ARM Processor Architecture

Adopted from National Chiao-Tung University
IP Core Design
Outline

- ARM Processor Core
- Memory Hierarchy
- Software Development
- Summary
ARM Processor Core
3-Stage Pipeline ARM Organization

- **Register Bank**
  - 2 read ports, 1 write ports, access any register
  - 1 additional read port, 1 additional write port for r15 (PC)

- **Barrel Shifter**
  - Shift or rotate the operand by any number of bits

- **ALU**

- **Address register and incrementer**

- **Data Registers**
  - Hold data passing to and from memory

- **Instruction Decoder and Control**
3-Stage Pipeline (1/2)

Fetch
- The instruction is fetched from memory and placed in the instruction pipeline

Decode
- The instruction is decoded and the datapath control signals prepared for the next cycle

Execute
- The register bank is read, an operand shifted, the ALU result generated and written back into destination register
3-Stage Pipeline (2/2)

- At any time slice, 3 different instructions may occupy each of these stages, so the hardware in each stage has to be capable of independent operations.

- When the processor is executing data processing instructions, the latency = 3 cycles and the throughput = 1 instruction/cycle.
Multi-Cycle Instruction

- Memory access (fetch, data transfer) in every cycle
- Datapath used in every cycle (execute, address calculation, data transfer)
- Decode logic generates the control signals for the data path use in next cycle (decode, address calculation)
Data Processing Instruction

- All operations take place in a single clock cycle

(a) register - register operations

(b) register - immediate operations
Data Transfer Instructions

- Computes a memory address similar to a data processing instruction
- Load instruction follows a similar pattern except that the data from memory only gets as far as the ‘data in’ register on the 2nd cycle and a 3rd cycle is needed to transfer the data from there to the destination register
Branch Instructions

- The third cycle, which is required to complete the pipeline refilling, is also used to mark the small correction to the value stored in the link register in order that it points directly at the instruction which follows the branch.
## Branch Pipeline Example

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Operation</th>
<th>Address</th>
<th>Fetch</th>
<th>Decode</th>
<th>Execute</th>
<th>Linkret</th>
<th>Adjust</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BL</td>
<td>0x8000</td>
<td>fetch</td>
<td>decode</td>
<td>execute</td>
<td>linkret</td>
<td>adjust</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>0x8004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>XX</td>
<td>0x8008</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>ADD</td>
<td>0x8FEC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>SUB</td>
<td>0xFFE0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>MOV</td>
<td>0xFFE4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Breaking the pipeline
- Note that the core is executing in the ARM state
5-Stage Pipeline ARM Organization

- \( T_{\text{prog}} = N_{\text{inst}} \times CPI / f_{\text{clk}} \)
  - \( T_{\text{prog}} \): the time that executes a given program
  - \( N_{\text{inst}} \): the number of ARM instructions executed in the program => compiler dependent
  - CPI: average number of clock cycles per instructions => hazard causes pipeline stalls
  - \( f_{\text{clk}} \): frequency

- Separate instruction and data memories => 5 stage pipeline

- Used in ARM9TDMI
5-Stage Pipeline Organization (1/2)

- **Fetch**
  - The instruction is fetched from memory and placed in the instruction pipeline.

- **Decode**
  - The instruction is decoded and register operands read from the register files. There are 3 operand read ports in the register file so most ARM instructions can source all their operands in one cycle.

- **Execute**
  - An operand is shifted and the ALU result generated. If the instruction is a load or store, the memory address is computed in the ALU.
5-Stage Pipeline Organization (2/2)

- **Buffer/Data**
  - Data memory is accessed if required. Otherwise the ALU result is simply buffered for one cycle.

- **Write back**
  - The result generated by the instruction are written back to the register file, including any data loaded from memory.
Pipeline Hazards

- There are situations, called hazards, that prevent the next instruction in the instruction stream from being executing during its designated clock cycle. Hazards reduce the performance from the ideal speedup gained by pipelining.

- There are three classes of hazards:
  - **Structural Hazards**
    - They arise from resource conflicts when the hardware cannot support all possible combinations of instructions in simultaneous overlapped execution.
  - **Data Hazards**
    - They arise when an instruction depends on the result of a previous instruction in a way that is exposed by the overlapping of instructions in the pipeline.
  - **Control Hazards**
    - They arise from the pipelining of branches and other instructions that change the PC.
Structural Hazards

- When a machine is pipelined, the overlapped execution of instructions requires pipelining of functional units and duplication of resources to allow all possible combinations of instructions in the pipeline.

