Entertainment is an important application for microprocessors today. A few years ago, it was difficult to predict that the important application of high-end 32- and 64-bit microprocessors would be home entertainment. Radio, TV, audio, and VCR electronics appliances generally provided our home entertainment—a carryover from the analog age. In essence, this medium is a one-way street where the centralized providers offer contents to the viewing audience. However, the arrival of the digital age changed the nature of entertainment.

Application of microelectronics for home entertainment is varied. The mainstream is the home game console such as the PlayStation, Nintendo64, and Dreamcast. These use microprocessors that process the data somewhere between 32 bits and 128 bits at a time. Once the gaming arcade machines boasted better hardware and performance, but today the home version and the arcade version use the same processor and same motherboard. Today, it is not farfetched to say that the fate of a CPU line hinges on its acceptance by a popular gaming console. For example, accord-

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ing to a MIPS Technologies press release, the contract revenue from Nintendo64 was 79% of its sales in 1Q99 and decreased to 49% in 2Q99 due to the increased sales of a 64-bit core license to the Sony PlayStation2. MIPS CPUs support many embedded systems, but in business terms the game market seems to play a very big role.

Today’s consoles

Let us look at the hardware of the current crop of gaming consoles. (See Table 1 for a list of the most recent game consoles.) PlayStation uses a 32-bit, 33.8-MHz MIPS CPU that is compatible with the R3000. It also uses a 1.5-million-polygons/second LSI geometry engine and an LSI rendering chip.

Nintendo64 contains a 64-bit, 93.75-MHz MIPS CPU compatible with the R4300. It also uses one LSI chip that performs both geometry calculation and rendering operations. Dreamcast, which recently began sales in the U S, uses Hitachi’s 32-bit, 200-MHz SH-4 CPU that has a built-in floating-point matrix calculation unit for geometrical calculation and a rendering LSI chip capable of drawing 3 million polygons/second.

The PlayStation2 slated for debut in 2000 includes the Emotion Engine, which consists of two 64-bit CPUs and two floating-point vector processors to handle 128-bit floating-point numbers running at 294.912 MHz. It uses 10.5 million devices and a graphics synthesizer, a 75-M polygon/s, 147.456-MHz graphics engine with 42.7 million devices. PlayStation2 will feature 32 Mbytes of main memory and a 4x DVD-ROM drive. Nintendo plans a gaming console called Dolphin that it is slating for debut by the end 2000. Dolphin will use a 400-MHz PowerPC CPU and is jointly developed by IBM and Matsushita Electric Industrial Co.

<table>
<thead>
<tr>
<th>Name</th>
<th>PlayStation</th>
<th>Nintendo64</th>
<th>Dreamcast</th>
<th>PlayStation2</th>
<th>Dolphin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vendor</td>
<td>SCE(1)</td>
<td>Nintendo</td>
<td>Sega</td>
<td>SCE</td>
<td>Nintendo</td>
</tr>
<tr>
<td>CPU</td>
<td>MIPS (R3000A)</td>
<td>MIPS (R4300)</td>
<td>SuperH (SH-4)</td>
<td>MIPS</td>
<td>PowerPC</td>
</tr>
<tr>
<td>Clock (MHz)</td>
<td>33.8</td>
<td>93.75</td>
<td>200</td>
<td>294.912</td>
<td>400</td>
</tr>
<tr>
<td>3D graphics</td>
<td>Geometry LSI</td>
<td>Graphics LSI(1)</td>
<td>In CPU</td>
<td>In CPU</td>
<td>N/A</td>
</tr>
<tr>
<td>M polygons/s</td>
<td>1.5</td>
<td>N/A</td>
<td>N/A (unofficial estimate: 5)</td>
<td>66</td>
<td>N/A</td>
</tr>
<tr>
<td>Rendering</td>
<td>Rendering LSI</td>
<td>Graphics LSI(1)</td>
<td>Rendering LSI</td>
<td>Rendering LSI</td>
<td>N/A</td>
</tr>
<tr>
<td>M polygons/s</td>
<td>0.36</td>
<td>N/A</td>
<td>3.0</td>
<td>75</td>
<td>N/A</td>
</tr>
<tr>
<td>Memory</td>
<td>RAM (Mbytes)</td>
<td>2</td>
<td>4.5</td>
<td>16</td>
<td>32</td>
</tr>
<tr>
<td>Memory bandwidth (bytes/s)</td>
<td>132M</td>
<td>500M</td>
<td>800M</td>
<td>3.2G</td>
<td>3.2G</td>
</tr>
<tr>
<td>Graphics RAM (Mbytes)</td>
<td>1</td>
<td>—</td>
<td>8</td>
<td>4(6)</td>
<td>N/A</td>
</tr>
<tr>
<td>Software media</td>
<td>CD-ROM</td>
<td>ROM cartridge</td>
<td>GD-ROM</td>
<td>DVD(CD-ROM)</td>
<td>DVD</td>
</tr>
</tbody>
</table>

