Embedded Systems
SDF Compiler

Task for an SDF compiler:

- Allocation of memory for the passing of data between nodes
- Scheduling of nodes onto processors in such a way that data is available for a block when it is invoked

Assumptions on the SDF graph:

- The SDF graph is nonterminating and does not deadlock
- The SDF graph is connected

Goal:

- Development of a periodic admissible parallel schedule (PAPS)
- or a periodic admissible sequential schedule (PASS)

(admissible = correct schedule, finite amount of memory required)
Assumption: Block 1: 1 time unit
Block 2: 2 time units
Block 3: 3 time units

Trivial Case - All computations are scheduled on same processor
The performance can be improved, if a schedule is constructed that exploits the potential parallelism in the SDF-graph. Here the schedule covers one single period.
The performance can be further improved, if the schedule is constructed over two periods.
Scheduling Choices

- SDF Scheduling Theorem guarantees a schedule will be found if it exists

- Systems often have many possible schedules

- How can we use this flexibility?
  - Reduced code size
  - Reduced buffer sizes
Looped Code Generation

- Obvious improvement: use loops

- Rewrite the schedule in “looped” form:
  
  $(3 \text{ B}) \ C \ (4 \text{ D}) \ (2 \text{ A})$

- Generated code becomes

  ```
  for ( i = 0 ; i < 3; i++) B;
  for ( i = 0 ; i < 4 ; i++) D;
  for ( i = 0 ; i < 2 ; i++) A;
  ```
The SDF model is very useful for regular DSP applications.

Used for: simulation, scheduling, memory allocation, code generation for Digital Signal Processors (HW and SW).

There is a mathematical framework to calculate a PASS or a PAPS and to determine the maximum size of buffers, if a PASS/PAPS exists.

The work on SDF can be used to derive single and multiple processor implementations.
# Selected Models of computation

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<th>Communication/local computations</th>
<th>Shared memory</th>
<th>Message passing</th>
<th>C/E nets, P/T nets, …</th>
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* Classification based on the implementation of HDLs
Models vs. languages

- How can we (precisely) capture behavior?
  - We may think of languages (C, C++), but *computation model is the key*

- Computation models *describe system behavior*
  - Conceptual notion, e.g., recipe, sequential program

- Languages *capture models*
  - Concrete form, e.g., English, C
Models vs. languages

- Variety of languages can capture one model
  - E.g., sequential program model $\rightarrow$ C, C++, Java

- One language can capture variety of models
  - E.g., C++ $\rightarrow$ sequential program model, object-oriented model, state machine model

- Certain languages better at capturing certain computation models

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**Recipe**
- Spanish
- English
- Japanese

**Sequent. program**
- C
- C++
- Java

**Poetry**
- English
- Spanish
- Japanese
Architecture Design – Models
Task graphs or dependency graph (DG)

- **Def.:** A dependence graph is a directed graph \( G=(V,E) \) in which \( E \subseteq V \times V \) is a partial order.

- If \((v1, v2) \in E\), then \(v1\) is called an immediate predecessor of \(v2\) and \(v2\) is called an immediate successor of \(v1\).

Nodes are assumed to be a „program“ described in some programming language, e.g. C or Java.
A dependence graph describes order relations for the execution of single operations or tasks. Nodes correspond to tasks or operations, edges correspond to relations ("executed after").

Usually, a dependence graph describes a partial ordering between operations and therefore, leaves freedom for scheduling (parallel or sequential). It represents parallelism in a program but no branches in control flow.

A dependence graph is acyclic.

Often, there are additional quantities associated to edges or nodes such as
- execution times, deadlines, arrival times
- communication demand
Single Assignment Form

Basic block

\[
\begin{align*}
x &= a + b; \\
y &= c - d; \\
z &= x \times y; \\
y1 &= b + d;
\end{align*}
\]

Single assignment form

dependence graph

\[
\begin{align*}
a &\rightarrow b \\
c &\rightarrow d \\
x &\rightarrow + \\
y &\rightarrow - \\
z &\rightarrow * \\
y1 &\rightarrow +
\end{align*}
\]

sequential program $\rightarrow$ optimized hardware
Control-Data Flow Graph (CDFG)

- **Goal:**
  - Description of control structures (for example branches) and data dependencies.