- If some combination of instructions cannot be accommodated because of a resource conflict, the machine is said to have a structural hazard.
A machine has shared a **single-memory** pipeline for data and instructions. As a result, when an instruction contains a data-memory reference (load), it will conflict with the instruction reference for a later instruction (instr 3):

<table>
<thead>
<tr>
<th>Clock cycle number</th>
<th>instr</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>load</td>
<td>IF</td>
<td>ID</td>
<td>EX</td>
<td><strong>MEM</strong></td>
<td>WB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Instr 1</td>
<td>IF</td>
<td>ID</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Instr 2</td>
<td>IF</td>
<td>ID</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Instr 3</td>
<td>IF</td>
<td>ID</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Solution (1/2)

- To resolve this, we *stall* the pipeline for one clock cycle when a data-memory access occurs. The effect of the stall is actually to occupy the resources for that instruction slot. The following table shows how the stalls are actually implemented.

<table>
<thead>
<tr>
<th>Clock cycle number</th>
</tr>
</thead>
<tbody>
<tr>
<td>instr</td>
</tr>
<tr>
<td>load</td>
</tr>
<tr>
<td>Instr 1</td>
</tr>
<tr>
<td>Instr 2</td>
</tr>
<tr>
<td>Instr 3</td>
</tr>
</tbody>
</table>
Another solution is to use separate instruction and data memories.

ARM belongs to the Harvard architecture, so it does not suffer from this hazard.
Data Hazards

Data hazards occur when the pipeline changes the order of read/write accesses to operands so that the order differs from the order seen by sequentially executing instructions on the unpipelined machine.

<table>
<thead>
<tr>
<th>Clock cycle number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD</td>
<td>R1,R2,R3</td>
<td>IF</td>
<td>ID</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUB</td>
<td>R4,R5,R1</td>
<td>IF</td>
<td>ID_{sub}</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AND</td>
<td>R6,R1,R7</td>
<td>IF</td>
<td>ID_{and}</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OR</td>
<td>R8,R1,R9</td>
<td>IF</td>
<td>ID_{or}</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XOR</td>
<td>R10,R1,R11</td>
<td>IF</td>
<td>ID_{xor}</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The problem with data hazards, introduced by this sequence of instructions can be solved with a simple hardware technique called **forwarding**.
Forwarding works as follows:

- The ALU result from the EX/MEM register is always **fed back** to the ALU input latches.
- If the forwarding hardware detects that the previous ALU operation has written the register corresponding to the source for the current ALU operation, **control logic** selects the forwarded result as the ALU input rather than the value read from the register file.
Forward Data

The first forwarding is for value of $R1$ from $EX_{add}$ to $EX_{sub}$. The second forwarding is also for value of $R1$ from $MEM_{add}$ to $EX_{and}$. This code now can be executed without stalls.

Forwarding can be generalized to include passing the result directly to the functional unit that requires it: a result is forwarded from the output of one unit to the input of another, rather than just from the result of a unit to the input of the same unit.

<table>
<thead>
<tr>
<th></th>
<th>Clock cycle number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>ADD</td>
<td>R1,R2,R3</td>
</tr>
<tr>
<td>SUB</td>
<td>R4,R5,R1</td>
</tr>
<tr>
<td>AND</td>
<td>R6,R1,R7</td>
</tr>
</tbody>
</table>
Without Forward

<table>
<thead>
<tr>
<th>Instruction</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD</td>
<td>R1,R2,R3</td>
<td>IF</td>
<td>ID</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUB</td>
<td>R4,R5,R1</td>
<td>IF</td>
<td></td>
<td>stall</td>
<td>stall</td>
<td>ID$_{sub}$</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
</tr>
<tr>
<td>AND</td>
<td>R6,R1,R7</td>
<td></td>
<td>stall</td>
<td>stall</td>
<td>IF</td>
<td>ID$_{and}$</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
</tr>
</tbody>
</table>
Data Forwarding

- Data dependency arises when an instruction needs to use the result of one of its predecessors before the result has returned to the register file => pipeline hazards
- Forwarding paths allow results to be passed between stages as soon as they are available
- 5-stage pipeline requires each of the three source operands to be forwarded from any of the intermediate result registers
- Still one load stall

```asm
LDR rN, [...]  
ADD r2,r1,rN ;use rN immediately  
  One stall  
  Compiler rescheduling
```
## Stalls are Required

