# PARALLEL ARCHITECTURES

## Course “Parallel Computing”

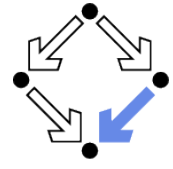
Wolfgang Schreiner

Research Institute for Symbolic Computation (RISC)

Wolfgang.Schreiner@risc.jku.at

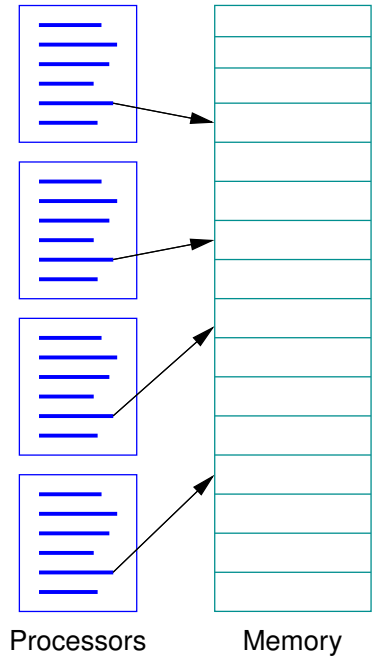
http://www.risc.jku.at

JOHANNES KEPLER UNIVERSITY LINZ



# Parallel Random Access Machine (PRAM)

- A simple abstract machine model.
  - Arbitrarily many processors execute same program on single shared memory.
  - Processors run synchronously in “lock-step”, possibly on different memory locations.
  - Cost of accessing memory is $O(1)$.
- Read/write conflicts have to be resolved.
  - EREW (exclusive read, exclusive write).
  - CREW (concurrent read, exclusive write).
  - CRCW (concurrent read, concurrent write) with multiple modes: common (only same value may be written), arbitrary (random value is written), priority (value of lowest numbered processor is written), . . .

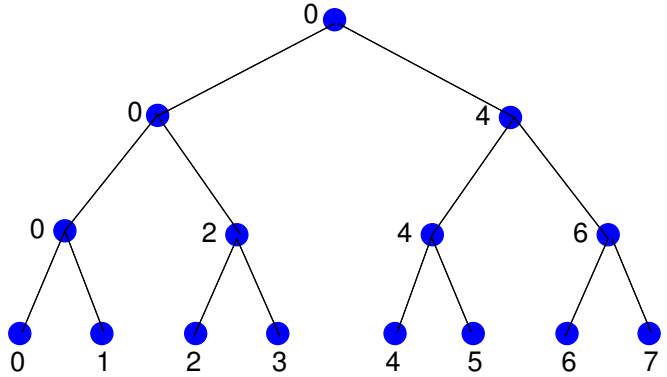



Traditional model for the analysis of parallel algorithms.

# A PRAM Program

Multiply two matrices $A$ and $B$ of dimension $n = 2^m$.

