Large amount of material adapted from MIT 6.004, “Computation Structures”, Morgan Kaufmann “Computer Organization and Design: The Hardware/Software Interface: RISC-V Edition”, and CS 152 Slides by Isaac Scherson
Why focus on parallelism?

- Of course, large jobs require large machines with many processors
  - Exploiting parallelism to make the best use of supercomputers have always been an extremely important topic
- But now even desktops and phones are multicore!
  - Why? The end of “Dennard Scaling”
Option 1: Continue Scaling Frequency at Increased Power Budget

But Moore’s Law Continues Beyond 2006

Moore’s Law – The number of transistors on integrated circuit chips (1971-2016)

Moore’s law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are strongly linked to Moore’s law.
State of Things at This Point (2006)

- Single-thread performance scaling ended
  - Frequency scaling ended (Dennard Scaling)
  - Instruction-level parallelism scaling stalled ... also around 2005

- Moore’s law continues
  - Double transistors every two years
  - What do we do with them?

K. Olukotun, “Intel CPU Trends”
Crisis Averted With Manycores?
Crisis Averted With Manycores?

We’ll get back to this point later. For now, multiprocessing!

The hardware for parallelism: Flynn taxonomy (1966) recap

<table>
<thead>
<tr>
<th>Instruction Stream</th>
<th>Single</th>
<th>Multi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>SISD (Single-Core Processors)</td>
<td>SIMD (GPUs, Intel SSE/AVX extensions, ...)</td>
</tr>
<tr>
<td>Multi</td>
<td>MISD (Systolic Arrays, ...)</td>
<td>MIMD (VLIW, Parallel Computers)</td>
</tr>
</tbody>
</table>
**Flynn taxonomy**

- **Single-Instruction Single-Data** (Single-Core Processors)
  - Data → Processing Unit
  - Instructions
- **Multi-Instruction Single-Data** (Systolic Arrays,...)
  - Data -> Processing Unit
  - Instructions
  - Data -> Processing Unit
  - Instructions

- **Single-Instruction Multi-Data** (GPUs, Intel SIMD Extensions)
  - Data → Processing Unit
  - Instructions
  - Data → Processing Unit
  - Instructions

- **Multi-Instruction Multi-Data** (Parallel Processors)
  - Data → Processing Unit
  - Instructions
  - Data → Processing Unit
  - Instructions
  - Data → Processing Unit
  - Instructions
Shared memory multiprocessor

- **Shared memory multiprocessor**
  - Hardware provides single physical address space for all processors
  - Synchronize shared variables using locks
  - Memory access time
    - UMA (uniform) vs. NUMA (nonuniform)

- **SMP: Symmetric multiprocessor**
  - The processors in the system are identical, and are treated equally

- **Typical chip-multiprocessor ("multicore") consumer computers**
UMA between cores sharing a package, but NUMA across cores in different packages. Overall, this is a NUMA system.
Memory System Bandwidth Snapshot

Cache Bandwidth Estimate
64 Bytes/Cycle \(\sim= 200 \text{ GB/s/Core} \)

DDR4 2666 MHz
128 GB/s

Ultra Path Interconnect
Unidirectional
20.8 GB/s

Memory/PCIe controller used to be on a separate “North bridge” chip, now integrated on-die
All sorts of things are now on-die! Even network controllers!
Memory system issues with multiprocessing (1)

- Suppose two CPU cores share a physical address space
  - Distributed caches (typically L1)
  - Write-through caches, but same problem for write-back as well

<table>
<thead>
<tr>
<th>Time step</th>
<th>Event</th>
<th>CPU A's cache</th>
<th>CPU B's cache</th>
<th>Memory</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>CPU A reads X</td>
<td>0</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>CPU B reads X</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>CPU A writes 1 to X</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Wrong data!
Memory system issues with multiprocessing (2)

- What are the possible outcomes from the two following codes?
  - A and B are initially zero
    - 1, 2, 3, 4 or 3, 4, 1, 2 etc: “01”
    - 1, 3, 2, 4 or 1, 3, 4, 2 etc: “11”
  - Can it print “10”, or “00”? Should it be able to?

“Memory model” defines what is possible and not
(Balance between performance and ease of use)
Memory problems with multiprocessing

Cache coherency (The two CPU example)
- Informally: Read to each address must return the most recent value
- Complex and difficult with many processors
- Typically: All writes must be visible at some point, and in proper order

Memory consistency (The two processes example)
- How updates to different addresses become visible (to other processors)
- Many models define various types of consistency
  - Sequential consistency, causal consistency, relaxed consistency, ...
- In our previous example, some models may allow “10” to happen, and we must program such a machine accordingly

Grad level topic...
CS152: Computer Systems Architecture
Cache Coherency Introduction

Sang-Woo Jun
2023

Large amount of material adapted from MIT 6.004, “Computation Structures”, Morgan Kaufmann “Computer Organization and Design: The Hardware/Software Interface: RISC-V Edition”, and CS 152 Slides by Isaac Scherson
The cache coherency problem

