Lecture 27: Pot-Pourri

- Today's topics:
  - Shared memory vs message-passing
  - Simultaneous multi-threading (SMT)
  - GPUs
  - Disks and reliability
Shared-Memory Vs. Message-Passing

**Shared-memory:**
- Well-understood programming model
- Communication is implicit and hardware handles protection
- Hardware-controlled caching

**Message-passing:**
- No cache coherence → simpler hardware
- Explicit communication → easier for the programmer to restructure code
- Software-controlled caching
- Sender can initiate data transfer
Procedure Solve(A) 
  begin 
    diff = done = 0; 
    while (!done) do 
      diff = 0; 
      for i ← 1 to n do 
        for j ← 1 to n do 
          temp = A[i,j]; 
          A[i,j] ← 0.2 * (A[i,j] + neighbors); 
          diff += abs(A[i,j] – temp); 
        end for 
      end for 
      if (diff < TOL) then done = 1; 
    end while 
  end procedure
Shared Address Space Model

```c
int n, nprocs;
float **A, diff;
LOCKDEC(diff_lock);
BARDEC(bar1);

main()
begin
read(n); read(nprocs);
A ← G_MALLOC();
initialize (A);
CREATE (nprocs,Solve,A);
WAIT_FOR_END (nprocs);
end main

procedure Solve(A)
int i, j, pid, done=0;
float temp, mydiff=0;
int mymin = 1 + (pid * n/procs);
int mymax = mymin + n/nprocs -1;
while (!done) do
   mydiff = diff = 0;
   BARRIER(bar1,nprocs);
   for i ← mymin to mymax
      for j ← 1 to n do
         ...
   endfor
   LOCK(diff_lock);
   diff += mydiff;
   UNLOCK(diff_lock);
   BARRIER (bar1, nprocs);
   if (diff < TOL) then done = 1;
endwhile
```

Message Passing Model

main()
read(n); read(nprocs);
CREATE (nprocs-1, Solve);
Solve();
WAIT_FOR_END (nprocs-1);

procedure Solve()
int i, j, pid, nn = n/nprocs, done=0;
float temp, tempdiff, mydiff = 0;
myA \leftarrow \text{malloc}(\ldots)
initialize(myA);
while (!done) do
  mydiff = 0;
  if (pid != 0)
    \text{SEND}(&myA[1,0], n, pid-1, \text{ROW});
  if (pid != nprocs-1)
    \text{SEND}(&myA[nn,0], n, pid+1, \text{ROW});
  if (pid != 0)
    \text{RECEIVE}(&myA[0,0], n, pid-1, \text{ROW});
  if (pid != nprocs-1)
    \text{RECEIVE}(&myA[nn+1,0], n, pid+1, \text{ROW});
  for i \leftarrow 1 \text{ to } nn \text{ do}
    for j \leftarrow 1 \text{ to } n \text{ do}
      \ldots
    endfor
  endfor
  if (pid != 0)
    \text{SEND}(mydiff, 1, 0, \text{DIFF});
  \text{RECEIVE}(done, 1, 0, \text{DONE});
  else
    for i \leftarrow 1 \text{ to } nprocs-1 \text{ do}
      \text{RECEIVE}(tempdiff, 1, *, \text{DIFF});
      mydiff += tempdiff;
    endfor
  endif
  if (mydiff < TOL) done = 1;
  for i \leftarrow 1 \text{ to } nprocs-1 \text{ do}
    \text{SEND}(done, 1, I, \text{DONE});
  endfor
endwhile
Multithreading Within a Processor

• Until now, we have executed multiple threads of an application on different processors – can multiple threads execute concurrently on the same processor?

• Why is this desireable?
  - inexpensive – one CPU, no external interconnects
  - no remote or coherence misses (more capacity misses)

• Why does this make sense?
  - most processors can’t find enough work – peak IPC is 6, average IPC is 1.5!
  - threads can share resources → we can increase threads without a corresponding linear increase in area
How are Resources Shared?

Each box represents an issue slot for a functional unit. Peak throughput is 4 IPC.

- Superscalar processor has high under-utilization – not enough work every cycle, especially when there is a cache miss
- Fine-grained multithreading can only issue instructions from a single thread in a cycle – can not find max work every cycle, but cache misses can be tolerated
- Simultaneous multithreading can issue instructions from any thread every cycle – has the highest probability of finding work for every issue slot
Performance Implications of SMT

• Single thread performance is likely to go down (caches, branch predictors, registers, etc. are shared) – this effect can be mitigated by trying to prioritize one thread

• With eight threads in a processor with many resources, SMT yields throughput improvements of roughly 2-4
SIMD Processors

• Single instruction, multiple data

• Such processors offer energy efficiency because a single instruction fetch can trigger many data operations

• Such data parallelism may be useful for many image/sound and numerical applications
GPUs

- Initially developed as graphics accelerators; now viewed as one of the densest compute engines available

- Many on-going efforts to run non-graphics workloads on GPUs, i.e., use them as general-purpose GPUs or GPGPUs

- C/C++ based programming platforms enable wider use of GPGPUs – CUDA from NVidia and OpenCL from an industry consortium

- A heterogeneous system has a regular host CPU and a GPU that handles (say) CUDA code (they can both be on the same chip)
The GPU Architecture

- SIMT – single instruction, multiple thread; a GPU has many SIMT cores

- A large data-parallel operation is partitioned into many thread blocks (one per SIMT core); a thread block is partitioned into many warps (one warp running at a time in the SIMT core); a warp is partitioned across many in-order pipelines (each is called a SIMD lane)