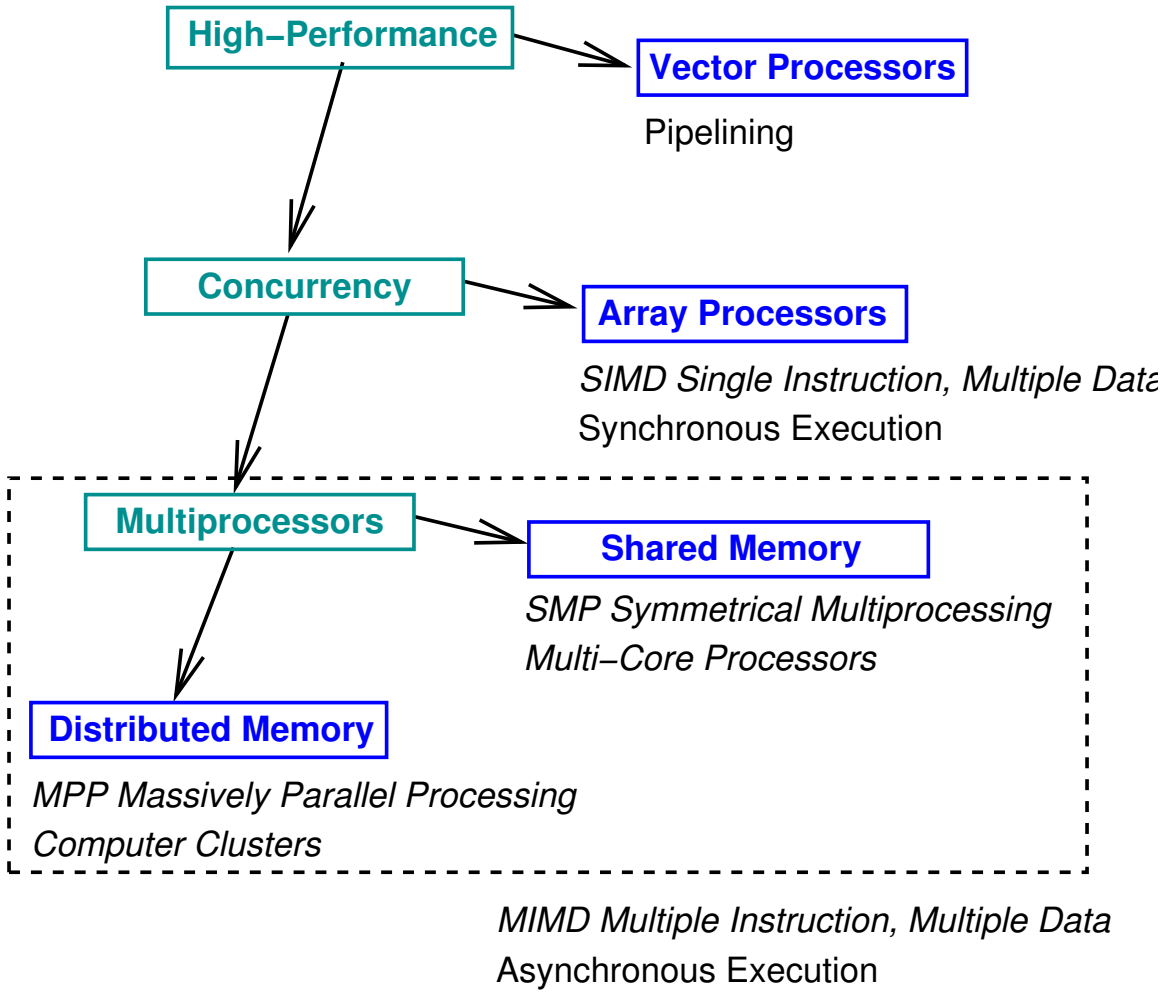
```
for i=0 to n-1 do in parallel
  for j=0 to n-1 do in parallel
    for k=0 to n-1 do in parallel
      P[i,j,k] = A[i,k]*B[k,j]
    for s=0 to m-1 do
       for t=0 to n-1 do in parallel
         if t%(2^(s+1)) = 0 then
           P[i,j,t] = P[i,j,t]+P[i,j,t+2^s]
    C[i,j] = P[i,j,0]
```




- First compute $P[i,j,k] = A[i,k] \times B[k,j]$ in time $O(1)$.
- Then compute $C[i,j] = \sum_k P[i,j,k]$ in time $O(\log n)$.
  - Computation of sum by $\log n$ stages of pairwise additions.

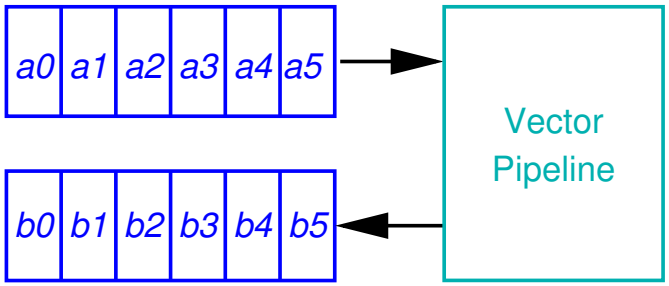
Matrix multiplication in time $O(\log n)$ with $O(n^3)$ processors.

