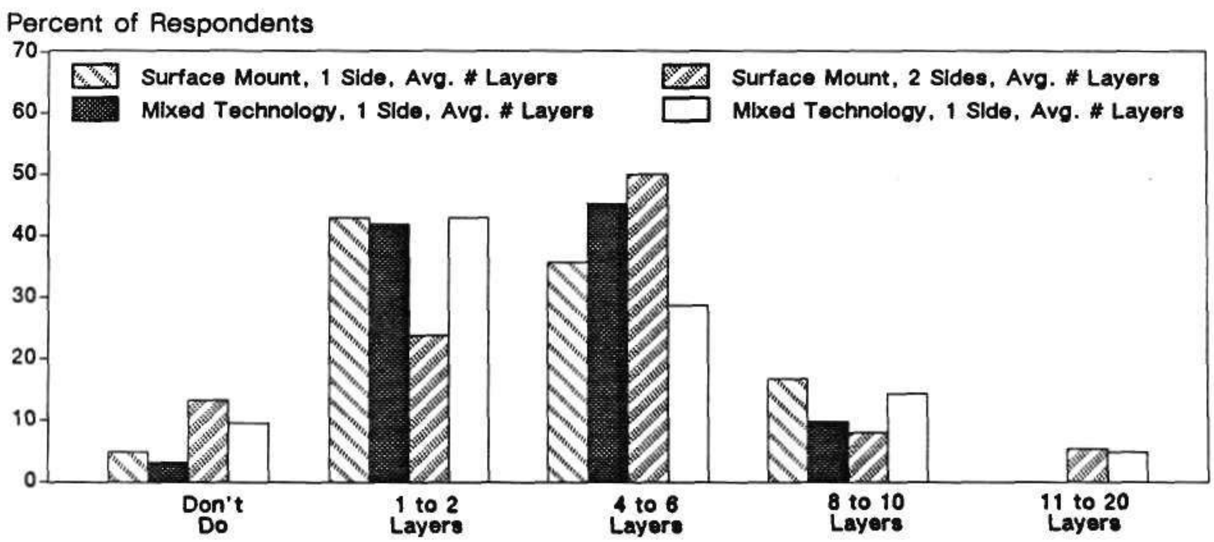
Figure 9

AVERAGE NUMBER OF LAYERS
BY BOARD TYPE



Source: Dataquest
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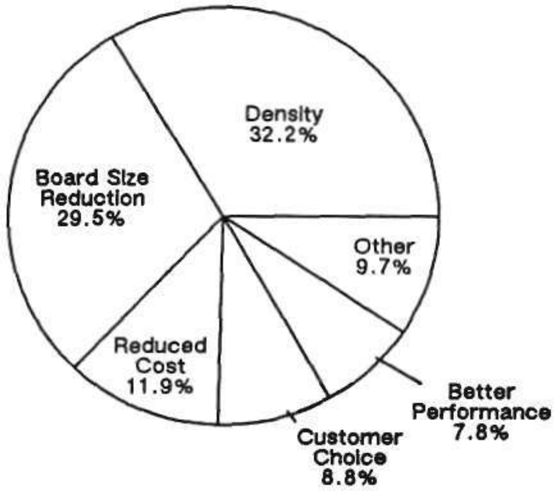
Figure 10

REASONS FOR USING SMT



Source: Dataquest
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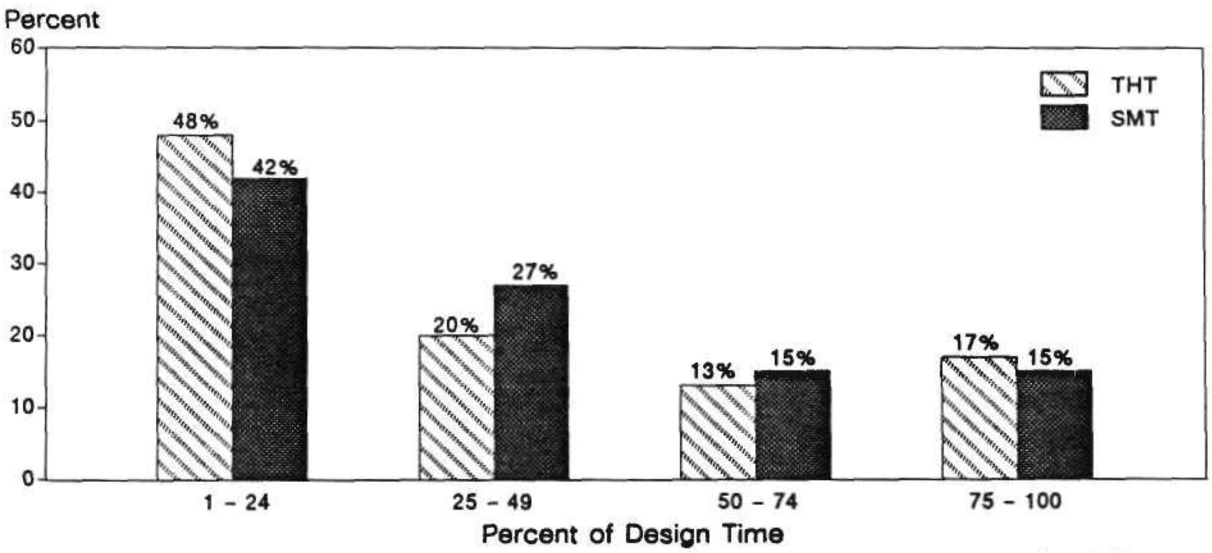
Figure 11

LAYOUT AS A PERCENT OF TOTAL DESIGN TIME



Source: Dataquest
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SMT and CAD

What Do End Users Think?

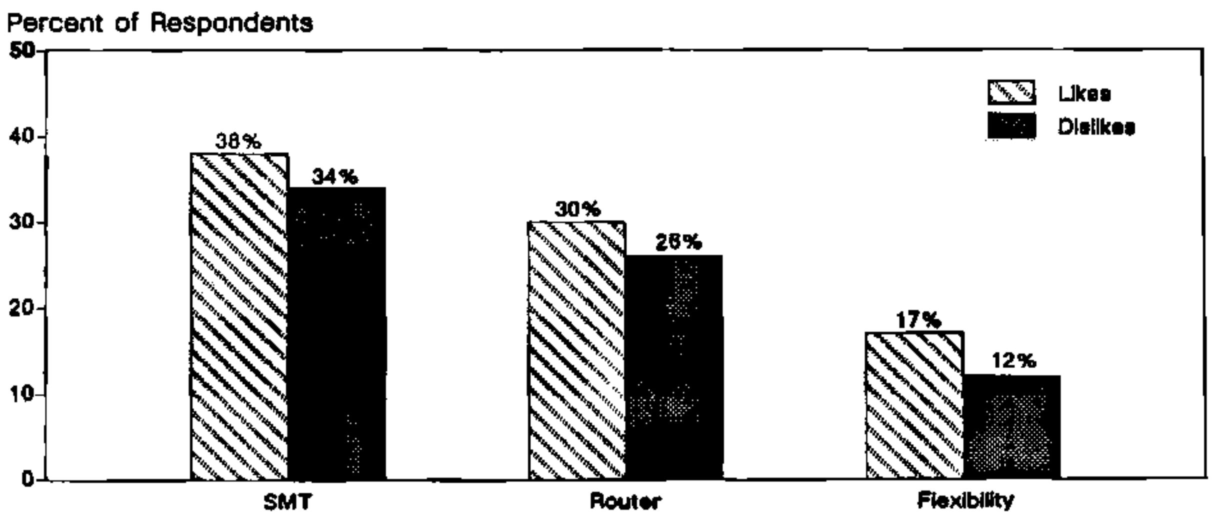
The attitude of most end users is less than optimistic regarding the currently available CAD tools. They feel that although CAD vendors have made a good start, they have a long way to go in terms of adequately supporting SMT. Other end users stated that they had been sold tricks and workarounds as true design solutions. Overall, less than 10 percent of the respondents were satisfied with the way their CAD systems support SMT.

As Figure 12 shows, the likes and dislikes of the end users closely parallel each other. Closer inspection of the data revealed no technological reasons, thus leaving us with one conclusion: The likes and dislikes cited are vendor-specific.

Ranking specific SMT support functions in order of importance, definition of pad geometries topped the list, followed by multilayer routing, off-grid design, and auto-routing of two-sided boards. End users are saying that, in order to support these important SMT functions, PCB CAD systems must be flexible and interactive enough to accommodate SMT as well as THT features.

Figure 12

END USER LIKES AND DISLIKES



Source: Dataquest
June 1987

Users are also saying that they view SMT support as a PCB CAD system feature that must be capable of integration into users' particular design environments. Because SMT is highly process dependent, users need to interface easily with manufacturing to ensure the manufacturability of the design.

Flexibility and integration are the two most important buying criteria for future SMT CAD purchases cited by respondents.

What Are the Challenges of SMT?

The following characteristics of SMT affect CAD systems that support through-hole technology:

- Footprints
- The lack of standards
- Access to internal layers of the board

It is the shape of SMT device footprints as well as the fact that they reside only on the surface of the board that affects PCB CAD systems. Most systems are set up to acknowledge the footprints of through-hole devices and are not surface intelligent.

The lack of standard geometries for the same device functionality was cited by respondents as the major drawback in converting designs to SMT. The lack of standards for SMD has created a need for a high degree of flexibility and interactivity in PCB CAD systems.

Because most PCB CAD systems are not surface intelligent, users have to trick the system into believing that it is routing a through-hole device. To accomplish this, designers place stringers (round pads) at the end of each rectangular pad so that the system thinks it is routing a component whose leads run through all layers of the board. Although this workaround does route the board, it does not provide a long-term design solution.

Size of the SMT Market

End users are budgeting for design solutions that support SMT. Nearly 60 percent of the respondents replied that they have budgeted up to $100,000 for SMT CAD tools in 1987. The highest amount budgeted for SMT CAD expenditures in 1987 was just slightly more than $1 million, cited by nearly 10 percent of the respondents.

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To quantify and qualify the SMT opportunity, we based the forecast in Figure 13 on a combination of factors:

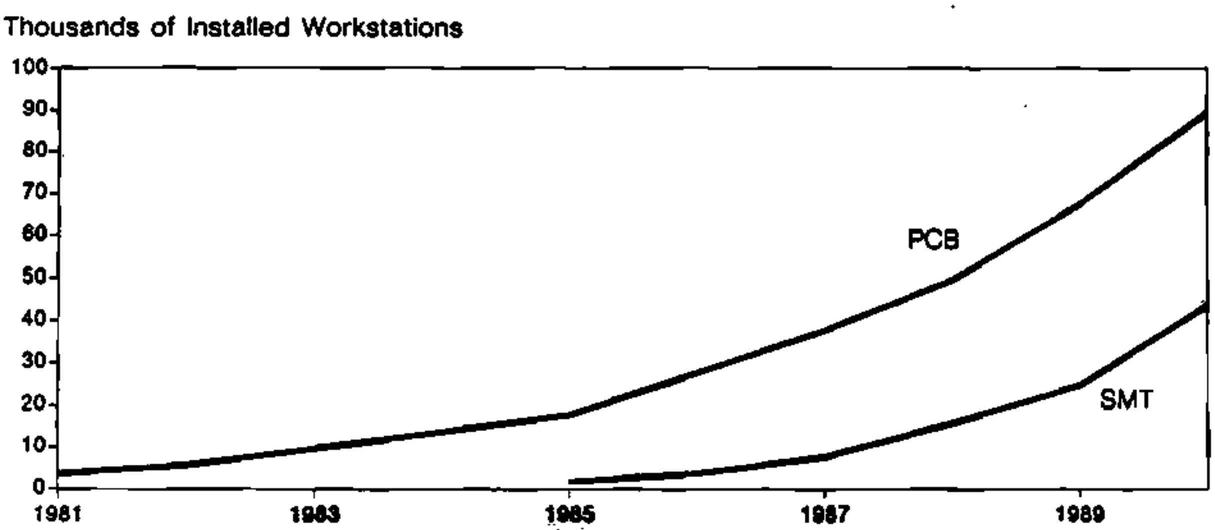
- Dataquest forecast data base, which consists of four years of research on more than 140 companies
- Data from another ECAD end-user survey, indicating number of designs and engineers
- The Dataquest Semiconductor Industry Service's forecast for SMDs that approximately 16 billion units will be shipped in 1990
- End users' forecast for 1987, where more than 61 percent indicated that they will use SMT in 15 to 25 percent of their designs

As Figure 13 shows, Dataquest estimated that in 1985, there were more than 17,000 workstations in the installed base for PCB CAD. Of those, we estimate that approximately 2,000 supported SMT. We forecast that by 1990 the installed base of workstations used for PCB applications will be more than 90,000 units, more than half of which will support SMT.

In compiling our forecast, we considered SMT to be a function of a PCB CAD system, not a turnkey product offering. Therefore, we believe that a number of software licenses may be sold as repeat business to a vendor's installed base as well as to new customers.

Figure 13

PCB WORKSTATION INSTALLED BASE WITH SMT CAPABILITY



Source: Dataquest June 1987

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Surface-Mount Technology Overview

SUMMARY

We believe that SMT is here to stay because end users need reduced board size with increased density, more reliable end products, and faster and less expensive manufacturing processes to keep up with their worldwide competition.

Dataquest believes that SMT support tools will be marketed as features of a CAD system, not standalone turnkey products. As such, meeting the technological differences with true design solutions is the challenge for CAD vendors in this market.

To recapitulate, the likes and dislikes of responding end users are vendor specific. We believe that in addition to watching the competition, vendors have to overcome the negative attitudes of end users by demonstrating that they understand the nature of their customers' problems.

Dataquest believes that the successful CAD vendors will be those who work closely with their customers to provide the needed solutions. To take advantage of the opportunity offered by SMT, vendors need to project that their products are what the end user wants: A means to an end--a quick turnaround on a manufacturable design.

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Research Newsletter

SIS Code: Newsletters 1989
DSP
0003271

DSP AND THE WAVE OF NEW RISC PRODUCTS

INTRODUCTION

The major news topic of the last six months in the semiconductor field has been the reduced-instruction-set computer (RISC) processor. Every major semiconductor and computer company now has a stated position on RISC in its product lines. Although much of the news is market posturing, there can be little question that the new RISC microprocessors represent a significant next generation for general-purpose computing. Independent of instruction set size, they embody the latest thinking from both computer science and market demand in today's VLSI technologies. Such opportunities for a completely fresh start on a processor architecture occur only rarely. Some suppliers are taking better advantage of the chance than others.

Any change in the general-purpose microprocessor market is important to digital signal processing (DSP) because it is consistently estimated that half of the volume of the integrated circuits used in DSP are conventional microprocessors. Their low price, wide familiarity, and variety of support tools always make them an attractive alternative to the higher-performance digital signal processor (DSMPU) solution. In addition, many of the mips and mflops performance figures of the new RISC processors are close to those expected only from digital signal processors. Even a casual glance shows RISC's architectural similarities to DSMPUs, such as deep data pipelining, the Harvard-style separation of instruction and data memories, and multiple execution units. RISC processor manufacturers are even talking about the same embedded controller markets that have been the domain of high-performance DSMPUs and about things like real-time operating systems.

What does this mean for the suppliers and users of single-chip DSMPUs in the future? We will explore that question in this newsletter. In addition, we will review some of the basic performance requirements for digital signal processors and see how these are met by the major new RISC processors. Next, we will look at the latest generation of high-performance DSMPUs and see how both are moving to solve some common new systems requirements. Comparing the two types of processors leads to some strategies for DSMPU makers to protect and expand their markets in the face of this potentially strong competition.

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DSP REQUIREMENTS AND THE NEW RISC PRODUCTS

Historically, signal processors have been distinct from general-purpose microprocessors because of the following three major requirements:

- Higher precision
- Higher speed
- Special functions operating on large amounts of data

Table 1 lists these requirements with some of the architectural or implementation techniques used to meet them. The first two columns indicate which of these techniques has generally been used in current-generation CISC microprocessors and in the first- or second-generation DSMPUs. The next two columns show the RISC processors and the latest (or third generation) of high-performance DSMPUs. Following the historical requirements are the additional DSP requirements considered to be important today as the result of larger, more complex systems.

Just looking at the relative predominance of the Xs over the Os in Table 1 confirms the general trends: New CISC microprocessors have few attributes other than precision to make them suited for DSP, whereas even the first-generation DSMPUs are a significant improvement. New higher-performance DSMPUs are complete in their use of such techniques, while RISC, for its own performance needs, has used more than even the early DSMPUs. The Xs and Os represent only rough averages across a number of products. Table 2 shows some of the specific features and performance parameters for four representative RISC products. Three high-performance DSMPUs are included for comparison on the same basis.

Table 1

Product Overlap in Meeting DSP Requirements

DSP Requirements	Implementation Technique	Products CISC	DSP-1&2	RISC	DSP-3
Historical DSP Requirements					
High precision	8-bit	X	O	X	X
	16-bit	X	X	X	X
	32-bit	X	O	X	X
	Floating-point	O	O	X	X
High speed	Pipelined data path	O	X	X	X
	Parallel operation				
	Data memories	O	X	X	X
	Instruction memory	O	X	X	X
	I/O controller	O	X	O	X
	Address generators	O	X	O	X
	Fixed and floating point	O	O	X	X
	Loop counters	O	X	O	X
	Full processors paralleled	O	O	X	X
	Memory speed-size hierarchy				
	Instruction caching	O	O	X	X
	I/O buffering	O	O	X	X
Special processing	Complex address generation				
	Vector	O	X	O	X
	2-D	O	O	O	X
	Arithmetic				
	Multiply-accumulate	O	X	X	X
	Saturation	O	X	O	X
Large amounts of data	Large memory space	O	O	X	X
	High-speed I/O	O	O	O	X
	Real-time control	O	X	X	X
New DSP Requirements					
High-level languages		X	O	X	X
Operating systems		X	O	X	X
Industry standard functions		X	O	X	O

Source: Dataquest
March 1989

Table 2

Major New RISC and DSMPU Feature and Performance Summary

	RISC				DSP		
	Motorola 88100	AMD 29000	SPARC 7C601	Intel i860	TI 320C30	AT&T 32C	Motorola 96002
Precision							
Integer	8-32	8-32	8-32	8-32	16, 32	8-24	32, 64
F-P	32, 64	Ext	Ext	32, 64	32, 40	32, 40	32, 96
Speed							
Cycle time (ns)	50	40	30	30	60	80	75
Execution unit data pipelines							
Integer	1	1	1	1	2	1	2
F-P	2	N/A	N/A	2	S	1	S
I/O	1	1/2	1	1	1	2	2
Concurrent data pipelines	3	3/2	2	4	3	3	3
Parallel processors	Y	N	Y	Y	Y	N	Y
Memory hierarchy							
Integer RF	32	192	136	32	16	22	10
F-P RF	S	N/A	N/A	32	S	4	S
Data cache	Ext	Ext	Ext	Y	N	N	N
Inst. cache	Ext	Ext	Ext	Y	Y	N	Y
Special processing							
Address generation	N	Y	N	Y	Y	Y	Y
Multiplier-accumulator							
Integer	N	N	N	N	Y	Y	Y
F-P	Y	N/A	N/A	Y	S	Y	Y
Address space (bits)							
Data 1	30	32	40	32	2x10	2x9	32
Data 2	-	-	-	-	12	10	S
Instruction	30	S	S	S	24 (S)	24 (S)	32
I/O bandwidth (MB/sec)	80	50	66	132	132	50	106
Interrupts	Y	Y	Y	Y	Y	Y	Y
Context switch	Y	Y	Y	Y	Y	N	Y
High-level language	Y	Y	Y	Y	Y	Y	Y
R-T operating system	Y	Y	Y	N	Y	N	N

Ext = External
N/A = Not Applicable
Y = Yes
N = No
S = Shared

Source: Dataquest
March 1989

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Precision and Speed

Precisions are at rough parity now. DSMPUs tend to preserve more bits for accumulation, but RISC processors often have greater word length flexibility, which can be useful for DSP image data. RISC meets the precision need. Basic data pipeline cycle times are shorter for RISC processors, and the difference is real for small vectors. Nevertheless, address generation times in the RISC integer ALU and data memory bottlenecks reduce performance for most signal processing operations below that of the DSMPUs. As the number of separate pipelines in the execution units and the concurrency figures show, however, the differences may not be large. Note that the 64-bit data busses of the i860 give it higher large-vector performance than the DSMPUs due to concurrency. Thus, RISC can meet many DSP speed requirements now. So-called vector processors are being considered by RISC suppliers now to provide multiport address generation for large real data memories to increase DSP and vector performance, so the gap may narrow in the future. NEC has even announced such a vector processor for its V-series product line, which employs traditional complex-instruction-set computer (CISC) architectures. RISC processors for the moment seem to lead DSPs in providing for paralleling of complete processors.