- All cores may have their own cached copies for a memory location
- Copies become stale if one core writes only to its own cache
- Cache updates must be propagated to other cores
  - All cores broadcasting all writes to all cores undermines the purpose of caches
  - We want to privately cache writes without broadcasting, whenever possible

```
Mem[X]++;  We expect Mem[X] == 2
Mem[X]++;

<table>
<thead>
<tr>
<th>Core 0</th>
<th>Cache</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addr</td>
<td>Value</td>
</tr>
<tr>
<td>Mem[X]</td>
<td>0</td>
</tr>
</tbody>
</table>

Wrong!

<table>
<thead>
<tr>
<th>Core 1</th>
<th>Cache</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addr</td>
<td>Value</td>
</tr>
<tr>
<td>Mem[X]</td>
<td>0</td>
</tr>
</tbody>
</table>

Wrong!
```
Background: On-chip interconnect

- An interconnect fabric connects cores and private caches to upper-level caches and main memory
  - Many different paradigms, architectures, and topologies
    - Packet-switched vs. Circuit-switched vs. ...
    - Ring topology vs. Tree topology vs. Torus topology vs. ...
- Data-driven decision of best performance/resource trade-off
Background: Bus interconnect

- A bus is simply a shared bundle of wires
  - All data transfers are broadcast, and all entities on the bus can listen to all communication
  - All communication is immediate, single cycle
  - Only one entity may be transmitting at any given clock cycle
  - If multiple entities want to send data (a "multi-master" configuration) a separate entity called the "bus arbiter" must assign which master can write at a given cycle
Background: Mesh interconnect

- Each core acts as a network switch
  - Compared to bus, much higher aggregate bandwidth
    - Bus: 1 message/cycle, Mesh: Potentially as many messages as there are links
  - Much better scalability with more cores
  - Variable cycles of latency
  - A lot more transistors to implement, compared to bus

Desktop-class multicores migrating from busses to meshes (As of 2022)

Here we use busses for simplicity of description
Keeping multiple caches coherent

- **Basic idea**
  - If a cache line is only read, many caches can have a copy
  - If a cache line is written to, only one cache at a time may have a copy

- **Writes can still be cached (and not broadcast)!**

- **Typically two ways of implementing this**
  - “Snooping-based”: All cores listen to requests made by others on the memory bus
  - “Directory-based”: All cores consult a separate entity called “directory” for each cache access
Snoopy cache coherence

- All caches listen ("snoop") to the traffic on the memory bus
  - Some new information is added to read/write requests
- Before writing to a cache line, each core must broadcast its intention
  - All other caches must invalidate its own copies
  - Algorithm variants exist to make this work effectively (MSI, MSIE, ...)

<table>
<thead>
<tr>
<th>CPU + Cache</th>
<th>Addr</th>
<th>Value</th>
<th>CPU + Cache</th>
<th>Addr</th>
<th>Value</th>
<th>CPU + Cache</th>
<th>Addr</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mem[X]</td>
<td>0</td>
<td></td>
<td>Mem[X]</td>
<td>0</td>
<td></td>
<td>Mem[X]</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

"I want to write to X"

"dirty" instance can exist in only one place!

Many cores writing to X may cause ping pong...

"I want to read from X"
Performance issue with cache coherence: False sharing

- Different memory locations, written to by different cores, mapped to same cache line
  - Core 1 performing “results[0]++;”
  - Core 2 performing “results[1]++;”

- Remember cache coherence
  - Every time a cache is written to, all other instances need to be invalidated!
  - “results” variable is ping-ponged across cache coherence every time
  - Bad when it happens on-chip, terrible over processor interconnect (QPI/UPI)

- Solution: Store often-written data in local variables
Some performance numbers with false sharing

Voice of Experience

Joe Duffy at Microsoft:

During our Beta1 performance milestone in Parallel Extensions, most of our performance problems came down to stamping out false sharing in numerous places.

With False Sharing

Without False Sharing
Hardware support for synchronization

- In parallel software, critical sections implemented via mutexes are critical for algorithmic correctness.

- Can we implement a mutex with the instructions we’ve seen so far?
  - e.g.,
    ```
    while (lock!=False);
    lock = True;
    // critical section
    lock = False;
    ```
  - Does this work with parallel threads?
Hardware support for synchronization

- By chance, both threads can think lock is not taken
  - e.g., Thread 2 thinks lock is not taken, before thread 1 takes it
  - Both threads think they have the lock

Thread 1

```c
while (lock!=False);
lock = True;
// critical section
lock = False;
```

Thread 2

```c
while (lock!=False);
lock = True;
// critical section
lock = False;
```

Algorithmic solutions exist! Dekker’s algorithm, Lamport’s bakery algorithm...
Hardware support for synchronization

- A high-performance solution is to add an “atomic instruction”
  - Memory read/write in a single instruction
  - No other instruction can read/write between the atomic read/write
  - e.g., “if (lock=False) lock=True”

Single instruction read/write is in the grey area of RISC paradigm...
RISC-V example

- Atomic instructions are provided as part of the “A” (Atomic) extension
- Two types of atomic instructions
  - Atomic memory operations (read, operation, write)
    - operation: swap, add, or, xor, ...
  - Pair of linked read/write instructions, where write returns fail if memory has been written after the read
    - More like RISC!
    - With bad luck, may cause livelock, where writes always fail
- Aside: It is known all synchronization primitives can be implemented with only atomic compare-and-swap (CAS)
  - RISC-V doesn’t define a CAS instruction though
Pipelined implementation of atomic operations

- In a pipelined implementation, even a single-instruction read-modify-write can be interleaved with other instructions
  - Multiple cycles through the pipeline

- Atomic memory operations
  - Modify cache coherence so that once an atomic operation starts, no other cache can access it
  - Other solutions?