# High-Performance Architectures

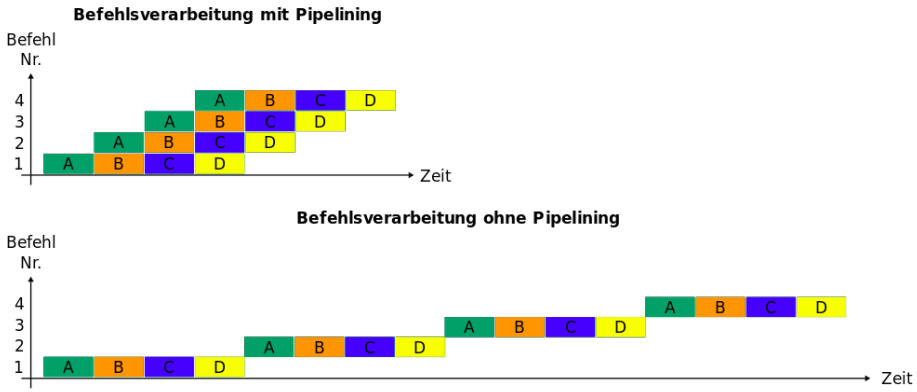



Flynn's Classification: SIMD versus MIMD.

# Vector Processors



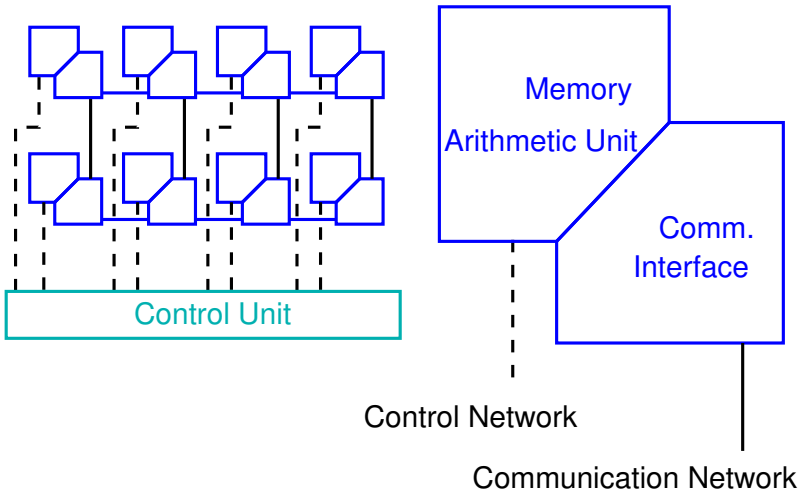

Vector Registers




*Pipeline (Processor), wikipedia.de*

Vectors of data are processed by pipelines; speedup is limited by the (fixed) pipeline depth.

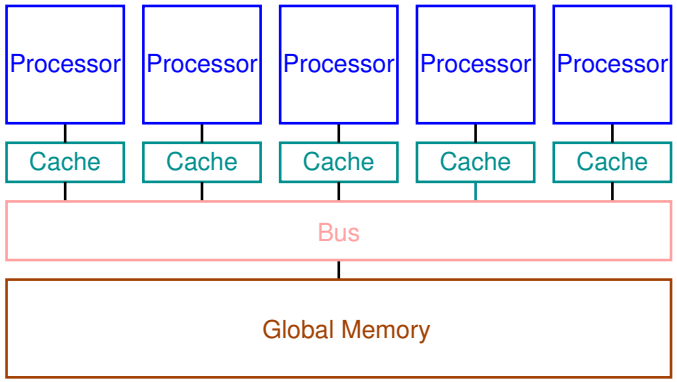
# Array Processors




```
plural double matrix_multiply(A, B)
  plural double A,B;
{
  int i;
  plural double C = 0.0;
  ...
  for (i=0; i<nxproc; i++) {
    C += A*B;
    xnetW[1].A = A;
    xnetN[1].B = B;
  }
  return C;
}
```

Array of arithmetic units operates in lock-step.