(1) Sony Computer Entertainment
(2) Floating-point processing unit
(3) Vector graphics engine
(4) Vector processing unit
(5) One LSI graphics chip with geometry and rendering functions
(6) On a LSI rendering chip
N/A Not available
All these hardware gadgets may make your head spin when you think about the progenitor of all these gaming consoles—the 1977 Atari 2600 programmable home video game machine. It included an 8-bit, 1.19-MHz 6502 microprocessor, and its RAM was a staggering 128 bytes.

The screens of these gaming consoles might become more realistic so that they will be hard to distinguish from the familiar video screen. However, video quality is not the only factor determining the success of a gaming device. Some recent games use the sensors and actuators in the controller to facilitate more realistic feedback to the player. For example, realistic flight simulator or fishing games have appealed to players because they give an almost real experience of piloting an aircraft or reeling in a catch by physical feedback. Computers can form their own virtual worlds, but players seem to seek real-world experiences from their games.

Game enhancements

Now if we add the trends typified by mobile/wearable/ubiquitous computing, another direction for games emerges.

One is a mobile game machine. Playing games anywhere appeals to many, although players can’t expect the realistic screen images available on a desktop machine from such small portable game machines. Despite this, sales of programmable, portable game devices including the popular Game Boy have reached 80 million units in 10 years all over the world. So real-like screen images alone don’t sell these games. The current Game Boy Color uses an 8-bit Z80 CPU, but the next-generation machine, Game Boy Advance slated for sales at the end of the year 2000, will contain a 32-bit ARM CPU. This new version will allow the owner to play games everywhere but also permit gaming contents to be downloaded from cellular phones or the game machine to act as a music player. Similar portable game machines aim at doubling as e-mail messaging consoles or electronic book readers.

Traditional toys also become high-tech. Toy pets or robots with built-in microprocessors have caught attention lately. We play in the virtual world of game machines, but robots share our living quarters. Furby, which began selling in 1998, has two microcontrollers plus a number of sensors, microswitches, lamps, and motors. It has become a bestseller. Its vocal learning capability surely helped its charm and sales. Considering the price tag of several dozen dollars, microelectronics probably is a large part of its manufacturing cost.

Lego MindStorms transforms the traditional Lego blocks with built-in motors, sensors, and a microprocessor controller called
The basic idea came from the MIT Media Lab, and Lego commercialized it and sold it in 1998. The initial version requires users to program the motion of the blocks using a proprietary application on the Windows platform and then downloading the command sequence to RCX before a unit moves. It seems to me that this is aimed at much older segments of buyers than those of the traditional blocks. Figure 1 shows a project built using Lego's Robotics Discover Set.

AIBO is a doglike robot Sony sold in limited quantities in June 1999 for US$2,500. (See Figure 2.) It uses a 64-bit, 100-MHz MIPS CPU and has a 16-M-byte main memory. The stored program simulates the emotional behavior of joy, rage, surprise, sadness, fear, and dislike, as well as the hunger, curiosity, and desire to move around. The mechanism has 18 degrees of freedom, and the robot as a whole moves like a puppy. There is no practical use for this robot. Its behavior is cute and thus some want to keep it around. This is the definition of a pet, isn’t it?

NEC announced an ongoing-development personal robot, the personal R100, in August 1999. The sales date is not available yet. As seen in Figure 3, this robot looks like a doll. A camera embedded in its eyes recognizes people’s faces, while three microphones in its ears and front torso detect voice direction. Its voice recognition capability works for any speaker. When someone speaks to it, it recognizes the speaker. It also has a learning skill: when someone speaks to it, it turns around, looks at the speaker’s face, and stores it in memory. Thus, the speaker can ask it to turn on/off the TV and other home appliances or pass a message to someone in the family.

