OUTLINE

- DSP applications
- DSP platforms
- The synthesis problem
- Models of computation

DIGITAL VS. ANALOG SIGNAL PROCESSING

- Digital signal processing (DSP) characterized by:
  - Time-discrete
    representation of signals: signals sampled at regular time intervals.
  - Quantized representation
    of signals: signal level is given by a finite number of bits.

APPLICATIONS OF DIGITAL SIGNAL PROCESSING

- Embedded digital signal processing is everywhere!
- Examples:
  - Speech
  - Audio
  - Video
  - Radio/wireless
  - Radar
  - Any application that processes signals in the digital domain.

TYPICAL ALGORITHMS

- Filtering: FIR, IIR, with fixed coefficients or adaptive
- Encoding/decoding
- Compression/decompression
- Frequency-domain processing
- Downconversion: shifting carrier frequency in communication
- Etc.
TYPICAL NUMBERS

- Speech: 8 kHz, 12-16 bits
- Audio: 44 kHz, 16-24 bits, two channels (stereo)
- Video, various formats, e.g.:
  - HDTV approx. 2000 by 1000 pixels at 50 frames per second resulting in data rates of 100 MHz, 3 colors of 8-12 bits each

REGISTER-TRANSFER (RT) VIEW OF HARDWARE

- Primary inputs
- Combinational logic
- Primary outputs
- New state
- Current state
- System clock
- Registers
- Register contents are updated at rising edge of system clock.

SAMPLE FREQUENCY VS. SYSTEM CLOCK FREQUENCY

- The ratio between the system clock frequency and the sample frequency determines the necessity for parallel processing.
- A single processor clocked at, say, 100 MHz may handle all audio processing on its own: it has thousands of clock cycles available per signal sample.
- Video processing may on the other hand require multiple processors and/or dedicated hardware.

STREAMING VS. BLOCK-BASED

- Streaming data:
  - Data samples are processed as they arrive
  - Requires little local storage
  - Time-domain processing
- Block-based processing:
  - Stores incoming data until some block size is filled
  - Processes entire block
  - Think e.g. of an FFT (Fast Fourier Transform) or DCT (Discrete Cosine Transform)
IMPLEMENTATION PLATFORMS (1)

- **General-purpose processor** (GPP), such as a Pentium
- **Digital signal processor** (DSP):
  - Much better suited (parallel arithmetic in data path, support for “multiply-accumulate” operation, Harvard architecture for parallel access to data and program memory, etc.)
- **Multicore GPPs or DSPs** (trend!)
- **Very large instruction word** (VLIW) processor:
  - Many parallel arithmetic units in data path, each controlled by appropriate bits in instruction word
- **Graphics processing unit** (GPU):
  - General purpose computation on GPUs (GPGPU)

IMPLEMENTATION PLATFORMS (2)

- Processor arrays:
  - Think of Montium processor tile as developed in the CAES group (starting from the early years 2000, continued by spin-off Recore Systems, now Technolution).
  - Often interconnected by a network on chip (NoC), an interconnection structure somewhat comparable to data networks connecting computers (may be circuit switched or packet switched).
- User-defined architectures:
  - ASIPs (application-specific instruction processors)
- Dedicated logic:
  - ASICs (application-specific integrated circuits)
  - FPGAs (field-programmable gate arrays)

MAPPING PROBLEM

- How do we get the most efficient implementations of DSP algorithms on our platforms?
- Optimization criteria:
  - Fastest
  - Smallest
  - Minimal energy
  - Shortest design time
- In general, **flexibility comes at the expense of efficiency**:
  - In view of the costs of manufacturing ASICs, programmable hardware is often very desirable.