Memory Hierarchy

RISC processors have large data register files that, for most functions, equate to the much larger separate data memories on the DSMPUs. Concurrent load/store I/O operations on the RISC processor can reduce this size difference; however, speed may degrade quickly due to I/O bottlenecks. The large number of registers or accumulators on the DSMPUs reflect the desire to support high-level language compilers. Caching of instruction memory is used in both RISC processors and DSMPUs, although the modes of operation are much different. A low-cost, low-complexity solution is possible with a RISC processor that is sufficient to meet signal processing needs. Data caching is handled overtly with partitioned memories and programmed control in DSMPUs rather than "automatically" as in RISC processors. The large on-chip data cache on the i860 with its 128-bit bus is a real performance booster for signal processing operations. Overall the RISC memory hierarchy may seem ill suited for signal processing, but it can be scaled down and be cost and performance effective for large DSP systems.

Special Processing

The addition of vector processors to RISC processors may more nearly even the score, but now DSMPUs clearly excel at the concurrent and complex address generation needed in large data spaces for signal processing. This extends to I/O with DMA controllers as well as for on-chip memory. The concurrent multiply-accumulate arithmetic function so central to DSP is not common in RISC except in the floating-point execution units. This directly affects DSP speed performance on the RISC processors.

Large Amounts of Real-Time Data

The important address space change for RISC is to separate data and instruction spaces for higher performance. DSMPUs have increased the size of both spaces in order to handle the larger programs from high-level languages and the graphics and image data bases. DSMPU memory spaces have become more linear (like RISC) as they have gone off-chip. Thus, RISC processors can meet the separate and large memory space requirements of current signal processing systems. DSMPU I/O bandwidths remain higher than RISC processors and generally can be more fully utilized, but RISC I/O rates exceed many early DSMPUs and can be sufficient in many DSP systems.

RISC processors have interrupts, stacks, and other context-switching hardware assists, but they often lack the deterministic response times necessary for real-time DSP. Cypress Semiconductor is moving to improve this in its implementation of the SPARC architecture, and it seems likely that others will also. RISC processors, likewise, have the more complete high-level language support but not in a real-time operating system environment.

TODAY'S HIGH-PERFORMANCE SYSTEMS AND THEIR MARKETS

This growing similarity between digital signal processors and general-purpose RISC microprocessors results from manufacturers of these products recognizing the needs of an increasingly common high-performance system. Figure 1 is a block representation of such systems. It represents functional blocks of the typical new high-performance systems and their varied CPU processing and software requirements. Typically, some physical process that generates a large amount of data is analyzed or controlled by computations on the data. The computations are altered by operator controls, often interactively, from results that are presented on a display. The display itself often involves much processing, as does the final output result on some peripheral device.

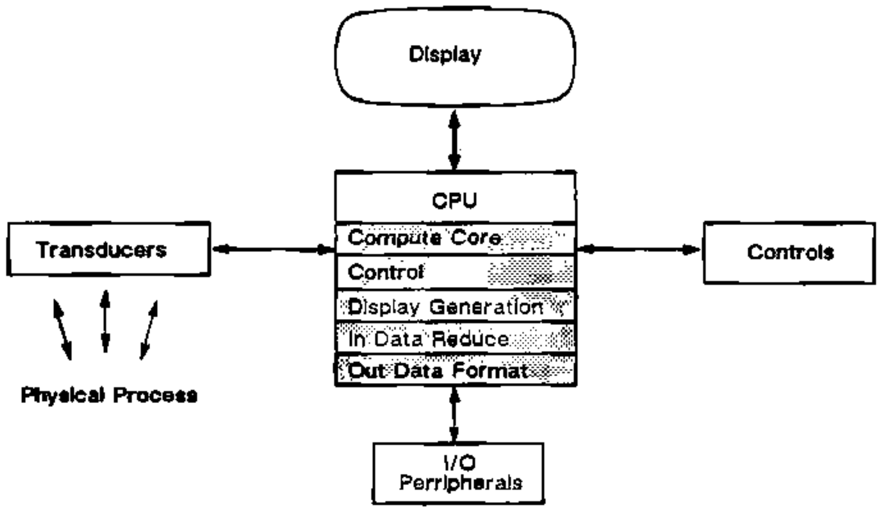
For economic reasons, and because not all processing is simultaneous, a single CPU is desired. Speed is important because of the large amount of data, the fact that the system is interactive, and the fact that it often must be real time in the strictest sense for closed-loop control purposes. The speed must be in I/O as well as arithmetic functions to support displays and the data collection.

Large amounts of high-level language applications code are used, often running under UNIX. This user- and third-party-supplied software accommodates industry standards processing and standard I/O peripherals, drivers, and formats. The high-level language improves maintainability, but often it is used initially because it allows the function to be transported in to get the system operating in a minimum amount of time. Critical time to market is improved.

Typical applications that use these systems are listed in Figure 2. Frequently, they are referred to collectively as high-performance embedded controller systems. Note that high-performance workstations in this context are a subset with less demanding real-time I/O.

Figure 1

New High-Performance Systems and Their Varied CPU Processing and Software Requirements



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Source: Dataquest
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Figure 2

Important High-Performance Markets for RISCs and DSMPUs

- Medical Tomography Imaging
- Ultrasound Imaging
- Communications Instrumentation
- Vibration Testing
- Electrical, Chemical, and Mechanical Design, Simulation, and Analysis Workstations
- Image Scanning and Electronic Publishing

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Source: Dataquest
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THE COMPETITIVE THREAT AND NEW DSP STRATEGIES

Few significant quantity shipments of RISC processors occur today, except for workstation shipments, and it will be two years before the important product families and markets can be confirmed. However, the prudent DSP product strategist cannot wait for market erosion to react.

Dataquest believes that certain DSP performance issues are important ones for DSMPU suppliers trying to maintain their markets. DSMPU suppliers must continued to do the following:

- Accommodate the real-time nature of DSP operations—The first requirement is to continue to accommodate the real-time nature of the processing while adapting to the need for operating system and high-level language benefits. This can be done through integrated hardware assists and real-time software function libraries that support industry standards and device independence yet do not get in the way of the other real-time processing required. Developing a standardized library of real-time functions and a suite of DSP performance measures, like the recent SPEC benchmarks, would help.

- Support greater memory flexibility

  - Even with the larger data bases and programs of DSP systems today, the memory hierarchy needed always will be different from the more general-purpose data processing system. The need for large, multiported nonvirtual memory always will exceed the RISC on-chip register file. Continued attention to this memory distinction will protect DSP markets.

  - Vector processors that provide concurrent address generation for arrays are expected to be added to both CISC and RISC microprocessors, but DSMPUs always should be able to exceed the performance achieved in a linear memory, particularly for 2-D functions and transforms like the FFT.

- Develop workable multiprocessor languages and interprocessor protocols—Paralleling complete processors to increase computing power is everyone's candidate for the next major leap in performance, yet progress has been very slow in systems that can be used today. Because DSP is so amenable to partitioning between parallel processors, it can take the lead in simple, workable languages and interprocessor communications conventions.

- Emphasize high-bandwidth, real-time I/O—A final area of emphasis for DSP should be input/output (I/O). Graphics and imaging have made I/O dataflow an issue for all processors; however, the serial telecommunications interfaces, complex multiplexing/demultiplexing, and high real-time bandwidths should allow important product distinctions.

DATAQUEST ANALYSIS

Dataquest believes that if DSP suppliers are successful in providing this special DSP performance, their growth will continue and they will remain an important portion of the semiconductor processor market. The discussion here has centered only on the high-performance, higher-cost devices, but they represent a major growth area now and the dominant products of the future. Failure to act could bring a repeat of the generation-earlier contest between DSP array processors and general-purpose minisupercomputers. In spite of FORTRAN library support and parallel processors, the array processors lost vital market share to the more general-purpose minisupercomputers when they had the same floating-point multiprocessor parity. The near demise of Floating Point Systems, the leading array processor company, at the hands of Alliant and Convex closed out the first significant generation of DSP high-performance systems. The parallel between those rival minicomputer systems and today's rival microprocessors bears careful attention by suppliers of DSP integrated circuits.

Robert E. Owen

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THE INVISIBLE DSP IC MARKET: GATE ARRAY, CELL-BASED, CUSTOM, AND SILICON COMPILER DESIGNS

SUMMARY

Application-specific digital signal processors (ASDSPs) constitute a large and rapidly growing segment of the general application-specific integrated circuit (ASIC) market. The major suppliers are broad-based ASIC firms that provide little DSP support, rather than the traditional DSP IC companies. By supporting the DSP designer better, DSP-focused suppliers can secure some of this market, which is nearly equal in size to the DSP microprocessor (DSMPU) market.

INTRODUCTION

DSMPUs, building blocks, and special-function DSP chips (SFDSPs) constitute a very visible market because of the large marketing promotions for these devices. Suppliers and users alike advertise the successful incorporation of these ICs into end products. Almost totally invisible are the custom ASDSPs developed by product manufacturers for their special DSP needs.

ASDSPs are a portion of the broad ASIC market and include all of the same techniques in their design: gate array; cell based—standard cell, as well as extensions to a microprocessor core; full-custom; or silicon compilation. However, they are distinct within DSP IC markets from the SFDSPs such as modems and FFT chips, which are designed and marketed broadly for specific functions rather than specific "applications."

These invisible ASDSP chip sales are very substantial, estimated at $131 million in 1988, or roughly the same as the $158 million for the highly visible DSMPUs. For many domestic ASIC suppliers, 20 to 30 percent of their output is DSP related, with some companies approaching 50 percent. The invisibility comes from the proprietary nature of the business, not its lack of market importance. This newsletter looks at what is happening in this market with the thought that its invisibility may be hiding DSP business opportunities and important trends. We first review the major general ASIC suppliers and their marketing positions toward DSP. Then we examine the major DSP suppliers and their involvement with ASDSPs.

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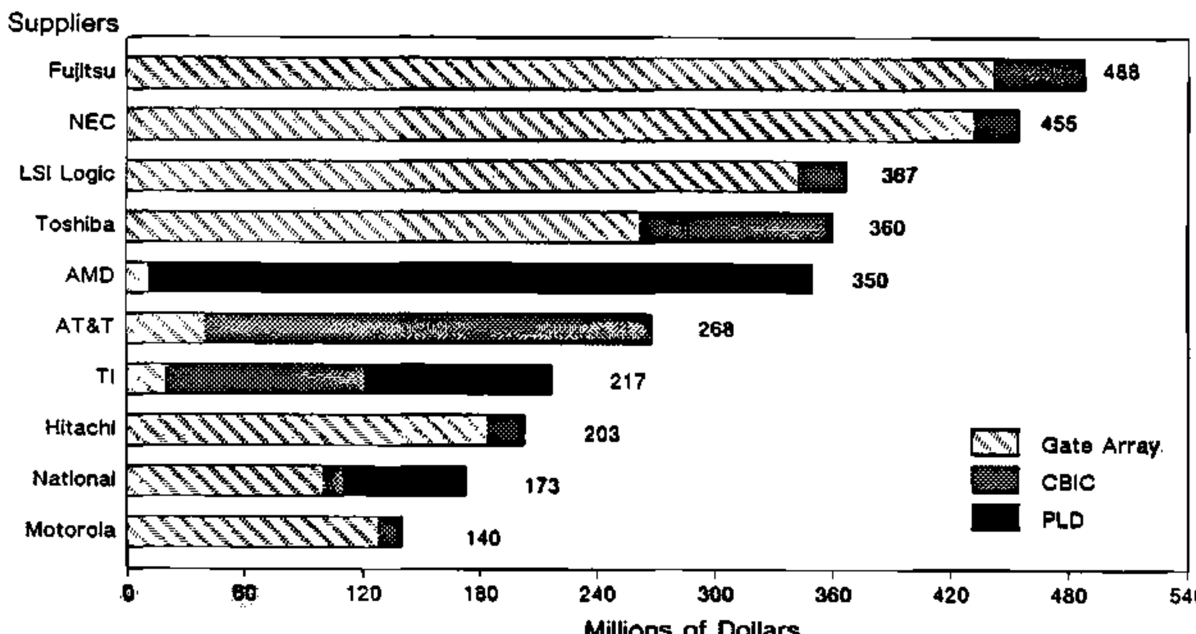
PRODUCTS AND DSP MARKETING POSITIONS OF MAJOR ASIC SUPPLIERS

The general ASIC market was $7.4 billion in 1988, nearly 20 percent of the total IC market, with a compound annual growth rate (CAGR) of 16 percent. Figure 1 shows the worldwide sales for the major suppliers in all technologies (MOS, bipolar, and BiCMOS) and design types (gate array, cell-based, etc.). Estimated North American ASIC consumption by application market is shown in Figure 2. Note the prominence of the communications and military areas, major DSP markets.

Figure 1

Estimated 1988 Worldwide ASIC Ranking



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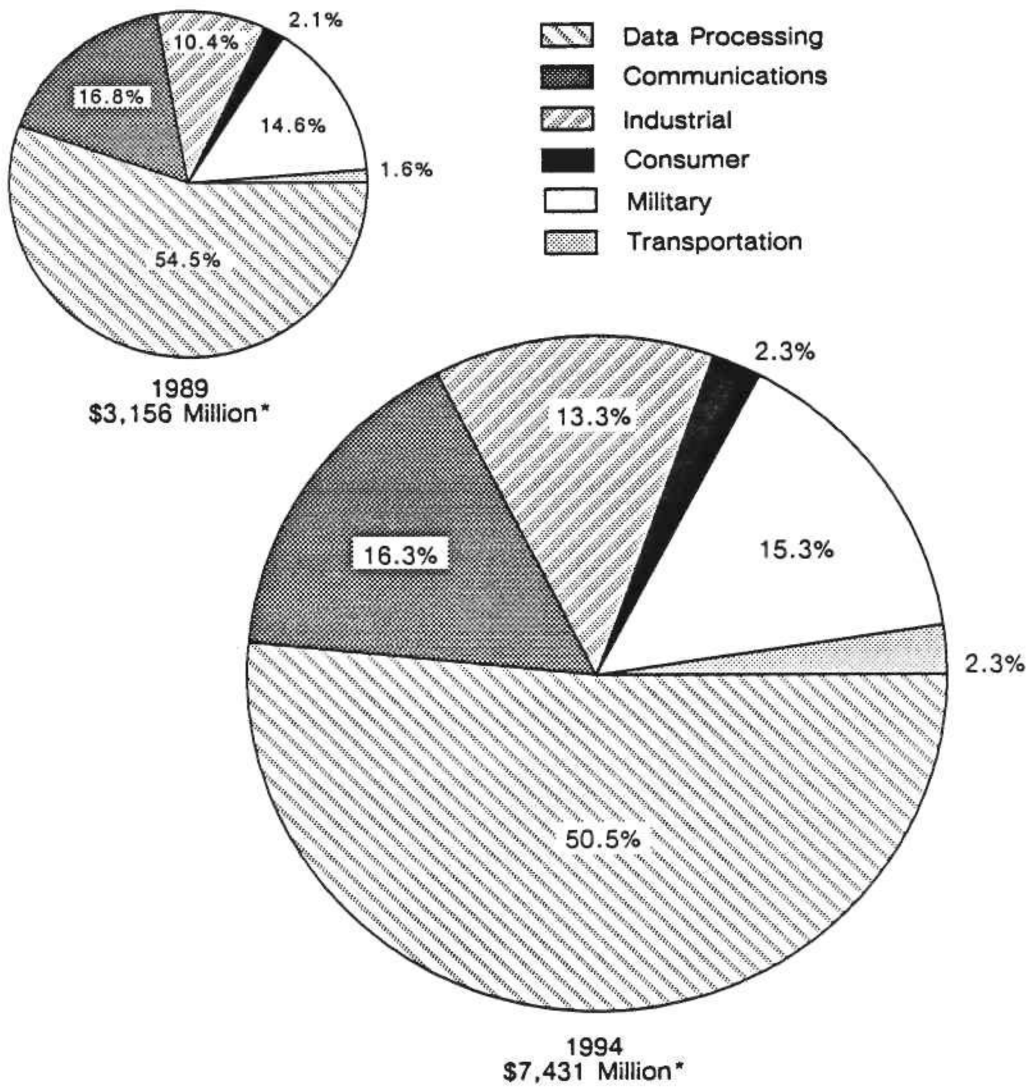
Source: Dataquest May 1989

Figure 2

Estimated North American ASIC Consumption by Application Market—Total (1989 and 1994)



*Excludes Full-Custom ICs

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Source: Dataquest May 1989

Gate Arrays

The largest ASIC segment is gate array designs, at $2.9 billion in 1988. The ranking five suppliers are the top four overall ASIC companies—Fujitsu, NEC, LSI Logic, and Toshiba—plus Hitachi. None, with the exception of LSI Logic, have significant design aids for DSP users. The closest thing is macrofunctions of the AMD Am2900 series building blocks, which are popular in DSP. LSI Logic, the top CMOS gate array supplier with an estimated 25 percent DSP business, has the MACGEN compiler for generating multiplier-accumulators of varying precision and arithmetic formats. Although backed up with a full arithmetic and functional simulator, it still lacks specific DSP features like overflow saturation and coverage of the often complex address generation and microprogramming functions needed for a full processor.

Cell-Based Designs

The smallest but fastest growing segment of the ASIC market is the so-called standard cells segment. In 1988, revenue was $1.3 billion, with AT&T, Texas Instruments, Toshiba, NCR, and VLSI Technology as the top-ranked suppliers. Growth was 43 percent last year. Here again, DSP support has been limited mostly to Am2900 series building blocks.

Full-Custom and Silicon Compilers

The second largest ($2.5 billion) portion of the ASIC market in 1988 was still the full-custom segment, but it is declining at a 3 percent annual rate. Silicon compilation, however, counters the overall figure with strong growth. DSP accounts for nearly half of all silicon compiler applications because of its acceptance by large communications and military systems companies. DSP support is a natural fit for silicon compilation, with its emphasis on high-level functional design, but even leader Silicon Compiler Systems, Inc., provides no specific DSP support.

The motivation for a full-custom design is often proprietary design protection and cost, but it also can be the high performance that DSP requires. The largest custom suppliers are NEC, Matsushita, Sharp, and Toshiba. Although much of their output is for consumer products (e.g., ultrasonic autofocus controllers for cameras), the companies are often solving DSP problems. That trend should continue as consumer products become smarter. Philips, the large European consumer products firm, estimates that half of its custom silicon output is for DSP functions.

MAJOR DSP SUPPLIERS' ROLES WITH ASDSPs

Dominant DSP supplier Texas Instruments has surely leveraged its position with application-specific designs, but these designs have been mostly full-custom done with internal design resources. One that became visible is the TMS 320C20, now a standard product, which grew from specific speech processing requirements at ITT. But Texas Instruments does not actively encourage ASDSPs, particularly those that involve users in any active role in their design. The new TMS 320C30 has a modular layout and a future as a processing core, but it is not a major thrust at this time.

Number two DSP supplier NEC has produced a myriad of DSP designs in most DSP applications, such as speech recognition, signal encoding and image processing, as well as in more experimental areas like data-flow processors. Most have been cell-based designs to keep development costs low and design times short. However, these devices have been mostly for internal telecommunications requirements, with no public attempt to secure ASDSP business using the cell libraries.

Similarly, Fujitsu has supplied a large internal telecommunications need with cell-based designs. It has had less commercial success with standard products. Perhaps because of this, Fujitsu has now made available its processing cores and cell-based peripherals and memory configurations in the MB8220/232 product line.

AT&T, a major internal ASIC and DSP supplier, has not used its limited commercial success with standard parts to expand its ASDSP business. Motorola and Analog Devices have no ASIC programs in DSP, even though Motorola's 56200 was a silicon compiler design that could presumably have been the start of an application-specific filter business.

TRW LSI Products is understood to have replaced much of its loss of merchant market share with custom DSP designs using its own design teams. There are no tools for public use. AMD's lack of participation in the general ASIC market has kept the company from capitalizing on the Am2900 series building blocks.

DATAQUEST CONCLUSIONS

The distinction between DSP and general-purpose data processing is becoming blurred, but clearly a large portion of the fastest growing segment of the IC business, ASICs, is DSP related. Dataquest expects ASDSP to be a $181 million market in 1989 (see Table 1). The major participants in this business are the traditional ASIC suppliers rather than the DSP IC firms. Business is being secured in spite of not having device libraries or support tailored to DSP designer needs. At this time, users are limited to sophisticated users who do not require much support.

