Computer Hardware Engineering (IS1200)
Computer Organization and Components (IS1500)

Spring 2018

Lecture 13: SIMD, MIMD, and Parallel Programming

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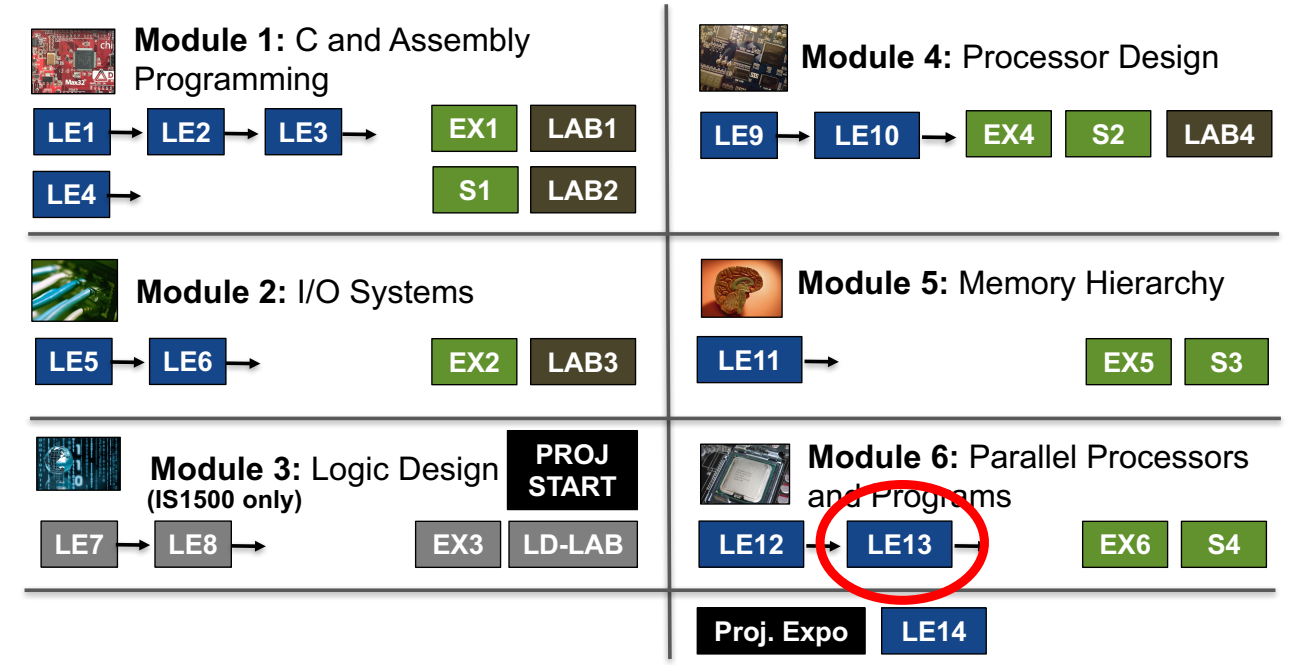
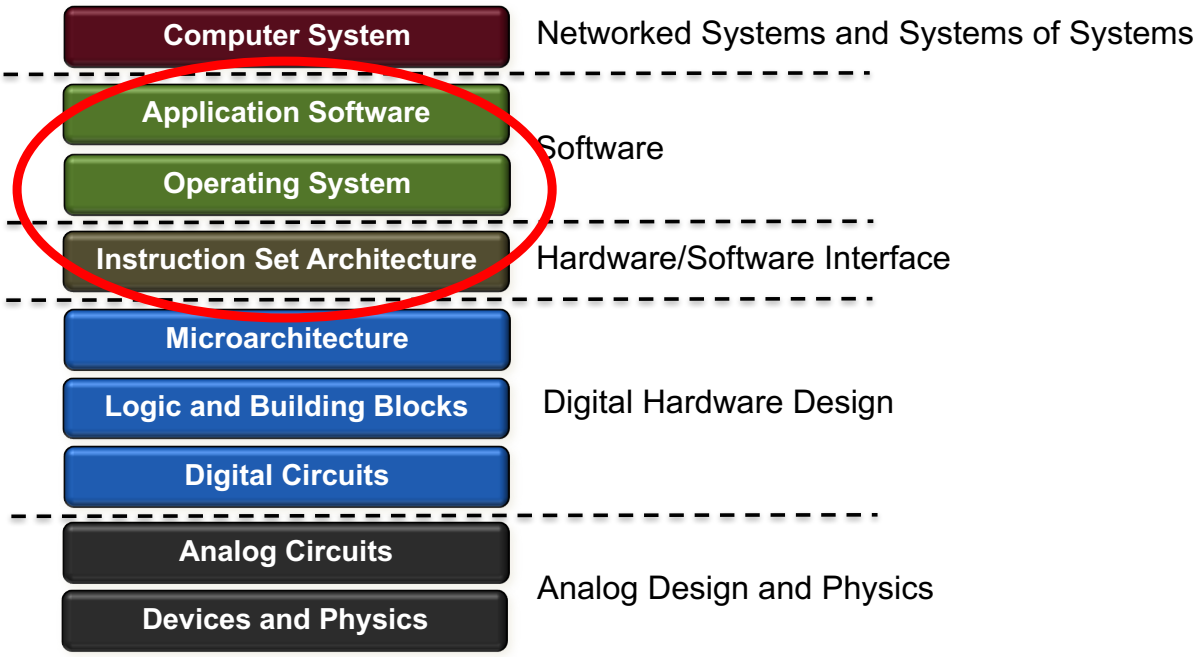
Slides version 1.1

