What is Signal Processing?

Example of Signals:
- **Analog**: Speech, Music, Photos, Video, radar, sonar, ...
- **Discrete-domain/Digital**:
  - digitized speech, digitized music, digitized images, digitized video, digitized radar and sonar signals, ...
  - stock market data, daily max temperature data, ...
What is Digital Signal Processing?

- Digital Signal in → Digital Processing → Digital Signal out

Operation, Transformation performed on digital signals (using a computer or other special-purpose digital hardware)

- But what about analog signals?

Analog Signal in → Analog-to-Digital (A/D) Conversion → Digital Processing → Digital-to-Analog (D/A) Conversion
Signal Processing Examples

Why Go Digital??
Step 1: Analog sensor picking analog signal (i.e: microphone picking sound)

Step 2: Analog to Digital Converter

Step 3: DSP processes the digital signals (e.g., compression, noise suppression)

Step 4: Digital to analog converter to recover the analog signal
What is DSP?

- DSP = Digital Signal Processing
- OR
- DSP = Digital Signal Processor?

- DSP used to denote both
  - meaning can be deduced from the context in which the term DSP is used.
- What is a Digital Signal Processor (DSP)?
  - Microprocessor specifically designed to perform fast DSP operations (e.g., Fast Fourier Transforms, Multiply, Divide, Multiply & Accumulate-MAC)
A Typical DSP System

- **DSP Chip**
- **Memory**
- **Converters (Optional)**
  - Analog to Digital
  - Digital to Analog
- **Communication Ports**
  - Serial
  - Parallel
Digital Computers

von Neuman Machine

STORED PROGRAM AND DATA

INPUT/OUTPUT

ARITHMETIC LOGIC UNIT

A = ADDRESS
D = DATA

Harvard Architecture

STORED PROGRAM

ARITHMETIC LOGIC UNIT

INPUT/OUTPUT

STORED DATA

A

D

A

D

A

D

A

D

A

D

A

D
‘C5510: The high runner ‘C55x DSP

VC5510 Device Specific Information

- **On-Chip Memory**
  - 160 KW SRAM
  - 16 KW ROM

- **I-Cache**
  - 24 KByte Cache

- **DMA**
  - Six-channel

- **3 Multi-channel Buffered Serial Ports**
  - 128 Channels Each

- **Enhanced HPI**
  - 16-bit

- **External Memory Interface (EMIF)**
  - Supports Cheaper & Faster Memories

- **Advanced Emulation**
  - Easier Debug

- **8 GP I/O Lines**
  - Connect Peripherals directly to the DSP

- **Package**
  - 240 Ball, 15x15uF BGA
Why Go Digital?

- **Programmability**
  - One hardware can perform several tasks.

  ![Diagram showing programmability](image)
  
  SOFTWARE 1  \(\rightarrow\) SAME HARDWARE  \(\rightarrow\) LOW-PASS FILTER
  SOFTWARE 2  \(\rightarrow\) \(\rightarrow\)
  SOFTWARE N  \(\rightarrow\) MOTOR CONTROL

- **Upgradeability and flexibility.**
  - DEVELOP NEW CODE \(\rightarrow\) UPGRADE
  - ANALOG \(\rightarrow\) SOLDER NEW COMPONENT
STABILITY AND REPEATABILITY

- ANALOG CIRCUITS ARE AFFECTED BY
  - TEMPERATURE
  - AGING

- TOLERANCE OF COMPONENTS
  - TWO ANALOG SYSTEMS
    - USING SAME DESIGN
    - USING SAME COMPONENTS
    - MAY DIFFER IN PERFORMANCE
DIGITAL REPEATABILITY

- PERFECT REPRODUCIBILITY
  - NEARLY IDENTICAL PERFORMANCE FROM UNIT TO UNIT
  - COMPONENT TOLERANCES DO NOT AFFECT PERFORMANCE
  - NO DRIFT IN PERFORMANCE DUE TO TEMPERATURE OR AGING
  - GUARANTEED ACCURACY

A CD PLAYER ALWAYS PLAYS THE SAME MUSIC QUALITY
Performance

Some special functions are best implemented digitally

- Lossless Compression
- Adaptive Filters
- Linear Phase Filters
Analog Advantages

- Low cost and simplicity in some applications
  - Attenuators/amplifiers
  - Simple filters
- Wide bandwidth (GHz)
- Low signal levels
- Infinite effective sampling rate
  - Infinite resolution in frequency
  - No aliasing/reconstruction issues
- Infinite resolution in amplitude
  - No quantitation noise
Digital Signal Processing (DSP) Advantages

- **Repeatability**
  - Low sensitivity to component tolerances
  - Low sensitivity to temperature changes
  - Low sensitivity to aging effects
    - Nearly identical performance from unit to unit
    - Matched circuits cost less