- **Applications:**
  - Describing the semantics of programming languages.
  - Internal representation in compilers for hardware and software.

- **Representation:**
  - Combination of control flow (sequential state machine) and dependence representation.
  - Many variants exist.
a) VHDL-Code:

```vhdl
... s := k; --1
LOOP
  EXIT WHEN k>9; --2
  IF (ok = TRUE) --3
    j:=j+1; --4
  ELSE
    j:= 0; --5
    ok:= TRUE; --6
  END IF;
  k:=k+1; --7
END LOOP;
r := j; --8
...
```

b) CDFG:

- DFG:
  - CFG
  - DFGs
  - NOP
  - s := t
  - k>9
  - k<=9
  - ok = TRUE
  - ok = FALSE

- PFG

- FSM
Sequence graph

- Hierarchy of chained units
  - units model data flow
  - hierarchy models control flow
- Special nodes
  - start/end nodes: NOP (no operation)
  - branch nodes (BR)
  - iteration nodes (LOOP)
  - module call nodes (CALL)
- Attributes
  - nodes: computation times, cost, ...
  - edges: conditions for branches and iterations
**Sequence Graph (SG)**

**Unit**

\[
\begin{align*}
w &= a + b; \\
x &= w * c; \\
y &= b * b; \\
z &= w - c;
\end{align*}
\]

**Branch**

\[
\begin{align*}
c &= a < b; \\
\text{IF } (c) \text{ THEN} \\
p &= m + n; \\
q &= m * n; \\
\text{ENDIF}
\end{align*}
\]

\[x = a - b;\]

**Loop**

\[
\begin{align*}
d &= 2*x; \\
\text{WHILE } (d < 5) \text{ DO} \\
&\quad \text{write}(d); \\
&\quad d = d + 1; \\
\text{ENDWHILE}
\end{align*}
\]

**Call**

\[
\begin{align*}
d &= x - y; \\
e &= d * x; \\
\text{sub}(x, y); \\
... \\
\text{PROCEDURE } \text{sub } (m,n) \\
p &= m + n; \\
q &= m * n; \\
\text{END } \text{sub}
\end{align*}
\]
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* Classification based on implementation
Hardware/System description languages

- **VDHL**
  - **VHDL-AMS**

- **SystemC**
  - **TLM**
Discrete event semantics

- Basic discrete event (DE) semantics
  - Queue of future actions, sorted by time
  - Loop:
    - Fetch next entry from queue
    - Perform function as listed in entry
      - May include generation of new entries
  - Until termination criterion = true

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<th>Queue</th>
<th>Time</th>
<th>Action</th>
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<tr>
<td>5</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>15</td>
<td>19</td>
<td></td>
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<tr>
<td></td>
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- Example:
  - a := 5
  - b := 7
  - c := 8
  - a := 6
  - a := 9
  - a := 10

REVIEW
Methods for executing algorithms

**Hardware (Application Specific Integrated Circuits)**

**Advantages:**
- very high performance and efficient

**Disadvantages:**
- not flexible (can’t be altered after fabrication)
- expensive

**Reconfigurable computing**

**Advantages:**
- fills the gap between hardware and software
- much higher performance than software
- higher level of flexibility than hardware

**Software-programmed processors**

**Advantages:**
- software is very flexible to change

**Disadvantages:**
- performance can suffer if clock is not fast
- fixed instruction set by hardware

REWVIEW
Basic Design Methodology

1. **Requirements**
2. **RTL Model**
   - Simulate
3. **Gate-level Model**
   - Synthesize
   - Simulate
4. **Timing Model**
   - Place & Route
   - Simulate
5. **ASIC or FPGA**
6. **Test Bench**
   - Simulate
   - Review
HDLs using discrete event (DE) semantics