Course Structure



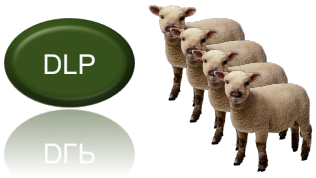
Abstractions in Computer Systems



Agenda

Part I

SIMD, Multithreading, and GPUs

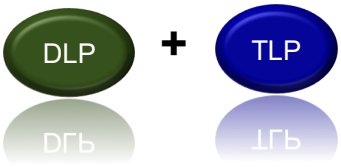


Part II

MIMD, Multicore, and Clusters

Part III

Parallelization in Practice

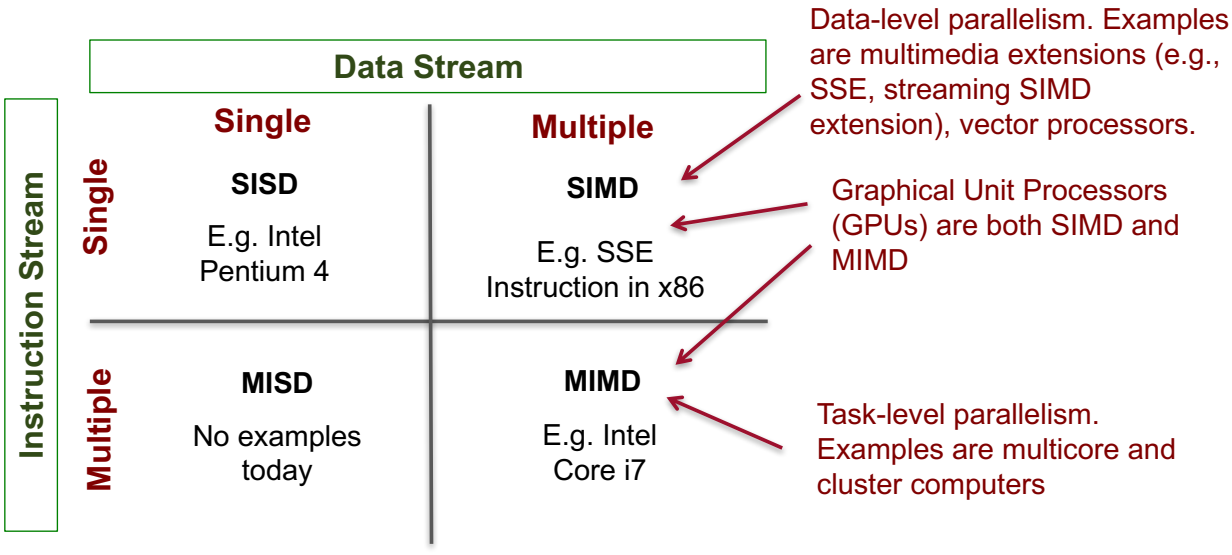


Part I

SIMD, Multithreading, and GPUs

Acknowledgement: The structure and several of the good examples are derived from the book "Computer Organization and Design" (2014) by David A. Patterson and John L. Hennessy