The major DSP suppliers, although they do high-volume, full-custom, application-specific designs, have not pursued this business either. Because their own standard products have usually been custom designed, they have not internally developed the libraries or tools that would assist them in the public ASDSP market. They also might view an aggressive ASDSP program as eroding the programmable solutions with their standard products in which they have made such an extended investment. This explains their cautious approach of expanding from a programmable core processor for ASDSPs. Within large IC companies, DSP and ASIC are often separate divisions, with many organizational forces working to impede cooperation on a workable strategy. Even in a narrowly focused company like LSI Logic, the DSP effort has been an attempt to establish a viable standard product line (something new for the company) rather than to strengthen its position in the ASDSP market.

Table 1

Application-Specific DSP (ASDSP) Market
(Millions of Dollars)

Estimated		
1986	1987	1988
$68	$98	$131

CAGR
1986-1992
37.6%

Forecast			
1989	1990	1991	1992
$181	$250	$340	$461

Source: Dataquest
May 1989

The ASDSP market is understandably undersupported at this time. Because both general ASIC suppliers and DSP firms have been growing rapidly, they have had other more important tasks. Each type of company would have to master a new set of skills to solidify a position, but as competition increases, some company will likely move to claim ASDSPs as its own. ASIC houses would seem to have a head start, but DSP manufacturers may have the strongest motivation.

As DSP increasingly becomes possible on general-purpose, particularly RISC, processors, a quick-response, application-specific approach to the remaining diversified DSP market will be necessary. Cell-based designs seem the best design approach today, besides being a good basis for any long-term plan for DSMPUs, or special-function or building block DSP standard products.

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NEW DSP PRODUCTS AND TRENDS AT ISSCC '89 AND CICC '88

SUMMARY

Significant new products were shown in all digital signal processing (DSP) segments at the major semiconductor conferences during the last year. Most new DSP products were in the video and image special-function segment. Recent product, architecture, and technology trends continued with programmed, functional block, and application-specific solutions coexisting. Reduced-instruction-set computing (RISC) processors and their floating-point coprocessors invited comparison with high-performance signal processors.

INTRODUCTION

The first public awareness of significant new integrated circuit products usually comes through papers presented at the International Solid State Circuits Conference (ISSCC) in February or the Custom Integrated Circuits Conference (CICC) in May. This certainly has been true for DSP, where whole sessions are usually devoted to the topic. An important part of Dataquest's DSP research is coverage and interpretation of new products and related technologies that are described at these two conferences. We also will be reporting on signal processing technology advances and products introduced at the International Conference on Acoustics, Speech, and Signal Processing (ICASSP) in April.

Of obvious interest are the new DSP microprocessors (DSMPUs), microprogrammable building blocks (MPDSPs), special-function DSPs (SFDSPs) for video and imaging, and application-specific circuits for DSPs (ASDSPs) in fields such as telecommunications. But related products like analog/digital converters, high-performance microprocessors, and coprocessors also affect DSP markets. Both conferences provide a guide to the latest design methodologies that can be important in fitting DSP techniques to new application needs rapidly. New semiconductor technologies described often impact DSP products early because of their need for the highest speeds and high density. Our purpose here is to collect those items that seem important for a thorough understanding of DSP product and technology directions. Completeness of coverage is considered more important than details and comparisons of specific products, due to the preliminary nature of this early information.

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DSP Microprocessors

Only one truly general-purpose, single-chip DSMPU was described at either conference; it was an upward-compatible, third-generation enhancement from Mitsubishi. However, Mitsubishi's new product's speed at 40ns per instruction cycle for 24-bit floating-point is noteworthy. The 24-bit (16E8) precision is an increase over the initial 18-bit (12E6). Other differences are a shared on-chip data and instruction cache and shared external memory space, in addition to the normal external instruction-only and data-only memories. Caching is increasingly being seen in DSPs, and here it includes a novel clock-scaling circuit to allow it to be easily loaded from slower external memory.

Although described as video processors, a 24-bit integer unit also from Mitsubishi and a 16-bit integer processor from NEC are really full-function programmable DSMPUs. Both are impressively fast, and as Table 1 shows, they have all the functions of the general-purpose Mitsubishi device except the serial telecommunication interface. The chief distinction between the video processors and the DSMPU is the richness of address generation capability, a welcome addition for most applications on a DSMPU, along with the faster speed. Prices will be higher for these two larger-size chips.

Special-Function DSPs

Video Processors

The special function receiving the most attention this year, as it has for the past several years, was video (see Table 2). This follows from the increased interest in HDTV and the establishment of ISDN video compression standards. The most flexible product is the 24-bit integer processor from Mitsubishi (also shown in Table 1). The three data execution units supported by two large dual-ported memories with three address generators driven by the 48-bit instructions provide very high performance. The data precision is high enough for transforms, yet the instruction set also makes it data byte efficient. Address generation is two-dimensional both on- and off-chip. Performance figures were given for a large number of video functions, but full attention was given to the video codec requirements for transforms, vector quantization, and motion compensation.

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Table 1

Significant New DSP Microprocessors (DSMPUs) at ISSCC '89

Features	Mitsubishi	Mitsubishi	NEC
Precision	24-bit FP (16E8) & integer	24-bit integer	16-bit integer
Instruction Cycle	40ns	50ns	25ns
Arithmetic Element Stages			
ALU	1	1	1
MPY	1	1	1
ACC	0	1	1
Address Generators	2	3	4
Memories			
Instruction			
Internal ROM	4Kx32	-	-
Internal RAM	-	512x48	512x32
External	60Kx32	16Kx48	-
Data & Instruction			
Internal RAM	64x32	-	-
External	4Kx32	-	-
Data			
Internal RAM 1	512x24 (DP)	512x24 (DP)	128x16
Internal RAM 2	-	512x24 (DP)	128x16
External 1	60Kx24	64Kx24	1Mx16
External 2	-	-	1Mx16
Input/Output			
Serial	1-bit	-	-
Parallel	24-bit	24-bit	16-bit
Technology			
Process	CMOS	CMOS	CMOS
Feature Size	1u	1u	1.2u
Transistor Count	300K	538K	220K
Pin Count	135	177	176
Die Size (mm)	7.0 x 8.6	13.8 x 15.5	14.0 x 13.4

Notes: FP = Floating-Point, DP = Dual-Port

Source: Dataquest
April 1989

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Table 2

Significant New Special-Function DSPs (SFDSPs) at ISSCC '89 and CICC '88

Company	Function	Instruction Cycle Time	Precision	Transistors
Video				
Mitsubishi	Broad, microprogrammable	40ns	24-bit	538K
NEC	Broad, microprogrammable	25ns	16-bit	220K
MicroElectronics Center	2-D FFT	100ns	11-bit	152K
Bellcore	2-D DCT	70ns	12-bit	73K
Toshiba	Codec	41ns	8-bit	288K
Kodak	Color correction	70ns	14-bit	94K
Image				
LSI Logic	FIR filter	50ns	8-bit	240K
	Template match	50ns	1-bit	94K
	Rank value	50ns	12-bit	140K
	Delay line	50ns	8-bit	110K
Siemens	MAC	40ns	18/32-bit	340K
	Correlation	40ns	32-bit (FP)	90K
Sony	16 MAC array, selectable	50ns	12-bit	124K
NEC	MAC (BiCMOS)	5ns	16-bit	20K
Fast Fourier Transform (FFT)				
Plessey	FFT, weighting	25ns	16-bit	500K
Filter				
Fujitsu	Adaptive filter	100ns	16-bit	42K

Notes: DCT = Discrete Cosine Transform, FP = Floating-Point

Source: Dataquest
April 1989

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The NEC chip is a 16-bit integer processor (also shown in Table 1) and is correspondingly faster than Mitsubishi's at 25ns. It compares with a simpler three-stage pipeline, 70ns version presented two years ago. The seven stages of the newest chip are in a sequence that is useful for most video tasks. NEC has provided for multiprocessor synchronization, because even with these data rates, more than one processor may be necessary for real-time performance.

These two programmable processors, with their writable control stores for instructions, are contrasted with the video processors from Toshiba and Kodak, which are fixed in function. Toshiba's video codec uses the time-compressed integration format for HDTV conversion in either direction. The link may be either analog, 400-Mbps digital, or video disk. For an established format, it offers functional flexibility in one large but potentially high-volume part. Kodak's processor serves a more narrow function—it provides the digital processing from color filter CCD arrays to create correct three-color video signals. The slower speed is acceptable because of the smaller number of pixels in current CCD arrays.

Image Processors

Video processing generally is seen as a subset of image processing that accommodates in some manner the specific real-time bandwidth requirements of video signals and makes use of the sequential raster nature of data and its storage. For more basic functions like multiply-accumulate, the distinction may not be meaningful. Sony's processor containing 16 multiplier-accumulators (MACs) and adders and NEC's BiCMOS MAC are described as video building blocks, while Siemens' products are aimed at "real-time images." The Siemens two-chip set and the Sony processor are programmed processors but fit together like building blocks. The input MAC is integer for 6-bit neighborhood data, while the arithmetic processing unit is 32-bit floating-point for full image 2-D operations like correlation. There are three concurrent floating-point data execution units and concurrent I/O. Sony's processor's limited functions, all based on the inner product operation, can be combined in systolic arrays to boost the 1.04 Giga-operations per second (GOPS) for a single chip. NEC, in one-fourth the chip area and with 65 percent of the power consumption, achieves 0.2 GOPS or one-fifth the performance—more of a BiCMOS test vehicle than part of any video or imaging product strategy.

Fast Fourier Transform (FFT) Products

With the flurry of new FFT chips recently introduced by Austek, Honeywell, TRW, UTC, and Zoran, interest was high in the new PDSP 16510 from Plessey. Its most notable feature is that it will do a full 1,024-point complex transform using only internal memory and in less than 100us. Most other products use large, fast, and expensive external memories and/or multiple processors to do transforms this large. Plessey's version is also very flexible in transform size, real or complex data type, use of data buffers, and selection of weighting functions. The 13.1 x 13.3mm area will make it not be cost competitive with DSMPUs for small transforms; however, in the many applications requiring midsize transforms, this product will be very attractive in price, size, and complexity of design. Plessey's FFT was the most significant pure DSP product introduced at ISSCC '89.

General–Purpose Microprocessors

Coprocessors

The major public product announcement at ISSCC was of course Intel's i860, and it was of not just a little interest to the DSP community. The hype was about RISC, UNIX, and standalone operation, but competitors' concerns were about a high–performance $750 coprocessor, and that is how we have compared it in Table 3. The significant trends among the coprocessors are toward multiple, fast pipeline stages; multiple execution units including I/O; and wider–than–32–bit data paths. All are moves toward DSP–like performance in a standard microprocessor system. This was particularly evidenced by the concurrent multiply–add and the vector address generation capability of NEC's new coprocessor for the V60, 70, and 80 series.

RISC Processors

RISC processors are the engines that drive coprocessors with high clock rates and wide 64–bit busses. A Digital Equipment Corporation spokesperson said in his session 7.1 presentation that a vector processor was a future part of this (non–VAX) family. The Matsushita chip, with its four parallel execution units, clearly rivals the i860 in power, and it, too, has features for multiprocessing.

Building Blocks

Multipliers are the traditional regular–function, medium–complexity test vehicles for any new technology, so it is not surprising to see some appear now in gallium arsenide (GaAs). Seldom are they significant in commercial DSP markets. However, Honeywell's GaAs multiplier introduced at ISSCC clearly was designed for DSP because it does a full 16–bit complex multiplication (four multiplies and two additions) and does it in only 8ns. Mitsubishi's 32–bit floating–point building block is highly pipelined with five 10ns stages and is self–timed. This technique, where data is passed from stage to stage only when the processing is complete, is bound to see wider use as multiple variable–length data pipelines become common. Mitsubishi does not use this technique in its purest form, but the company has a head start at learning about its use. This product was the most significant DSP circuit/architecture innovation presented at ISSCC '89.

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Table 3

Significant New General-Purpose Microprocessors and Building Blocks (MPDSPs) at ISSCC '89

	Functional Unit	Pipeline Delay	Pipeline Depth	Precision
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Intel i860*	Integer ALU	30ns	1	32-bit
	FP ALU	30ns	3	32/64-bit
	FP MPY	30ns	3	32/64-bit
	I/O	60ns	1-3	64-bit
NEC	FP ALU	50ns	8	32/64/80-bit
	FP MPY	50ns	9/11/12	32/64/80-bit
GE	32-bit Integer or			
	FP ALU or MPY or MAC	25ns	3	32/64-bit
	I/O	25ns	1	32-bit
Digital	FP ALU or MPY	20ns	4/5	32/64-bit
RISC Processors				
Digital (7.1)	Integer ALU	20ns		32/64-bit
Matsushita	Integer ALU	50ns		24-bit
	FP MPY	50ns		64-bit
	FP MPY	50ns		64-bit
	I/O	50ns		64-bit
Digital (7.3)	Integer ALU	28ns		32-bit
	I/O	28ns		64-bit
HP	Integer ALU	33ns		32-bit
Digital (7.5)	Integer ALU	40ns		32-bit
	I/O	40ns		64-bit
Building Blocks				
Honeywell (GaAs)	Integer MPY (complex)	2ns	3	16-bit
Mitsubishi	Integer & FP ALU	10ns	5	32-bit
	Integer & FP MAC	10ns	5	32-bit

Notes: ALU = Arithmetic Logic Unit, FP = Floating-Point, MAC = Multiplier-Accumulator, MPY = Multiplier

*Intel's i860 processor is considered a standalone RISC processor with integrated floating-point and 3-D graphics. For purposes of this comparison, we will focus only on the floating-point portion of the i860.

Source: Dataquest
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Applications

It is always interesting to check on the migration of DSP techniques into chips for complete applications. There is a concern that all of the high-volume applications will be met this way and that there will be no lasting market for the general-purpose programmable solutions. Oki's modem chip showed that this high-volume application's requirements can be met with a DSMPU core and specialized on-chip A/D and D/A peripheral circuits.

Panel Discussions

The regular "Future of DSP" panel session was less partisan and more penetrating than usual. A major topic was questioning the need of the latest large, full-featured DSMPUs. Is there a place for other than "lean and mean" (simple and fast) processors? As part of that topic, the usual floating-point versus integer discussion ensued, but this time it ended differently than usual. AT&T virtually acknowledged that floating-point had been put in its DSP-32 because it was the next step and not because it was clearly justified. And sure enough, AT&T said, the most successful application had been graphics transformations, not a traditional DSP function at all.

CICC '88

Products

At last year's Custom Integrated Circuits Conference, the DSP products were all special-function products, as one might expect, and there was more information about DSP-specific design methodologies. Video and imaging dominated again. For example, Bellcore's discrete cosine transform chip does 16 x 16 pixels in real-time for video coding. It is a multiplierless design using only additions and ROM lookup tables for compactness.

The MicroElectronics Center (MEC) 2-D FFT array of chips processes 256 x 256 pixels in real-time at a 30Hz rate. It uses the long-forgotten shift register method of FFT data sequencing to advantage.

Two papers by LSI Logic introduced a family of 20-MHz image-processing chips that has since grown to six and increased in speed. They were the most significant DSP papers presented at CICC '88 because in one short span of time LSI has made available a complete processor and memory building block set for imaging. This came from a thorough product line plan, fast turnaround design tools, and a commitment to provide what was needed even if it resulted in large chips. The FIR filter, for example, has 64 MACs and is 1.4cm on a side. Rarely is there such a complete product thrust into a market that is in an early development stage. The commercial battle line is clearly drawn now between programmable processors and functional blocks in this DSP application area.

Fujitsu described an adaptive filter that offers improved I/O and multichannel processing over a DSMPU. It is unusually well supported with design software and documentation.

Design Methods

CICC papers have more discussion of design tools than circuit design details, and the silicon compiler session always includes DSP because DSP data processing is more regular and amenable to description and synthesis. The University of California at Berkeley and IMEC in Belgium are both centers of much of this compiler work, and their progress is steady, with effects being seen in commercial products at Philips and LSI Logic. No company is visible yet that has made silicon compilation a cornerstone of its DSP product strategy.

DATAQUEST CONCLUSIONS

What did these two important conferences say about the major DSP issues being watched today? They confirmed first that general-purpose microprocessors in the form of RISC and their coprocessors are getting function and performance levels close to high-end DSMPUs. Secondly, in the growing area of video/image processing, a special-function DSP segment, there are still new product examples of programmable, functional block, and application-specific implementations. These three forms may continue to coexist with no clear indication of a single product "best" strategy.

The product trends for each of the segments were as follows:

- DSMPU—Little new; the third generation is still being digested.
- SFDSP—Video/image is the function getting the most attention recently.
- MPDSP—No major products except at new technology frontiers.
- ASDSP—Core DSP processors are expanding into this area more than compilers/design tools are adapting to DSP.

The architectural trend is to separate highly pipelined data execution units for higher performance and more run-time assists to control them. One micron is the new technology norm, and BiCMOS' impact, if any, is yet to be felt in DSP.

Generally, DSP integrated circuit progress is strong and healthy, but one feels a little cautious when all of the excitement is about general-purpose processors with speeds and precisions that were only so recently the sole domain of DSP.

Robert E. Owen

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NEW DSP PRODUCTS AND TRENDS AT ISSCC '89 AND CICC '88

SUMMARY

Significant new products were shown in all digital signal processing (DSP) segments at the major semiconductor conferences during the last year. Most new DSP products were in the video and image special-function segment. Recent product, architecture, and technology trends continued with programmed, functional block, and application-specific solutions coexisting. Reduced-instruction-set computing (RISC) processors and their floating-point coprocessors invited comparison with high-performance signal processors.

INTRODUCTION

The first public awareness of significant new integrated circuit products usually comes through papers presented at the International Solid State Circuits Conference (ISSCC) in February or the Custom Integrated Circuits Conference (CICC) in May. This certainly has been true for DSP, where whole sessions are usually devoted to the topic. An important part of Dataquest's DSP research is coverage and interpretation of new products and related technologies that are described at these two conferences. We also will be reporting on signal processing technology advances and products introduced at the International Conference on Acoustics, Speech, and Signal Processing (ICASSP) in April.

Of obvious interest are the new DSP microprocessors (DSMPUs), microprogrammable building blocks (MPDSPs), special-function DSPs (SFDSPs) for video and imaging, and application-specific circuits for DSPs (ASDSPs) in fields such as telecommunications. But related products like analog/digital converters, high-performance microprocessors, and coprocessors also affect DSP markets. Both conferences provide a guide to the latest design methodologies that can be important in fitting DSP techniques to new application needs rapidly. New semiconductor technologies described often impact DSP products early because of their need for the highest speeds and high density. Our purpose here is to collect those items that seem important for a thorough understanding of DSP product and technology directions. Completeness of coverage is considered more important than details and comparisons of specific products, due to the preliminary nature of this early information.

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DSP Microprocessors

Only one truly general-purpose, single-chip DSMPU was described at either conference; it was an upward-compatible, third-generation enhancement from Mitsubishi. However, Mitsubishi's new product's speed at 40ns per instruction cycle for 24-bit floating-point is noteworthy. The 24-bit (16E8) precision is an increase over the initial 18-bit (12E6). Other differences are a shared on-chip data and instruction cache and shared external memory space, in addition to the normal external instruction-only and data-only memories. Caching is increasingly being seen in DSPs, and here it includes a novel clock-scaling circuit to allow it to be easily loaded from slower external memory.

Although described as video processors, a 24-bit integer unit also from Mitsubishi and a 16-bit integer processor from NEC are really full-function programmable DSMPUs. Both are impressively fast, and as Table 1 shows, they have all the functions of the general-purpose Mitsubishi device except the serial telecommunication interface. The chief distinction between the video processors and the DSMPU is the richness of address generation capability, a welcome addition for most applications on a DSMPU, along with the faster speed. Prices will be higher for these two larger-size chips.

Special-Function DSPs

Video Processors

The special function receiving the most attention this year, as it has for the past several years, was video (see Table 2). This follows from the increased interest in HDTV and the establishment of ISDN video compression standards. The most flexible product is the 24-bit integer processor from Mitsubishi (also shown in Table 1). The three data execution units supported by two large dual-ported memories with three address generators driven by the 48-bit instructions provide very high performance. The data precision is high enough for transforms, yet the instruction set also makes it data byte efficient. Address generation is two-dimensional both on- and off-chip. Performance figures were given for a large number of video functions, but full attention was given to the video codec requirements for transforms, vector quantization, and motion compensation.

