Introduction

- Goal: replacing large inefficient processors with many smaller, efficient processors to get better performance per joule
  - Multiprocessors, cluster
  - Scalability, availability, power efficiency
- Task-level (process-level) parallelism
  - High throughput for independent jobs
- Parallel processing program
  - Single program run on multiple processors
- Multicore microprocessors
  - Chips with multiple processors (cores)
  - Shared Memory Processors (SMP)

Hardware & Software

串行 并行

硬件 Serial parallel

软件 Sequential concurrent

顺序 并发.

- Challenge: hardware and software design that enables parallel processing programs, which can be efficiently executed (in performance and energy) when number of cores scales.
- Hardware
  - Serial: e.g., Pentium 4
  - Parallel: e.g., quad-core Xeon e5345
- Software
  - Sequential: e.g., matrix multiplication
  - Concurrent: e.g., operating system
- Sequential/concurrent software can run on serial/parallel hardware
- We use "parallel processing program" to mean either sequential or concurrent software running on parallel hardware

Parallel Programming

- It's hard to create parallel software
- Parallel programming needs to achieve significant performance improvement
  - Otherwise, just use a faster uniprocessor, since it's easier!
- Difficulties of parallel programming:
  - Partitioning
  - Coordination
  - Communications overhead

Amdahl's Law

- Sequential part can limit speedup
- Example: 100 processors, how to achieve 90× speedup?
  - 1 processor: $F_{sequential}+F_{paralizable}=1(T_{old})$
  - 100 processors: $T_{new} = F_{sequential} + F_{parallelizable}/100$

$$\text{Speedup} = \frac{1}{(1-F_{parallelizable})+F_{parallelizable}/100} = 90$$

  - ➔ $F_{parallelizable} = 0.999$
- sequential part should be no more than 0.1% of total task

Scaling Example

- Workload: sum of 10 scalars, and 10 × 10 matrix sum
  - Assume the sum of 10 scalars cannot be paralleled
  - Calculate the speedup of 10 processors and 40 processors
- Single processor: Time = (10 + 100) × t_{add}
- 10 processors
  - Time = 10 × t_{add} + 100/10 × t_{add} = 20 × t_{add}
  - Speedup = 110/20 = 5.5 (5.5/10=55% of potential)
- 40 processors
  - Time = 10 × t_{add} + 100/40 × t_{add} = 12.5 × t_{add}
  - Speedup = 110/12.5 = 8.8 (8.8/40=22% of potential)
- Assumes load can be balanced across processors
- What if matrix size is 20 × 20?
- Single processor: Time = (10 + 400) × t_{add}
- 10 processors
  - Time = 10 × t_{add} + 400/10 × t_{add} = 50 × t_{add}
  - Speedup = 410/50 = 8.2 (8.2/10=82% of potential)
- 40 processors
  - Time = 10 × t_{add} + 400/40 × t_{add} = 20 × t_{add}
  - Speedup = 410/20 = 20.5 (20.5/40=51% of potential)
- Assuming load balanced

Strong vs. Weak Scaling

- Speedup:

task / No. of cores	10 scaler 10*10 matrix	10 scaler 20*20 matrix
10	5.5 (55% of potential)	8.2 (82% of potential)
40	8.8 (22% of potential)	20.5 (51% of potential)

- Strong scaling: keep problem size fixed, time is reverse proportional to number of processors: T(N,P)=T(1,P)/N
- Weak scaling: constant time cost when problem size is proportional to number of processors: $T(N_1,P_1)=T(N_2,P_2)$
  - 10 processors (N_1), 10 × 10 matrix (P_1)
    - Time = 20 × t_{add}
  - 40 processors (N_2), 20 × 20 matrix (P_2)
    - Time = 10 × t_{add} + 400/40 × t_{add} = 20 × t_{add}
  - Constant performance in this example

强比例缩放：保持问题规模不变，时间与处理器数量成反比。

弱比例缩放：保持时间不变，问题规模与处理器数量成正比。

Load Balancing

- In the above example
  - 40 processors are used to achieve 20.5 speedup
  - 40 processors are assumed to have balanced load (2.5% each)
- how about one processor with high load (5%)?
  - one processor takes 5%*400=20 adds, the others takes the rest 400-20=380 adds
  - Time = max(380t/39, 20t/1)+10t = 30t
  - speedup = 410t/30t = 14, smaller than 20.5
- how about one processor with higher load (12.5%)?