SISD, SIMD, and MIMD (Revisited)

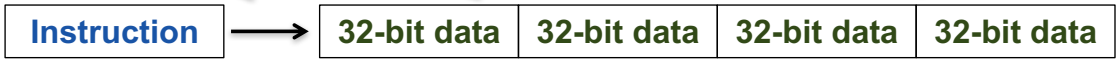


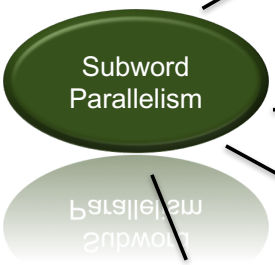
Subword Parallelism and Multimedia Extensions

Subword parallelism is when a wide data word is operated on in parallel.

This is the same as SIMD or data-level parallelism.

One instruction operates on multiple data items.





MMX (MultiMedia eXtension), first SIMD by Intel Pentium processors (introduced 1997). Only on Integers.

3D Now! AMD, included single-precision floating-point (1998)

SSE (Streaming SIMD Extension) introduced by Intel in Pentium III (year 1999). Included single-precision FP.

AVX (Advanced Vector Extension), supported by both Intel and AMD (processors available in 2011). Added support for 256 bits and double-precision FP.

NEON multimedia extension for ARMv7 and ARMv8 (32 registers 8 bytes wide or 16 registers 16 bytes wide)

Streaming SIMD Extension (SSE) and Advanced Vector Extension (AVX)

In SSE (and the later version SSE2), assembly instructions are using two-operand format.

```
addpd %xmm0, %xmm4
```

meaning: `%xmm4 = %xmm4 + %xmm0`
Note the reversed order.

Registers (e.g. `%xmm4`) are 128-bits in SSE/SEE2.

Added the "v" for vector to distinguish AVX from SSE and renamed registers to %ymm that are now 256-bit

"pd" means Packed Double precision FP. It can operate on as many FP that fits in the register

```
vaddpd  %ymm0, %ymm1, %ymm4
vmovapd %ymm4, (%r11)
```

Question: How many FP additions does `vaddpd` perform in parallel?

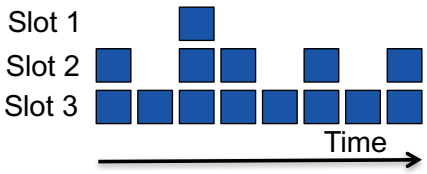
Answer: 4

AVX introduced three-operand format
Meaning: `%ymm4 = %ymm0 + %ymm1`

Moves the result to the memory address stored in %r11 (a 64-bit register). Stores the four 64-bit FP in consecutive order in memory.

Recall the idea of a multi-issue uniprocesor

Thread A | Thread B | Thread C



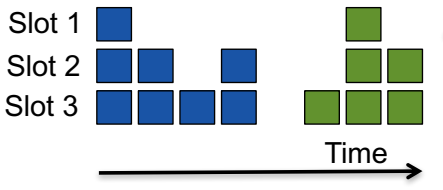
Typically, all functional units cannot be fully utilized in a single-threaded program (white space is unused slot/functional unit).

Hardware Multithreading

Thread A | Thread B | Thread C

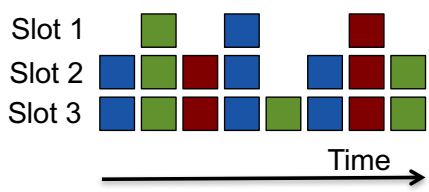
In a **multithreaded processor**, several hardware threads share the same functional units.

The purpose of multithreading is to hide latencies and avoid stalls due to cache misses etc.



Coarse-grained multithreading, switches threads only at costly stalls, e.g., last-level cache misses.

Cannot overcome throughput losses in short stalls.

