

# Parallel and Distributed Programming Introduction

Kenjiro Taura

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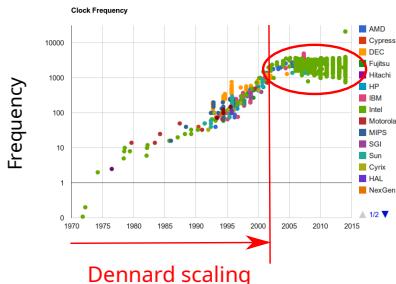
- 1 Why Parallel Programming?
- 2 What Parallel Machines Look Like, and Where Performance Come From?
- 3 How to Program Parallel Machines?

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# Why parallel?

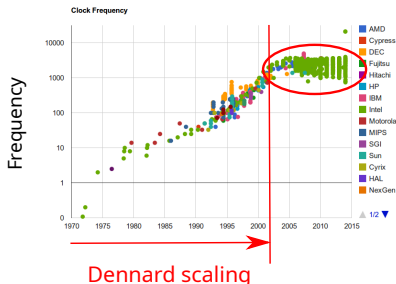
- frequencies no longer increase (end of Dennard scaling)



source: <http://cpudb.stanford.edu/>

# Why parallel?

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- techniques to increase performance (Instruction-Level Parallelism, or ILP) of serial programs are increasingly difficult to pay off (Pollack's law)

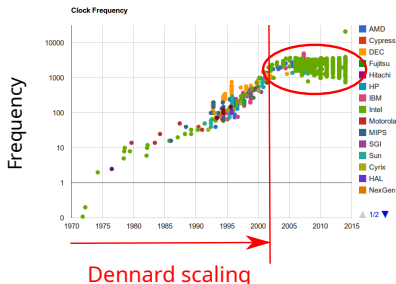


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# Why parallel?

- frequencies no longer increase (end of Dennard scaling)
- techniques to increase performance (Instruction-Level Parallelism, or ILP) of serial programs are increasingly difficult to pay off (Pollack's law)
- multicore, manycore, and GPUs are in part response to it

*have more transistors?  $\Rightarrow$  have more cores*



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# There are no serial machines any more

- virtually all CPUs are now *multicore*
- high performance accelerators (GPUs and Xeon Phi) run at even low frequencies and have many more cores (*manycore*)

# Processors for supercomputers are ordinary, perhaps even more so

1	Frontier - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE DOE/SC/Oak Ridge National Laboratory United States	8,730,112	1,102.00	1,685.65	21,100
2	Supercomputer Fugaku - Supercomputer Fugaku, A64FX 48C 2.26GHz, Tofu interconnect D, Fujitsu RIKEN Center for Computational Science Japan	7,630,848	442.01	537.21	29,899
3	LUMI - HPE Cray EX235a, AMD Optimized 3rd Generation EPYC 64C 2GHz, AMD Instinct MI250X, Slingshot-11, HPE EuroHPC/CSC Finland	1,110,144	151.90	214.35	2,942
4	Summit - IBM Power System AC922, IBM POWER9 22C 3.07GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM DOE/SC/Oak Ridge National Laboratory United States	2,414,592	148.60	200.79	10,096
5	Sierra - IBM Power System AC922, IBM POWER9 22C 3.10GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM / NVIDIA / Mellanox DOE/NNSA/LLNL United States	1,572,480	94.64	125.71	7,438
6	Sunway TaihuLight - Sunway MPP, Sunway SW26010 260C 1.45GHz, Sunway, NRCPC National Supercomputing Center in Wuxi China	10,649,600	93.01	125.44	15,371

<https://www.top500.org/lists/top500/2022/06/>



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- existing serial SWs do not get (dramatically) faster on new CPUs
- just writing it in C/C++ goes nowhere close to machine's potential performance, unless you know how to exploit parallelism of the machine
- you need to understand
  - does it use multiple cores (and how the work is distributed)?
  - does it use SIMD instructions?
  - does it have good instruction level parallelism?