Parallel Processing

- The following techniques can enable parallel processing
  - SIMD, vector (section 6.3)
  - Multithreading (section 6.4)
  - SMPs and clusters (section 6.5)
  - GPUs (section 6.6)

SISD, MIMD, SPMD, SIMD and vector

- SISD: single instruction stream, single data stream
  - Uniprocessor, Intel Pentium 4
- MIMD : multiple instruction, multiple data
  - Multi-core processor, Intel Core i7
- SPMD: single program, multiple data
  - Typical way to write program on a multi-core processor
  - One program run on multiple processors
  - Different processors execute on different sections of code

SIMD

- Operate on vectors of data
  - Provide data level parallelism
  - E.g., MMX (MultiMedia eXtension) and SSE (Streaming SIMD Extension) instructions in x86
    - Multiple data elements in 128-bit wide registers
- All processors execute the same instruction at the same time
  - Each with different data address, etc.
- Simplifies synchronization
- Reduced instruction control hardware
- Works best for highly data-parallel applications

Vector Processors

- Processor unit which is designed for vector operation
- Pipelined execution units, instead of multiple ALUs
- Stream data from/to vector registers to units
  - Data collected from memory into registers
  - Results stored from registers to memory
- Example: Vector extension to MIPS
  - 32 × 64-element registers (64-bit elements)
  - Vector instructions
    - `lv`, `sv`: load/store vector
    - `addv.d`: add vectors of double
    - `addvs.d`: add scalar to each element of vector of double
- Significantly reduces instruction-fetch bandwidth

An example using vector instruction

Calculate:

$$Y = a \times X + Y$$

- X and Y are vectors of 64 double precision numbers
- the starting addresses of X and Y are in $s0 and $s1

```
        l.d     $f0,a($sp)      :load scalar a
        addiu   $t0,$s0,#512    :upper bound of what to load
loop:   l.d     $f2,0($s0)      :load x(i)
        mul.d   $f2,$f2,$f0     :a*x(i)
        l.d     $f4,0($s1)      :load y(i)
        add.d   $f4,$f4,$f2     :a*x(i) + y(i)
        s.d     $f4,0($s1)      :store into y(i)
        addiu   $s0,$s0,#8      :increment index to x
        addiu   $s1,$s1,#8      :increment index to y
        subu    $t1,$t0,$s0     :compute bound
        bne     $t1,$zero,loop  :check if done
```

Code using vector instructions:

```
        l.d     $f0,a($sp)      :load scalar a
        lv      $v1,0($s0)      :load vector x
        mulvs.d $v2,$v1,$f0     :vector-scalar multiply
        lv      $v3,0($s1)      :load vector y
        addv.d  $v4,$v2,$v3     :add y to product
        sv      $v4,0($s1)      :store the result
```

Multithreading

- A related concept to MIMD, allows multiple threads to share a single processor
  - Threads: a lightweight process, share single address space
- Fine-grain multithreading
  - Switch threads after each cycle
  - Interleave instruction execution
  - If one thread stalls, others are executed
- Coarse-grain multithreading
  - Only switch on long stall (e.g., L2-cache miss)
  - Simplifies hardware, but doesn't hide short stalls (eg, data hazards)

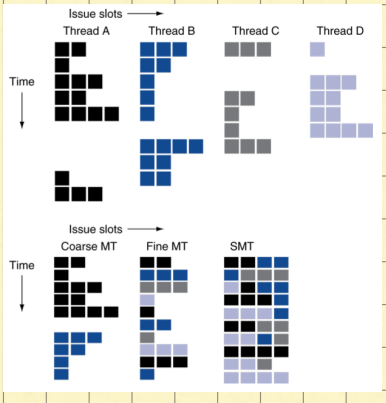
进程(process)：一个程序要一个进程
线程(thread)：同一程序中不同的分配

不同进程用不同 data 空间，
同一进程不同线程在同一 data 空间。

Simultaneous Multithreading (SMT)

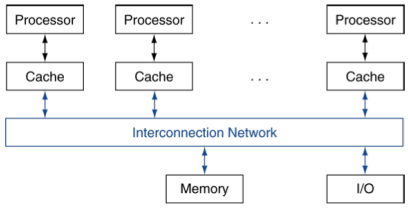
- In multiple-issue dynamically scheduled processor
  - Schedule instructions from multiple threads
  - Instructions from independent threads execute when function units are available
  - Within threads, dependencies handled by scheduling and register renaming
- Example: Intel Pentium-4 HT (Hyper Threading)
  - Two threads: duplicated registers, shared function units and caches

Multithreading Example



Shared Memory Multiprocessors

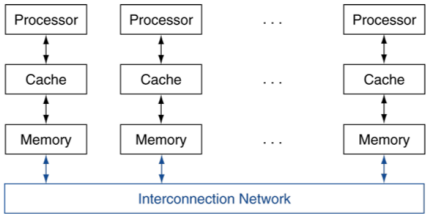
- Multithreading improves efficiency of one processor
- How to efficiently programming on multiprocessor?
  - Don't want to rewrite old programs in single processor
  - Share memory among multiple cores
- SMP: shared memory multiprocessor



memory 和 IO 是所有机器共有的. 通过 Interconnection network 交互.