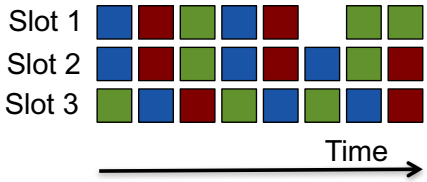


Fine-grained multithreading switches between hardware threads every cycle. Better utilization.

Simultaneous multithreading (SMT)

Simultaneous multithreading (SMT) combines multithreading with a multiple-issue, dynamically scheduled pipeline.

Thread A | Thread B | Thread C

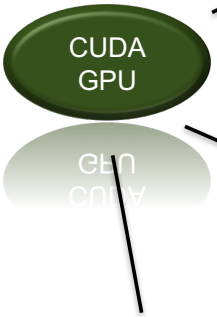


Can fill in the holes that multiple-issue cannot utilize with cycles from other hardware threads. Thus, better utilization.

Example: **Hyper-threading** is Intel's name and implementation of SMT. That is why a processor can have 2 real cores, but the OS shows 4 cores (4 hardware threads).

Graphical Processing Units (GPUs)

A Graphical Processing Unit (GPU) utilizes multithreading, MIMD, SIMD, and ILP. The main form of parallelism that can be used is data-level parallelism.



CUDA (Compute Unified Device Architecture) is a parallel computing platform and programming model from NVIDIA.

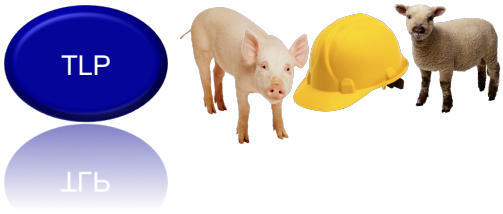
The parallelism is expressed as CUDA threads. Therefore, the model is also called **Single Instruction Multiple Thread (SIMT).**

A GPU consists of a set of **multithreaded SIMD processors** (called streaming multiprocessor using NVIDIA terms). For instance 16 processors.

The main idea is to execute a massive number of threads and to use **multithreading** to hide latency. However, the latest GPUs also include caches.

Part II

MIMD, Multicore, and Clusters



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Shared Memory Multiprocessor (SMP)

A Shared Memory Multiprocessor (SMP) has *a single physical address space* across all processors.

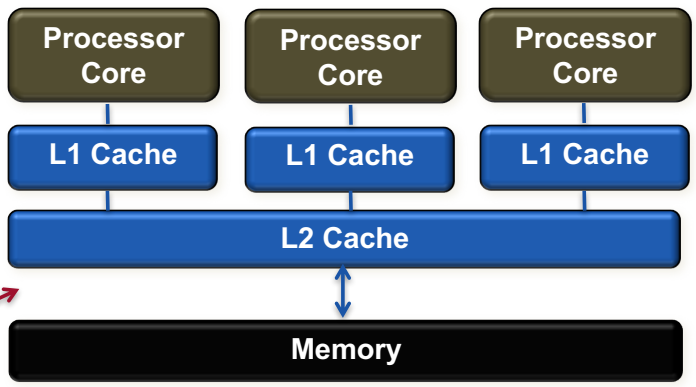
An SMP is almost always the same as a **multicore processor**.

In a **uniform memory access (UMA)** multiprocessor, the latency of accessing memory does not depend on the processor.

In a **nonuniform memory access (NUMA)** multiprocessor, memory can be divided between processor and result in different latencies.

Processors (cores) in a SMP communicate via **shared memory**.