# Shared Memory Multi-Processors

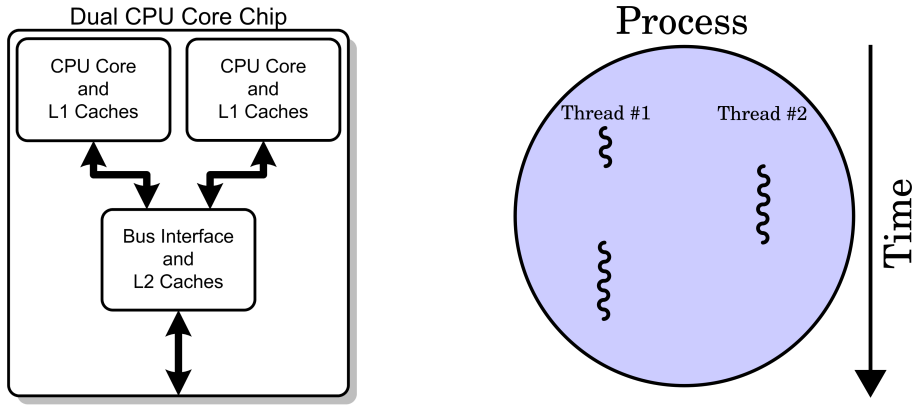



Alternative Term: SMP (Symmetric Multiprocessing)

- Multiple asynchronously operating processors.
- Single OS image schedules processes to processors.
- Single shared memory accessible via central bus.
  - Only one processor at a time can read/write memory.
  - Processors connected to bus via *coherent* caches.
  - *Snooping protocol:* whenever a cache sees another processor's write, it updates its local cache copies.

Scalable to 16 processsors or so.

# Multi-Core Processors

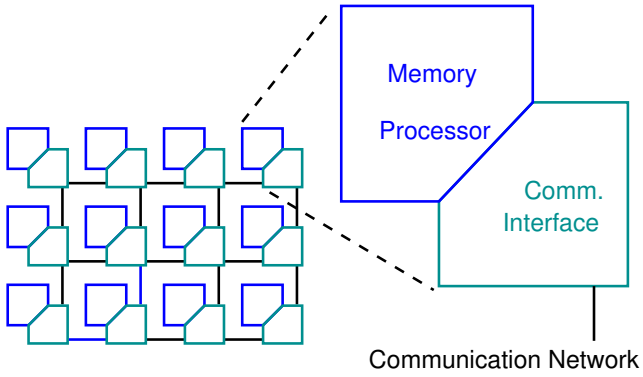



*Multi-core processor*, *Thread*, en.wikipedia.org

- Processors hold multiple processing units (“cores”).
  - Each core has a separate Level 1 cache.
  - Cores share a common Level 2 cache.
- Cores may execute multiple threads independently.
  - Threads: light-weight processes that can be independently scheduled for execution.
  - Processes: containers that hold multiple threads that have access to the same memory.

Today, actually every processor is by itself an SMP system.

# Distributed Memory Multi-Processors

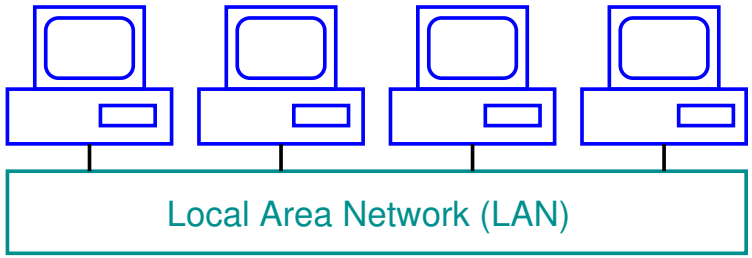



Alternative Term: MPP (Massively Parallel Processing)

- Many identical nodes that operate asynchronously.
  - Processor, local memory, communication interface.
- Each node runs its own OS image.
  - New processes are scheduled to the local processor.
- Nodes connected by high-bandwidth/low-latency network.
  - Different topologies (grid, tree, hypercube, . . . ).
  - Different network technologies (InfiniBand, OmniPath, . . . )
  - Remote processes can communicate by *message passing*.