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Table 1

Significant New DSP Microprocessors (DSMPUs) at ISSCC '89

Features	Mitsubishi	Mitsubishi	NEC
Precision	24-bit FP (16E8) & integer	24-bit integer	16-bit integer
Instruction Cycle	40ns	50ns	25ns
Arithmetic Element Stages			
ALU	1	1	1
MPY	1	1	1
ACC	0	1	1
Address Generators	2	3	4
Memories			
Instruction			
Internal ROM	4Kx32	-	-
Internal RAM	-	512x48	512x32
External	60Kx32	16Kx48	-
Data & Instruction			
Internal RAM	64x32	-	-
External	4Kx32	-	-
Data			
Internal RAM 1	512x24 (DP)	512x24 (DP)	128x16
Internal RAM 2	-	512x24 (DP)	128x16
External 1	60Kx24	64Kx24	1Mx16
External 2	-	-	1Mx16
Input/Output			
Serial	1-bit	-	-
Parallel	24-bit	24-bit	16-bit
Technology			
Process	CMOS	CMOS	CMOS
Feature Size	1u	1u	1.2u
Transistor Count	300K	538K	220K
Pin Count	135	177	176
Die Size (mm)	7.0 x 8.6	13.8 x 15.5	14.0 x 13.4

Notes: FP = Floating-Point, DP = Dual-Port

Source: Dataquest
April 1989

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Table 2

Significant New Special-Function DSPs (SFDSPs) at ISSCC '89 and CICC '88

Company	Function	Instruction Cycle Time	Precision	Transistors
Video				
Mitsubishi	Broad, microprogrammable	40ns	24-bit	538K
NEC	Broad, microprogrammable	25ns	16-bit	220K
MicroElectronics Center	2-D FFT	100ns	11-bit	152K
Bellcore	2-D DCT	70ns	12-bit	73K
Toshiba	Codec	41ns	8-bit	288K
Kodak	Color correction	70ns	14-bit	94K
Image				
LSI Logic	FIR filter	50ns	8-bit	240K
	Template match	50ns	1-bit	94K
	Rank value	50ns	12-bit	140K
	Delay line	50ns	8-bit	110K
Siemens	MAC	40ns	18/32-bit	340K
	Correlation	40ns	32-bit (FP)	90K
Sony	16 MAC array, selectable	50ns	12-bit	124K
NEC	MAC (BiCMOS)	5ns	16-bit	20K
Fast Fourier Transform (FFT)				
Plessey	FFT, weighting	25ns	16-bit	500K
Filter				
Fujitsu	Adaptive filter	100ns	16-bit	42K

Notes: DCT = Discrete Cosine Transform, FP = Floating-Point

Source: Dataquest
April 1989

The NEC chip is a 16-bit integer processor (also shown in Table 1) and is correspondingly faster than Mitsubishi's at 25ns. It compares with a simpler three-stage pipeline, 70ns version presented two years ago. The seven stages of the newest chip are in a sequence that is useful for most video tasks. NEC has provided for multiprocessor synchronization, because even with these data rates, more than one processor may be necessary for real-time performance.

These two programmable processors, with their writable control stores for instructions, are contrasted with the video processors from Toshiba and Kodak, which are fixed in function. Toshiba's video codec uses the time-compressed integration format for HDTV conversion in either direction. The link may be either analog, 400-Mbps digital, or video disk. For an established format, it offers functional flexibility in one large but potentially high-volume part. Kodak's processor serves a more narrow function—it provides the digital processing from color filter CCD arrays to create correct three-color video signals. The slower speed is acceptable because of the smaller number of pixels in current CCD arrays.

Image Processors

Video processing generally is seen as a subset of image processing that accommodates in some manner the specific real-time bandwidth requirements of video signals and makes use of the sequential raster nature of data and its storage. For more basic functions like multiply-accumulate, the distinction may not be meaningful. Sony's processor containing 16 multiplier-accumulators (MACs) and adders and NEC's BiCMOS MAC are described as video building blocks, while Siemens' products are aimed at "real-time images." The Siemens two-chip set and the Sony processor are programmed processors but fit together like building blocks. The input MAC is integer for 6-bit neighborhood data, while the arithmetic processing unit is 32-bit floating-point for full image 2-D operations like correlation. There are three concurrent floating-point data execution units and concurrent I/O. Sony's processor's limited functions, all based on the inner product operation, can be combined in systolic arrays to boost the 1.04 Giga-operations per second (GOPS) for a single chip. NEC, in one-fourth the chip area and with 65 percent of the power consumption, achieves 0.2 GOPS or one-fifth the performance—more of a BiCMOS test vehicle than part of any video or imaging product strategy.

Fast Fourier Transform (FFT) Products

With the flurry of new FFT chips recently introduced by Austek, Honeywell, TRW, UTC, and Zoran, interest was high in the new PDSP 16510 from Plessey. Its most notable feature is that it will do a full 1,024-point complex transform using only internal memory and in less than 100us. Most other products use large, fast, and expensive external memories and/or multiple processors to do transforms this large. Plessey's version is also very flexible in transform size, real or complex data type, use of data buffers, and selection of weighting functions. The 13.1 x 13.3mm area will make it not be cost competitive with DSMPUs for small transforms; however, in the many applications requiring midsize transforms, this product will be very attractive in price, size, and complexity of design. Plessey's FFT was the most significant pure DSP product introduced at ISSCC '89.

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THE INVISIBLE DSP IC MARKET: GATE ARRAY, CELL-BASED, CUSTOM, AND SILICON COMPILER DESIGNS

SUMMARY

Application-specific digital signal processors (ASDSPs) constitute a large and rapidly growing segment of the general application-specific integrated circuit (ASIC) market. The major suppliers are broad-based ASIC firms that provide little DSP support, rather than the traditional DSP IC companies. By supporting the DSP designer better, DSP-focused suppliers can secure some of this market, which is nearly equal in size to the DSP microprocessor (DSMPU) market.

INTRODUCTION

DSMPUs, building blocks, and special-function DSP chips (SFDSPs) constitute a very visible market because of the large marketing promotions for these devices. Suppliers and users alike advertise the successful incorporation of these ICs into end products. Almost totally invisible are the custom ASDSPs developed by product manufacturers for their special DSP needs.

ASDSPs are a portion of the broad ASIC market and include all of the same techniques in their design: gate array; cell based—standard cell, as well as extensions to a microprocessor core; full-custom; or silicon compilation. However, they are distinct within DSP IC markets from the SFDSPs such as modems and FFT chips, which are designed and marketed broadly for specific functions rather than specific "applications."

These invisible ASDSP chip sales are very substantial, estimated at $131 million in 1988, or roughly the same as the $158 million for the highly visible DSMPUs. For many domestic ASIC suppliers, 20 to 30 percent of their output is DSP related, with some companies approaching 50 percent. The invisibility comes from the proprietary nature of the business, not its lack of market importance. This newsletter looks at what is happening in this market with the thought that its invisibility may be hiding DSP business opportunities and important trends. We first review the major general ASIC suppliers and their marketing positions toward DSP. Then we examine the major DSP suppliers and their involvement with ASDSPs.

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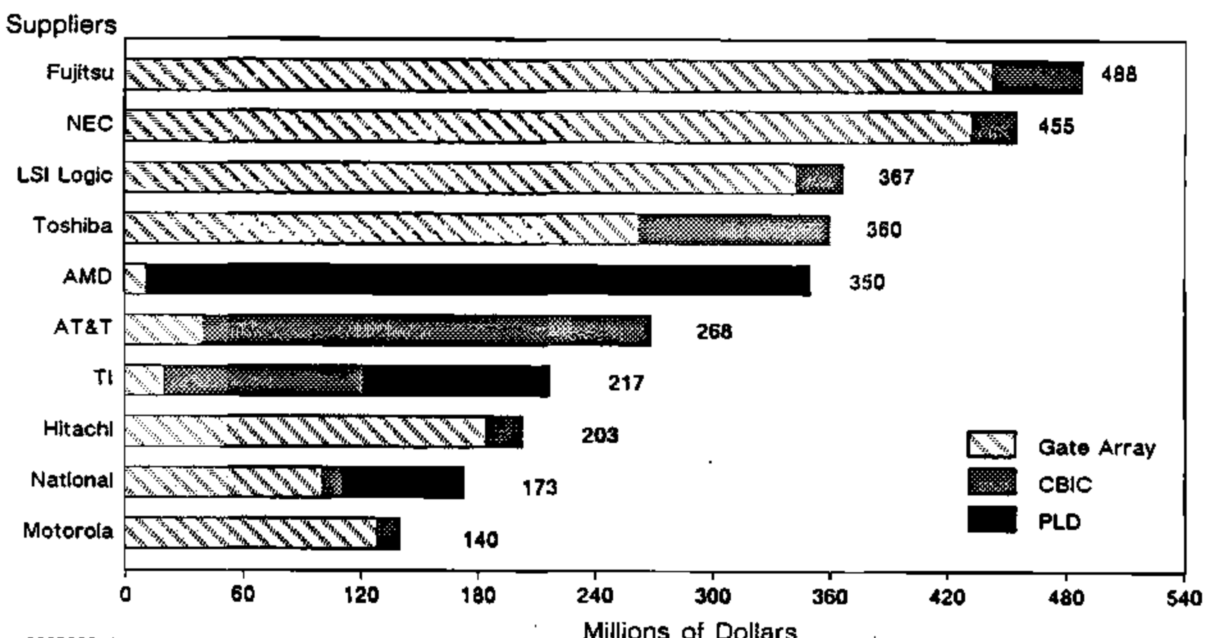
PRODUCTS AND DSP MARKETING POSITIONS OF MAJOR ASIC SUPPLIERS

The general ASIC market was $7.4 billion in 1988, nearly 20 percent of the total IC market, with a compound annual growth rate (CAGR) of 16 percent. Figure 1 shows the worldwide sales for the major suppliers in all technologies (MOS, bipolar, and BiCMOS) and design types (gate array, cell-based, etc.). Estimated North American ASIC consumption by application market is shown in Figure 2. Note the prominence of the communications and military areas, major DSP markets.

Figure 1

Estimated 1988 Worldwide ASIC Ranking



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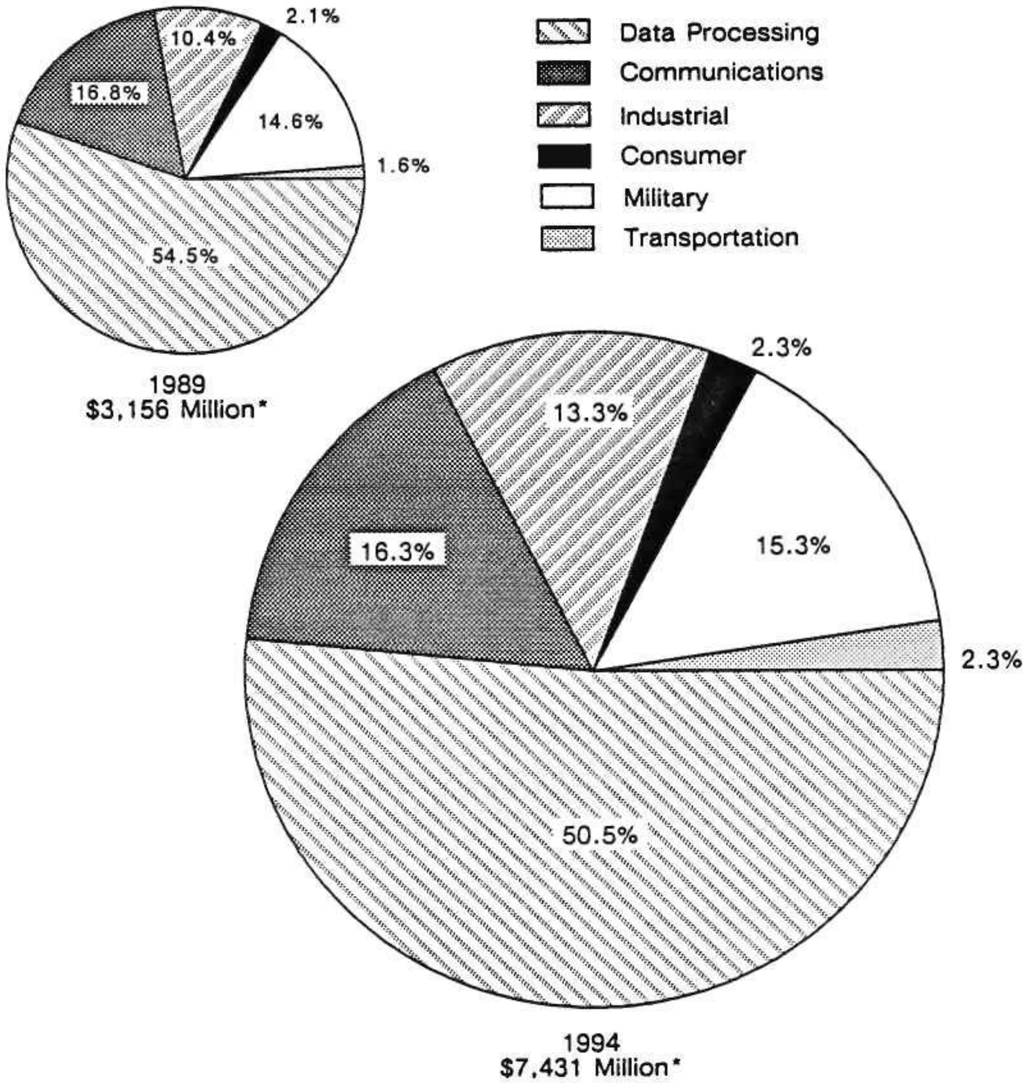
Source: Dataquest May 1989

Figure 2

Estimated North American ASIC Consumption by Application Market—Total (1989 and 1994)



*Excludes Full-Custom ICs

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Source: Dataquest May 1989

Gate Arrays

The largest ASIC segment is gate array designs, at $2.9 billion in 1988. The ranking five suppliers are the top four overall ASIC companies—Fujitsu, NEC, LSI Logic, and Toshiba—plus Hitachi. None, with the exception of LSI Logic, have significant design aids for DSP users. The closest thing is macrofunctions of the AMD Am2900 series building blocks, which are popular in DSP. LSI Logic, the top CMOS gate array supplier with an estimated 25 percent DSP business, has the MACGEN compiler for generating multiplier-accumulators of varying precision and arithmetic formats. Although backed up with a full arithmetic and functional simulator, it still lacks specific DSP features like overflow saturation and coverage of the often complex address generation and microprogramming functions needed for a full processor.

Cell-Based Designs

The smallest but fastest growing segment of the ASIC market is the so-called standard cells segment. In 1988, revenue was $1.3 billion, with AT&T, Texas Instruments, Toshiba, NCR, and VLSI Technology as the top-ranked suppliers. Growth was 43 percent last year. Here again, DSP support has been limited mostly to Am2900 series building blocks.

Full-Custom and Silicon Compilers

The second largest ($2.5 billion) portion of the ASIC market in 1988 was still the full-custom segment, but it is declining at a 3 percent annual rate. Silicon compilation, however, counters the overall figure with strong growth. DSP accounts for nearly half of all silicon compiler applications because of its acceptance by large communications and military systems companies. DSP support is a natural fit for silicon compilation, with its emphasis on high-level functional design, but even leader Silicon Compiler Systems, Inc., provides no specific DSP support.

The motivation for a full-custom design is often proprietary design protection and cost, but it also can be the high performance that DSP requires. The largest custom suppliers are NEC, Matsushita, Sharp, and Toshiba. Although much of their output is for consumer products (e.g., ultrasonic autofocus controllers for cameras), the companies are often solving DSP problems. That trend should continue as consumer products become smarter. Philips, the large European consumer products firm, estimates that half of its custom silicon output is for DSP functions.

MAJOR DSP SUPPLIERS' ROLES WITH ASDSPs

Dominant DSP supplier Texas Instruments has surely leveraged its position with application-specific designs, but these designs have been mostly full-custom done with internal design resources. One that became visible is the TMS 320C20, now a standard product, which grew from specific speech processing requirements at ITT. But Texas Instruments does not actively encourage ASDSPs, particularly those that involve users in any active role in their design. The new TMS 320C30 has a modular layout and a future as a processing core, but it is not a major thrust at this time.

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Number two DSP supplier NEC has produced a myriad of DSP designs in most DSP applications, such as speech recognition, signal encoding and image processing, as well as in more experimental areas like data-flow processors. Most have been cell-based designs to keep development costs low and design times short. However, these devices have been mostly for internal telecommunications requirements, with no public attempt to secure ASDSP business using the cell libraries.

Similarly, Fujitsu has supplied a large internal telecommunications need with cell-based designs. It has had less commercial success with standard products. Perhaps because of this, Fujitsu has now made available its processing cores and cell-based peripherals and memory configurations in the MB8220/232 product line.

AT&T, a major internal ASIC and DSP supplier, has not used its limited commercial success with standard parts to expand its ASDSP business. Motorola and Analog Devices have no ASIC programs in DSP, even though Motorola's 56200 was a silicon compiler design that could presumably have been the start of an application-specific filter business.

TRW LSI Products is understood to have replaced much of its loss of merchant market share with custom DSP designs using its own design teams. There are no tools for public use. AMD's lack of participation in the general ASIC market has kept the company from capitalizing on the Am2900 series building blocks.

DATAQUEST CONCLUSIONS

The distinction between DSP and general-purpose data processing is becoming blurred, but clearly a large portion of the fastest growing segment of the IC business, ASICs, is DSP related. Dataquest expects ASDSP to be a $181 million market in 1989 (see Table 1). The major participants in this business are the traditional ASIC suppliers rather than the DSP IC firms. Business is being secured in spite of not having device libraries or support tailored to DSP designer needs. At this time, users are limited to sophisticated users who do not require much support.

The major DSP suppliers, although they do high-volume, full-custom, application-specific designs, have not pursued this business either. Because their own standard products have usually been custom designed, they have not internally developed the libraries or tools that would assist them in the public ASDSP market. They also might view an aggressive ASDSP program as eroding the programmable solutions with their standard products in which they have made such an extended investment. This explains their cautious approach of expanding from a programmable core processor for ASDSPs. Within large IC companies, DSP and ASIC are often separate divisions, with many organizational forces working to impede cooperation on a workable strategy. Even in a narrowly focused company like LSI Logic, the DSP effort has been an attempt to establish a viable standard product line (something new for the company) rather than to strengthen its position in the ASDSP market.

Table 1

Application-Specific DSP (ASDSP) Market
(Millions of Dollars)

Estimated		
1986	1987	1988
$68	$98	$131

CAGR 1986-1992
37.6%

Forecast			
1989	1990	1991	1992
$181	$250	$340	$461

Source: Dataquest
May 1989

The ASDSP market is understandably undersupported at this time. Because both general ASIC suppliers and DSP firms have been growing rapidly, they have had other more important tasks. Each type of company would have to master a new set of skills to solidify a position, but as competition increases, some company will likely move to claim ASDSPs as its own. ASIC houses would seem to have a head start, but DSP manufacturers may have the strongest motivation.

As DSP increasingly becomes possible on general-purpose, particularly RISC, processors, a quick-response, application-specific approach to the remaining diversified DSP market will be necessary. Cell-based designs seem the best design approach today, besides being a good basis for any long-term plan for DSMPUs, or special-function or building block DSP standard products.

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Research Newsletter

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0003271

DSP AND THE WAVE OF NEW RISC PRODUCTS

INTRODUCTION

The major news topic of the last six months in the semiconductor field has been the reduced-instruction-set computer (RISC) processor. Every major semiconductor and computer company now has a stated position on RISC in its product lines. Although much of the news is market posturing, there can be little question that the new RISC microprocessors represent a significant next generation for general-purpose computing. Independent of instruction set size, they embody the latest thinking from both computer science and market demand in today's VLSI technologies. Such opportunities for a completely fresh start on a processor architecture occur only rarely. Some suppliers are taking better advantage of the chance than others.

Any change in the general-purpose microprocessor market is important to digital signal processing (DSP) because it is consistently estimated that half of the volume of the integrated circuits used in DSP are conventional microprocessors. Their low price, wide familiarity, and variety of support tools always make them an attractive alternative to the higher-performance digital signal processor (DSMPU) solution. In addition, many of the mips and mflops performance figures of the new RISC processors are close to those expected only from digital signal processors. Even a casual glance shows RISC's architectural similarities to DSMPUs, such as deep data pipelining, the Harvard-style separation of instruction and data memories, and multiple execution units. RISC processor manufacturers are even talking about the same embedded controller markets that have been the domain of high-performance DSMPUs and about things like real-time operating systems.

What does this mean for the suppliers and users of single-chip DSMPUs in the future? We will explore that question in this newsletter. In addition, we will review some of the basic performance requirements for digital signal processors and see how these are met by the major new RISC processors. Next, we will look at the latest generation of high-performance DSMPUs and see how both are moving to solve some common new systems requirements. Comparing the two types of processors leads to some strategies for DSMPU makers to protect and expand their markets in the face of this potentially strong competition.