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDR</td>
<td>R1,@(R2)</td>
<td>IF</td>
<td>ID</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUB</td>
<td>R4,R1,R5</td>
<td>IF</td>
<td>ID</td>
<td>EX&lt;sub&gt;sub&lt;/sub&gt;</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AND</td>
<td>R6,R1,R7</td>
<td>IF</td>
<td>ID</td>
<td>EX&lt;sub&gt;and&lt;/sub&gt;</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OR</td>
<td>R8,R1,R9</td>
<td>IF</td>
<td>ID</td>
<td>EXE</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The load instruction has a delay or latency that cannot be eliminated by forwarding alone.
The Pipeline with one Stall

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDR</td>
<td>R1,@(R2)</td>
<td>IF</td>
<td>ID</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUB</td>
<td>R4,R1,R5</td>
<td>IF</td>
<td>ID</td>
<td>stall</td>
<td>EXsub</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AND</td>
<td>R6,R1,R7</td>
<td>IF</td>
<td>stall</td>
<td>ID</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OR</td>
<td>R8,R1,R9</td>
<td>stall</td>
<td>IF</td>
<td>ID</td>
<td>EX</td>
<td>MEM</td>
<td>WB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The only necessary forwarding is done for R1 from `MEM` to `EXsub`.
LDR Interlock

<table>
<thead>
<tr>
<th>Cycle</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADD R1, R1, R2</td>
<td>F</td>
<td>D</td>
<td>E</td>
<td>W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUB R3, R4, R1</td>
<td>F</td>
<td>D</td>
<td>E</td>
<td>W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDR R4, [R7]</td>
<td>F</td>
<td>D</td>
<td>E</td>
<td>M</td>
<td>W</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ORR R8, R3, R4</td>
<td>F</td>
<td>D</td>
<td>I</td>
<td>E</td>
<td>W</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AND R6, R3, R1</td>
<td>F</td>
<td>I</td>
<td>D</td>
<td>E</td>
<td>W</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EOR R3, R1, R2</td>
<td>F</td>
<td>D</td>
<td>E</td>
<td>W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- In this example, it takes 7 clock cycles to execute 6 instructions, CPI of 1.2
- The LDR instruction immediately followed by a data operation using the same register cause an interlock
In this example, it takes 6 clock cycles to execute 6 instructions, CPI of 1
The LDR instruction does not cause the pipeline to interlock
In this example, it takes 8 clock cycles to execute 5 instructions, CPI of 1.6.

During the LDM there are parallel memory and writeback cycles.
In this example, it takes 9 clock cycles to execute 5 instructions, CPI of 1.8

The SUB incurs a further cycle of interlock due to it using the highest specified register in the LDM instruction.
ARM7TDMI Processor Core

- Current low-end ARM core for applications like digital mobile phones

- TDMI
  - T: Thumb, 16-bit compressed instruction set
  - D: on-chip Debug support, enabling the processor to halt in response to a debug request
  - M: enhanced Multiplier, yield a full 64-bit result, high performance
  - I: Embedded ICE hardware

- Von Neumann architecture

- 3-stage pipeline, CPI ~ 1.9
ARM7TDMI Interface Signals (2/4)

Clock control
- All state change within the processor are controlled by $mclk$, the memory clock
- Internal clock = $mclk$ AND $\\text{wait}$
- $eclk$ clock output reflects the clock used by the core

Memory interface
- 32-bit address $A[31:0]$, bidirectional data bus $D[31:0]$, separate data out $Dout[31:0]$, data in $Din[31:0]$
- $\\text{mreq}$ indicates that the memory address will be sequential to that used in the previous cycle

<table>
<thead>
<tr>
<th>mreq</th>
<th>seq</th>
<th>Cycle</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>N</td>
<td>Non-sequential memory access</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>S</td>
<td>Sequential memory access</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>I</td>
<td>Internal cycle – bus and memory inactive</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>C</td>
<td>Coprocessor register transfer – memory inactive</td>
</tr>
</tbody>
</table>
ARM7TDMI Interface Signals (3/4)

- Lock indicates that the processor should keep the bus to ensure the atomicity of the read and write phase of a SWAP instruction
- \textbackslash r/w, read or write
- \textbackslash mas[1:0], encode memory access size – byte, half-word or word
- \textbackslash bl[3:0], externally controlled enables on latches on each of the 4 bytes on the data input bus