Scalable to thousands of processors.

# Computer Clusters



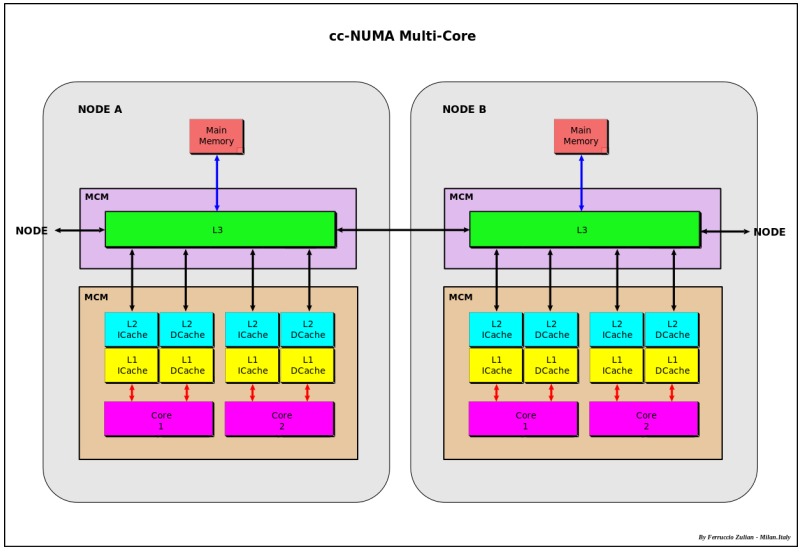

Also called “Beowulf” systems.

- A cheap alternative to MPP systems.
  - Each node is an independend of-the-shelf computer.
  - Connectivity provided by conventional Ethernet (or dedicated high-speed, e.g., InfiniBand) connections.
- A software stack implements MPP capabilities.
  - MPI, cluster managers, workload schedulers, . . .
- Special programming and data processing software.
  - Apache Hadoop/MapReduce, Apache Spark, . . .

Also MPPs are based on cluster-technology, so categories blur.

# Virtual Shared Memory Multi-Processors

- ccNUMA: “cache coherent non-uniform memory access”.
  - All local memories combined to single address space.
  - NUMA: access to remote memory is more expensive.
  - Directory keeps track of which nodes hold cache copies of which lines of local memory.
  - If local memory line is updated, nodes with copies are informed.



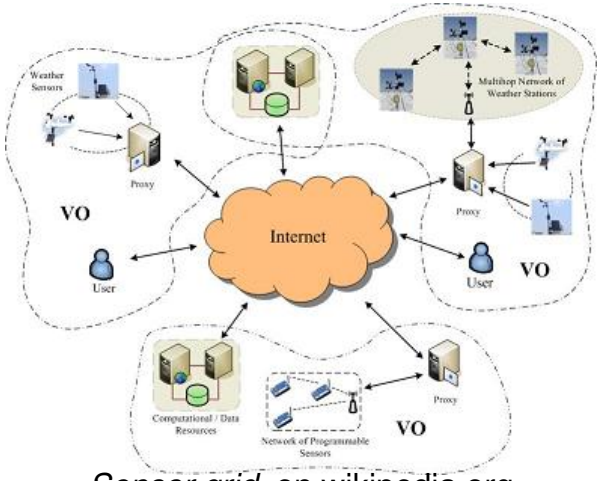

*Cache memory*, en.wikipedia.org

Implementation of SMP model on top of MPP hardware.