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DSP REQUIREMENTS AND THE NEW RISC PRODUCTS

Historically, signal processors have been distinct from general-purpose microprocessors because of the following three major requirements:

- Higher precision
- Higher speed
- Special functions operating on large amounts of data

Table 1 lists these requirements with some of the architectural or implementation techniques used to meet them. The first two columns indicate which of these techniques has generally been used in current-generation CISC microprocessors and in the first- or second-generation DSMPUs. The next two columns show the RISC processors and the latest (or third generation) of high-performance DSMPUs. Following the historical requirements are the additional DSP requirements considered to be important today as the result of larger, more complex systems.

Just looking at the relative predominance of the Xs over the Os in Table 1 confirms the general trends: New CISC microprocessors have few attributes other than precision to make them suited for DSP, whereas even the first-generation DSMPUs are a significant improvement. New higher-performance DSMPUs are complete in their use of such techniques, while RISC, for its own performance needs, has used more than even the early DSMPUs. The Xs and Os represent only rough averages across a number of products. Table 2 shows some of the specific features and performance parameters for four representative RISC products. Three high-performance DSMPUs are included for comparison on the same basis.

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Table 1

Product Overlap in Meeting DSP Requirements

DSP Requirements	Implementation Technique	Products			
		CISC	DSP-1&2	RISC	DSP-3
Historical DSP Requirements					
High precision	8-bit	X	0	X	X
	16-bit	X	X	X	X
	32-bit	X	0	X	X
	Floating-point	0	0	X	X
High speed	Pipelined data path	0	X	X	X
	Parallel operation				
	Data memories	0	X	X	X
	Instruction memory	0	X	X	X
	I/O controller	0	X	0	X
	Address generators	0	X	0	X
	Fixed and floating point	0	0	X	X
	Loop counters	0	X	0	X
	Full processors paralleled	0	0	X	X
	Memory speed-size hierarchy				
	Instruction caching	0	0	X	X
	I/O buffering	0	0	X	X
Special processing	Complex address generation				
	Vector	0	X	0	X
	2-D	0	0	0	X
	Arithmetic				
	Multiply-accumulate	0	X	X	X
	Saturation	0	X	0	X
Large amounts of data	Large memory space	0	0	X	X
	High-speed I/O	0	0	0	X
	Real-time control	0	X	X	X
New DSP Requirements					
High-level languages		X	0	X	X
Operating systems		X	0	X	X
Industry standard functions		X	0	X	0

Source: Dataquest
March 1989

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Table 2

Major New RISC and DSMPU Feature and Performance Summary

	RISC				DSP		
	Motorola 88100	AMD 29000	SPARC 7C601	Intel i860	TI 320C30	AT&T 32C	Motorola 96002
Precision							
Integer	8-32	8-32	8-32	8-32	16, 32	8-24	32, 64
F-P	32, 64	Ext	Ext	32, 64	32, 40	32, 40	32, 96
Speed							
Cycle time (ns)	50	40	30	30	60	80	75
Execution unit data pipelines							
Integer	1	1	1	1	2	1	2
F-P	2	N/A	N/A	2	S	1	S
I/O	1	1/2	1	1	1	2	2
Concurrent data pipelines	3	3/2	2	4	3	3	3
Parallel processors	Y	N	Y	Y	Y	N	Y
Memory hierarchy							
Integer RF	32	192	136	32	16	22	10
F-P RF	S	N/A	N/A	32	S	4	S
Data cache	Ext	Ext	Ext	Y	N	N	N
Inst. cache	Ext	Ext	Ext	Y	Y	N	Y
Special processing							
Address generation	N	Y	N	Y	Y	Y	Y
Multiplier-accumulator							
Integer	N	N	N	N	Y	Y	Y
F-P	Y	N/A	N/A	Y	S	Y	Y
Address space (bits)							
Data 1	30	32	40	32	2x10	2x9	32
Data 2	-	-	-	-	12	10	S
Instruction	30	S	S	S	24 (S)	24 (S)	32
I/O bandwidth (MB/sec)	80	50	66	132	132	50	106
Interrupts	Y	Y	Y	Y	Y	Y	Y
Context switch	Y	Y	Y	Y	Y	N	Y
High-level language	Y	Y	Y	Y	Y	Y	Y
R-T operating system	Y	Y	Y	N	Y	N	N

Ext = External
N/A = Not Applicable
Y = Yes
N = No
S = Shared

Source: Dataquest
March 1989

Precision and Speed

Precisions are at rough parity now. DSMPUs tend to preserve more bits for accumulation, but RISC processors often have greater word length flexibility, which can be useful for DSP image data. RISC meets the precision need. Basic data pipeline cycle times are shorter for RISC processors, and the difference is real for small vectors. Nevertheless, address generation times in the RISC integer ALU and data memory bottlenecks reduce performance for most signal processing operations below that of the DSMPUs. As the number of separate pipelines in the execution units and the concurrency figures show, however, the differences may not be large. Note that the 64-bit data busses of the i860 give it higher large-vector performance than the DSMPUs due to concurrency. Thus, RISC can meet many DSP speed requirements now. So-called vector processors are being considered by RISC suppliers now to provide multiport address generation for large real data memories to increase DSP and vector performance, so the gap may narrow in the future. NEC has even announced such a vector processor for its V-series product line, which employs traditional complex-instruction-set computer (CISC) architectures. RISC processors for the moment seem to lead DSPs in providing for paralleling of complete processors.

Memory Hierarchy

RISC processors have large data register files that, for most functions, equate to the much larger separate data memories on the DSMPUs. Concurrent load/store I/O operations on the RISC processor can reduce this size difference; however, speed may degrade quickly due to I/O bottlenecks. The large number of registers or accumulators on the DSMPUs reflect the desire to support high-level language compilers. Caching of instruction memory is used in both RISC processors and DSMPUs, although the modes of operation are much different. A low-cost, low-complexity solution is possible with a RISC processor that is sufficient to meet signal processing needs. Data caching is handled overtly with partitioned memories and programmed control in DSMPUs rather than "automatically" as in RISC processors. The large on-chip data cache on the i860 with its 128-bit bus is a real performance booster for signal processing operations. Overall the RISC memory hierarchy may seem ill suited for signal processing, but it can be scaled down and be cost and performance effective for large DSP systems.

Special Processing

The addition of vector processors to RISC processors may more nearly even the score, but now DSMPUs clearly excel at the concurrent and complex address generation needed in large data spaces for signal processing. This extends to I/O with DMA controllers as well as for on-chip memory. The concurrent multiply-accumulate arithmetic function so central to DSP is not common in RISC except in the floating-point execution units. This directly affects DSP speed performance on the RISC processors.

Large Amounts of Real-Time Data

The important address space change for RISC is to separate data and instruction spaces for higher performance. DSMPUs have increased the size of both spaces in order to handle the larger programs from high-level languages and the graphics and image data bases. DSMPU memory spaces have become more linear (like RISC) as they have gone off-chip. Thus, RISC processors can meet the separate and large memory space requirements of current signal processing systems. DSMPU I/O bandwidths remain higher than RISC processors and generally can be more fully utilized, but RISC I/O rates exceed many early DSMPUs and can be sufficient in many DSP systems.

RISC processors have interrupts, stacks, and other context-switching hardware assists, but they often lack the deterministic response times necessary for real-time DSP. Cypress Semiconductor is moving to improve this in its implementation of the SPARC architecture, and it seems likely that others will also. RISC processors, likewise, have the more complete high-level language support but not in a real-time operating system environment.

TODAY'S HIGH-PERFORMANCE SYSTEMS AND THEIR MARKETS

This growing similarity between digital signal processors and general-purpose RISC microprocessors results from manufacturers of these products recognizing the needs of an increasingly common high-performance system. Figure 1 is a block representation of such systems. It represents functional blocks of the typical new high-performance systems and their varied CPU processing and software requirements. Typically, some physical process that generates a large amount of data is analyzed or controlled by computations on the data. The computations are altered by operator controls, often interactively, from results that are presented on a display. The display itself often involves much processing, as does the final output result on some peripheral device.

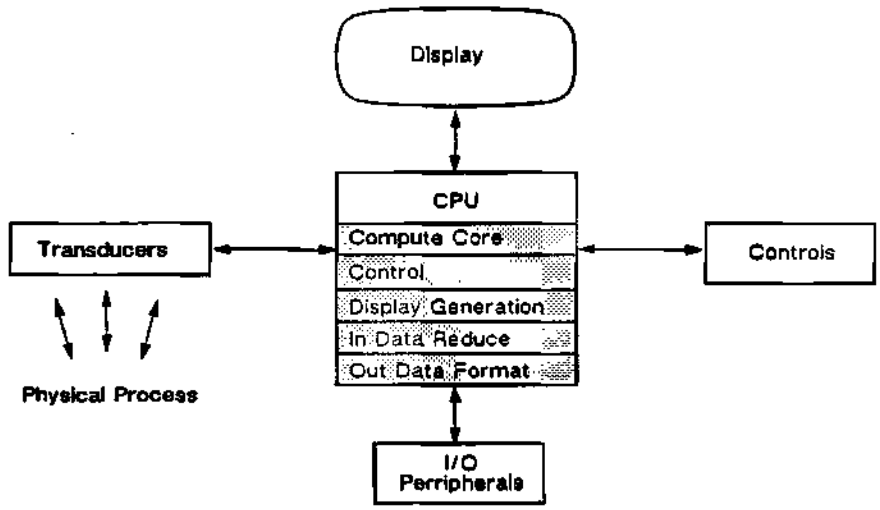
For economic reasons, and because not all processing is simultaneous, a single CPU is desired. Speed is important because of the large amount of data, the fact that the system is interactive, and the fact that it often must be real time in the strictest sense for closed-loop control purposes. The speed must be in I/O as well as arithmetic functions to support displays and the data collection.

Large amounts of high-level language applications code are used, often running under UNIX. This user- and third-party-supplied software accommodates industry standards processing and standard I/O peripherals, drivers, and formats. The high-level language improves maintainability, but often it is used initially because it allows the function to be transported in to get the system operating in a minimum amount of time. Critical time to market is improved.

Typical applications that use these systems are listed in Figure 2. Frequently, they are referred to collectively as high-performance embedded controller systems. Note that high-performance workstations in this context are a subset with less demanding real-time I/O.

Figure 1

New High-Performance Systems and Their Varied CPU Processing and Software Requirements



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Source: Dataquest
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Figure 2

Important High-Performance Markets for RISCs and DSMPUs

- Medical Tomography Imaging
- Ultrasound Imaging
- Communications Instrumentation
- Vibration Testing
- Electrical, Chemical, and Mechanical Design, Simulation, and Analysis Workstations
- Image Scanning and Electronic Publishing

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Source: Dataquest
March 1989

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THE COMPETITIVE THREAT AND NEW DSP STRATEGIES

Few significant quantity shipments of RISC processors occur today, except for workstation shipments, and it will be two years before the important product families and markets can be confirmed. However, the prudent DSP product strategist cannot wait for market erosion to react.

Dataquest believes that certain DSP performance issues are important ones for DSMPU suppliers trying to maintain their markets. DSMPU suppliers must continued to do the following:

- Accommodate the real-time nature of DSP operations—The first requirement is to continue to accommodate the real-time nature of the processing while adapting to the need for operating system and high-level language benefits. This can be done through integrated hardware assists and real-time software function libraries that support industry standards and device independence yet do not get in the way of the other real-time processing required. Developing a standardized library of real-time functions and a suite of DSP performance measures, like the recent SPEC benchmarks, would help.

- Support greater memory flexibility

  - Even with the larger data bases and programs of DSP systems today, the memory hierarchy needed always will be different from the more general-purpose data processing system. The need for large, multiported nonvirtual memory always will exceed the RISC on-chip register file. Continued attention to this memory distinction will protect DSP markets.

  - Vector processors that provide concurrent address generation for arrays are expected to be added to both CISC and RISC microprocessors, but DSMPUs always should be able to exceed the performance achieved in a linear memory, particularly for 2-D functions and transforms like the FFT.

- Develop workable multiprocessor languages and interprocessor protocols—Paralleling complete processors to increase computing power is everyone's candidate for the next major leap in performance, yet progress has been very slow in systems that can be used today. Because DSP is so amenable to partitioning between parallel processors, it can take the lead in simple, workable languages and interprocessor communications conventions.

- Emphasize high-bandwidth, real-time I/O—A final area of emphasis for DSP should be input/output (I/O). Graphics and imaging have made I/O dataflow an issue for all processors; however, the serial telecommunications interfaces, complex multiplexing/demultiplexing, and high real-time bandwidths should allow important product distinctions.

DATAQUEST ANALYSIS

Dataquest believes that if DSP suppliers are successful in providing this special DSP performance, their growth will continue and they will remain an important portion of the semiconductor processor market. The discussion here has centered only on the high-performance, higher-cost devices, but they represent a major growth area now and the dominant products of the future. Failure to act could bring a repeat of the generation-earlier contest between DSP array processors and general-purpose minisupercomputers. In spite of FORTRAN library support and parallel processors, the array processors lost vital market share to the more general-purpose minisupercomputers when they had the same floating-point multiprocessor parity. The near demise of Floating Point Systems, the leading array processor company, at the hands of Alliant and Convex closed out the first significant generation of DSP high-performance systems. The parallel between those rival minicomputer systems and today's rival microprocessors bears careful attention by suppliers of DSP integrated circuits.

Robert E. Owen

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Research Newsletter

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NEW FLOATING-POINT DSP PRODUCTS THREATEN TI'S LEAD

SUMMARY

With the 1983 introduction of its first digital signal processing product, the TMS32010, Texas Instruments (TI) established a seemingly unshakeable lead in the emerging digital signal processing (DSP) market. Today, the heavy investments made by TI and others in educating the technical community to the wonders of DSP are paying off. DSP product use is becoming more pervasive. In addition, DSP product technology is currently evolving from 16-bit integer products to high-performance 32-bit floating-point products. As highlighted in Table 1, 1988 will be a banner year for DSP microprocessor (DSMPU) product introductions.

Table 1

A Sampling of High-Performance DSMPU Products

Company	Product	Expected Availability	Description
AT&T	DSP32	Available now	32-bit Floating Point
	DSP32C	Q2 1988	32-bit Floating Point
Fujitsu	MB86232	Q1 1988	32-bit Floating Point
	MB86220	Q3 1988	24-bit Floating Point
Motorola	DSP56000	Available now	24-bit Integer
NEC	uPD77230	Available now	32-bit Floating Point
	uPD77220	Q2 1988	24-bit Integer
Oki	M6992	Available now	22-bit Floating Point
	M699210	Q1 1988	22-bit Floating Point
TI	TMS320C30	Q2 1988	32-bit Floating Point
Zoran	VSP325	Q3 1988	32-bit Floating Point

Source: Dataquest
February 1988

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What does this mean for Texas Instruments? It means that, for the first time, TI may not be alone with the latest technology in the DSP market. TI's TMS320C30 will most certainly experience heavy competition from this new crop of products and the competitors that TI faces are not new to this market, either. These vendors are all on their second- or third-generation DSP products.

In the last five years, TI has built a strong customer-support structure. If the TMS320C30 can be delivered close to its targeted introduction date and for its projected price, TI shouldn't lose much ground at the high end of the DSP market. However, the new midrange 22- and 24-bit products, which promise 32-bit floating-point performance at 16-bit integer prices, do pose a threat in such emerging new DSP markets as digital audio.

MARKET OUTLOOK

A half dozen vendors are trying to get a jump on Texas Instruments and stake out some high ground in the digital signal processing market. Their products fall into the following two broad categories:

- High-performance 32-bit floating-point DSMPUs
- Midrange 22- and 24-bit floating-point DSMPUs

First, there are 32-bit floating-point superchips that will compete with TI's announced TMS320C30. These DSMPUs are some of the most powerful silicon yet produced. They can multiply two numbers as fast as a Weitek arithmetic processor, have more transistors than Intel's 80386, and will replace some building block systems with a single chip.

Secondly, there is emerging a class of 22- and 24-bit floating-point DSMPUs that promise floating-point capability at the price of midrange, 16-bit integer DSP chips. Also not to be overlooked in this category are the 24-bit integer processors from Motorola and NEC. These products, while lacking floating-point capability, do offer the customer another 8 bits of dynamic range to play with.

Floating-point processors can be both easier to use and more powerful than fixed-point processors—a great combination! All this activity in floating-point products raises two interesting market-related questions:

- How fast will customers move to these parts?
- How will they affect TI's dominance of the DSP market?

In this newsletter, we will examine the products listed in Table 1 with respect to their market potential and probable effect on Texas Instruments' lead in this market. Located at the end of this newsletter, Table 2 compares and contrasts the features of each product reviewed.

High-End Market Prognosis

The new 32-bit floating-point products will find their first uses in applications that currently are implemented by building blocks (i.e., high-performance bit slices and multipliers). These areas are:

- High-end graphics
- Imaging
- Array processors
- Military systems

These applications are more driven by performance than by cost. Thus, a $300 or $400 DSP product may well provide a cost-effective solution. Because performance is what counts in these areas, the competition is just getting started for the 32-bit floating-point market. Products with sub-100-nanosecond cycle times—such as those from AT&T, Fujitsu, and Texas Instruments—look like contenders.

While this market may be bounded by building block applications in the short term, one would be foolish to expect that to last. Forces that will help move these products into a broad spectrum of applications include:

- Price reductions
- Availability of C compilers
- An increase in customer awareness of product capabilities

The bright spot for TI's competitors is that engineers now using building blocks are perhaps the most sophisticated consumers of DSP products. They will tend to choose DSP products mainly because of performance, and they will be less influenced by TI's imposing presence and customer-support structure.

Market Participants

AT&T. AT&T's second-generation 32-bit floating-point DSP product, the DSP32C, appears competitive from a hardware standpoint; it is twice as fast as its predecessor. AT&T's earlier product and NEC's initial 32-bit product, the uPD77230, are both too slow in comparison with the newer products and limited in external memory addressing capability.

Perhaps more importantly, AT&T is providing serious software support to its new product. The DSP32C's 32-bit arithmetic unit is limited to floating-point operations, however, while the Fujitsu and Texas Instruments products can also perform 32-bit fixed-point adds, subtracts, and logical operations.

Fujitsu. Fujitsu's MB86232 will likely be the first of this new generation of products. This product and the Zoran VSP325 are the only devices that directly handle the IEEE 754 single-precision floating-point format. Additionally, the MB86232 has highly parallel memory addressing. A big "if" is whether or not Fujitsu can overcome the somewhat stereotypical Japanese company's weakness in supporting complicated processors.

Texas Instruments. Texas Instruments clearly has the lead in the DSMPU market today. Its latest product, the TMS320C30, should be as fast as the competitors' chips with more on-chip memory. Additionally, TI's software experience and extensive customer-support network will work to the company's advantage.

It is probably realistic to assume that the high-end 32-bit market will develop slowly. And, as stated earlier, if the TMS320C30 can maintain its targeted introduction date and projected price, TI shouldn't lose much ground in this market. The only question concerns how imposing TI's lead will be. However, should the introduction date slip appreciably, TI may find itself sharing more of the market than it had expected or wanted.

Zoran. Zoran's VSP325, like its 16-bit predecessor, is hardwired to perform DSP functions. This gives the VSP325 the highest performance available for applications that it fits, but this also narrows its appeal quite a bit. However, because the 32-bit DSMPU market is a performance-driven market, Zoran has a chance to do better than it did in the 16-bit DSMPU market.

High-End Pricing

Initial samples of some of these 32-bit floating-point DSMPUs may cost more than $1,000 apiece, which is a serious price for an integrated circuit. Prices are expected to drop below $500 each (in 1K quantities) before the end of the year—still a significant price!

Midrange Market Prognosis

The threat to Texas Instruments' market domination comes not so much from the flagship 32-bit products as it does from the new 22- and 24-bit floating-point products, such as those from Fujitsu and Oki. If these products can be delivered for the price of midrange 16-bit integer DSMPUs, they pose a very attractive option. Even with a qualitatively more advanced architecture and a superior price/performance ratio, however, strong customer support and an assertive selling effort will be needed to capitalize on this opportunity. Figure 1 illustrates the potential DSP opportunities in consumer electronic products that could fuel the development of a midrange DSP market.

Figure 1

DSP Opportunities in Consumer Products

*Refers to improved-definition (IDTV), extended-definition (EDTV), and high-definition television (HDTV) standards.