# Example: matrix multiply

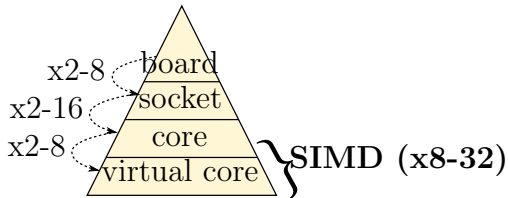
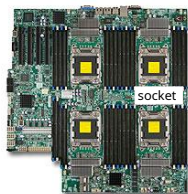
- how much can we improve this on a single machine?

```
1 void gemm(long M, long N, long K,  
2           float A[M][K], float B[K][N], float C[M][N]) {  
3     long i, j, k;  
4     for (i = 0; i < M; i++)  
5       for (j = 0; j < N; j++)  
6         for (k = 0; k < K; k++)  
7           C[i][j] += A[i][k] * B[k][j];  
8 }
```

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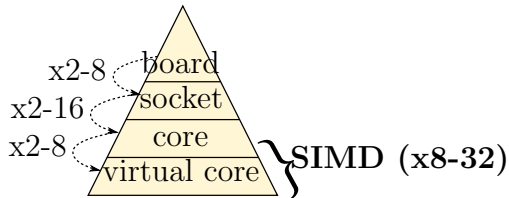
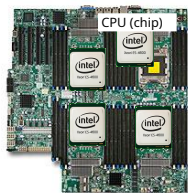
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# What a single parallel machine (node) looks like



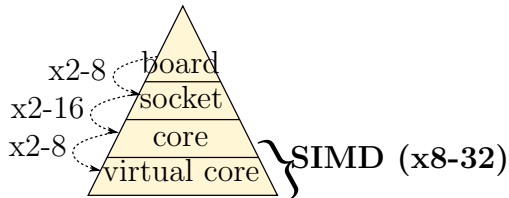
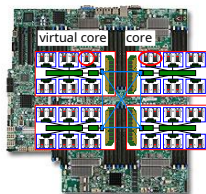
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- a single instruction applies the same operation (e.g., add

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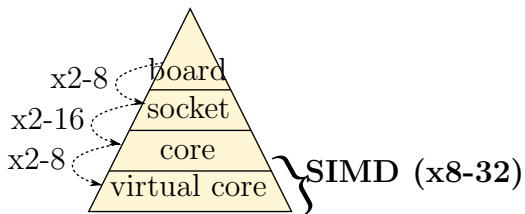
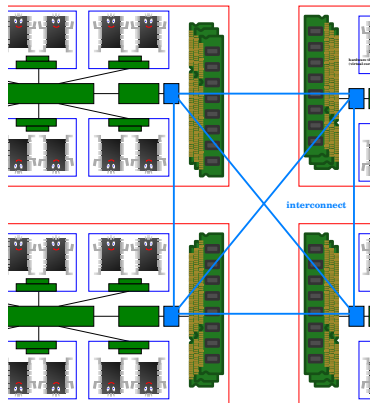
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# What a machine looks like



- performance comes from *multiplying* parallelism of many levels
- parallelism (per CPU)

# What a GPU looks like?

## Streaming Multiprocessor



- a GPU consists of many *Streaming Multiprocessors (SM)*
- each SM is highly multithreaded and can interleave many *warps*
- each warp consists of 32 *CUDA threads*; in a single cycle, threads in a warp can execute the same single instruction

# What a GPU looks like?

- despite very different terminologies, there are more commonalities than differences

GPU	CPU
SM multithreading in an SM a warp (32 CUDA threads)	core simultaneous multithreading a thread executing SIMD instructions multiple instructions from a single thread

- there are significant differences too, which we'll cover later

# How much parallelism?

- Intel CPUs

arch model	SIMD width SP/DP	FMAs /cycle /core	freq GHz	core	peak GFLOPS SP/DP	TDP W
Haswell E78880Lv3	8/4	2	2.0	18	1152/576	115
Broadwell 2699v4	8/4	2	2.2	22	1548/604	145
Cascade Lake 9282	16/8	2	2.6	56	9318/4659	400
Ice Lake 8368	16/8	2	2.4	38	5836/2918	270