# Computational Grids

Infrastructures composed of resources from multiple networks.

- Heterogenous combination of various kinds of resources.
  - Computing power, data storage, sensors, . . .
  - Located in different administrative domains.
- Connected by “Grid middleware”.
  - Globus Toolkit, gLite, Unicore, . . .



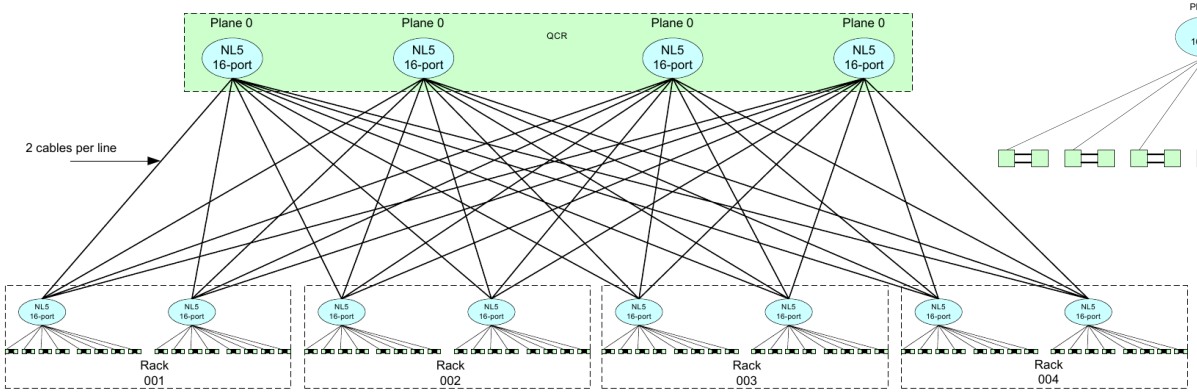

*Sensor grid*, en.wikipedia.org

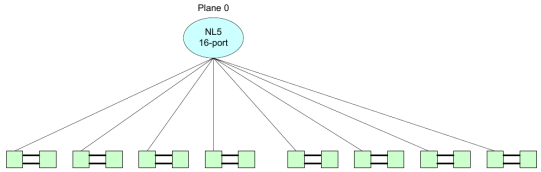
Software-based implementation of a (widely distributed) “virtual supercomputer”.

# The JKU Supercomputer “Mach”

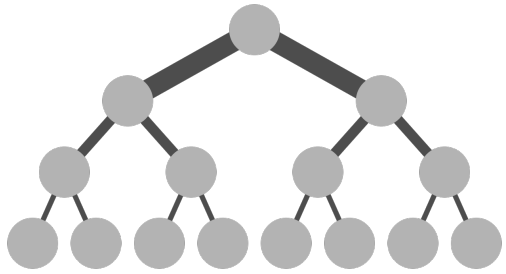
## SGI UV-1000 an der Johannes Kepler Universität

- **Rechnerarchitektur** — **SGI UV-1000 shared Memory/cc-numa Architektur**
- **Prozessortyp** — **Intel E78837 (Westmere - EX)**
  **X86-64, 2.66GHz / 8-Cores / 24MB Cache**
- **Prozessoranzahl** — **256 (2048 Cores)**
- **Speicher** — **16 TB shared Memory**
- **Betriebssystem** — **Linux – Suse SLES 11 mit SGI Performance Suite**
- **Prozessorleistung** — **gesamt Peak = 21,3 TFlops**
  **Spec_2006_INT Rate = ~39.000**
  **Spec_2006_FP Rate = ~29.000**
  **Stream = 5,8 Tbyte/s**
  **Linpack 100 = ~2,2 Gflop/s**
  **Linpack NxN = 18,5 Tflop/s**
- **Memory-Bandbreite** — **7,5 TB / s**
- **Bisection-Bandbreite** — **480 GB / s**