HIERARCHY AND OPTIMIZATION

- Design choices at higher hierarchical levels have the most impact:
  - Modifying your algorithm (e.g. getting rid of some computation in the inner loop) is often better than modifying your architecture (e.g. adding more arithmetic units).
  - Modifying your architecture (e.g. distributed memory instead of central memory) can be better than logic-level modifications (replacing ripple adders by carry look-ahead adders).
  - There is still place for dedicated logic for signal processing (e.g. phasor rotation).
AUTOMATED MAPPING

- Already familiar with register-transfer level (RTL) synthesis (clock-cycle true descriptions in VHDL mapped on cells from standard-cell library, see e.g. System-on-Chip Design course)
- Architectural synthesis (also called high-level synthesis, HLS) will automatically decide about the mapping of computations across clock cycles and architectural primitives.
  - Requires a formal representation of computations
  - And a formal representation of architectures

SILICON COMPILATION

- RTL synthesis is a mature technology:
  - All current-day digital IC design and FPGA design makes use of it.
  - Most RTL is hand-coded (in VHDL, Verilog)
  - HLS delivers machine-generated RTL.
- HLS is being talked about since the 1980s, tools exist, but they are not widely adopted.
  - To be covered later on in this course.
- HLS was also called silicon compilation (no longer popular):
  - A software (SW) compiler hides assembly-level details from the user.
  - A silicon compiler should hide RT-level details from the hardware designer.
- Next: SW compilation for DSP.

SW COMPILATION PROBLEM (1)

- When mapping on given programmable hardware, one talks of compilation rather than synthesis.
- Commercial processors often come with their own compilers.
- Designing an ASIP requires both:
  - The design of the hardware, and
  - The design of a compiler to map user programs onto the hardware.
- Compiling for DSPs, VLIW processors, etc. is more difficult than compiling for CPUs:
  - The challenge is how to optimally use the available parallel hardware,
  - Especially when the source code is sequential.

SW COMPILATION PROBLEM (2)

- Approaches:
  - Leave all to the compiler. This means that it is left to the compiler to discover the available parallelism in sequential code like C.
  - Language extensions. Extend a language like C with constructs (pragmas etc.) that explicitly describe parallelism. Use the information to optimally exploit parallelism in target hardware.
  - Extensions with APIs (application programming interface). Have a library of routines that optimally exploit the parallel hardware and force user to use these APIs.
MULTICORE PROGRAMMING

- Often based on threads, sequential pieces of code that run on a single processor.
- Parallel computing amounts to distributing threads across the available processors.
- Communication and synchronization is based on:
  - Shared memory
  - Message passing

OPENMP

- OpenMP (open multi-processing):
  - Language extension with annotations for C/C++/Fortran
  - Supported by GCC
- Example: for loop will be split in multiple threads executing on multiple cores

Question: why is the code easy to be executed in parallel?

GOALS OF MODELING

- Verification by simulation:
  - mostly executed on one CPU;
  - should provide the relevant degree of accuracy.
- Models are also used for formal verification.
- Synthesis; maps model on a realization consisting of:
  - a single processor (general purpose/digital signal processor);
  - multiple processors;
  - dedicated hardware;
  - a mixture of dedicated hardware and processors.

MODELING OF TIME

- Continuous time:
  - solve differential equations for analog simulation.
- Discrete time:
  - delay from input to output of hardware blocks;
  - clock signals may be involved (register-transfer level, RTL);
  - event-driven simulation may be used.
- Untimed:
  - no delay inside hardware blocks;
  - timing controlled by external signals and flow-control blocks such as FIFO (first-in first-out) buffers.
MODELING OF SIGNALS

- Analog values:
  - voltages, currents;
  - floating-point data types.

- Digital values:
  - bits and bit vectors;
  - bit vectors need an interpretation: e.g. unsigned, 2’s complement signed, fixed-point or floating-point numbers.

- More complex data types: e.g. records.

“CLASSICAL” SIMULATION

- Based on simple generation of stimuli and designer inspection of waveforms or text output for determination of correctness.
- It is quite common to base stimuli generation and output registration on data streams read from and written to a file.

SHORTCOMINGS OF CLASSICAL SIMULATION

- There is only one design, the “implementation”. The “reference” is in designer’s and verification engineer’s mind.
  - Good idea to have separate verification engineer, for a “second opinion” on the interpretation of specification.
- DUV is at RT level and becomes available in a late stage of the design:
  - Software development cannot start easily in time; verification with software will delay the tape-out.
  - RTL code is slow to simulate; it is only feasible to simulate small software programs.

