ECE 571 – Advanced Microprocessor-Based Design Lecture 4

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Announcements

- Homework #1 is due.
- Homework #2 will be posted. Reading on measurement bias.

Advanced CPUs

Some sample code

```
int i;
int x[128];

for(i=0;i<128;i++) {
        x[i]=0;
}
```

How do you convert this to something the CPU understands?

Roughly Equivelent Assembler

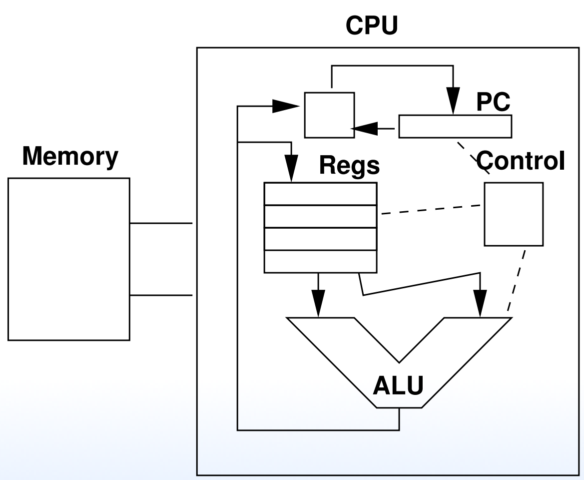
```
    mov r0,#0          ; i=0
loop:
    ldr r1,=x          ; point r1 to x array
    lsl r2,r0,#2       ; r2=i*4
    mov r3,#0          ; want to write 0 to x[i]
    str r3,[r1,r2]     ; x[i]=0
    add r0,r0,#1       ; i++
    cmp r0,#128        ; is i==128?
    bne loop           ; if not, keep looping

    ; Note: can do lots of code hoisting here

.bss
.lcomm  x,128*4
```

Simple CPUs

- Ran one instruction at a time.
- Could take one or multiple cycles (IPC 1.0 or less)
- Example – single instruction take 1-5 cycles?



IPC Metric

- Instructions per Cycle
- Higher is better
- Inverse of CPI (cycles per instruction)

How can we increase IPC?

- Simple CPU must have cycles as slow as slowest instruction

- What if we break instructions up to take multiple cycles?

- What if we could overlap them?

Pipelined CPUs

- 5-stage MIPS pipeline

IF	ID	EX	MEM	WB

Pipelined CPUs

- IF = Instruction Fetch, Update PC
  Fetch 32-bit instruction from L1-cache
- ID = Decode, Fetch Register
- EX = execute (ALU, maybe shifter, multiplier, divide)
  Memory address calculated
- MEM = Memory – if memory had to be accessed, happens now.
- WB = register values written back to the register file

Cycle 1

IF	`mov r0,#0`
ID	
EX	
MEM	
WB	

Cycle 2

IF	`mov r1,x`
ID	`mov r0,#0`
EX	
MEM	
WB	

Cycle 3

IF	`lsl r2,r0,#2`
ID	`mov r1,x`
EX	`mov r0,#0`
MEM	
WB	

Cycle 4

IF	`mov r3,#0`
ID	`lsl r2,r0,#2`
EX	`mov r1,x`
MEM	`mov r0,#0`
WB	

Cycle 5

IF	`str r3,[r1,r2]`
ID	`mov r3,#0`
EX	`lsl r2,r0,#2`
MEM	`mov r1,x`
WB	`mov r0,#0`

Benefits/Downside

- From 2-stage to Pentium 4 31-stage
- Latency higher (5 cycles) but average might be 1 cycle
- Why bother? Can you run the clock faster?

Data Hazards

Happen because instructions might depend on results from instructions ahead of them in the pipeline that haven't been written back yet.

- RAW – "true" dependency – problem. Bypassing?
- WAR – "anti" dependency – not a problem if commit in order
- WAW – "output" dependency – not a problem as long as ordered
- RAR – not a problem

Structural Hazards

- CPU can't just provide. Not enough multipliers for example

Control Hazards

- How quickly can we know outcome of a branch
- Branch prediction? Branch delay slot?

Branch Prediction

- Predict (guess) if a branch is taken or not.
- What do we do if guess wrong? (have to have some way to cancel and start over)
- Modern predictors can be very good, greater than 99%
- Designs are complex and could fill an entire class

Memory Delay

- Memory/cache is slow

- Need to bubble / Memory Delay Slot

The Memory Wall

- Wulf and McKee
- Processors getting faster more quickly than memory
- Processors can spend large amounts of time waiting for memory to be available
- How do we hide this?

Caches

- Basic idea is that you have small, faster memories that are closer to the CPU and much faster
- Data from main memory is cached in these caches
- Data is automatically brought in as needed.
  Also can be pre-fetched, either explicitly by program or by the hardware guessing.
- What are the downsides of pre-fetching?
- Modern systems often have multiple levels of cache. Usually a small (32k or so each) L1 instruction and data,

a larger (128k?) shared L2, then L3 and even L4.

- Modern systems also might share caches between processors, more on that later
- Again, could teach a whole class on caches

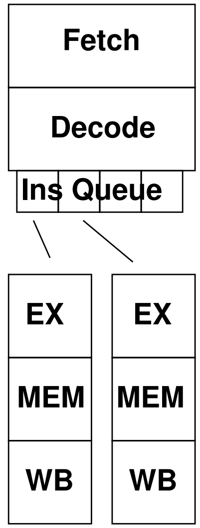
Exploiting Parallelism

- How can we take advantage of parallelism in the control stream?

- Can we execute more than one instruction at a time?