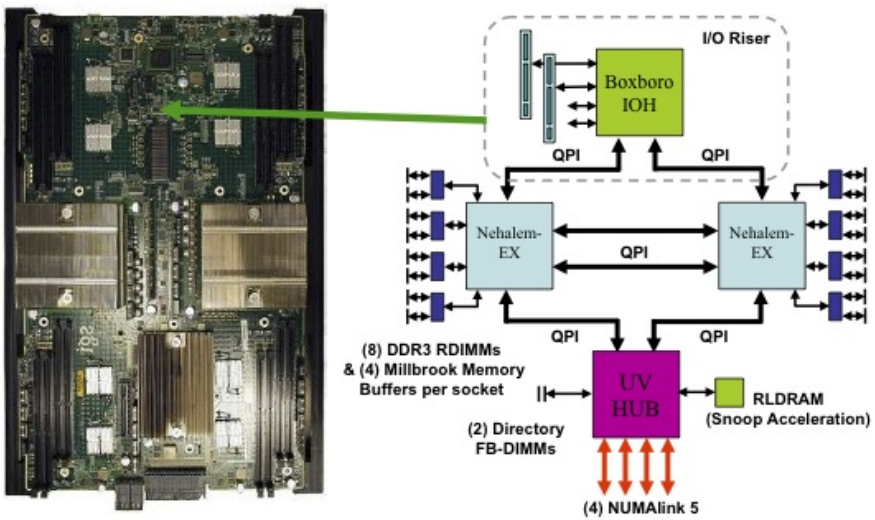



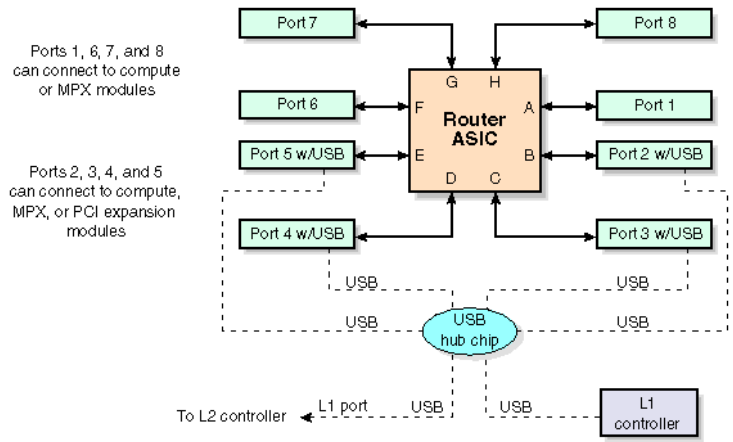

# The Interconnection Topology “Fat Tree”



*Fat tree*, en.wikipedia.org

- Data links nearer to the top have higher bandwidth.
- Approximately same bisection bandwidth at each level.
- Implemented by proprietary NUMAlink© technology.



# The Data Access Hierarchy

| Data Hierarchy Layer | Latency | Normalized Access Time |
|---|---|---|
| L1 Cache | 1.4 ns | $1\times$ |
| L3 Cache | 23 ns | $16\times$ |
| Local Memory | 75 ns | $53\times$ |
| Remote Memory | 1 $\mu$s | $700\times$ |
| Disk | 2 ms | $3.6{\cdot}10^6\times$ |

| Processors | Cores | Router Hops |
|---|---|---|
| 2 | 16 | 0 |
| 32 | 256 | 1 |
| 256 | 2048 | 3 |

Considering the placement of processes and data is important for achieving high performance on a NUMA system.

# Our Course Machine

Actually, we are going to use Mach's "little brother" Zusie.

- Configurations
  - 1 blade: 2×8=16 cores, 128 GB RAM, 24 MB cache.
  - Mach: 4×32=128 blades, 2048 cores, 16 TB RAM.
  - Zusie: 32 blades, 512 cores, 2 TB RAM.
- Login

```
ssh -X -l ... zusie.jku.at
```

  - Only from JKU network.
  - Another possibility for use from other networks.

Be considerate: this machine is shared by many users.