NEC says that the enhancement and replacement of modularized software components should be easy: the R100 contains modules for image recognition, voice recognition, sensor management, behavior simulation, emotion simulation, memory simulation, mechanical control, behavior pattern library, and others. At this stage of development, the doll robot includes a PC and communicates with external computers via a radio link so that heavy-duty computation such as image recognition and voice recognition is offloaded to external computers.

Some readers might recall that home robots appeared at the beginning of the 1980s. The Heathkit Hero-1 represents the robots that appeared at that time. Hero-1 somewhat reminded me of R2D2 of the Star Wars movies. The price was US$2,500 for a finished model, a price tag not much different from AIBO today. The early robot was large, and its degree of freedom of motion was small. It could not do a lot and didn’t catch on.

Today, the selling robots seem to aim just at being a small toy and do not try to offer practical services.

Mobile computing, of course, includes mobile entertainment terminals. The MP3 (MPEG Audio Layer 3) player market has grown in the one year since its birth. Playing the sound stored in the semiconductor memory using an MP3 player is good enough to satisfy many users. Other portable terminals also now incorporate playful functions. Low-power processors and semiconductor memo-
ry, especially flash memory—developed by Fujio Masuoka then at Toshiba in 1984—made silicon music, silicon maps, and silicon pictures possible. When coupled with a GPS to show maps of current location and a digital camera for image editing, new toys will certainly emerge.

The large game console market has made it possible for companies to dedicate large amounts of manpower and money to the development of hardware. The development of PlayStation2 and Dolphin clearly shows that these companies can produce a special high-performance CPU for games. It is interesting to note that current trends in scientific computing combine off-the-shelf components to create inexpensive supercomputers of a sort. The future of the home robot this time around is also an interesting topic. Will they wither as in the past or prosper this time?

We can clearly see the importance of the network for future embedded computer systems including toys and games. The first result would be the connection of home appliances via the Internet, but the important factor would be the wide bandwidth for such connections. Radio links will connect these appliances, which was not possible before without wire links. The connected system of home appliances and home control center will give us better service at a different grade.

The contents, be it a game or music or whatever, will become more important. MP3 and the distribution of MP3 music via the Internet have proven the practicality of bypassing storefronts to distribute music. The problem of illegal copies will be here to stay for a while, but the copy protection schemes and new business modules will deal with it eventually. The intellectual property value of the contents will be honored, and the distribution will be based on fees, but the infrastructure for distribution, replay, and so on will be open and will be provided for free (or almost for free).

This special issue

Now let us turn to the contents of this special theme issue on edutainment: four articles and one interview. Two articles feature the home-gaming console: Masaki Oka and Masakazu Suzuki of Sony Entertainment write about CPUs in the PlayStation2, a current buzz machine among hard-core game players. Shiro Hagiwara and Ian Oliver of Sega Enterprises write about the Dreamcast that has begun sales in North America recently. The MIT Media Lab article alerts us to ongoing research about computer use and also some future toys. Ichiya Nakamura and Hideki Mori tell us what the MIT Media Lab is up to currently.

The Tech Museum of Innovation is a very modern computerized museum. Such a museum is a good example of using computers for edutainment. Davin S. L. Ing describes the museum and its usage of computers. MicroView this issue features a Lego Mindstorms interview with Director of Development, Mike Dooley.

We hope you enjoy this issue, which you'll receive just before the upcoming holiday season.

Ken Sakamura is a professor in the Digital Museum Laboratory, the University Museum, at the University of Tokyo. His primary interests lie in computer architecture and digital museums as well as real-time processing and computer-augmented environments. He initiated the TRON project in 1984 to help build computers in the 1990s and beyond. Under his leadership, over 100 manufacturers participate in the project. Since he is now also interested in how computer use will change society in the 21st century, his design activities extend to electronic appliances, furniture, houses, buildings, and urban planning. He is currently constructing the Digital Museum, which uses various computer technologies. Sakamura received BS, ME, and PhD degrees in electrical engineering from Keio University in Yokohama. He is a senior member of the IEEE and a member of the ACM. He is the Editor-in-Chief of IEEE Micro.

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