** Pulse code modulated.

Source: Dataquest
February 1988

Market Participants

Fujitsu. Fujitsu's 24-bit floating-point product, the MB86220, has the potential to be very successful. Its projected pricing is extremely competitive. In addition, its word size and format are excellent for digital audio applications. Digital audio may become the largest application for midrange DSP products, as design wins in consumer applications mean big volumes.

Motorola. Motorola's DSP56000 is a 24-bit integer device. Although it doesn't have the convenience of a floating-point device, its ALU is 8 bits wider than other integer DSMPUs. This translates roughly to an additional 48db of dynamic range. The DSP56000 also rates as one of the fastest of the midrange products. Another plus for the product is that people are comfortable buying advanced processors from Motorola. Comfort is a big factor in the DSP market—a market dominated by Texas Instruments.

NEC. NEC's uPD77230 is a bit schizophrenic. It simply does not have the raw speed of the newer 32-bit parts. Its relatively low price, however, makes it a viable alternative for midrange applications. Another big plus for the product is that it is available now. Die shrinks with resultant increases in clock speed could even make the uPD77230 more competitive at the high end. Not to be ignored, of course, is NEC's position as the number two market leader behind Texas Instruments.

NEC will soon spin off a lower-cost 24-bit integer version of this chip. The new product, the uPD77220, will be upwardly compatible with the uPD77230. Ironically, although floating-point products should make development less complicated, NEC feels that customers are still just learning about floating point. This attitude further illustrates the amount of education and selling required for DSP products.

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Oki. Oki's 22-bit M699210 is an upgrade and die shrink of its M6992. It is a 1.5-micron CMOS full-custom design. The M6992 was a 2.0-micron standard cell design. The die-size reduction offered by the full-custom design should move Oki's pricing further down the learning curve, and Oki is supplying good software tools. The company believes that engineers who have had to implement products based on the fixed-point TMS320 family are good candidates for their floating-point devices.

Midrange Pricing

Existing midrange products, such as TI's TMS320C25 and NEC's uPD77230, are currently priced at slightly more than $100 each in 1K quantities. To be competitive in the midrange market, prices need to drop below $50 (for moderate quantities) by the end of the year.

DATAQUEST ANALYSIS

The Rationale for Floating Point

Telecommunications has been the single largest market for DSMPUs to date. These applications are well served by the 16-bit integer products. Additionally, most DSP applications require interface to the real world through A/D and D/A converters, which are normally 8 to 16 bits in resolution. So the question is: Do customers really want or need floating-point digital signal processors?

The answer is "yes" in a surprisingly high percentage of applications. A key point is that each calculation results in an increased number of bits in the output. The more calculations, the larger the resultant word. Rounding of the results to fit a 16-bit word leads to loss of resolution. In highly iterative algorithms, this round-off error can be quite large.

Seemingly innocuous applications can quickly outgrow a 16-bit word. For example, suppose you wish to design a digital equalizer to work with a compact disc (CD) player. Compact disc players use a 16-bit data word. At first glance, a 16-bit integer DSP chip may seem a good match.

The natural way to implement a digital equalizer is by doing a fast Fourier transform (FFT), modifying the spectrum the way you want, and then doing an inverse FFT. An FFT can grow as much as one bit per stage; however, and we have to remember that for an equalizer, the more bands the better. Thus, for a 256-band equalizer, the growth could be as much as 9 bits. That means that the equalizer needs at least a 25-bit integer DSP chip in order to ensure maximum resolution. And, because people are fanatic about audio quality, they will want those bits.

Applications that require two-dimensional FFTs, such as medical imaging, robotics, or video data compression, experience bit growth in both the row and the column FFT results. So an N x N transform will have twice the bit growth of a length N transform. Therefore, even 8-bit video signals could benefit from using floating-point DSMPUs.

Even if resolution is not a problem, fixed-point programs usually require some software scaling and checking for overflow. This additional code can be quite substantial. It slows down program execution, and programmers would be quite happy not to have to do it. Because DSP algorithms are often developed on computers that use floating-point arithmetic, the need for scaling and overflow checking can be an unpleasant surprise. Floating-point DSMPUs handle these issues automatically, shortening algorithm development time.

The Threat to TI's Lead

Texas Instruments enjoys a dominant position in the DSP market—a position in which the company has invested heavily. However, it is facing more competition than ever before. Today's competition is seasoned, having encountered TI's immense third-party software/hardware vendor network and customer-support structure in the past. While TI is still recognized as the leader in customer support, the level of customer support offered by other DSP vendors has improved with each succeeding generation of products.

As software and hardware support lessens as an issue, the technical merits of a product and the price/performance ratio become more important. At the high end of the DSP market, TI's TMS320C30 compares very favorably with its competition. It is expected to be one of the fastest products available, in addition to having more on-chip memory than any of its competitors (see Table 2). Furthermore, the TMS320C30 is software compatible with its predecessors in the TMS320 family. The TMS320C30 will not be the first 32-bit floating-point DSMPU to be available; nevertheless, if its targeted introduction date doesn't slip appreciably, TI should maintain its impressive grasp of the high-end DSP market.

TI is vulnerable, however, in the new developing midrange market. Their current products address the high-end 32-bit floating-point and low-end 16-bit integer markets. TI doesn't have a midrange product similar in price/performance to those of Fujitsu and Oki. If a midrange market such as digital audio develops, TI will be out in the cold on two counts. The first factor is that the company lacks a midrange product. The second factor is that such a market will be heavily influenced by Japanese consumer product manufacturers.

Alice K. Leeper

Table 2

DSMPU Product Comparison

Supplier:	AT&T	AT&T	Fujitsu	Fujitsu
Part:	DSP32	DSP32C	86232	86220
Word:	32 FP	32 FP	32 FP	24 FP
Word Format:	24E8	24E8	24E8	18E6
Cycle Time:	160ns	80ns	75ns (2 mac)	80ns
Clock:	25 MHz	50 MHz	40 MHz	25 MHz
Internal RAM:	512 x 32 x 2	512 x 32 x 3	512 x 32	256 x 24 x 2
External Data RAM:	14K x 32	4M x 32	1M x 32	64K x 24
Internal Program ROM:	512 x 32	1K x 32	1K x 32	2K x 30
Internal Data ROM:	Shared	Shared	Shared	Shared
External Program Memory	Shared	Shared	64K x 32	4K x 30
Wait States:	-	Yes	Yes	-
DMA:	PIO	PIO	Yes	External
Accumulators:	4 x 40	4 x 40	2 x 40	1 x 24
PIO:	1 x 8	1 x 16	1 x 32	1 x 8
SIO:	1	1	2	1
1K Complex FFT:	14ms	4ms	N/A	N/A
Process:	1.5 NMOS	0.75 CMOS	1.3 CMOS	1.3 CMOS
Package:	40 DIP 100 PGA	133 PGA -	208 PGA -	135 PGA 80 FPT
Estimated 1K Price:	$170	$300	$500	$30

(Continued)

Table 2 (Continued)

DSMPU Product Comparison

Supplier:	Motorola	NEC	NEC	Oki
Part:	56000	77230	77220	6992
Word:	24 Int	32 FP	24 Int	22 FP
Word Format:	N/M	24E8	N/M	16E6
Cycle Time:	75ns	150ns	122ns	100ns
Clock:	26.7 MHz	13.3 MHz	16.4 MHz	40 MHz
Internal RAM:	256 x 24 x 2	512 x 32 x 2	256 x 24 x 2	128 x 22 x 2
External Data RAM:	64K x 24 x 2	8K x 32	8K x 24	64K x 22
Internal Program ROM:	2K x 24	2K x 32	2K x 32	1K x 32
Internal Data ROM:	256 x 24 x 2	1K x 32	1K x 24	Shared
External Program Memory	64K x 24	4K x 32	4K x 32	64K x 32
Wait States:	Yes	No	No	No
DMA:	No	No	No	External
Accumulators:	2 x 56	8 x 55	8 x 47	2 x 22
PIO:	1 x 8	Shared	Shared	Shared
SIO:	2	1	1	-
1K Complex FFT:	2.6ms	12.5ms	10ms	7ms
Process:	1.5 CMOS	1.75 CMOS	1.75 CMOS	2.0 CMOS
Package:	88 PGA 88 SLAM	68 PGA	68 PGA 68 PLCC	132 PGA -
Estimated 1K Price:	$120	$115	$70	$165

(Continued)

Table 2 (Continued)

DSMPU Product Comparison

Supplier:	Oki	TI	Zoran
Part:	699210	320C30	VSP325
Word:	22 FP	32 FP	32 FP
Word Format:	16E6	24E8	24E8
Cycle Time:	100ns	60ns	80ns
Clock:	40 MHz	33 MHz	25 MHz
Internal RAM:	256 x 22 x 2	1K x 32 x 2	64 x 32 x 2
External Data RAM:	64K x 22	16M x 32 8K x 32	64M x 32
Internal Program ROM:	2K x 32	4K x 32	-
Internal Data ROM:	Shared	Shared	1K x 32 x 2
External Program Memory	Shared	Shared	Shared
Wait States:	Yes	Yes	Yes
DMA:	External	Yes	External
Accumulators:	2 x 22	8 x 40	2 x 32
PIO:	Shared	Shared	Shared
SIO:	-	2	-
1K Complex FFT:	7ms	3ms	1.7ms
Process:	1.5 CMOS	1.0 CMOS	1.5 CMOS
Package:	84 PLCC 100 Flat	180 PGA 100 PGA	84PGA -
Estimated 1K Price:	$80	$400	$395

N/A = Not Available
N/M = Not Meaningful

Notes: Fastest parts are shown. FFT benchmarks are not consistent as to radix 2 or radix 4, including or not including bit reversal, including or not including data transfer onto and off chip. Price is estimated only.

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PERSPECTIVE ON ICASSP '88

INTRODUCTION

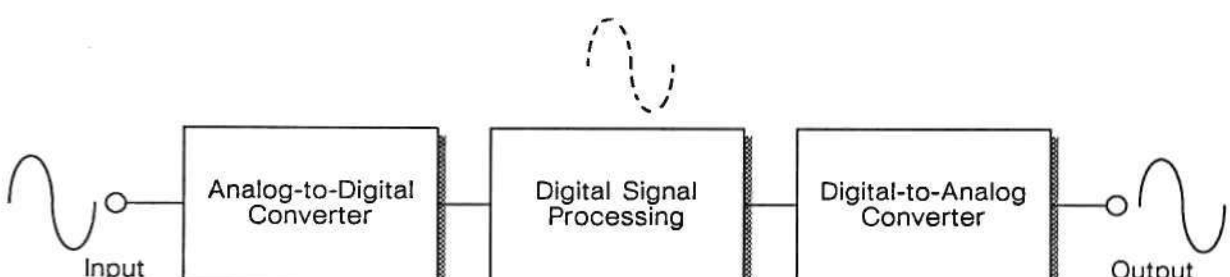
The thirteenth annual International Conference on Acoustics, Speech, and Signal Processing (ICASSP) hosted by the IEEE was held at the New York Hilton from April 11 through April 14, 1988. This year boasted the largest ICASSP attendance ever, with 46 exhibitors, 1,950 attendees, and more than 700 presentations.

The main focus of ICASSP since the first conference in 1976 has been to provide a forum where academic advancements in digital signal processing (DSP) technology can be presented and discussed. ICASSP has remained true to its technical charter through the years, even with the recent inclusion of exhibitor booths in the early 1980s. It remains the premier industry conference dealing with general topics in digital signal processing.

As the name "digital signal processing" implies, DSP is a technology used for processing signals digitally. These digital signals are often acquired from analog signals by using an analog-to-digital converter, as illustrated in Figure 1. The output of DSP systems is sometimes converted back into an analog form by using a digital-to-analog converter, also shown in Figure 1. The processing of these digital signals between the data converters is broadly categorized as digital signal processing.

Figure 1

A Generic Digital Signal Processing System



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The size of the transaction volumes from ICASSP '88 is testimony to the largely infinite amount of digital processing that can be performed on signals. This year's transactions consist of nearly 3,000 pages in five volumes that total seven inches in thickness.

ICASSP EVOLUTION

The IEEE Acoustics, Speech, and Signal Processing (ASSP) society of today evolved from the old IEEE Audio and Electroacoustics society. The first ICASSP conference was held in 1976 and consisted of more than 200 papers presented and 600 participants.

Both the attendance and the number of presentations at ICASSP have more than tripled since the first conference. Additionally, a number of other conferences focus on other areas in which DSP is significant, such as applications and VLSI implementations. (As an example of DSP proliferation at other conferences, please refer to April 1988 SIS Research Newsletter number GA4/DS2, entitled "DSP Evolution Evident at 35th ISSCC." It highlights the fact that about 30 percent of the papers presented at the February 1988 ISSCC conference described semiconductor devices oriented toward digital signal processing.)

In recent years, ICASSP has taken on an additional dimension with the inclusion in the early 1980s of exhibits by a variety of semiconductor, hardware, software, systems, and publishing vendors. Products from these companies are targeted at a variety of people in the DSP community: research engineers, systems and algorithm engineers, hardware designers, and software designers. The addition of exhibits adds a level of maturity and credibility to the conference (and the industry) that should continue to build over the next decade.

THE SESSIONS

Presentation sessions were organized into seven broad categories, as follows:

- Digital Signal Processing
- Spectral Estimation and Modeling
- Speech Processing: Coding, Analysis, Synthesis, and Recognition
- Multidimensional Signal Processing
- VLSI for Signal Processing
- Underwater Acoustic Signal Processing
- Audio and Electroacoustics

The following paragraphs will examine special topics and applications of interest in some of these categories from a variety of the sessions. Future newsletters will go into additional detail on these and other issues.

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Speech Processing

The speech processing category boasted the largest number of sessions (14) and presentations (178). This is not a new trend, as all aspects of speech processing have received tremendous amounts of research over the years. In fact, five to eight years ago, most of the major U.S. semiconductor companies had engineering organizations designing VLSI products for speech processing, including Advanced Micro Devices, General Instrument, Motorola, National Semiconductor, and Texas Instruments. In all cases, the VLSI activities at these companies have been disbanded. It is fair to say that Texas Instruments still supports speech from an applications standpoint, but the hardware implementation of speech algorithms is almost exclusively done using general-purpose digital signal processors such as the TMS320—not using custom VLSI. In many cases, the speech groups from these companies were redirected into more general digital signal processing organizations.

Audio and Electroacoustics

The smallest category was Audio and Electroacoustics, with only 3 sessions and 32 presentations. In Dataquest's opinion, however, one of these sessions was one of the most interesting at the conference. It discussed (in part) hearing and speech aids for the handicapped.

As an introduction, according to the Ear Research Institute in Southern California, there are 2 million people in the United States who either are totally deaf or lack the ability to detect speech without aid. External-aid techniques in the form of either electrical stimulation of the cochlea by implanted electrodes or tactile cutaneous stimulation are often used in order to simulate hearing for the deaf. Another 12 million "hearing-impaired" individuals, who suffer from serious hearing loss, often are treated using conventional analog hearing aids. A number of different digital signal processing techniques are being developed to aid both groups of people, providing a level of hearing quality not achievable today using analog technology. Seven papers were presented at ICASSP discussing a variety of these techniques.

VLSI

The second smallest presentation category was that of VLSI signal processing implementations, containing 4 sessions and 54 papers. A related session entitled "Hardware and Software in Signal Processing" was actually in another category, but it will also be counted here because it is related to the VLSI category. This session added another 20 papers.

Papers on VLSI focused largely on hardware architectures designed to solve a variety of signal processing problems. Of special note were products that either are available now or will soon be from a variety of different semiconductor manufacturers. A summary of these follows.

LSI Logic described a set of four chips optimized for high-performance signal processing applications with data sampling rates greater than 5 MHz, such as image and radar processing. One of the processors is a 64-tap transversal filter (MFIR) containing 64 8x8 multipliers on one die. This device can operate as a one-dimensional 64-tap filter or can be reconfigured to operate as an 8x8 two-dimensional filter. A second device in the set is a 64-tap rank-value filter (RVF) that can also operate in both one and two dimensions. Common operations with the RVF are minimum, median, and maximum value filtering. A third device in the set is a binary filter and template matcher (BFIR). It is optimized to perform 1-bit filtering, morphology, and template matching. The final device in the set is a video shift register that will hold 4K 8-bit pixels. The lengths (in pixels) of the video lines are configurable from as few as 8 pixels per line up to 4,000 pixels per line. This device is configurable also as a two-dimensional array of pixel buffers to work with the other devices in the family.

Honeywell described a chip set (processor plus controller) with an architecture optimized for high-throughput fast Fourier transforms (FFTs). The processor is able to process data at up to 500 million arithmetic operations per second. The worst-case performance benchmark for a 1K complex FFT is 204.8 microseconds. Using different memory configurations and cascading multiple processors, this execution time can be reduced to 20.48 microseconds.

AT&T presented the architecture for its new 25-mflops DSP-32C general-purpose floating-point digital signal processor. It is an extension to the architecture of the company's DSP-32, which has been in production for more than a year. Because the DSP-32C has been previously announced, it will not be described in detail here.

Zoran Corporation presented the architecture of its new floating-point vector signal processor. This processor differs from many general-purpose digital signal processors in the way it handles data. Most processors operate on single data samples in each instruction. The vector processor is optimized to operate on multiple data samples in each instruction, which is achieved by use of a "high-level" instruction set that is microcoded into the processor. Its instruction set resembles that of an array processor. For instance, single-instruction commands exist in the processor to do finite-impulse response (FIR) filtering as well as fast Fourier transforms (FFTs). This architecture allows very high performance when the function desired is already microcoded into the device. The processor tends to be less efficient if the desired function is not already microcoded into the processor.

A very important issue for designers building systems using digital signal processors is one of software development support. In many ways, the issues facing software developers for DSP systems parallel those facing microprocessor system developers. Early generations of DSP processors required that users program them at the level of assembly code (analogous to the way early microprocessors were programmed). Programming at this level is tedious when dealing with sophisticated algorithms. On the other hand, assembly coding of algorithms also provides the highest level of performance, important in most DSP applications. For programmers, the ideal solution to this dichotomy is to have available optimized high-level language (such as C or FORTRAN) compilers that translate code efficiently to the instruction set of the DSP microprocessor.

Recent generations of DSP microprocessors have been introduced with C compilers to help solve these programming problems. A number of papers were presented describing C compilers optimized for DSP microprocessors, including papers by Texas Instruments and AT&T for their new processors.

Image Compression

Another prominent topic spread through a number of different sessions dealt with algorithm and architecture implementations of the discrete cosine transform (DCT). This mathematical transform is usually implemented in two dimensions as part of the signal processing chain for compressing images. Image compression promises to be an exciting area in the next few years as we begin handling and transmitting images (pictures) using our personal computers and the telephone network. Already a number of companies are selling commercial products that transmit images over a standard telephone network. AT&T's original introduction of the picture-phone was only 20 years too early!

For example, a good-quality color photograph stored on a computer hard disk without compression can take 3 Mbytes or more. The transmission of this image using a standard 2,400-bps modem would take 10,000 seconds—nearly three hours! Fortunately, compression techniques such as cosine transforms can help reduce the storage or transmission time requirements of an image by a factor of 10 to 50, depending on the resulting quality desired. Thus, nearly three hours of transmission time can be reduced to about three minutes.

THE EXHIBITORS

This year's ICASSP drew 46 exhibitors, more than have attended the conference at any time in the past. Most of the major U.S. DSP semiconductor manufacturers were present, including Analog Devices, AT&T, Microchip Technologies, Motorola, and Texas Instruments. (Microchip Technologies is the newly named company spun off recently from General Instrument's microelectronics division.) The two most prominent exhibitors at the show were Texas Instruments and Motorola, both of whom had large booths directly in the center of the exhibition area. Both of these companies also had evening presentation sessions to discuss their recently announced 32-bit floating-point DSP microprocessors.

In addition, Texas Instruments (TI) also had the die of its floating-point TMS320C30 on display under a microscope. The die contains some 700,000 transistors and is more than 500 mils on a side in a 1-micron CMOS technology. Observing the die through the microscope, one can see the impressive functional modularity designed into the die layout. Each of the functional blocks appears on the die much as one might draw a block diagram of the architecture on a piece of paper. The obvious implication of this organization is the ability to customize the product for targeted application areas (or customers) by adding or deleting unique functional blocks. The architecture supports this concept with what TI calls its "peripheral bus."

TI announced that the TMS320C30 functional blocks will be available to customers as standard cells in the future. It also announced that the TMS32010 architecture will be available in the next year as an ASIC core.

The Motorola booth display was effective also. A number of Motorola's existing and potential customers were given space in the booth to demonstrate current and future products using Motorola's DSP processors. The company's third-party developers also were present, demonstrating hardware and software development tools.