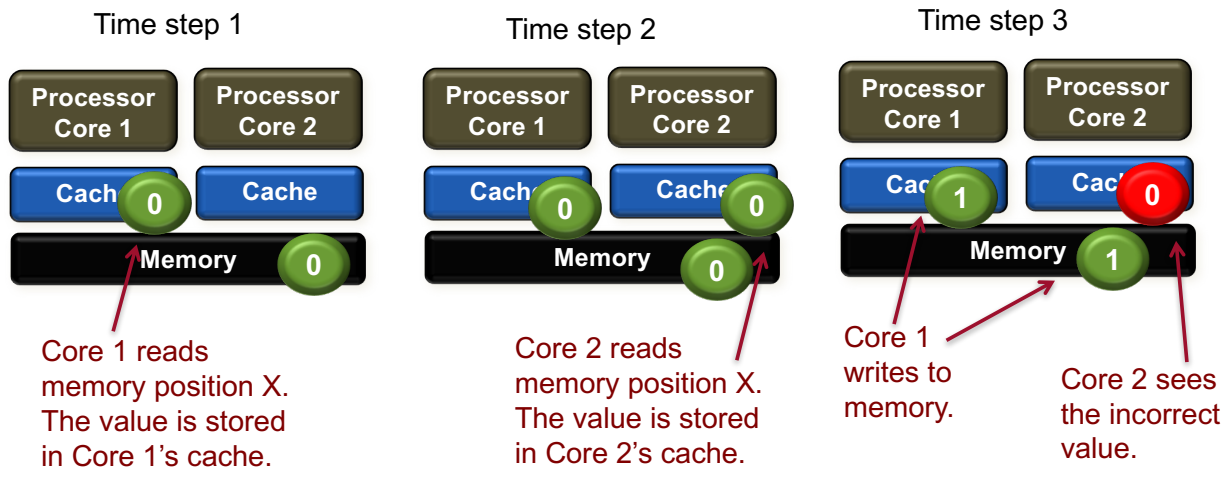
Alternative: Network on Chip (NoC)



Cache Coherence

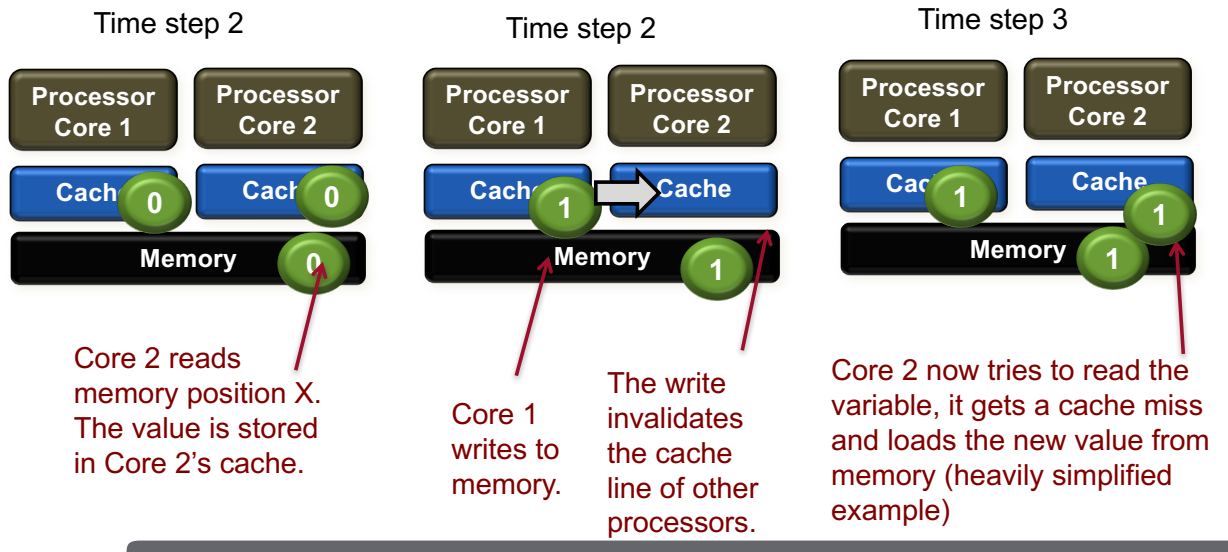
Different cores' local caches could result in that different cores see different values for the same memory address.

This is called the **cache coherency** problem.