- **High noise immunity**

- **In many applications DSP offers higher performance and lower cost**
  - CD players versus phonographic turntable
Analog’s Place in DSP

- Most transducers are analog by nature
  - Microphones, speakers, etc.
- Analog circuits are required to pre-process low level signals before ADC
- Analog filters may be required to limit the bandwidth of signals
  - Anti-alias (before ADC) and reconstruction filters (after DAC)
- Analog circuits may be required to drive output transducers
  - A power amplifier is required to enable a DAC to drive a speaker
Signal Processing Applications

- **Speech processing**
  - Speech compression
  - Speech recognition
  - Speaker Identification, Verification
  - Speech synthesis
  - Speech enhancement, Echo cancellation

- **Audio Processing**
  - Compression
  - 3-D reproduction
DSP Applications – Image Processing

- **Image Processing**
  - Image compression
  - Pattern recognition
  - Ghost cancellation
  - Noise reduction
  - Deblurring
  - Object tracking
  - Image fusion

- **Video Processing/compression, tracking...**
DSP Applications Communications

- **MODEM**
  - correlators (matched filters)
  - echo cancellers
  - equalizers
- **Cellular Telephony**
  - speech compression
  - diversity combining
  - array processing
- **Software Radio**
End Equipments

- Telecom
  - T1 – E1 PABX
  - VoIP, VoATM, VoDSL
  - Access gateways
  - IP-Phones, Public phones
  - Vsat systems
  - Fiber Optic test equipments
  - Switches
  - ADSL, Modems, Fax
  - P.O.S.

- Voice over IP
  - Networking
  - Terminal
  - Modems

- Consumer
  - Multimedia Jukebox
  - Digital still camera
  - Internet Audio
  - Web phones
  - STB
  - Gaming
  - Alarm systems

- Audio
  - Video
  - Imaging
  - Internet appliances

- Emerging
  - Telematics, Hands-Free Kits
  - Fingerprint recognition
  - Tire pressure monitoring
  - Medical equipments
  - Power line comms, GPS
  - Access gate, Secured POS
  - E-commerce

- Automotive
  - Biometrics
  - Voice recognition

Over 500 million C5000 DSPs shipped in more than 1000 different applications

- Over 80% of VoIP Gateway market
- Used in 8 of top 10 wireless infrastructures Mfrs.
- Used in 7 of top 8 digital still Camera Mfrs.
- Used in 8 of top 10 internet consumer electronic Mfrs.
- D-Ins in 4 of top 5 European Hands – Free Kit mfrs.
- Over 30 D-Ins in Biometrics
Communications applications (i.e: wireless) Jumped from 68.3% in 2003 to 82% in 2005.

Expectations:
1) DSP market will increase by 9% in 2006
2) Followed by an 18% increase in 2007.
3) A boom of 27% in 2008
TI Extends World’s Most Popular DSP Platform

Power Efficiency/System Density

Code Compatible

In Silicon

Announcement

Roadmap

Feature Integration
C55x DSP

The Solution for Portable Applications

Power-Efficient, High-performance and Programmable Solutions for Hand-held Applications

C5510 and C5509

Software Libraries, Proven Development Environment, and EVMs Enable Rapid design of imaging and video applications and projects
DSP Targets: Cell Phone

- RF Receiver
- RF Codec
- Microprocessor Chip
- DSP Chip
- Voice Codec
- Cell Peripherals

Controlled by Power Management Unit

- Speech Coders
- Speech Recognition
- Equalizers
- Antenna noise cancellation
- Image enhancement techniques
DSP Targets: PORTABLE MEDIA DEVICES

Audio Coding
Speech Recognition
Image Compression
Image Enhancement
Portable Applications

- Embedded signal and image processing tasks are becoming more demanding
  - Wireless communications (e.g., 3G, UWB): higher data rates, more complex systems and air interfaces
  - Video processing (DTV, HDTV, Camcorders, 3DTV): compression, decompression, enhancement, superresolution, feature extraction
  - Still image processing: cameras, copiers, printers, image-based rendering
- High efficiency: 100s of MOPS/mW (GOPS/mW), 10s GOPS/$
- Programmability: multiple modes, evolving standards, evolving features
What is Special about Signal Processing Applications?

- Large number of samples being continuously fed to the system (samples or blocks).
- Repetitive Operations:
  - The same operation being applied to different set of samples
  - Parallel processing
- Vector and Matrix Operations
- Real time operations
The two most common real-time digital filters are:
- Finite Impulse Filter (FIR)
- Infinite Impulse Filter (IIR)

The basic FIR Filter equation is:

\[ y[n] = \sum_{k} h[k] \cdot x[n - k] \]

where \( h[k] \) is an array of constants.