- MMU interface
  - \textbackslash trans (translation control), 0: user mode, 1: privileged mode
  - \textbackslash mode[4:0], bottom 5 bits of the CPSR (inverted)
  - Abort, disallow access

- State
  - T bit, whether the processor is currently executing ARM or Thumb instructions

- Configuration
  - Bigend, big-endian or little-endian
Interrupt
- \texttt{fiq}, fast interrupt request, higher priority
- \texttt{irq}, normal interrupt request
- \texttt{isync}, allow the interrupt synchronizer to be passed

Initialization
- \texttt{reset}, starts the processor from a known state, executing from address $00000000_{16}$

ARM7TDMI characteristics

<table>
<thead>
<tr>
<th>Process</th>
<th>0.35 um</th>
<th>Transistors</th>
<th>74,209</th>
<th>MIPS</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal layers</td>
<td>3</td>
<td>Core area</td>
<td>2.1 mm</td>
<td>Power</td>
<td>87 mW</td>
</tr>
<tr>
<td>Vdd</td>
<td>3.3 V</td>
<td>Clock</td>
<td>0 to 66 MHz</td>
<td>MIPS/W</td>
<td>690</td>
</tr>
</tbody>
</table>
Memory Access

- The ARM7 is a Von Neumann, load/store architecture, i.e.,
  - Only 32 bit data bus for both instr. and data.
  - Only the load/store instr. (and SWP) access memory.
- Memory is addressed as a 32 bit address space
- Data type can be 8 bit bytes, 16 bit half-words or 32 bit words, and may be seen as a byte line folded into 4-byte words
- Words must be aligned to 4 byte boundaries, and half-words to 2 byte boundaries.
- Always ensure that memory controller supports all three access sizes
ARM Memory Interface

- **Sequential (S cycle)**
  - \((nMREQ, SEQ) = (0, 1)\)
  - The ARM core requests a transfer to or from an address which is either the same, or one word or one-half-word greater than the preceding address.

- **Non-sequential (N cycle)**
  - \((nMREQ, SEQ) = (0, 0)\)
  - The ARM core requests a transfer to or from an address which is unrelated to the address used in the preceding address.

- **Internal (I cycle)**
  - \((nMREQ, SEQ) = (1, 0)\)
  - The ARM core does not require a transfer, as it is performing an internal function, and no useful prefetching can be performed at the same time.

- **Coprocessor register transfer (C cycle)**
  - \((nMREQ, SEQ) = (1, 1)\)
  - The ARM core wished to use the data bus to communicate with a coprocessor, but does not require any action by the memory system.
Cached ARM7TDMI Macrocells

- **ARM710T**
  - 8K unified write through cache
  - Full memory management unit supporting virtual memory
  - Write buffer

- **ARM720T**
  - As ARM 710T but with WinCE support

- **ARM 740T**
  - 8K unified write through cache
  - Memory protection unit
  - Write buffer
Higher performance than ARM7
- By increasing the clock rate
- By reducing the CPI
  - Higher memory bandwidth, 64-bit wide memory
  - Separate memories for instruction and data accesses

ARM 8
- ARM9TDMI
- ARM10TDMI

Core Organization
- The prefetch unit is responsible for fetching instructions from memory and buffering them (exploiting the double bandwidth memory)
- It is also responsible for branch prediction and use static prediction based on the branch prediction (backward: predicted ‘taken’; forward: predicted ‘not taken’)
Pipeline Organization

- 5-stage, prefetch unit occupies the 1st stage, integer unit occupies the remainder

1. Instruction prefetch
2. Instruction decode and register read
3. Execute (shift and ALU)
4. Data memory access
5. Write back results
Integer Unit Organization

coprocessor
instructions

instructions
PC+8

inst. decode

register read

multiplier

ALU/shifter

write

data

address

read
data

forwarding
paths

+4

mux

write
pipeline

rot/sgn ex

register write

decode

execute

memory

write
ARM810
- 8Kbyte unified instruction and data cache
- Copy-back
- Double-bandwidth
- MMU
- Coprocessor
- Write buffer
ARM9TDMI

- Harvard architecture
  - Increases available memory bandwidth
    - Instruction memory interface
    - Data memory interface
  - Simultaneous accesses to instruction and data memory can be achieved