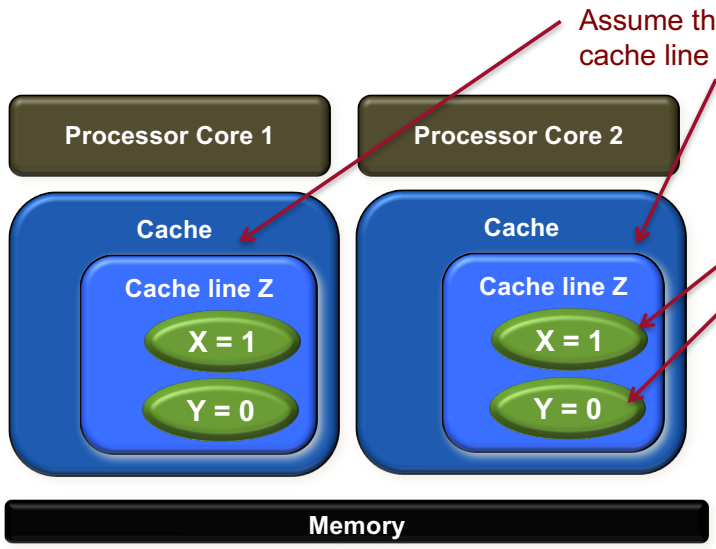


Snooping Protocol

Cache coherence can be enforced using a cache coherence protocol. For instance a *write invalidate protocol*, such as the **snooping protocol**.



False Sharing

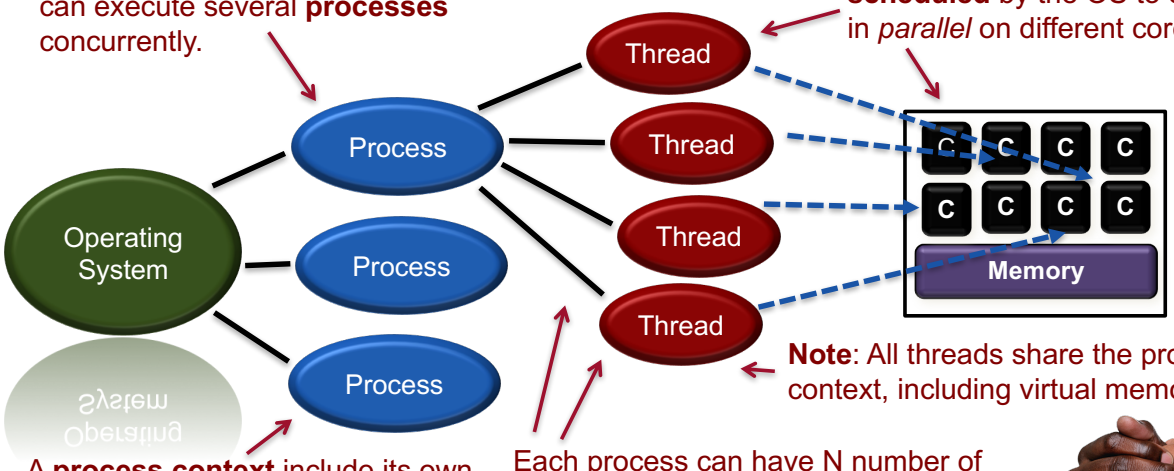


This is called **false sharing**.

Processes, Threads, and Cores

A modern **operating system (OS)** can execute several **processes** concurrently.

Concurrent threads are **scheduled** by the OS to execute in *parallel* on different cores.



Note: All threads share the process context, including virtual memory etc.

A **process context** include its own virtual memory space, IO files, read-only code, heap, shared library, process id (PID) etc.

Each process can have N number of **concurrent threads**. The **thread context** includes thread ID, stack, stack pointer, program counter etc.

Programming with Threads and Shared Variables

POSIX threads (pthreads) is a common way of programming concurrency and utilizing multicores for parallel computation.

```
#include <stdio.h>
#include <pthread.h>

volatile int counter = 0;

void *count(void *data){
  int i;
  int max = *((int*)data);
  for(i=0; i<max; i++)
    counter++;
  pthread_exit(NULL);
}
```

```
int main(){
  pthread_t tid1, tid2;
  int max;
  max = 40000;
  pthread_create(&tid1, NULL, count, &max);

  max = 60000;
  pthread_create(&tid2, NULL, count, &max);

  pthread_join(tid1, NULL);
  pthread_join(tid2, NULL);
  printf("counter = %d\n", counter);
  pthread_exit(NULL);
}
```

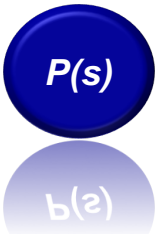
Creates two threads, each is counting a shared variable.

Exercise: What is the output?