In C language:

```c
y[n] = 0;
for (n=0; n<N; n++) {
    for (k = 0; k<N; k++)
        //inner loop
        y[n] = y[n] + h[k]*x[n-k];
}
```

Only Multiply and Accumulate (MAC) is needed!
MAC using General Purpose Processor (GPP)

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clr A</td>
<td>Clear Accumulator A</td>
</tr>
<tr>
<td>Clr B</td>
<td>Clear Accumulator B</td>
</tr>
<tr>
<td>Loop</td>
<td>Move data from memory location 1 to register Y0</td>
</tr>
<tr>
<td>Mov *R0,Y0</td>
<td>Move data from memory location 2 to register X0</td>
</tr>
<tr>
<td>Mpy X0,Y0,A</td>
<td>X0*Y0 -&gt; A</td>
</tr>
<tr>
<td>Add A,B</td>
<td>A + B -&gt; B</td>
</tr>
<tr>
<td>Inc R0</td>
<td>R0 + 1 -&gt; R0</td>
</tr>
<tr>
<td>Inc R1</td>
<td>R1 + 1 -&gt; R1</td>
</tr>
<tr>
<td>Dec N</td>
<td>Dec N (initially equals to 3)</td>
</tr>
<tr>
<td>Tst N</td>
<td>Test for the value</td>
</tr>
<tr>
<td>Jnz Loop</td>
<td>Different than zero loop again</td>
</tr>
<tr>
<td>Mov B,*R2</td>
<td>Move result to memory</td>
</tr>
</tbody>
</table>
MAC using DSP

<table>
<thead>
<tr>
<th>Instruction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clr A</td>
<td>; Clear Accumulator A</td>
</tr>
<tr>
<td>Rep N</td>
<td>; Rep N times the next instruction</td>
</tr>
<tr>
<td>MAC *(R0)+, *(R1)+, A</td>
<td>; Fetch the two memory locations pointed by R0 and R1, multiply them together and add the result to A, the final result is stored back in A</td>
</tr>
<tr>
<td>Mov A, +R2</td>
<td>; Move result to memory</td>
</tr>
</tbody>
</table>
DSP versus GPP

- Multiple parallel units
  - multiply accumulate (possibly several units)
  - address calculation in parallel to processing
  - barrel shifter

- Memory Access
  - special ALU for address calculation
  - Bit reversed addressing
  - circular addressing

- Automatic loops
  - Software looping: writing assembly code to perform branching
  - Hardware looping: dedicated hardware loop counter register

- Hardware support for managing arithmetic computation (in GPP it needs multiple cycles)
  - Shifters
  - Guard bits
  - Saturation

Preventing Overflow!!
Digital Signal Processor (DSP) - Overview

- **DSP Core includes:**
  - Address buses
  - Data buses
  - Data arithmetic logic unit (ALU)
  - Address generation unit (AGU)
  - Program controller
  - Bit-manipulation unit
  - Enhanced debugging module

- **Peripherals on chip**
  - Timer
  - serial link
  - communication links
    - DSP to DSP
    - Ethernet
    - ATM
  - host ports
  - input/output pins

- **Adaptation for FFT**
  - bit reverse addressing

- **Special instructions**
  - Parallel move support
  - Loop instructions; special hardware instructions (i.e.: FIR)
Enhancing DSP Architectures

- More parallelism
  - Increase the number of operations that can be performed in each instruction
    - Adding More Executing units (i.e: Multipliers)
  - Increase the number of instructions that can be issued and executed in every cycle
- Highly specialized hardware in core
- Co-processors
- Multi-Core DSPs
Example: TI OMAP Chip

- Integrates a TMS320C55x™ DSP core with an ARM GPP on a Single Chip
- Targeted for embedded applications
- ARM interfacing peripherals:
  - Bluetooth
  - IrDA
  - Keypad
  - Touch Screen
- C55x to perform DSP algorithms
  - Mobile Messaging
  - Handwriting Recognition
  - Digital Cameras Image processing
- OMAP 2 (released May 2005) Architecture includes a dedicated
  - Image and video accelerator
  - 3D graphics accelerator
Example: TI DaVinci Processors

- Released in Dec 2005.
- Also known as TMS320DM644x series.
- While OMAP targets mainly wireless and handled applications, DaVinci targets home entertainment, surveillance, and other video applications.
- Include camera and video interfaces.
Why Consider DSP Alternatives

- Wireless Systems requires more and more high performance and higher bandwidth

<table>
<thead>
<tr>
<th>Bit Rate</th>
<th>2G</th>
<th>2.5G</th>
<th>3G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>~100 MIPS</td>
<td>~10,000 MIPS</td>
<td>~100,000 MIPS</td>
</tr>
<tr>
<td></td>
<td>8-13 Kbps</td>
<td>64-384 Kbps</td>
<td>384-2000 Kbps</td>
</tr>
</tbody>
</table>