Message Parsing Multiprocessors

- Each processor has private physical address space
- Hardware sends/receives messages between processors



每个机器都有私有 memory，但通过 Interconnection network 交互.

Loosely Coupled Clusters

- Network of independent computers
  - Each has private memory and OS
  - Connected using I/O system
    - E.g., Ethernet/switch, Internet
- Suitable for applications with independent tasks
  - Web servers, databases, simulations, ...
- High availability, scalable, affordable
- Problems
  - Administration cost (prefer virtual machines)
  - Low interconnect bandwidth
    - c.f. processor/memory bandwidth on an SMP

用网络将电脑连起来.

只适用于独立的任务.

高有效性.

管理成本高. 常用 VM.

交互效果较差

Cloud Computering and Data Center

- Cloud computing
  - Warehouse Scale Computers (WSC)
  - Software as a Service (SaaS)
  - Portion of software run on a PMD (personal mobile device) and a portion run in the Cloud
  - Amazon and Google
- Data centers
  - Millions of computers connected by off-the-shelf networking devices

Google Data Centers

Introduction of GPUs.

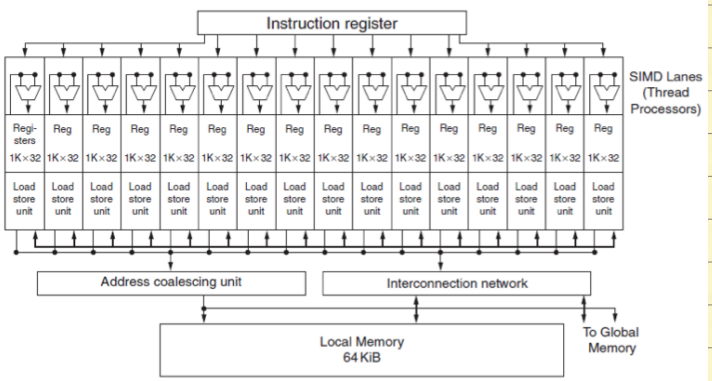
- Development of GPU
  - General-purpose CPU not suitable for graphic processing
  - Game industry drive the improvement of graphic processing
  - GPU (graphic processing unit) appear and developed faster than general-purpose CPU, high performance, low cost
  - Easy-use programming language helps GPU's popularity
- Difference between GPU and CPU
  - GPU supplement CPU, doesn't replace it. GPU doesn't need to perform all tasks of CPU
  - GPU problem size is MB to GB, not hundreds of GB.

GPU Architectures

- Processing is highly data-parallel
  - GPUs are highly multithreaded, 16-32 threads
- GPU memory oriented towards bandwidth rather then latency
  - Graphics memory is wide and high-bandwidth
  - GPU memory is smaller than CPU. 4-6GB, instead of 256GB or above
    - Less reliance on multi-level caches
- Trend toward general purpose GPUs
  - Heterogeneous CPU/GPU systems
  - CPU for sequential code, GPU for parallel code
- Programming languages/APIs
  - DirectX, OpenGL
  - C for Graphics (Cg), High Level Shader Language (HLSL)
  - Compute Unified Device Architecture (CUDA)

Block Diagram of a SIMD processor in GPU

- A GPU consists of multiple multi-thread SIMD processors



xPUs

- CPU: good for control, sequential programming
- GPU: good for graphics, parallel programming
  - CPU/GPU mixed architecture
- TPU: Tenser processing unit
  - Proposed by Google, targeting at acceleration for tenserflow platform
  - Suitable for machine learning model training and testing
- DPU: deep learning processing unit
  - Proposed by DeePhi Tech, FPGA-based processing unit
- NPU: neural network processing unit
  - IBM TrueNorth
- BPU: brain processing unit

Concluding Remarks

- Goal: higher performance by using multiple processors
- Difficulties
  - Developing parallel software
  - Devising appropriate architectures
- From multicore to data centre
- Performance per dollar and performance per Joule drive both mobile and WSC