A number of independent hardware and software development companies were present with a plethora of tools to aid the designer. Most of these companies are small, with a limited ability to market and distribute their products. Some of these companies are trying to make arrangements with the main DSP semiconductor manufacturers for distribution of their products. Although considerable opportunities exist for third-party development tools, many seem to be "me-too" kinds of products. For instance, about six different small companies were displaying various versions of filter design programs. Each product had its own small uniqueness relative to the others, but they were all created to solve the same basic problem, that of designing FIR and infinite-impulse response (IIR) filters. It seems likely that many of these companies will not be able to survive the intense competition without finding a unique market position or distribution channel.

One impressive development tool was displayed by a small company called MicroWorkshop, located in Bohemia, New York. This company has a Microsoft Windows-based development tool for the 32010 DSP microprocessor. It combines truly easy-to-use text editor, assembler, signal editing, debug, and board driver software with a hardware development board for the processor, all of which runs on a PC. The board contains a 32-MHz DSP-320C10 built by Microchip Technologies of Chandler, Arizona. MicroWorkshop promises additional development tools for other processors in the future.

DATAQUEST CONCLUSIONS

A tremendous number of interesting topics were discussed, presented, and further advanced at this year's ICASSP. The vast majority of ICASSP presentations are generated in universities and research laboratories from around the world, however, and are oriented toward the academic community; most will never have the ability to directly affect our lives. To this end, most will never see ultimate implementation in hardware. Nevertheless, it is through forums of this nature that we obtain insight into future directions for theoretical work, applications, algorithms, and VLSI architectures that will ultimately affect all of us. Future newsletters will address many of these topics in greater detail.

David M. Taylor

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THE FINAL FRONTIER IN VOICEBAND MODEMS

SUMMARY

Fueled by advances in semiconductor digital signal processing (DSP) architectures, the final frontier in voiceband modems is now beginning to unfold. This frontier provides transmission rates of 9,600 bits per second (bps) over the standard switched telephone network. The 9,600-bps transmission rate approaches the theoretical maximum information rate achievable over the limited bandwidth of the telephone network, effectively prohibiting significantly higher modem data rates. Higher transmission rates eventually will occur, but are most likely to use future digital networks such as the Integrated Services Digital Network (ISDN).

Transmission speeds of switched-network modems have evolved rapidly in the last ten years, moving from the primitive acoustically coupled 300-bps modem boxes that dominated the market through the 1970s, to the sophisticated direct-connect 9,600-bps modems now beginning to appear. It is interesting to note that the "bits-per-second" rating for modem transmission speed has roughly doubled every two years, nearly keeping pace with the more widely watched indicator representing the increase in capacity of dynamic random-access memory (DRAM) chips.

A number of incompatible techniques currently exist for 9,600-bps modem transmission over the switched telephone network. This problem is often encountered when new, higher-speed modems are introduced. Clearly the leading contender to ultimately dominate the personal computer marketplace at 9,600 bps is the V.32, which was defined by the Consultative Committee for International Telephony and Telegraphy (CCITT).

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BACKGROUND

Modem technology has evolved swiftly since the Federal Communications Commission (FCC) ruled in 1978 that any manufacturer could apply for registration to connect its communications equipment directly to the telephone network. Until that time, acoustically coupled 300-bps Bell 103 modems dominated the market for more than 20 years. After this important FCC decision, 1,200-bps Bell 212A modems requiring direct connection began to gain in popularity.

Beginning in 1982, a number of major semiconductor companies (including Advanced Micro Devices, Motorola, National Semiconductor, and Texas Instruments) began supplying single-chip 300-bps modems. Most design approaches at that time relied on an integrated analog design combined with switched capacitor filter technology. AMD was a leading innovator by building a true digital signal processing architecture that included both analog-to-digital and digital-to-analog converters on its chip, all optimized to solve the modem function.

These new devices significantly drove down prices of low-speed box modems, giving additional life (albeit short) to the low-speed modem market. These same devices also allowed for the birth of the embedded personal computer modem.

The semiconductor content of 1,200-bps Bell 212A modems evolved a bit differently. Many of the same semiconductor companies that competed in the 300-bps marketplace also introduced single-chip Bell 212A modems beginning in 1984. However, the early 1980s also saw the introduction of the first single-chip digital signal processors. Texas Instruments ultimately abandoned its single-chip Bell 212A modem in favor of implementing the modem function on its general-purpose TMS32010 DSP microprocessor. Thus began the trend that is still important in today's higher-speed modem technology. Modems that operate at 2,400 bps (and higher speeds) require digital signal processing approaches to implement sophisticated functions such as adaptive equalizers (to correct for telephone line distortions) and echo cancelers. In fact, the modem marketplace is still the single largest consumer of DSP microprocessors.

To have broad appeal, high-speed modems must also support the popular slower standards: V.22bis at 2,400 bps, Bell 212A at 1,200 bps, and Bell 103 at 300 bps. This is cost-effectively implemented in firmware on a DSP microprocessor. The interest in modems that support multiple standards extends both to leased-lines that have dial-up standards as a backup and to fax modem standards for the electronic office.

At least nine manufacturers currently supply 2,400-bps V.22bis chip sets. Interestingly enough, only one of these chip sets—the K224 from Silicon Systems, Inc.—is a single-chip solution combining all of the analog and digital processing on one device. The K224 is currently being sampled. The other chip sets are built around ROM-coded, DSP microprocessors. TI's DSP2400 uses a TMS32011, Telebit's T24 uses a TMS320C10, and VLSI Technology's chip set uses an ASIC version of Intel's 8096. Silicon Systems also has a chip-set (2404) solution using a ROM-coded version of the NEC 7720. Competition here is pushing prices down to $25 in quantities of 10,000 for a chip-set solution. This is within $10 of a 1,200-bps, Bell 212A solution.

To complete the modem chip set (except for the SSI K224 product) an additional one to three parts are necessary to implement the front-end and back-end analog processing. TI adds a preprogrammed TMS7042 plus two analog front-end chips (a 29C19 codec plus an SC11005 filter) to the TMS32011. Telebit adds a preprogrammed 80C51 and an Oki analog front-end chip (the 6950B). VLSI Technology adds its own analog part (the VL7C224A). Silicon Systems adds its own 73M214 front end to the 2404.

DATAQUEST ANALYSIS OF 9,600-bps MODEMS

The 9,600-bps marketplace is currently dominated by modems obeying the CCITT V.29 half-duplex specification. The original V.29 modems were used on leased telephone lines, but more recently have been used on the switched network as well. The largest application for this modem is in facsimile machines where the bulk of the data transmission is unidirectional. Dataquest estimates that the total number of 9,600-bps modems shipped in 1987 was about 3 million, with approximately 80 percent of these in fax machines. Only about 1 percent of the total shipments were dial-up modems. The remaining modems were used in 4-wire and other dedicated applications.

The requirements of personal computer users, though, differ from those of dedicated fax machine users. Personal computer users require bidirectional data transmission, although not necessarily simultaneously. This characteristic implies that a simpler half-duplex modem is really all that PC users require.

However, Dataquest believes that history will again repeat itself as it did in the early 1980s when the full-duplex Bell 212A modem gained nearly exclusive market dominance over the less-expensive, half-duplex Bell 202 modems for personal computer applications. Dataquest expects the more-complicated CCITT V.32 modem specification to win easily in the 9,600-bps personal computer marketplace over simpler rival modem specifications. The reasons for this are as follows:

- The CCITT V.32 9,600-bps modem specification has been ratified internationally.
- The availability of low-cost V.32 chip-sets can and will impose standards.
- Full-duplex data transmission protocols between modems are easier to implement (and standardize) than the line-turnaround required for half-duplex transmission.
- Most incompatible V.32 modems will talk only with identical modems from the same manufacturer.

It is important to understand, though, that alternative 9,600-bps modem standards (primarily V.29) will not disappear. They will remain important for specific applications because of their inherently simpler operation and lower cost. However, their future growth rate is expected to be much lower than that of V.32 modems.

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CCITT V.32 Modem Specification

Implementation requirements for the CCITT V.32 modem specification are certainly the most sophisticated yet to be introduced for telephony modems. It allows 9,600-bps full-duplex transmission over the switched telephone network. The entire telephone bandwidth is used simultaneously for both the transmit and receive channels. This differs from all other full-duplex modems, which use a frequency-division technique; i.e., the transmit and receive channels split the available 3-kHz bandwidth in half, so there is (in theory) no interference between channels.

In order for V.32 modems to use the entire telephone bandwidth simultaneously for both transmission and reception, they employ echo cancelers in the receiver to eliminate:

- The crosstalk caused by the local transmitter
- The far-end echo caused by impedance mismatches in the telephone network

Also used is a sophisticated data-encoding technique called trellis coding, which embeds error correction capability in the modulation. Trellis-coding techniques provide an approximate 3dB signal-to-noise (SNR) performance improvement. It is the incorporation of the echo-canceling and trellis-coding techniques that make building V.32 modems more expensive.

V.32 Chip Sets

V.32 chip sets that are low enough in cost to allow 9,600-bps modems to compete in the personal computer market will appear beginning in 1988. The most competitive of these will comprise two $15 to $25 DSP microprocessors, one $6 to $10 analog front end, a $4 to $15 single-chip microcontroller, and $5 to $8 worth of static RAM. These sets will cause retail prices of 9,600-bps modems to drop precipitously from their current range of $1,500 to $1,800, to less than $300 by 1992 for plug-in modem cards—the price of current 2,400-bps modems. Currently, the major semiconductor companies that have announced products for the V.32 modem marketplace include Rockwell and SGS/Thomson. A third company, Phylon Communications, while not a semiconductor company, has announced a V.32 modem module, which is expected to directly compete with the chip-set solutions being introduced by semiconductor companies.

Figure 1 illustrates the historical and projected future pricing of modem chip sets (in volume) versus time for four different transmission rates. In this case, the chip set refers only to the data pump; e.g., the specific modem function. Not included are costs of the telephone line interface nor intelligent-modem features such as auto-dialing. Note that the dramatic decline in projected prices for 9,600-bps chip sets between 1988 and 1992 follows a trend similar to the one expected for V.22bis modems between 1986 and 1990.

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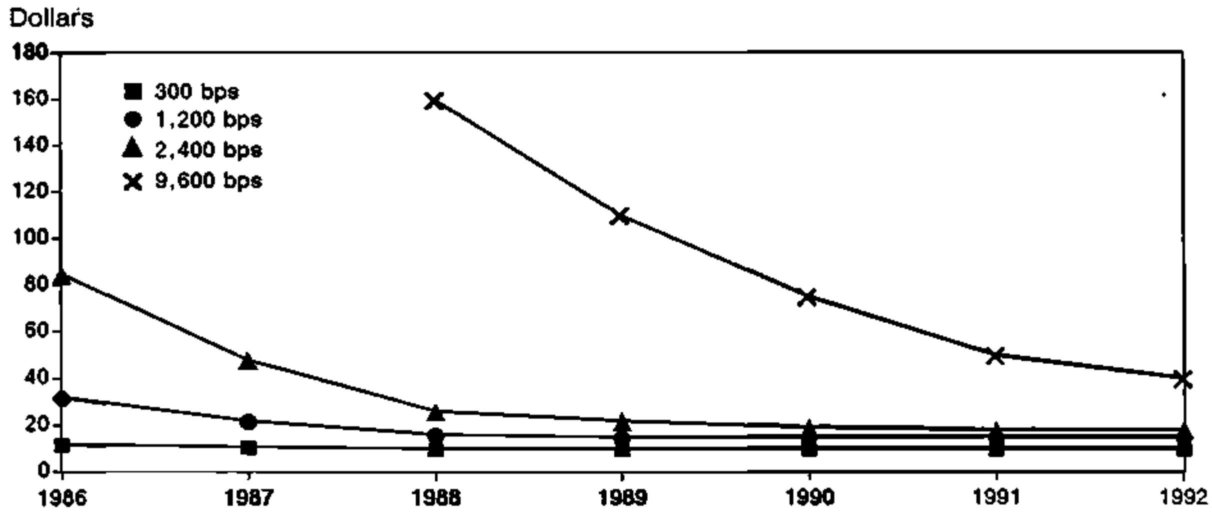
Figure 1

Volume Selling Prices of Modem Data Pump Chip Sets



Source: Dataquest June 1988

Rockwell

Rockwell is the major high-speed manufacturer of modem chip sets. It was the first company to offer a 2,400-bps V.22bis chip set: the R2424. Rockwell advertises that it has shipped over 1 million V.22bis sets. Dataquest estimates that Rockwell controls nearly 50 percent of this market. Dataquest also estimates that Rockwell chip sets are being used in approximately 90 percent of the V.29 modems in production.

In 1987, Rockwell introduced the R9696DP, a V.32 module solution. It is the only V.32 solution currently available to OEMs, although shipments to date have been relatively small. The R9696DP consists of five processor chips—three proprietary DSP microprocessors, a DSP echo canceler chip, and an analog front end chip—all on a 12-square-inch board. Initially, Rockwell should do well selling this board to high-end modem manufacturers, who will add value such as "intelligent" features to the module. Its current price of $350 in quantities of 1,000 is expected to spur growth for the PC marketplace. Dataquest expects this price to drop as competition increases.

SGS/Thomson

SGS/Thomson's first V.32 offering will be a six-chip set, to be priced at $150 in quantities of 10,000. It consists of three of SGS/Thomson's 68930 DSP microprocessors (one for transmission, one for reception, one for echo canceling), two analog front-end ICs, and a clock generator. In May, SGS/Thomson released the chip set, which uses external ROMs. Samples of its internally ROM-coded devices are scheduled for the fourth quarter of 1988. A CMOS version of its DSP microprocessor is expected to be available in the third quarter. Porting the modem firmware to the CMOS parts should follow by October. SGS/Thomson will also sell its echo canceler chip and analog front ends individually.

Phylon Communications

Also of significance is a new product from Phylon Communications, of Santa Clara, California. The PHY-96 is a V.32 modem module designed as a direct functional, physical, and electrical replacement for the Rockwell V.32 module. It reportedly goes beyond Rockwell's capabilities by also including V.22bis, Bell 212A, V.22, Bell 103, and V.21 modem standards as part of the module. The module uses two DSP microprocessors plus a two-chip analog front end to implement all of the modem signal processing operations. Phylon expects to begin production shipments in the third quarter of 1988.

Other 9,600-bps Standards: The Electronic Tower of Babel

A number of box modem manufacturers are promoting their own 9,600 bps (and higher) standards, most of which are incompatible with the others. Some of them may even be technically superior to the V.32 although this point is arguable. However, once V.32 chip sets are in production, Dataquest expects that volumes will grow, prices will fall, and alternative solutions will diminish. One can recall the failure of Racal-Vadic's proprietary pre-Bell-212A 1,200-bps modem, which was acknowledged by the technical community to be superior in performance to the Bell 212A. It failed due in large part to the creation of a de facto standard by the major communications company in the world—AT&T—which preempted Racal-Vadic's superior implementation.

Telebit

The Telebit Trailblazer is currently the most technically advanced voiceband modem. It transmits and receives data in the frequency domain using fast Fourier transform (FFT) techniques in order to take full advantage of the bandwidth and signal-to-noise characteristics present in a telephone connection. It adapts to the telephone line it is using and packetizes the information it has to transmit.

In Telebit's zealousness to keep its competitive edge, the company kept its admittedly unique technology too proprietary just as 9,600-bps modem standards were evolving. It is the timing on just that kind of decision which can spell success or disaster for a young company. In the case of modems, where standards are ever-important, Telebit was not quick enough to license its technology to others. Had it done so, Telebit might have had more influence in the evolution of the 9,600-bps modem standard.

One caveat remains for the Telebit implementation: A current proposal in front of CCITT Study Group XVII includes the Telebit multicarrier approach as an alternative to V.32. However, the chances of this approach gaining wide acceptance in the marketplace over the V.32 are slim indeed. Telebit's current installed base is approximately 20,000 units, whereas it is reasonable to anticipate the U.S. market to be using 200,000 V.32 chip sets annually by 1990.

Pseudo-V.32 Implementations

The concept behind pseudo-V.32 implementations is to use the V.32 modulation at half duplex, not supporting true full-duplex transmission. Hence, when data are to go in the other direction, the line must be "turned around." In order to simulate full-duplex transmission, buffering of data occurs on the side that is not currently transmitting. The

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advantage to this approach is the elimination of the echo canceler required in the receive path of true full-duplex V.32 modems. The echo canceler is undoubtedly the most sophisticated part of the signal processing chain. Unfortunately, most pseudo-V.32 implementations are incompatible between different manufacturers.

Hayes is certainly one of the champions of pseudo-V.32 modems. It claims that its line turnaround is very fast and transparent to the user. U.S. Robotics was the first company to introduce a pseudo-V.32 modem. Its method, which is incompatible with that of Hayes, uses an asymmetrical technique that combines a 9,600-bps forward channel and a 300-bps back channel. Still other 9,600-bps approaches are also competing in the marketplace. For example, Microcom and Racal-Vadic use half-duplex V.29 modulation.

However, Concord Data Systems recently performed detailed tests on all of the existing 9,600-bps approaches and presented the results to CCITT Study Group XVII. The results indicate that under all test conditions, V.32-compliant modems perform better than any of the other V.29 or multicarrier half-duplex modulation techniques.

Dataquest expects many of the modem companies now providing modems that are incompatible with V.32 to begin offering V.32-compliant solutions combined with their existing incompatible solution. In other words, a company might package its existing incompatible modem in the same box with a new entry into the V.32 market. This keeps these companies from alienating their existing installed bases while also addressing the mainstream V.32 market.

High-Speed Networks Should Encourage Growth of High-Speed Modems

The proliferation of digital ISDN and Ethernet networks may actually encourage the growth of high-speed modems. After all, even a 9,600-bps modem is slow compared to 56-Kbps ISDN or 10-Mbps Ethernet. It is generally acknowledged that both ISDN and Ethernet will exist in the office environment long before they invade the general switched network. While office workers will be able to communicate within a given plant location at ISDN or Ethernet rates, communication outside that location will still require the use of the switched network. Dataquest believes that the high rates at which these networks transmit data will demand that switched-network transmission rates increase to 9,600 bps.

Public data networks are both an indicator and an influence on the direction in which switched-network modems are headed. Tymnet, one of the largest public data networks, started using Concord Data Systems V.32 modems about three months ago. Similarly, Dow Jones Retrieval Service has been using Concord's V.32 for almost two years.

Compuserve has entered into a joint venture with Hayes to provide 9,600-bps service using the Hayes V-Series 9,600-bps modems. The service is expected to be operable within a few months. However, this Hayes modem is not V.32 compatible (as described earlier). It is clearly an attempt by Hayes to use its clout in the modem business to create a de facto standard using its noncompatible V.32 modem. It will be interesting to see how events evolve for both Hayes and Compuserve as they appear to be bucking what seems to be a growing tide toward adherence to the V.32 standard.

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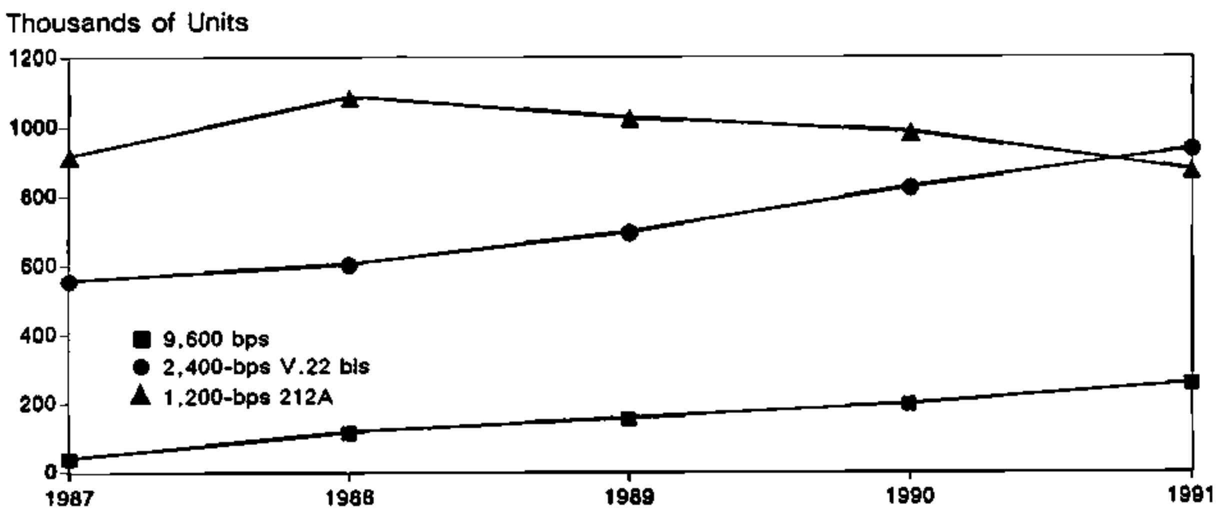
V.32 MODEM MARKET FORECASTS

Figure 2 illustrates Dataquest's projections for the growth of the dial-up modem marketplace. The curve for 9,600-bps includes both the V.32 and the pseudo-V.32 modems that are incompatible with the specification. Of the estimated 43,000 9,600-bps dial-up modems shipped worldwide in 1987, less than 10 percent were V.32-compliant. However, Dataquest estimates that by 1990, nearly 90 percent of the estimated 200,000 units shipped will be V.32-compliant.

