XMOS Architecture
XS1 Chips

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XMOS
Introduction

Electronic products: design cycles shortening and product diversity increasing

Replace hardware components with software components

Use standard concurrent hardware components to execute diverse concurrent software components

Standard hardware exploits economies of scale in manufacturing

Software supports short design cycles, re-use, diversity, open-source ...
Architecture

An architecture for a range of concurrent processing components

Multi-threaded XCore processors connected by links and switches

XCores interface directly with external devices via integrated ports

Deterministic execution and interface timing

Initial products optimised for embedded applications

Systems built on multi-core chips, in packages or on boards
Example System
Programming

C-based language (along with C and C++) supporting
- deterministic concurrent and multi-core programming
- deterministic real-time and input-output programming

Simple concurrent programming using message-passing

Compiled directly to cores - no kernel or RTOS needed

Real-time performance guaranteed by tools and architecture

*An alternative to complex, non-deterministic, cache-coherent shared memory*
Scalability

On-core memory, threads, links, ports can all be varied

ISA supports different wordlengths - and has space for new instructions

Switch-based interconnect with scalable throughput

Memory, processing, communication, event-handling scale with cores

From one to hundreds of cores per chip
Threads

Each XCore provides *hardware* resources for a number of threads, including:

- a set of *registers* for each thread
- a *scheduler* which dynamically selects which thread to execute
- a set of *synchronisers* for thread synchronisation
- a set of *channels* for communication with other threads
- a set of *ports* used for input and output
- a set of *timers* to control real-time execution

Memory for code and data is shared between the threads

Threads are used for latency hiding or to implement ‘hardware’ functions such as DMA controllers and specialised interfaces
XCore Architecture
Instruction set

Each thread has its own register set

Dedicated registers for program counter, stack pointer, data pointer and constant pool

12 general purpose operand registers - allowing three operands to be encoded using 11 bits (because $12 \times 12 \times 12 < 2048$) leaving 5 opcode bits.

Most instructions encoded in 16 bits

Prefix instructions used to
  - extend the immediate range for jumps and offsets
  - provide up to 6-operand instructions
# XCore Instruction Encodings

## Short 16b Encodings (80%)

<table>
<thead>
<tr>
<th>3 operand</th>
<th>Mostly arithmetic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>opcode</td>
<td>op1, 2 &amp; 3</td>
</tr>
<tr>
<td>20 out of 32</td>
<td>27 out of 32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2/1/0 oper</th>
<th>Mostly resources</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>opcode</td>
<td>op1 &amp; 2</td>
</tr>
<tr>
<td>20 out of 32</td>
<td>5 out of 32</td>
</tr>
</tbody>
</table>

## Big offset

<table>
<thead>
<tr>
<th></th>
<th>Function calls</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>opcode</td>
<td>immediate</td>
</tr>
<tr>
<td>6 out of 22</td>
<td>1024</td>
</tr>
</tbody>
</table>

## Reg+offset

<table>
<thead>
<tr>
<th></th>
<th>Branches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>opcode</td>
<td>op1</td>
</tr>
<tr>
<td>13 out of 22</td>
<td>64</td>
</tr>
</tbody>
</table>

## Long 32b Encodings (20%)

<table>
<thead>
<tr>
<th>ImmPrefix</th>
<th>Immediate extension</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>111100</td>
<td>immediate</td>
</tr>
<tr>
<td>1 out of 22</td>
<td>1024</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>InstrPrefix</th>
<th>4, 5, and 6 operand</th>
</tr>
</thead>
<tbody>
<tr>
<td>11111</td>
<td></td>
</tr>
<tr>
<td>1 out of 32</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>
Thread Scheduler

The thread scheduler maintains a set of runnable threads, \( run \), from which it takes instructions in turn.

A thread is not in the \( run \) set when:

- it is waiting to synchronise with another thread before continuing or terminating.
- it has attempted an input but there is no data available.
- it has attempted an output but there is no room for the data.
- it is waiting for a timer.
- it is waiting for one of a number of events.

An XCore can power down when all of its threads are waiting - event-driven processing
Thread Scheduler

Core

Threads Waiting Inuse

0 ...
1 ...
2 ...
3 ...
4 ...
5 ...
6 ...
N ...

Scheduling queue

Threads 6..N

Execution pipeline

R Write/Decode

Thread 5

Register Read

Thread 4

ALU 1

Thread 1

ALU 2

Thread 0
Concurrency and Thread Scheduler

Fast initiation and termination of threads - forking and joining.

Fast barrier synchronisation - one instruction per thread

 Guarantee that each of \( n \) threads has \( 1/n \) core cycles.

A chip with 128 cores each able to execute 8 threads can be used as if it were a chip with 1024 cores each operating at one eighth of the clock rate.

Each core behaves as symmetric multiprocessor with 8 cores sharing a memory with no access collisions and with no caches needed.
Instruction Execution

Each thread has a short instruction buffer sufficient to hold at least four instructions.

Instructions are issued from the *runnable* threads in a round-robin manner - at most *one* instruction per thread in the pipeline.

Instruction fetch is performed within the execution pipeline, in the same way as data access.

If an instruction buffer is empty when an instruction should be issued, a *no-op* is issued to fetch the next instruction.

Most *no-ops* are eliminated by compiler instruction scheduling.
XCore pipeline

1. Decode
2. Register Read
3. Memory Address
4. ALU 1
5. Resource Test
6. ALU 2
7. Resource Op & Schedule
8. Register Write
9. Memory LD/ST/Fetch
Communication

Communication is performed using hardware *channels*, which provide bidirectional data transfer between threads

- in the same core
- in different cores on the same chip
- in cores on different chips

A channel can be used as a destination by any number of threads - *server threads* can be programmed

The channel addresses are system-wide and can themselves be communicated

Channel protocol provides *control* and *data* tokens; applications optimised protocols can be implemented in *software*. 
Channels and Interconnect

Each core has several bidirectional links to a switch enabling several simultaneous data streams.