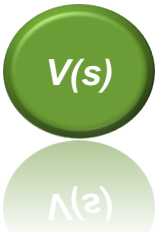
Answer: Different values each time…

Semaphores

A **semaphore** is a global variable that can hold a nonnegative integer value. It can only be changed by the following two operations.



P(s): If *s* > *0*, then decrement s and return. If *s* = *0*, then wait until *s* > *0*, then decrement *s* and return.



V(s): Increment *s*.

Note that the check and return of P(s) and increment of V(s) must be **atomic**, meaning that appears to be "instantaneously".

Semaphores were invented by Edsger Dijkstra, who was originally from the Nederland. P and V is supposed to stand for **Prolaag** (probeer te verlagen, "*try to reduce*") and **Verhogen** (*increase*).

Mutex

A semaphore can be used for mutual exclusion, meaning that only one thread can access a particular resource at the same time. Such **a binary semaphore** is called a **mutex**.

A global binary semaphore is initiated to 1.

```
semaphore s = 1

One of more threads execute:
  P(s);
     Code to
     protected...
  V(s);
```

One or more threads are executing code that needs to be protected.

P(s), also called wait(s), checks if the semaphore is nonzero. If so, **lock the mutex**, else wait.

In the critical section, it is ensured that not more than one thread can execute the code at the same time.

V(s), also called post, **unlocks the mutex** and increments the semaphore.

Programming with Threads and Shared Variables with Semaphores

Problem. We update the value max, that is also shared…

```
volatile int counter = 0;
sem_t *mutex;

void *count(void *data){
  int i;
  int max = *((int*)data);
  for(i=0; i<max; i++){
    sem_wait(mutex); /* P()*/
    counter++;
    sem_post(mutex); /* V(m)*/
  }
  pthread_exit(NULL);
}
```

Exercise: Is it correct this time?

```
int main(){
  pthread_t tid1, tid2;
  int max;

  mutex = sem_open("/semaphore", O_CREAT,
                   O_RDWR, 1);
  max = 40000;
  pthread_create(&tid1, NULL, count, &max);
  max = 60000;
  pthread_create(&tid2, NULL, count, &max);

  pthread_join(tid1, NULL);
  pthread_join(tid2, NULL);
  printf("counter = %d\n", counter);
  sem_close(mutex);
  pthread_exit(NULL);
}
```

Programming with Threads and Shared Variables with Semaphores

Correct solution…

```
volatile int counter = 0;
sem_t *mutex;

void *count(void *data){
  int i;
  int max = *((int*)data);
  for(i=0; i<max; i++){
    sem_wait(mutex); /*P()*/
    counter++;
    sem_post(mutex); /*V(m)*/
  }
  pthread_exit(NULL);
}
```

Simple solution. Use different variables.

```
int main(){
  pthread_t tid1, tid2;
  int max1 = 40000;
  int max2 = 60000;

  mutex = sem_open("/semaphore", O_CREAT,
                   0777, 1);
  pthread_create(&tid1, NULL, count, &max1);
  pthread_create(&tid2, NULL, count, &max2);

  pthread_join(tid1, NULL);
  pthread_join(tid2, NULL);
  printf("counter = %d\n", counter);
  sem_close(mutex);
  pthread_exit(NULL);
}
```

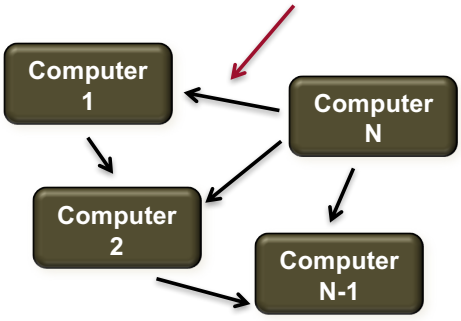

Clusters and Warehouse Scale Computers

Photo by Robert Harker

A **cluster** is a set of computers that are connected over a local area network (LAN). May be viewed as one large multiprocessor.

Warehouse-Scale Computers are very large cluster that can include 100 000 servers that act as one giant computer (e.g., Facebook, Google, Apple).