TRANSACTION-LEVEL MODELING

- Abstract way of looking at hardware:
  - I/O signals not at the bit level, but as abstract data structures
  - Behavior specified in terms of transactions
  - In general, not clock-cycle accurate
- Example:
  - “Write to memory” is a transaction; its implementation will involve preparing data, address and control signals with the required timing relations.
- Transactors translate transactions to bit-level signal changes and back.
FEATURES OF ADVANCED SIMULATION

- **Self-checking** testbenches: waveform inspection only for debugging.
- Transaction-level “golden reference design” built into testbench.
- Golden reference design, being not clock-cycle accurate, executes much faster and can be used for software verification at an early stage.
- Stimuli generation makes use of *constrained random pattern generation* to increase code coverage.
- Transactors evolve together with RT-level implementation.
- Assertions are extensively exploited.

ADVANCED TESTBENCH STRUCTURE

- **Testbench**
  - (Constrained random) stimuli generator
  - Golden reference at transaction level
  - Output comparison
  - High-to-low transactor
  - Low-to-high transactor
  - DUV at RT level

SNEAK PREVIEW: GFSK PROJECT

- DUV = design under verification
- TVC = test-vector controller; TB = testbench

COMPUTATION AND COMMUNICATION

- The issue is the modeling of *parallelism* present in hardware. A system consists of:
  - entities computing output signals from input signals.
  - a structure interconnecting the entities.
- Interconnection may be *direct* or *buffered*. 
KAHN PROCESS NETWORK (KPN)

- Network of entities (nodes) interconnected by FIFO buffers.
  - Reads are blocking, i.e. a computation waits until there is data available to read.
  - Writes are non-blocking, i.e. writes are always allowed implying that the FIFO buffers have unbounded depths.
- The behavior of the nodes can be given in a traditional sequential programming language.

EXAMPLE OF A KPN ADDER NODE

```
read(a);
read(b);
c = a + b;
write(c);
```

The addition can only be executed when input data are available; otherwise, the operation waits.

DATA-FLOW BASICS

- A data-flow graph (DFG) consists of nodes (vertices) and edges.
- In its most general form, a DFG is equivalent to a KPN.
- Nodes perform computations.
- Edges indicate precedence relations and behave as FIFOs.
- Data flow is best understood in terms of tokens, carriers of data.
- A node will fire when a sufficient number of tokens is available on all its inputs.
- The result of firing is that tokens are consumed at the inputs and tokens are produced at the outputs.

TOKEN FLOW EXAMPLE:

\[ R = \sqrt{a^2 + b^2} \]
SYNCHRONOUS DATA FLOW (SDF)

- Characterized by fixed consumption and production numbers for each node invocation.
- Suitable for the specification of multi-rate DSP algorithms.

CONSISTENCY IN SDF

- It is relatively easy to check whether:
  - No deadlock occurs;
  - Number of tokens on an edge does not grow indefinitely;
  - There are sufficient initial tokens to keep loops going.
- A consistent graph:
  - Has a repetitions vector indicating how often a node needs to be invoked for one computation of the graph;
  - Can be scheduled statically, without the need to implement FIFO buffers for the edges.

SOFTWARE SYNTHESIS

- Example graph:
  ```
  A 1 3
  B 2
  C 3
  D 2
  ```
  Rep. vector: (3) (1) (2) (3)

  - Possible single-processor schedule: (3A)B(2C)(3D)

DATA-FLOW GRAPH EXAMPLE

- Second-order IIR filter
- \( T_0 = \text{delay element} \)
- \( T_0 = \text{edge with one initial token} \)
DIY: DFG FOR MOVING AVERAGING

Simplify to 4-day moving average

DFG FOR MOVING AVERAGING (1)

\[ x[n] \xrightarrow{T_0} y[n] \]

Conclusion: for one and the same problem, one can have multiple data-flow graphs with a varying degree of parallelism.

HIERARCHICAL DFGS

- Nodes in a DFG do not need to be atomic (indivisible computations) but could be expanded into DFGs themselves.
- In this way, one gets hierarchical DFGs.
- Nodes that do not have subgraphs are called primitive.
GRAPHICAL VS. TEXTUAL FORMATS

- It is obvious that DFGs are very suitable as an internal representation format of a synthesis tool.
- DFGs are, however, not always the most suitable format for a designer to specify a computation; one does not want to draw separate addition nodes for each addition and interconnect these nodes.
- The solution is to start with a textual representation and convert it to a DFG by means of data-flow extraction.
- Graphical-entry tools are mainly useful for specifying complex computations with hierarchy; primitive nodes (that do not have subnodes) are normally specified in a textual format.