Figure 2

Estimated Worldwide Market for Dial-Up Telephone Modems



Source: Dataquest
June 1988

DATAQUEST CONCLUSIONS

The 2,400-bps V.22bis modems are now mass-market items, due in large part to the low-cost DSP semiconductor chip sets used to build them. A modem that is faster, downward compatible, and has a small price premium will displace lower-speed modems. One can no longer find advertisements for 300-bps-only modems in personal computer magazines. They have gone the way of the 16K dynamic RAM.

Dataquest believes that market forces are beginning to encourage 9,600-bps modem transmission rates over the switched-telephone network. The question is no longer "if" but "when" V.32 modems will exceed V.22bis modems in production volume for personal computer applications. V.32 implementation issues are technically complex, but curiously enough, the effort required is largely for algorithms and software, not hardware. The final implementations will probably make almost exclusive use of single-chip digital signal processors programmed for the V.32 function. Dataquest expects many of the semiconductor companies to begin selling their own (or somebody else's) DSP microprocessors as V.32 modem chips. There is plenty of incentive for manufacturers to do this, as the modem market is extremely large. It is likely that nearly 200,000 V.32 units will be shipped in 1990.

While the market for V.32 modems will be quite large, Dataquest does not expect V.32 modems to be the only 9,600-bps modems in production. Other standards such as V.29 will also be used, but mainly for specific applications such as facsimile.

(Statistical support for this newsletter was provided by Larry Cynar of Dataquest's Telecommunications Industry Service.)

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DATAQUEST DSP OPINION: CONDITIONS FOR SURVIVAL IN THE GENERAL-PURPOSE DSP MARKETPLACE

SUMMARY

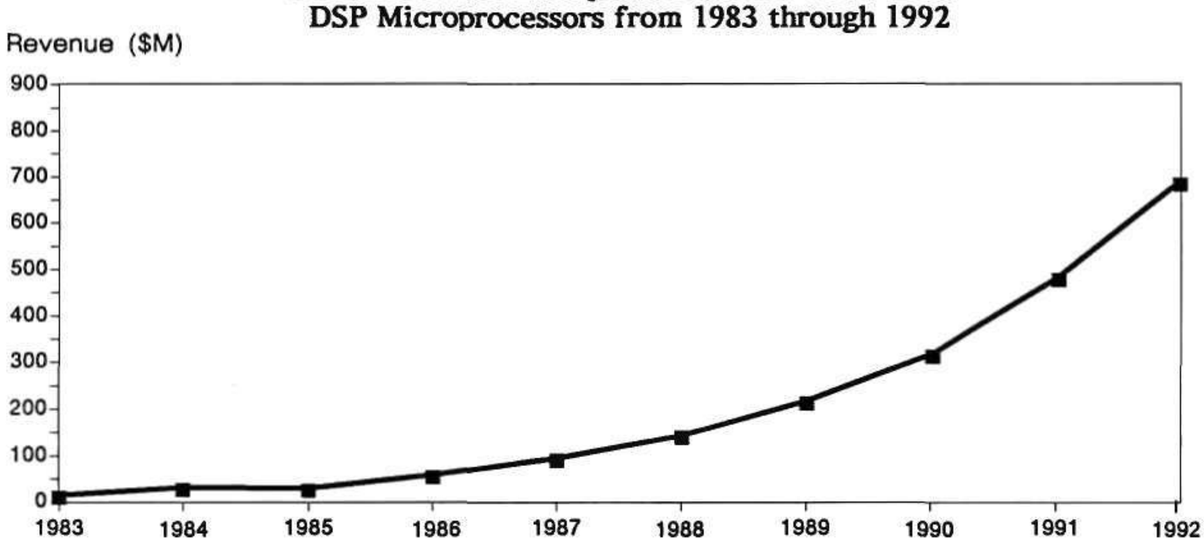
The digital signal processing (DSP) marketplace is partitioned by Dataquest into the following four different integrated circuit product areas:

- General-purpose DSP microprocessors (DSMPUs)
- Microprogrammable DSP (MPDSP)
- Special-function DSP (SFDSP)
- Application-specific DSP (ASDSP)

Certainly the most visible of these product categories through the middle portion of the 1980s has been DSMPUs. Revenue has blossomed from roughly $18 million in 1983 to nearly $100 million in 1987, as shown in Figure 1. Dataquest expects DSMPU revenue to accelerate rapidly past revenue for the relatively flat MPDSP market during calendar year 1989. DSMPU revenue growth is expected to slow only minimally to about 47 percent from the 53 percent compounded growth it experienced from 1983 through 1987.

Figure 1

Historical and Anticipated Revenue Growth for DSP Microprocessors from 1983 through 1992



Source: Dataquest
August 1988

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Although such growth potential presents many opportunities for new entrants to service this market, there are also plenty of risks involved. The remainder of this newsletter examines some of the issues important to the market success of general-purpose DSP microprocessor architectures.

STATE OF THE ART

A minimum of 13 different manufacturers have introduced families of proprietary DSMPU architectures. Although each processor family has architectural characteristics that certainly help distinguish it from competitive products, these features often introduce incremental advantages to designers of DSP systems. Illustrating this point, three key DSP benchmarks are shown in Table 1 for four of the new floating-point DSP processors introduced recently by AT&T, Motorola, Texas Instruments, and Zoran.

Table 1

Comparative Benchmarks for Four Recently Introduced DSP Microprocessors*

Company	FIR Filter (per tap)	IIR Filter (2nd-order biquad)	1K Complex FFT (radix-2 with bit reversal)
AT&T DSP-32C	80ns	400ns	3.2ms
Motorola 96000	75ns	375ns	2.45ms
TI TMS320C30	60ns	360ns	4.12ms
Zoran ZR34325	80ns	400ns	1.7ms

*Performance benchmarks obtained from manufacturers

Source: Dataquest
August 1988

As observed, the benchmarks indicating device performance are reasonably similar. Of course, additional subtleties introduced by the architectures will affect other signal processing operations. Generally, however, each of these processors can be used effectively to solve a wide range of problems.

NECESSARY (BUT NOT NECESSARILY SUFFICIENT) CONDITIONS FOR SUCCESS

Dataquest believes that the long-term success of these architectures ultimately will be determined by the product support provided by the manufacturer to the customer. Support in this case refers to:

- Training, education, and applications assistance
- Hardware and software development tools including simulators, assemblers, compilers, and emulators
- Software libraries

DSP microprocessors require an even larger investment in customer development assistance than do conventional microprocessors.

Training and Education

The required base knowledge by designers of DSP systems is quite high. The traditional skill of microprocessor system design is essential, coupled with a knowledge of digital signal processing theory, hardware, and software design techniques. The number of designers possessing both backgrounds is relatively few. In order for semiconductor companies to be successful in propagating and expanding their digital signal processing products, they must help provide the appropriate training and education for their customers.

Development Tools

As the architectures of many DSP products on the market are maturing, designers of DSP systems are demanding more sophisticated hardware and software development tools. These tools, analogous to those available for traditional microprocessor systems, include C compilers and hardware emulators. DSP algorithm purists rightfully claim that compilers generate less efficient code than can be generated by hand coding coupled with an assembler. However, as the complexity of the software effort for DSP systems increases, the traditional reasons for using high-level languages becomes ever more important for DSP systems.

Additional tools also are important for DSP systems including software simulators and development boards. These tools allow designers of DSP systems to develop and debug many of their software algorithms prior to actually building a piece of hardware.

Software Libraries

DSP systems often require lengthy hardware and software development cycles. However, shared by many systems are a few "key" DSP algorithms that are easily identified, such as fast Fourier transforms, finite-impulse response, and infinite-impulse response filters. Manufacturers can greatly aid the software effort of their customers by publishing "standard" DSP algorithm code in readily available libraries. Observing the large amount of software available for Texas Instruments DSP processors provide testimonial to the importance of libraries.

As happened in the microprocessor marketplace in the early 1980s, and for similar reasons, Dataquest expects the number of true winners in the DSMPU marketplace—as judged by unit and revenue growth—to be limited to three or four. Other minor players may exist but will be limited largely to specialty applications on the fringes of the mainstream DSMPU marketplace.

The fallout in suppliers to the DSMPU market already has begun to occur. Probably the most notable has been National Semiconductor's exit from the market in 1987. Zoran Corporation has not exited the DSP business, but it is refocusing its strategy after never having achieved the revenue growth expected after its visible market entry in 1986.

DATAQUEST CONCLUSIONS

It is important for DSMPU manufacturers to remember that a product is not simply a device, such as a DSP processor, but rather a complete package purchased by the customer. This package includes tangibles such as the device, development tools, software libraries, and applications assistance; it also includes intangibles such as the reputation and stability of the manufacturer.

Dataquest expects the fallout among general-purpose DSP microprocessor manufacturers to accelerate over the next two years. Adoption and implementation of the stated support requirements are not sufficient to guarantee success; they are necessary conditions for manufacturers to be considered among the contenders for success.

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DSP EVOLUTION EVIDENT AT 35TH ISSCC

SUMMARY

The International Solid State Circuits Conference (ISSCC), held February 17 through 19, 1988, in San Francisco, celebrated its 35th year of reporting continuing progress in semiconductor technology. One hundred papers by more than 600 industry and academic participants emphasized the rapid rate of evolution of IC functions. Significantly, a record 30 percent of these were specifically oriented to digital signal processing (DSP) chips, and another 50 percent described general-purpose functions that are directly usable in DSP applications.

Dataquest broadly categorizes DSP IC functions as signal processing, graphics generation, image processing, and scientific computing products. This newsletter examines major ISSCC presentations in each of these areas, then discusses their impact on trends in products, technology, and applications.

ANALYSIS AND DISCUSSION

Since the first 4-bit microprocessor of 1970, microprocessor chips have evolved to 32-bit word length, CMOS and GaAs processing, <1-micron design rules, clock rates beyond 30 MHz, and throughputs measured in tens to hundreds of mops. Where appropriate, on-board EPROM or EEPROM is used for microcontrol storage. The DSP functions presented at this conference represent a continuation of this progress.

Some of the major developments discussed at the conference are summarized in Table 1. All of the devices shown use CMOS processing, with transistor counts as high as 368,000. All incorporate two-layer metal and/or double-poly interconnections for efficient use of chip area. Minimum geometries are on the order of 0.8 to 2.0 microns. Power dissipation for each of the two largest functions is 4 watts.

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Table 1

1988 ISSCC—Major Silicon DSP Chips

Characteristic	Hitachi	Matsushita	National	NTT	Toshiba	VITI
Function	Video signal processing	3-D hidden surface processing	Video signal processing	Geometric mapping processing	Graphics processing	Parallel image processing
Gate Count	9,000	N/A	N/A	105,000	N/A	50,000
Transistor Count	36,000	330,000	40,000	N/A	368,000	200,000
Process	CMOS	Twin-tub CMOS	CMOS, 2L poly	CMOS	Twin-tub CMOS	CMOS
Minimum Feature Size (u)	1.0	1.2	2.0	1.2	0.8	2.0
Metal	2L Al	2L	N/A	2L	2L	2L
Die Size (cm^2)	6.8 x 5.5	11.1 x 11.5	7.0 x 5.5	14.5 x 14.5	10.9 x 12.2	11.7 x 10.7
Clock Rate	N/A	20 MHz	27 MHz	50 MHz	40 MHz	N/A
Performance	50 mips	N/A	N/A	N/A	40M pixels/s	114 mops
Pinouts (S + P)	80	57 + 7	37 + 3	280	144	119 + 30
Package	N/A	N/A	DIP	PIP	Ceramic FP	PGA
Voltage(s)	+5V	+5V	+5V, -5V	+5V	+5V	V_{DD}, V_{SS}
Power Consumption	N/A	4W	500mW	4W	800mW	N/A
Remarks		256-pixel processing	Maximum rate--30 MHz			12 transistors per register bit

N/A = Not Available

Source: Aztek Associates

Signal Processing Products

Companies and other organizations presenting information on developments in signal processing products include AT&T Bell Laboratories, Fujitsu, General Electric, Hitachi, Matsushita, National Semiconductor, NEC, Philips, Siemens, and Stanford University. Notable are the AT&T communications signal processing chips, the 4Gb/s optical repeater by Fujitsu, and Sony's CMOS thermal printer head LSI logic/driver chip containing 11,448 transistors and parallel heating elements.

Numerous improvements in A/D and D/A conversion were evident. Philips and others continue to advance the state of the art of audio signal processing using digital techniques. Several telecommunications functions were presented, including an echo canceller and switching functions including cross-point switches. These are included in Table 2.

Table 2

1988 ISSCC Developments in Signal Processing Chips

Company	Chip Developments
AT&T Bell Labs	45-MHz P/FLL (phase/frequency-locked loop) timing recovery circuit, 146Mb/s time/space switch, 64 x 17 nonblocking cross-point switch, 2-GHz CMOS dual-modulus prescaler
Catholic University (Leuven, Belgium)	Micropower monolithic data acquisition
Fujitsu Opto Systems Lab	4Gb/s repeater chip set
General Electric	A mixed A/D chip for phased array single processing
Hitachi	Voice-band DSP chip with A/D and D/A, 10Mb/s link-level CMOS processor
Matsushita ERL	GaAs programmable timer with 125ps resolution
National Semiconductor	33Mb/s data-synchronizing phase-locked loop (PLL)
NEC, BSR (Newton, Massachusetts)	18-bit oversampling A/D converter for digital audio
Philips	Stereo 16-bit CMOS D/A for digital audio, algorithmic 15-bit CMOS D/A converter

(Continued)

Table 2 (Continued)

1988 ISSCC Developments in Signal Processing Chips

Company	Chip Developments
Siemens	2u CMOS equalizer for quadriture amplitude modulation (QAM) digital radio, self-calibrating 16-bit CMOS A/D converter
Sony	Thermal printer head with CMOS logic and drivers
Stanford University	Asynchronous multiplexer for biotelemetry
University of California at Berkeley ERL	250 Mbit/s CMOS cross-point switch

Source: Dataquest
April 1988

Graphics-Generation Products

Charge-coupled device (CCD) chips topped the list of graphics-generation functions discussed at the 1988 ISSCC. The largest of these, a 2 million-pixel chip by Toshiba, is organized in high-definition television (HDTV) format, 1,920 horizontal by 1,036 vertical pixels, allowing a 9:16 aspect ratio. The unit cell measures 7.3 x 7.6 microns, with a charge-handling capacity of 200,000 electrons per picture element. At F11 illumination, a signal current of 300nA has been obtained.

Texas Instruments' 128Kx8 video RAM allows storage and manipulation of 256 individual colors or shades of gray at standard HDTV resolution and frequency. Philips engineers have developed a 835Kb video serial memory and a 400K-pixel CCD imager, both aimed at HDTV. Table 3 summarizes the graphics-generation product developments.

Table 3

1988 ISSCC Developments in Graphics-Generation Functions

Company	Chip Developments
Philips	835-Kbit video serial memory (VSM), 400K-pixel CCD imager
Sony	Comb filter
Texas Instruments	128Kx8, 70-MHz video RAM
Toshiba	2M-pixel CCD imager

Source: Dataquest
April 1988

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Image Processing Products

Video signal processing (VSP) functions have evolved to include 3-D manipulation and elimination of hidden areas from processed images. Matsushita presented an approach to this problem that incorporates a skewed systolic architecture fabricated on a 11.1 x 11.5mm^2 die containing 330,000 transistors. This chip is detailed in Table 1.

Significant developments were described by the France's National Telecommunications Center, General Electric, Hitachi Central Research Laboratories, Matsushita Central Research Laboratories, Nippon Telegraph and Telephone, Toshiba, and Visual Information Technology, Inc. (VITI). The parallel image processor (PIP) chip by VITI is a graphics computer incorporating the properties of two-dimensional DSP of pixel data, pixel enhancement, and interactive processing rates. Performance of 50 mips is achieved in CMOS with relatively conservative design rules of 2 microns. VITI's chip is detailed in Table 1. Table 4 is a summary of image processing product developments presented at the conference.

Table 4

1988 ISSCC Developments in Image Processing

Company	Chip Developments
French Government	27-MHz D/A VSP
General Electric	10-MHz ICs for graphics processing designed on a silicon compiler
Hitachi CRL	20ns CMOS DSP core for VSP
Matsushita CRL	Hidden surface processor
NTT	50-MHz CMOS geometrical mapping processor
Toshiba	32-bit 3-D graphics processor with 10M-pixels/s Gouraud shading, 40M-pixels/s graphics processor
VITI	PIP chip

Source: Dataquest
April 1988

Scientific Computing Products

Table 5 identifies the major developments in scientific computing products described by LSI Logic's Stanford Research Laboratory, Rockwell, a Stanford team, and Texas Instruments.

Table 5

1988 ISSCC Developments in Scientific Computing Chips

Company	Chip Developments
LSI Logic SRL	30-mflops, 32-bit CMOS floating point processor
Rockwell	150-mops GaAs 8-bit slice
Stanford University	Pipeline 64x64 array multiplexer
Texas Instruments	200-mips GaAs 32-bit microprocessor

Source: Dataquest
April 1988

Technology Trends

While CMOS processing at 0.8- to 2.0-micron geometries represents the present "workhorse" technology, advances in silicon emitter-coupled logic (ECL) and GaAs processing were visible in the presentations. The yield data for GaAs devices at LSI density levels indicate significant improvements during the last 12 to 18 months. Dataquest believes that more applications will shift toward GaAs as speed becomes a larger factor in new applications. Table 6 compares two approaches to DSP using GaAs hardware developed by Rockwell and Texas Instruments.

Table 6

GaAs Microprocessor IC Comparison

Characteristic	Company: Rockwell Design	Company: Texas Instruments/CDC Design
Function	150 mops 8-bit ALU (1,750 type)	32-bit RISC microprocessor
Architecture	3-bus bit slice (expandable to 16 bits)	6-stage pipeline
Performance	150 mops	200 mips
Operations	Add, subtract, modified Booth multiply, divide, bit operations	4 address modes, 16 ALU and 5 control instructions, 10 memory instructions
Power (Watts)	Low--4.2, high--9.2	Estimated 20 maximum
Die Size--mm	4.9 x 3.9	7.6 x 7.6
Chip Complexity	9,400 transistors, 3,000 diodes	12,872 gates (typical gate is 1 transistor and 5 resistors)
I/Os: Signal + Power/Gnd	64 + 29	256 + 70
Process	1.0u GaAs D-MESFET	1.5u GaAs HBT
Logic Form	Buffered FET logic (BFL)	I^2L (modified RTL)
Cell Speed/Power	120ps/1.6mW (register)	160ps/2mW (gate)
Yield Data	18 percent	Experienced 2 percent, projected 8 percent

Source: Aztek Associates

Product Trends

The development of several VSP devices by ISSCC participants is an indication of an emerging product area for chips oriented toward solving the unique problems incurred in high-definition video system designs. A similar evolution is occurring in voice-processing hardware. An estimated 50 other papers described DRAMs and SRAMs, microprocessors, and other DSP-related functions. These gave evidence of trends toward continuing increase in SRAM, DRAM, and DSP function densities and speeds with accompanying decreases in power per bit.

Application Trends

Enhancing human interface with systems is a major new thrust in semiconductor applications. The main focus of this year's ISSCC developments in chip architectures is toward improving the human-system interface. This was portrayed by the focus of many papers on voice and graphics communication and processing. HDTV is a major application addressed by many chip suppliers, followed by optical communications and massive main memories. Dataquest expects many product announcements in these applications areas in the near future.

DATAQUEST CONCLUSIONS

The IC world is rapidly evolving toward submicron processing of chips ranging above 1 million transistors in complexity (silicon CMOS), with GaAs now within a factor of 16 in complexity and 4 to 5 times faster in speed. The competing technologies are causing a proliferation of application-specific DSP designs. Dataquest expects DSP functions to play an increasingly important role in IC suppliers' product portfolios for at least the next two to three years. Realignments among IC competitors are expected as these developments accelerate the obsolescence of many existing products.

Gene Miles