- Used in hardware description languages (HDLs):
  - Description of concurrency is a must for HW description languages!
    - Many HW components are operating concurrently
    - Typically mapped to “processes“
    - These processes communicate via “signals“
  - Examples:
    - MIMOLA [Zimmermann/Marwedel], ~1975
    - …
    - VHDL (very prominent example in DE modeling)
      One of the 3 most important HDLs:
      VHDL, Verilog, SystemC
VHDL

- HDL = hardware description language
- VHDL = VHSIC hardware description language
- VHSIC = very high speed integrated circuit
  - Consortium which developed VHDL (Intermetrics Inc., IBM, Texas Instruments)
  - Early 80’s, initiated by US Department of Defense
- Modeling of digital circuits
- 1987 IEEE Standard 1076

Standard in (European) industry

- Extension: VHDL-AMS, includes analog modeling
VHDL

- Main goal was modeling of digital circuits
  - Modelling at various levels of abstraction
  - Technology-independent
  - Re-Usability of specifications
VHDL

- Standard
  Portability (different synthesis and analysis tools possible)

- Validation of designs based on the same description language for different levels of abstraction

- **Powerful** description language
Modeling Digital Systems

- Reasons for modeling
  - requirements specification
  - documentation
  - testing using simulation
  - formal verification
  - synthesis

- Goal
  - most reliable design process, with minimum cost and time
  - avoid design errors!
A higher level architecture instantiates lower level entities.
Abstraction

- Abstraction is hiding of details:
  Differentiation between essential and nonessential information

- Creation of abstraction levels:
  On every abstraction level only the essential information is considered, nonessential information is left out
Abstraction Levels

System specification, models of standard assemblies
ASIC/FPGA synthesis synthesizable models
Gate level PLD development
Full custom design

Algorithmic level
Modelling of bus systems, Stimuli
Machine independent description
Registers, logic, clock
Netlists, gate structure
Technology dependent (e.g. CMOS 0.35 µm)

Example

\[ o = f(n) \]

\[ o \leq transport \, I_1 + I_2 \cdot I_3 \text{ after 100 ns}; \]
VHDL

• Disadvantages:
  – A change of culture
    • Away from Schematic-based Design
    • towards Language-based Design

"We don't know if to 'harden' a Software engineer or to 'soften' a Hardware engineer",

– Cost of getting started
  • Selecting and paying for tools
Things to Remember

• **VHDL is a programming language**
  – Many good and bad programs have been (will be) written
  – Contains also many aspects of imperative programming languages
    VHDL is able to describe software, too.

• **Functionality is important BUT not enough!**
  – Style is important (“VHDL cookbook”)
  – Clarity is important

• **Synthesis is hard**

• **Decomposition of a large design into smaller, understandable sub-parts is essential**
Y-Chart

- 3 design views
  - Behavior (functionality)
  - Structure (netlist)
  - Physical (layout)

- 5 abstraction levels
• Basic VHDL
• Structural VHDL
• Behavioral VHDL
• VHDL-AMS

**ES course:** Only some aspects of VHDL, not complete language.
• Basic VHDL
Module Outline

- VHDL Design Example
- VHDL Model Components
  - Entity Declarations
  - Architecture Descriptions
- Basic VHDL Constructs
  - Data types
  - Objects
  - Sequential and concurrent statements
  - Packages and libraries
  - Attributes
  - Predefined operators
- Summary
Entities and architectures

- In VHDL, HW components correspond to “entities”
- Entities comprise processes
- Each design unit is called an entity.
- Entities are comprised of entity declarations and one or several architectures.

Each architecture includes a model of the entity. By default, the most recently analyzed architecture is used. The use of another architecture can be requested in a configuration.
Problem: Design a single bit half adder with carry and enable

Specifications
- Inputs and outputs are each one bit
- When enable is high, result gets \( x + y \)
- When enable is high, carry gets any carry of \( x + y \)
- Outputs are zero when enable input is low
As a first step, the entity declaration describes the interface of the component:

- input and output ports are declared.
A high level description can be used to describe the function of the adder.