Multi-Issue (Super-Scalar)

- Decode up to X instructions at a time, and if no dependencies issue at same time.
- Types
  - Static Multi-Issue – at compile time, VLIW
  - Dynamic
- Dual issue example. Can have theoretical IPC of 2.0
- Can have unequal pipelines.


Fetch
Decode
Ins Queue
EX
EX
MEM
MEM
WB
WB

Register Renaming

- Loop unrolling
- If only a "name" dependence
- Architectural register doesn't have to be updated until written to
- Once written to it is essentially a separate register despite the same name

```
ldr r1,[1024]     ; ldr   r100,[1024]
add r1,#5         ; add   r100,#5
str r1,[2048]     ; str   r100,[2048]
ldr r1,[1025]     ; ldr   r101,[1025]
add r1,#5         ; add   r100,#5
str r1[2049]      ; str   r100,[2049]
```

Out-of-Order

- Tries to exploit instruction-level parallelism
- Instead of being stuck waiting for a resource to become available for an instruction (cache, multiplier, etc) keep executing instructions beyond as long as there are no dependencies
- Need to insure that instructions commit in order
  Need to make sure loads/stores happen in order.
- Precise exceptions (skid?)
- What happens on exception? (interrupt, branch

mispredict, etc)

- Register Renaming
- Re-order buffer
- Speculative execution / Branch Prediction?

Perf Counters related to Stalls

- Front-end stalls – fetch, decode, icache misses
- Back-end stalls – memory accesses

Instruction Level Parallelism

- Using super-scalar and/or OoO (Out of Order) execution try to find parallelism within your serial code
- Chip companies want to speed up existing code. Why? (it's a pain to change, you might not have source, etc.)

Other Ways to get better Parallelism

SIMD / Vector Instructions

- x86: MMX/SSE/SSE2/AVX/AVX2
  semi-related FMA
- MMX (mostly deprecated), AMD's 3DNow! (deprecated)
- PowerPC Altivec
- ARM: Neon

SSE / x86

- SSE (streaming SIMD): 128-bit registers XMM0 - XMM7, can be used as 4 32-bit floats
- SSE2 : 2*64bit int or float, 4 * 32-bit int or float, 8x16 bit int, 16x8-bit int
- SSE3 : minor update, add dsp and others
- SSSE3 (the s is for supplemental): shuffle, horizontal add
- SSE4 : popcnt, dot product

AVX / x86

- AVX (advanced vector extensions) – now 256 bits, YMM0-YMM15 low bits are the XMM registers. Now twice as many.
  Also adds three operand instructions a=b+c
- AVX2 – 3 operand Fused-Multiply Add, more 256 instructions
- AVX-512 – version used on Xeon Phis (knights landing) and Skylake – now 512 bits, ZMM0-XMM31

Multi-core

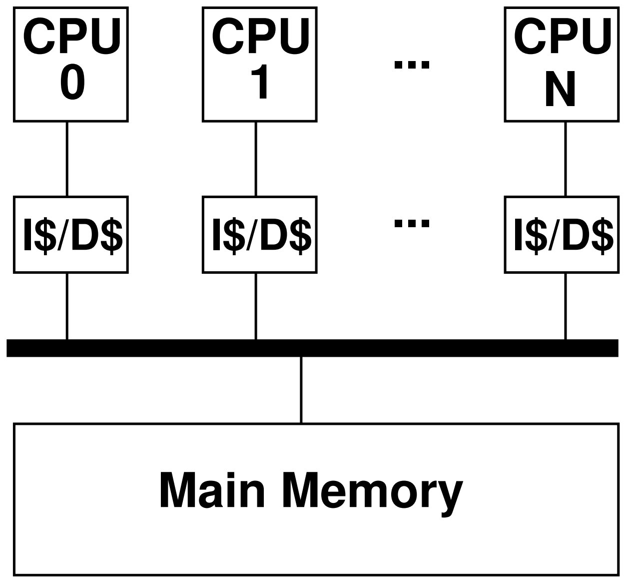
- More's law gives you lots of transistors. Hit limit of how fast to make a single processor, so why not just put more on the die?
- Exploits multi-programmed parallelism rather than instruction-level parallelism

Multi-threaded

- SMT (simultaneous multithreading), Intel Hyperthreading
- Hyrbid of multi-core and multi-pipeline
- Your pipelines might not always be full, especially if waiting on memory
- Why not duplicate fetch/decode logic, and have two programs execute at once on same set of pipelines.
- If one is idle/stalled, run instructions from other thread

- Looks to OS as if you have two cores, but really just one with two instruction dispatch stages
- Extra logic to make sure that pipelines used fairly, the results get committed to the right register file, etc.

CMP Diagram



Hardware Multi-Threading

- Idea is to re-use a pipeline to execute multiple threads at once, *without* fully replicating the entire CPU (so less than multicore)
- You will have to replicate some things (program counter for each, etc)
- Usually they appear to the CPU as full separate processors even though they are not.
- Various ways to do this:

- ◦ Fine-grained – rotate threads every cycle
- ◦ Coarse-grained – rotate threads only if long latency event happens (cache miss)
- ◦ Simultaneous – issue from any combination of threads, to maximize use of pipeline (have to be superscalar)

- Why do this? Often on superscalar running only one thread will leave parts idle, try to make use of these.
- Bad side effects?
  Can actually slow down code (especially if both threads

trying to use same functional units, also if both using memory heavily as cache is often shared)

- Sometimes see it talked about as SMT (Simultaneous Multithreading), Intel Hyperthreading is more or less the same thing

SMT Diagram

Cache Coherency

- How do you handle data being worked on by multiple processors, each with own cache of main memory?
- Cache coherency protocols.
- Many and varied. MESI is a common one
- Directory vs Snoopy

MESI

- Modified, Exclusive, Shared, Invalid