Tools Seminar

Week 10 - Parallel Computing

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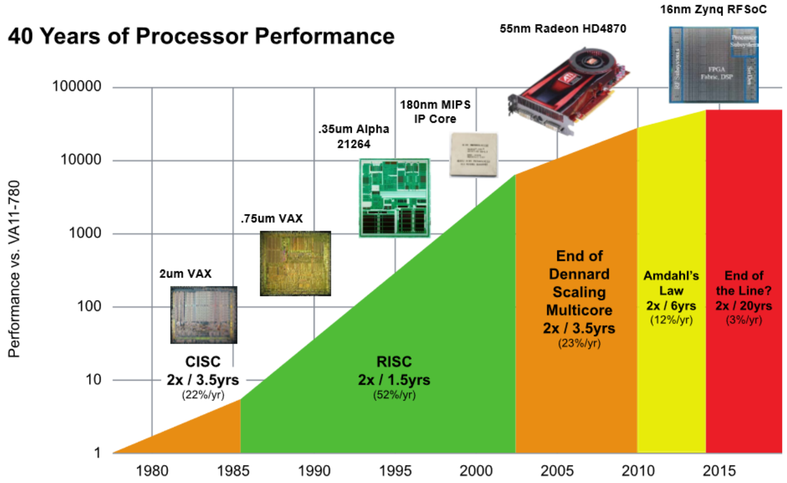
Introduction

Challenges: The End of Moore's Law and Scaling



Source: John Hennessy and David Patterson, Computer Architecture: A Quantitative Approach, 6/e 2018

* That's why Intel is called "toothpaste factory" now

The End of Moore's Law and Scaling

This shift toward **increasing parallelism** *is not a triumphant stride forward based on breakthroughs in novel software and architectures for parallelism; instead, this plunge into parallelism is actually a* **retreat** *from even greater challenges that thwart efficient silicon implementation of traditional uniprocessor architectures.*
— The Landscape of Parallel Computing Research: A View from Berkeley, 2006

The End of Moore's Law and Scaling

This shift toward **increasing parallelism** *is not a triumphant stride forward based on breakthroughs in novel software and architectures for parallelism; instead, this plunge into parallelism is actually a* **retreat** *from even greater challenges that thwart efficient silicon implementation of traditional uniprocessor architectures.*
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- All the CPUs now have multiple cores, so the system always works in parallel!
- Multicore processors put burdens from hardware to software, which needs programmers to code **parallel programs**.

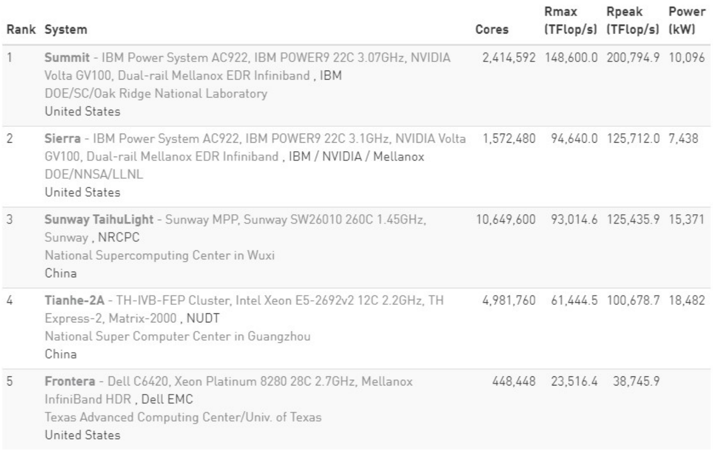
Parallel Computing

Tightly associated with scientific computing (big data!)

- Computational biology (gene, protein)
- Weather/Climate prediction
- Ocean circulation
- Astronomy
- Material
- Physics