The model can then be simulated to verify correct functionality of the component.
A second method is to use logic equations to develop a data flow description.

```
ARCHITECTURE half_adder_b OF half_adder IS
BEGIN
    carry <= enable AND (x AND y);
    result <= enable AND (x XOR y);
END half_adder_b;
```

Again, the model can be simulated at this level to confirm the logic equations.
VHDL Design Example
Structural Specification

- As a third method, a structural description can be created from predefined components. These gates can be pulled from a library of parts.
ARCHITECTURE half_adder_c OF half_adder IS

COMPONENT and2
  PORT (in0, in1 : IN BIT;
       out0 : OUT BIT);
END COMPONENT;

COMPONENT and3
  PORT (in0, in1, in2 : IN BIT;
       out0 : OUT BIT);
END COMPONENT;

COMPONENT xor2
  PORT (in0, in1 : IN BIT;
       out0 : OUT BIT);
END COMPONENT;

FOR ALL : and2 USE ENTITY gate_lib.and2_Nty(and2_a);
FOR ALL : and3 USE ENTITY gate_lib.and3_Nty(and3_a);
FOR ALL : xor2 USE ENTITY gate_lib.xor2_Nty(xor2_a);

-- description is continued on next slide
-- continuing half_adder_c description

SIGNAL xor_res : BIT; -- internal signal
   -- Note that other signals are already declared in entity

BEGIN

   A0 : and2 PORT MAP (enable, xor_res, result);
   A1 : and3 PORT MAP (x, y, enable, carry);
   X0 : xor2 PORT MAP (x, y, xor_res);

END half_adder_c;

body of the architecture shows the component *instantiations* and how they are interconnected to each other and the outside world via the attaching of signals in their PORT MAPs.
The **entity** represents the interface specification (I/O) of the component. It defines the components external view, sometimes referred to as its "pins".
Putting It All Together

**Generics**

- provide a method to communicate static information to an architecture from the external environment
- are passed through the entity construct

**Packages**

- are used to provide a collection of common declarations, constants, and/or subprograms to entities and architectures

**Ports**

- provide the mechanism for a device to communicate with its environment

**Entity**

- **Generics**
- **Ports**

**Architectures**

- **Concurrency Statements**

**Process**

- **Sequential Statements**
architecture is the behavioral description in which the functional and possibly timing characteristics are described using VHDL concurrent statements and processes. The process is a concurrent statement of an architecture.

architecture, containing only concurrent statements, is commonly referred to as a dataflow description. Concurrent statements execute when data is available on their inputs.

architecture describes the structure of the design in terms of its sub-components and their interconnections.
Simulation Cycle
Sequential vs Concurrent Statements

- VHDL is inherently a concurrent language
  - All VHDL processes execute concurrently
  - Concurrent signal assignment statements are actually one-line processes

- VHDL statements execute sequentially within a process

- Concurrent processes with sequential execution within a process offers maximum flexibility
  - Supports various levels of abstraction
  - Supports modeling of concurrent and sequential events as observed in real systems
Concurrent Statements

- Basic granularity of concurrency is the process
  - Processes are executed concurrently
  - Concurrent signal assignment statements are one-line processes

- Mechanism for achieving concurrency:
  - Processes communicate with each other via signals
  - Signal assignments require delay before new value is assumed
  - Simulation time advances when all active processes complete
  - Effect is concurrent processing
    - i.e. order in which processes are actually executed by simulator does not affect behavior
Delta Delay

- Default signal assignment propagation delay if no delay is explicitly prescribed
  - VHDL signal assignments do not take place immediately
  - Delta is an infinitesimal VHDL time unit so that all signal assignments can result in signals assuming their values at a future time.
  - E.g.

```
Output <= NOT Input;
-- Output assumes new value in one delta cycle
```

- Supports a model of concurrent VHDL process execution
- Order in which processes are executed by simulator does not affect simulation output
1) all active processes can execute in the same simulation cycle

2) each active process will suspend at wait statement (sensitive list → process finish)

3) when all processes are suspended simulation is advanced the minimum time necessary so that some signals can take on their new values

4) processes then determine if the new signal values satisfy the conditions to proceed from the wait statement at which they are suspended

5) all processes are suspended and no signal update:

\[ t_n \rightarrow t_{n+1} \quad \text{(new entries in the event queue)} \]