# Architecture Information

```
zusie> topology
Serial number: UV-00000044
Partition number: 0
      32 Blades
    1024 CPUs
 2002.99 Gb Memory Total
   64.00 Gb Max Memory on any blade
    0.00 Gb Partition Base Address
 4031.98 Gb Partition Last Address
       4 I/O Risers
       1 InfiniBand Controller
       4 Network Controllers
       2 SCSI Controllers
       8 USB Controllers
       1 VGA GPU
```

```
zusie> cat /proc/cpuinfo
processor       : 0
vendor_id       : GenuineIntel
cpu family      : 6
model           : 46
model name      : Intel(R) Xeon(R) CPU
stepping        : 6
cpu MHz         : 2267.156
cache size      : 24576 KB
....
processor       : 1023
vendor_id       : GenuineIntel
...
```

Hyper-Threading: 2 virtual cores per physical core,
thus 1024 virtual cores in total.

# User and Process Information

```
zusie> who
root     console      2016-07-11 09:06
ws98     pts/0        2016-09-30 12:29
hans     pts/2        2017-02-21 17:04
hans     pts/3        2017-02-22 08:24 (:2.0)
hans     pts/4        2017-01-13 14:31 (lilli.edvz.uni-linz.ac.at)
k313270  pts/5        2017-02-22 08:38 (amir.risc.uni-linz.ac.at)
k313270  pts/6        2017-02-22 08:42 (amir.risc.uni-linz.ac.at)
...

zusie> ps -fu k313270
UID          PID    PPID  C STIME TTY          TIME CMD
k313270    82369       1  0 Feb13 ?        00:00:00 ssh -N -L 9999:localhost:37
k313270   447710  447708  0 08:38 ?        00:00:00 sshd: k313270@pts/5
k313270   447711  447710  0 08:38 pts/5    00:00:00 -bash
k313270   449736  447800 99 08:50 pts/6    00:00:01 ps -fu k313270
```

Displays all users and all processes running on your behalf.

# Thread Information

```
zusie> top -H -u k313270
top - 08:52:17 up 226 days, 52 min, 21 users,  load average: 214.24, 227.65, 24
Tasks: 17374 total, 218 running, 17155 sleeping,   1 stopped,   0 zombie
Cpu(s): 91.5%us,  5.7%sy,  2.3%ni,  0.3%id,  0.1%wa,  0.0%hi,  0.1%si,  0.0%st
Mem:   2051061M total,  1288263M used,   762798M free,        0M buffers
Swap:   131071M total,      568M used,   130503M free,  1119275M cached

   PID USER      PR  NI  VIRT  RES  SHR S %CPU %MEM    TIME+  COMMAND
 449747 k313270   20   0 62600  15m 1880 R   77  0.0   0:02.51 top
  82369 k313270   20   0 60672 3432 2532 S    0  0.0   0:00.11 ssh
 447710 k313270   20   0  106m 2540 1476 S    0  0.0   0:00.00 sshd
 447711 k313270   20   0 55824 5684 2760 S    0  0.0   0:00.11 bash
 447799 k313270   20   0  106m 2556 1476 S    0  0.0   0:00.16 sshd
 447800 k313270   20   0 55824 5756 2800 S    0  0.0   0:00.28 bash
```

Displays all threads that are running on your behalf.

# CPU Sets

```
zusie> cpuset -i /Upper256sh
zusie> my_cpuset.csh
cpuset: /Upper256sh
allowed resource Ids:
Cpus_allowed_list: 256-511
Mems_allowed_list: 32-63
zusie> jkutop -s /Upper256sh
...
zusie> man jkutop
...
  JKUtop  is a rewrite of top geared towards speed, especially on big SMP
  systems. ... It also has no functionality  to
  display  individual  threads.  Thanks  to  these measures it achieves a
  noticeable speedup on ridiculously large SMP systems  compared  to  top
  from procps.
...
```

Creates new shell that confines processes to certain nodes.