Clusters do not communicate over shared memory (as for SMP) but are using **message passing.**



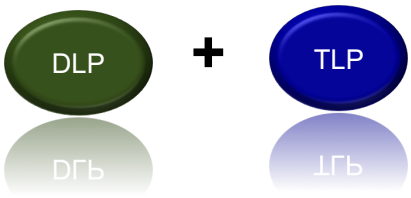
MapReduce is a programming model that is popular for batch processing.

1. **Map** applies a programmer defined function on all data items.
2. **Reduce** collects the output and collapse the data using another programmer defined function.

The map step is highly parallel. The reduce stage may be parallelized to some extent.

Part III

Parallelization in Practice



General Matrix Multiplication (GEMM)

Simple matrix multiplication

Uses matrix size n as a parameter and single dimension for performance.

```
void dgemm(int n, double* A, double* B, double* C){
  for(int i = 0; i < n; ++i)
    for(int j = 0; j < n; ++j){
      double cij = C[i+j*n];
      for(int k = 0; k < n; k++)
         cij += A[i+k*n] * B[k+j*n];
      C[i+j*n] = cij;
    }
}
```

Parallelizing GEMM

Unoptimized	Unoptimzed C version (previous page). Using one core.	1.7 GigaFLOPS (32x32) 0.8 GigaFLOPS (960x960)
SIMD	Use AVX instructions **`vaddpd`** and **`vmulpd`** to do 4 double precision floating-point operations in parallel.	6.4 GigaFLOPS (32x32) 2.5 GigaFLOPS (960x960)
ILP	AVX + unroll parts of the loop, so that the multiple-issue, out-of-order processor have more instructions to schedule.	14.6 GigaFLOPS (32x32) 5.1 GigaFLOPS (960x960)
Cache	AVX + unroll + blocking (dividing the problem into submatrices). This avoids cache misses.	13.6 GigaFLOPS (32x32) 12.0 GigaFLOPS (960x960)
Multi-core	AVX + unroll + blocking + multi core (multithreading using OpenMP)	23 GigaFLOPS (960x960, 2 cores) 44 GigaFLOPS (960x960, 4 cores) 174 GigaFLOPS (960x960, 16 cores)

Experiment by P&H on a 2.6GHz Intel Core i7 with Turbo mode turned off.

For details see P&H, 5th edtion, sections 3.8, 4.12, 5.14, and 6.12

Future perspective: MIMD, SIMD, ILP, and Caches

"For x86 computers, we expect to see two additional cores per chip every two years and the SIMD width to double every four years."

Hennessy & Patterson, Computer Architecture – A Quantitative Approach, 5th edition, 2013 (page 263)

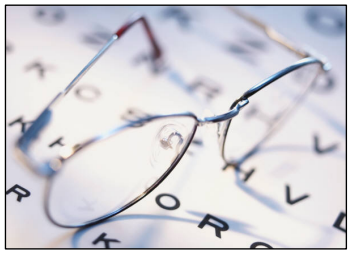
We must understand and utilize **both MIMD** and **SIMD** to gain maximal speedups in the future, although MIMD (multicore) has gained much more attention lately.

The previous example showed that **the way** we program for **ILP** and **caches**, also matters significantly.

It's about time to…

…relax

Reading Guidelines



Module 6: Parallel Processors and Programs

Lecture 12: Parallelism, Concurrency, Speedup, and ILP
- H&H Chapter 1.8, 3.6, 7.8.3-7.8.5
- P&H5 Chapters 1.7-1.8, 1.10, 4.10, 6.1-6.2
  or P&H4 Chapters 1.5-1.6, 1.8, 4.10, 7.1-7.2

Lecture 13: SIMD, MIMD, and Parallel Programming
- H&H Chapter 7.8.6-7.8.9
- P&H5 Chapters 2.11, 3.6, 5.10, 6.3-6.7
  or P&H4 Chapters 2.11, 3,6, 5.8, 7.3-7.7

Reading Guidelines
See the course webpage for more information.

Summary

Some key take away points:

- **SIMD and GPUs** can efficiently parallelize problems that have data-level parallelism
- **MIMD, Multicores, and Clusters** can be used to parallelize problems that have task-level parallelism.
- In the future, we should try to **combine** and use both **SIMD** and **MIMD**!

Thanks for listening!