- A SIMT core can have multiple active warps at a time, i.e., the SIMT core stores the registers for each warp; warps can be context-switched at low cost; a warp scheduler keeps track of runnable warps and schedules a new warp if the currently running warp stalls
The GPU Architecture
Architecture Features

• Simple in-order pipelines that rely on thread-level parallelism to hide long latencies

• Many registers (~1K) per in-order pipeline (lane) to support many active warps

• When a branch is encountered, some of the lanes proceed along the “then” case depending on their data values; later, the other lanes evaluate the “else” case; a branch cuts the data-level parallelism by half (branch divergence)

• When a load/store is encountered, the requests from all lanes are coalesced into a few 128B cache line requests; each request may return at a different time (mem divergence)
GPU Memory Hierarchy

- Each SIMT core has a private L1 cache (shared by the warps on that core)

- A large L2 is shared by all SIMT cores; each L2 bank services a subset of all addresses

- Each L2 partition is connected to its own memory controller and memory channel

- The GDDR5 memory system runs at higher frequencies, and uses chips with more banks, wide IO, and better power delivery networks

- A portion of GDDR5 memory is private to the GPU and the rest is accessible to the host CPU (the GPU performs copies)
Role of Disks

- Activities external to the CPU/memory are typically orders of magnitude slower.

- Example: while CPU performance has improved by 50% per year, disk latencies have improved by 10% every year.

- Typical strategy on I/O: switch contexts and work on something else.

- Other metrics, such as bandwidth, reliability, availability, and capacity, often receive more attention than performance.
Magnetic Disks

• A magnetic disk consists of 1-12 *platters* (metal or glass disk covered with magnetic recording material on both sides), with diameters between 1-3.5 inches

• Each platter is comprised of concentric *tracks* (5-30K) and each track is divided into *sectors* (100 – 500 per track, each about 512 bytes)

• A movable arm holds the read/write heads for each disk surface and moves them all in tandem – a *cylinder* of data is accessible at a time
Disk Latency

• To read/write data, the arm has to be placed on the correct track – this *seek time* usually takes 5 to 12 ms on average – can take less if there is spatial locality

• *Rotational latency* is the time taken to rotate the correct sector under the head – average is typically more than 2 ms (15,000 RPM)

• *Transfer time* is the time taken to transfer a block of bits out of the disk and is typically 3 – 65 MB/second

• A disk controller maintains a disk cache (spatial locality can be exploited) and sets up the transfer on the bus (*controller overhead*)
Defining Reliability and Availability

• A system toggles between
  - Service accomplishment: service matches specifications
  - Service interruption: service deviates from specs

• The toggle is caused by *failures* and *restorations*

• Reliability measures continuous service accomplishment and is usually expressed as mean time to failure (MTTF)

• Availability measures fraction of time that service matches specifications, expressed as $\frac{MTTF}{MTTF + MTTR}$
RAID

- Reliability and availability are important metrics for disks
- RAID: redundant array of inexpensive (independent) disks
- Redundancy can deal with one or more failures
- Each sector of a disk records check information that allows it to determine if the disk has an error or not (in other words, redundancy already exists within a disk)
- When the disk read flags an error, we turn elsewhere for correct data
RAID 0 and RAID 1

• RAID 0 has no additional redundancy (misnomer) – it uses an array of disks and stripes (interleaves) data across the arrays to improve parallelism and throughput.

• RAID 1 mirrors or shadows every disk – every write happens to two disks.

• Reads to the mirror may happen only when the primary disk fails – or, you may try to read both together and the quicker response is accepted.

• Expensive solution: high reliability at twice the cost.
RAID 3

- Data is bit-interleaved across several disks and a separate disk maintains parity information for a set of bits.

- For example: with 8 disks, bit 0 is in disk-0, bit 1 is in disk-1, ..., bit 7 is in disk-7; disk-8 maintains parity for all 8 bits.

- For any read, 8 disks must be accessed (as we usually read more than a byte at a time) and for any write, 9 disks must be accessed as parity has to be re-calculated.

- High throughput for a single request, low cost for redundancy (overhead: 12.5%), low task-level parallelism.
RAID 4 and RAID 5

• Data is block interleaved – this allows us to get all our data from a single disk on a read – in case of a disk error, read all 9 disks

• Block interleaving reduces throughput for a single request (as only a single disk drive is servicing the request), but improves task-level parallelism as other disk drives are free to service other requests

• On a write, we access the disk that stores the data and the parity disk – parity information can be updated simply by checking if the new data differs from the old data
RAID 5

- If we have a single disk for parity, multiple writes can not happen in parallel (as all writes must update parity info)

- RAID 5 distributes the parity block to allow simultaneous writes
RAID Summary

• RAID 1-5 can tolerate a single fault – mirroring (RAID 1) has a 100% overhead, while parity (RAID 3, 4, 5) has modest overhead

• Can tolerate multiple faults by having multiple check functions – each additional check can cost an additional disk (RAID 6)

• RAID 6 and RAID 2 (memory-style ECC) are not commercially employed
Memory Protection

- Most common approach: SECDED – single error correction, double error detection – an 8-bit code for every 64-bit word -- can correct a single error in any 64-bit word – also used in caches

- Extends a 64-bit memory channel to a 72-bit channel and requires ECC DIMMs (e.g., a word is fetched from 9 chips instead of 8)

- Chipkill is a form of error protection where failures in an entire memory chip can be corrected
Computation Errors – TMR

• Errors in ALUs and cores are typically handled by performing the computation n times and voting for the correct answer

• n=3 is common and is referred to as triple modular redundancy
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