- 5-stage pipeline

- Changes implemented to
  - Improve CPI to ~1.5
  - Improve maximum clock frequency
ARM9TDMI Organization
ARM9TDMI Pipeline Operations (1/2)

ARM7TDMI:

- **Fetch**
  - Instruction fetch
  - Thumb decompress
  - ARM decode

ARM9TDMI:

- **Fetch**
  - Instruction fetch
- **Decode**
  - R. read decode
  - Shift/ALU
- **Execute**
  - Data memory access
  - Reg write

Not sufficient slack time to translate Thumb instructions into ARM instructions and then decode, instead the hardware decode both ARM and Thumb instructions directly.
ARM9TDMI Pipeline Operations (2/2)

- **Coprocessor support**
  - Coprocessors: floating-point, digital signal processing, special-purpose hardware accelerator

- **On-chip debugger**
  - Additional features compared to ARM7TDMI
    - Hardware single stepping
    - Breakpoint can be set on exceptions

- **ARM9TDMI characteristics**

<table>
<thead>
<tr>
<th>Process</th>
<th>0.25 μm</th>
<th>Transistors</th>
<th>110,000</th>
<th>MIPS</th>
<th>220</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal layers</td>
<td>3</td>
<td>Core area</td>
<td>2.1 mm</td>
<td>Power</td>
<td>150 mW</td>
</tr>
<tr>
<td>Vdd</td>
<td>2.5 V</td>
<td>Clock</td>
<td>0 to 200 MHz</td>
<td>MIPS/W</td>
<td>1500</td>
</tr>
</tbody>
</table>
ARM9TDMI Macrocells (1/2)

- **ARM920T**
  - 2 × 16K caches
  - Full memory management unit supporting virtual addressing and memory protection
  - Write buffer
ARM9TDMI Macrocells (2/2)

- ARM 940T
  - 2 4K caches
  - Memory protection Unit
  - Write buffer
ARM9E-S Family Overview

- ARM9E-S is based on an ARM9TDMI with the following extensions:
  - Single cycle 32*6 multiplier implementation
  - EmbeddedICE logic RT
  - Improved ARM/Thumb interworking
  - New 32*16 and 16*16 multiply instructions
  - New count leading zero instruction
  - New saturated math instructions

- ARM946E-S
  - ARM9E-S core
  - Instruction and data caches, selectable sizes
  - Instruction and data RAMs, selectable sizes
  - Protection unit
  - AHB bus interface

Architecture v5TE
ARM10TDMI (1/2)

- Current high-end ARM processor core
- Performance on the same IC process

ARM10TDMI  \(\xrightarrow{300\text{MHz}}\) ARM9TDMI  \(\xrightarrow{0.25\mu\text{m CMOS}}\) ARM7TDMI

- 300MHz, 0.25µm CMOS
- Increase clock rate

### ARM10TDMI

- **Fetch**
  - Instruction fetch
- **Issue**
  - Decode
  - r. read decode
- **Decode**
  - addr. calc.
  - shift/ALU
  - multiply
  - multiplier
  - partials add
- **Execute**
  - data memory access
- **Memory**
  - data write
- **Write**
  - reg write

#### ARM10TDMI Flow

- Branch prediction
Reduce CPI

- Branch prediction
- Non-blocking load and store execution
- 64-bit data memory \(\xrightarrow{}\) transfer 2 registers in each cycle
ARM1020T Overview

- Architecture v5T
  - ARM1020E will be v5TE
- CPI ~ 1.3
- 6-stage pipeline
- Static branch prediction
- 32KB instruction and 32KB data caches
  - ‘hit under miss’ support
- 64 bits per cycle LDM/STM operations
- Embedded ICE Logic RT-II
- Support for new VFPv1 architecture
- ARM10200 test chip
  - ARM1020T
  - VFP10
  - SDRAM memory interface
  - PLL
Summary (1/2)

- **ARM7TDMI**
  - Von Neumann architecture
  - 3-stage pipeline
  - CPI ~ 1.9

- **ARM9TDMI, ARM9E-S**
  - Harvard architecture
  - 5-stage pipeline
  - CPI ~ 1.5

- **ARM10TDMI**
  - Harvard architecture
  - 6-stage pipeline
  - CPI ~ 1.3
Summary (2/2)

Cache
- Direct-mapped cache
- Set-associative cache
- Fully associative cache

Software Development
- CodeWarrior
- AXD
References