A route is opened by sending a destination channel address and closed by sending an *end-of-message* token.

The interconnect can be used under software control to establish *virtual circuits* or perform dynamic *packet routing*.

A set of links can be configured to provide several independent networks - important for diverse traffic loads - or can be grouped to increase throughput.
Communication: Addressing

Core 16
Channels

0 18 2
1 16 2
2 16 1
N

Core 17
Channels

0
1
2 18 1
N

Core 18
Channels

0
1 17 2
2 16 0
N

Switch

Switch

Switch
Communication: Messages & Streams

Core 16
IN r0, 0
CHKCT 0, END

Core 17
CHKCT 2, END

Core 18
OUT 2, 0x12345678
OUTCT 1, END
OUTCT 2, END

Channels

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>18</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>16</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Channels

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>18</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Channels

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>17</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Switch

12

Switch

34

Header

00

1702

Switch

5678END

www.xmos.com
Communication: Sharing

Core 16
IN r0, 0
CHKCT 0, END

Core 17
OUT 0, 0x12345678
OUTCT 0, END

Core 18
OUTCT 2, END

Channels

0 | XX | X
1 |
2 |
N |

0 | 16 | 0
1 |
2 | 18 | 1
N |

Switch

Switch

Switch

12

345678

END
Routing

Simple hardware operating on the first few bits of each message

Incoming bits compared with switch address, bit-by-bit

If all pairs match, then a core on this switch is the destination

If not, the number of the first non-matching pair is used to select an outgoing direction from the switch via a lookup table

This is sufficient to perform deadlock-free routing in all \( n \)-dimensional grids - and many other structures
Routing Example

Binary addresses

Leftmost bit mismatch determines next 'direction':

D: Down
U: Up
L: Left
R: Right

Example routes
0100 to 1010
1111 to 0001
Link Protocol

Data token 00100011 then RTZ

Two Wire

0
DATA 0 0 0 0 0
1
1 1 RTZ

Five Wire

00
00 00
01
10 RTZ
11 11 RTZ
E
E E

Data token 00100011 Control token END&RTZ
Ports, Input and Output

Inputs and outputs using ports provide
- direct access to I/O pins
- accesses synchronised with a clock
- accesses timed under program control

An input can be delayed until a specified condition is met
- the time at which the condition is met can be *timestamped*

The internal timing of input and output program execution is decoupled from the timing of the input and output interfaces.

Ports and threads can implement ‘hardware’ interfaces
Event-based scheduling

A thread can wait for an event from a set of channels, ports or timers

An entry point is set for each resource; a wait instruction waits until an event transfers control directly to its associated entry point

The data needed to handle each event have been initialised prior to waiting, and will be instantly available when the event occurs

Compilers optimise repeated event-handling in inner loops. The thread is operating as a programmable state machine and events can often be handled by short instruction sequences

This is much faster and more energy-efficient that interrupts.
Events

Core

<table>
<thead>
<tr>
<th>Resources</th>
<th>Owner Vector</th>
<th>Interrupt Enabled</th>
<th>In use</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 10140</td>
<td>7 0 11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 0011</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 10160</td>
<td>7 1 11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 0000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 10150</td>
<td>7 0 11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 4001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 0000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N 0000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Code for thread 7:

```plaintext
SETV 0, 10140
SETV 2, 10160
SETV 4, 10150
SETC 0, INTERRUPT
EEU 0
EEU 2
EEU 4
WAITEU

10140:
IN r1,0
...
WAITEU

10150:
IN r1,4
...
WAITEU

10160:
...KRÉT
```
Applications

Customers in audio, industrial control, motor control, robotics, vision, and other real-time and embedded domains

Example: AVB endpoint
## XMOS XS1-G4

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four cores</td>
<td>400 MHz, 1600 MIPS; 32 threads</td>
</tr>
<tr>
<td>DSP</td>
<td>&gt; 400 MMACs per second</td>
</tr>
<tr>
<td>Events</td>
<td>400 MEvents per second</td>
</tr>
<tr>
<td>Switch</td>
<td>4 links per core; 16 external links</td>
</tr>
<tr>
<td>Links</td>
<td>16 at 400Mbits/second</td>
</tr>
<tr>
<td>SRAM</td>
<td>64k bytes per core</td>
</tr>
<tr>
<td>Synchronisers</td>
<td>7 per core</td>
</tr>
<tr>
<td>Timers</td>
<td>10 per core</td>
</tr>
<tr>
<td>Channels</td>
<td>32 per core</td>
</tr>
<tr>
<td>Ports</td>
<td>1, 4, 8, 16, 32-bit</td>
</tr>
<tr>
<td>Node</td>
<td>90 nm</td>
</tr>
<tr>
<td>Costs</td>
<td>less than $10 in volume</td>
</tr>
</tbody>
</table>
XMOS XS1-L1

One core: 500 MHz, 500 MIPS; 8 threads
DSP: > 125 MMACs per second
Events: 125 MEvents per second
Switch: 4 links for the core; 8 external links
Links: 4 at 400Mbits/second
SRAM: 64k bytes per core
Synchronisers: 7 per core
Timers: 10 per core
Channels: 32 per core
Ports: 1, 4, 8, 16, 32-bit
Node: 65 nm
Costs: less than $2 in volume