- NVIDIA GPUs (numbers are without Tensor Cores)

arch model	threads /warp	FMAs /cycle /SM SP/DP	freq GHz	SM	peak GFLOPS SP/DP	TDP W
Pascal P100	32	2/1	1.328	56	9519/4760	300
Volta v100	32	2/1	1.530	80	15667/7833	300
Ampere A100	32	2/1	1.410	108	19353/9676	400

# Peak (SP) FLOPS

Ice Lake 8368

$$\begin{aligned} &= (2 \times 16) \text{ [flops/FMA insn]} \\ &\times 2 \text{ [FMA insns/cycle/core]} \\ &\times 2.4\text{G [cycles/sec]} \\ &\times 38 \text{ [cores]} \\ &= 5836 \text{ GFLOPS} \end{aligned}$$

A100

$$\begin{aligned} &= (2 \times 32) \text{ [flops/FMA insn]} \\ &\times 2 \text{ [FMA insns/cycle/SM]} \\ &\times 1.41\text{G [cycles/sec]} \\ &\times 108 \text{ [SMs]} \\ &= 19353 \text{ GFLOPS} \end{aligned}$$

# NVIDIA: Tensor Cores

- performance shown so far is limited by the fact that a single (FMA) instruction can perform 2 flops (1 multiply + 1 add)
- Tensor Core, a special execution unit for a small matrix-multiply-add, changes that
- A100's each Tensor Core can do  $C = A \times B + C$  (where  $A : 4 \times 4$ ,  $B : 4 \times 8$ ) per cycle ( $A : 4 \times 4$  TF32,  $B : 4 \times 8$  TF32,  $C$  and  $D$  are SP)

$$2 \times 4 \times 4 \times 8 = 256 \text{ flops/cycle}$$

- each SM of A100 GPU has 4 Tensor Cores, so a single A100 device can do

$$\begin{aligned} & (2 \times 4 \times 4 \times 8) \text{ [flops/cycle]} \\ & \times 1.41\text{G [cycles/sec]} \\ & \times 4 \times 108 \text{ [Tensor Cores]} \\ & = 155934.72 \text{ GFLOPS} \end{aligned}$$

- processors' performance improvement is getting less and less “generic” or “transparent”
  - frequency + instruction level parallelism
    - explicit parallelism (multicore/manycore)
    - special execution unit for macro operations (e.g., MMA)
    - application-specific instructions (?)
- performance is getting more and more dependent on programming

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# So how to program it?

- no matter how you program it, you want to maximally utilize all forms of parallelism
- “how” depends on devices and programming languages

# Language constructs for multiple cores / GPUs

from low level to high levels

- (CPU) OS-level threads
- (GPU) CUDA threads
- **SPMD**  $\approx$  the entire program runs with  $N$  threads
- **parallel loops**
- dynamically created **tasks**
- internally parallelized **libraries** (e.g., matrix operations)
- high-level languages executing pre-determined operations (e.g., matrix operations, **map & reduce**-like patterns, deep learning) in parallel

# Language constructs for CPU SIMD

from low level to high levels

- assembly
- intrinsics
- vector types
- vectorized loops
- internally vectorized libraries (e.g., matrix operations)

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those who want to:

- have a first-hand experience in parallel and high performance programming (OpenMP, CUDA, SIMD, ...)

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- understand when you can get “close-to-peak” CPU/GPU performance and how to get it (SIMD and instruction level parallelism)

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- learn many reasons why you don’t get good parallel performance

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- understand when you can get “close-to-peak” CPU/GPU performance and how to get it (SIMD and instruction level parallelism)
- learn many reasons why you don’t get good parallel performance
- have a good understanding about caches and memory and why they matter so much for performance