DSP performance might not be enough for future applications.
What are the alternatives

- High-performance GPPs with DSP enhancements.
  - Eliminating the need of a DSP and GPP for many products and thus reducing cost
  - Example: Pentium 4
    - Single Instruction Multiple Data (SIMD) instructions allowing identical operations on multiple pieces of data in parallel.
    - 144 new special instructions providing advanced capabilities for applications such as 3D graphics, video encoding/decoding, and speech recognition.
    - Several Data Types (floating/integer)

- Multi-Core DSPs

- Application Specific Integrated Circuits (ASIC)

- Field Programmable Gate Array (FPGA)
ASIC (application-specific integrated circuit)

- Uses hard-wired logic with varied architectures according to the application (i.e: 256 point hardware implemented FFT)
- Sometimes includes proprietary processor cores (i.e: licensed Intellectual Properties – IP)
ASIC - Advantages

- Speed
- Reduced Power Consumption
- Cost/performance
- Design Flexibility
ASIC - Disadvantage

- Large development costs
- Lengthy development cycles
- Inflexibility

Another Solution

FPGA
What is FPGA

- It is a network of reconfigurable hardware with reconfigurable interconnect controlled by a switching matrix
- Historically used for prototyping
- Recently includes DSP features
  - Major Companies DSP + FPGA: ALTERA (e.g.: Stratex) & XILINX (e.g.: Virtex II)
FPGA - Advantages

- More Flexible than ASIC
- Huge Performance Gain in Some Applications
- Re-use Hardware for different applications
FPGA - Disadvantages

- Long Development Cycle
- Expensive compared to DSP
- Much higher power consumption compared to DSP
- Slow time to market compared to DSP
Why Still use DSP?

- Several applications are not suited to be implemented in FPGA
  - Parallelism is sometimes inherently limited
  - Speed is not always the highest factor to consider
- FPGA is still very expensive for terminal products (i.e: cell phones)
Why Still use DSP?

- **Comparison: DSP, FPGA, ASIC** (ref: Bill Dally, Stanford University, IEEE ICASSP04 Talk)

  **DSP**
  - < 10 MOPS/mW
  - ~0.1 GOPS/$
  - < 10 GOPS peak performance
  - 1 M $ programming cost
  - Programmable

  **ASIC**
  - 50-200 MOPS/mW
  - 2-10 GOPS/$
  - Up to 1000 GOPS peak performance
  - 10M-15M $ design cost
  - Fixed

  **FPGA**
  - 2-10 MOPS/mW
  - ~1 GOPS/$
  - Up to 500 GOPS peak performance
  - ~5M $ design cost
  - Reconfigurable

- New improved DSPs with more efficiency and parallelism (e.g., multi-core)
Types of DSP

- **Low End Fixed Point**
  - TMS320C2XX, ADSP21XX, DSP56XXX

- **High End Fixed Point**
  - TMS320C55XX, DSP16XXX,
  - ADSP215XX, DSP56800

- **Floating Point**
  - TMS320C3X, C67XX, ADSP210XX, DSP96000, DSP32XX
Fixed Point Vs Floating Point

- Fixed Point/Floating Point
  - fixed point processor are:
    - cheaper
    - smaller
    - less power consuming
    - Harder to program
      - Watch for errors: truncation, overflow, rounding
    - Limited dynamic range
    - Used in 95% of consumer products
  - floating point processors
    - have larger accuracy
    - are much easier to program
    - can access larger memory
  - It is harder to create an efficient program in C on a fixed point processors than on floating point processors
## Fixed Point Vs Floating Point

### Floating Point Applications
- Modems
- Digital Subscriber Line (DSL)
- Wireless Basestations
- Central Office Switches
- Private Branch Exchange (PBX)
- Digital Imaging
- 3D Graphics
- Speech Recognition
- Voice over IP

### Fixed Point Applications
- Portable Products
- 2G, 2.5G and 3G Cell Phones
- Digital Audio Players
- Digital Still Cameras
- Electronic Books
- Voice Recognition
- GPS Receivers
- Headsets
- Biometrics
- Fingerprint Recognition
TI Families Summary

- C24x and C28x families: low performance 16-bit fixed point used for control purpose
- C54x family: mid-range performance 16-bit fixed point
- C55x family: mid-range performance 16-bit fixed point with reduced power consumption and increased parallelism
- C5000 + RISC microprocessor: used for embedded applications such as cell phone and PDAs
- C62x: high-range performance 16-bit fixed point supporting VLIW architecture
- C64x: very high performance 16-bit fixed point with extension capabilities of C62x with higher clock frequency (>2500 MIPS)
- C3x: first generation low performance 32-bit floating point
- C67xx family: very high performance 32-bit floating point