Supercomputer itself is a highly distributed parallel architecture

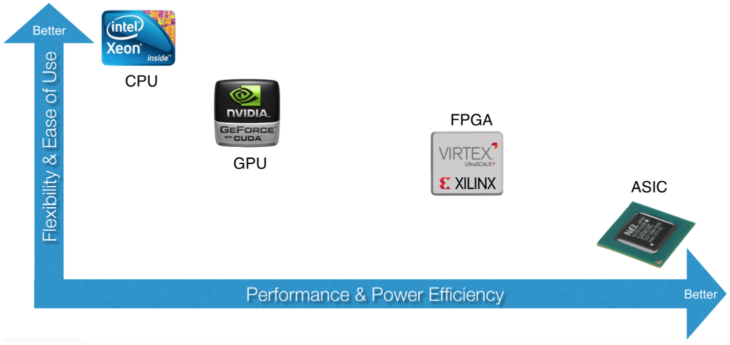
Supercomputing



Rank	System	Cores	Rmax (TFlop/s)	Rpeak (TFlop/s)	Power (kW)
1	**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	148,600.0	200,794.9	10,096
2	**Sierra** - IBM Power System AC922, IBM POWER9 22C 3.1GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband , IBM / NVIDIA / Mellanox DOE/NNSA/LLNL United States	1,572,480	94,640.0	125,712.0	7,438
3	**Sunway TaihuLight** - Sunway MPP, Sunway SW26010 260C 1.45GHz, Sunway , NRCPC National Supercomputing Center in Wuxi China	10,649,600	93,014.6	125,435.9	15,371
4	**Tianhe-2A** - TH-IVB-FEP Cluster, Intel Xeon E5-2692v2 12C 2.2GHz, TH Express-2, Matrix-2000 , NUDT National Super Computer Center in Guangzhou China	4,981,760	61,444.5	100,678.7	18,482
5	**Frontera** - Dell C6420, Xeon Platinum 8280 28C 2.7GHz, Mellanox InfiniBand HDR , Dell EMC Texas Advanced Computing Center/Univ. of Texas United States	448,448	23,516.4	38,745.9	

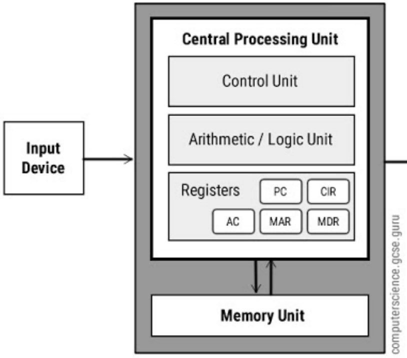
Top 500 List November 2019

Different hardware

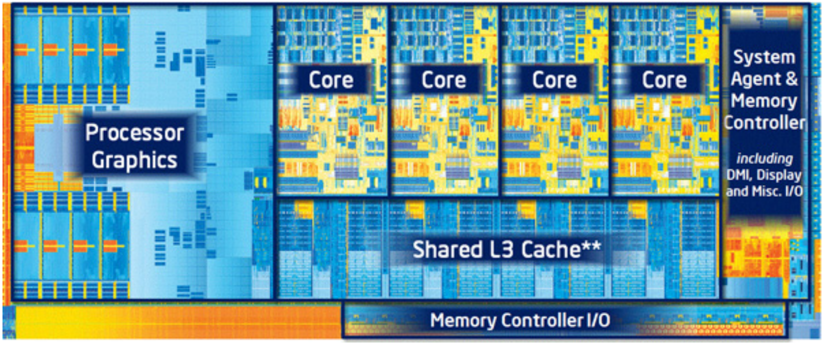


- CPU (Central Processing Unit): Intel, AMD, Arm
- GPU (Graphical Processing Unit): Intel, Nvidia
- FPGA (Field-Programmable Gate Array): Intel (Altera), Xilinx
- ASIC (Application-Specific Integrated Circuit): Intel, Samsung, Quantum, Hisilicon

Von Neumann Architecture

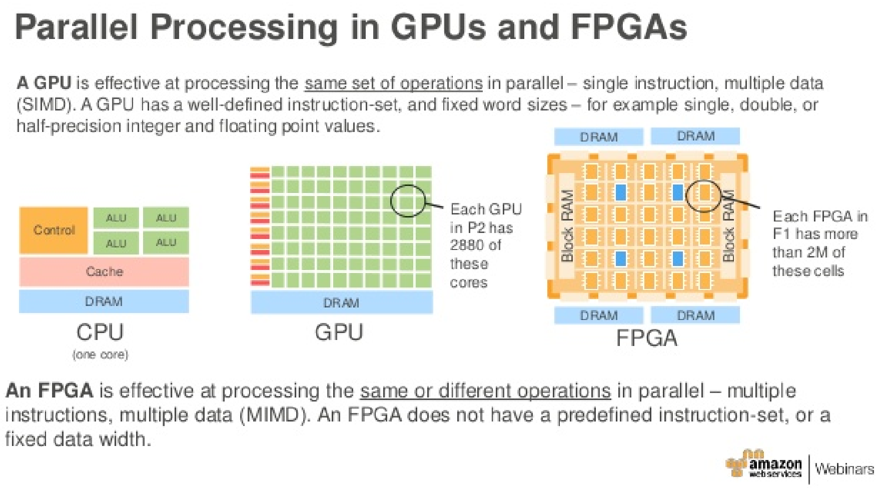


CPU Architecture



Intel core i7 CPU (Ivy Bridge)

* See CSAPP



Parallel Processing in GPUs and FPGAs

A GPU is effective at processing the same set of operations in parallel – single instruction, multiple data (SIMD). A GPU has a well-defined instruction-set, and fixed word sizes – for example single, double, or half-precision integer and floating point values.

An FPGA is effective at processing the same or different operations in parallel – multiple instructions, multiple data (MIMD). An FPGA does not have a predefined instruction-set, or a fixed data width.

- CPU & GPU: Traditional von Neumann architecture with instruction interpretation overheads
- FPGA: Directly program **circuits**!

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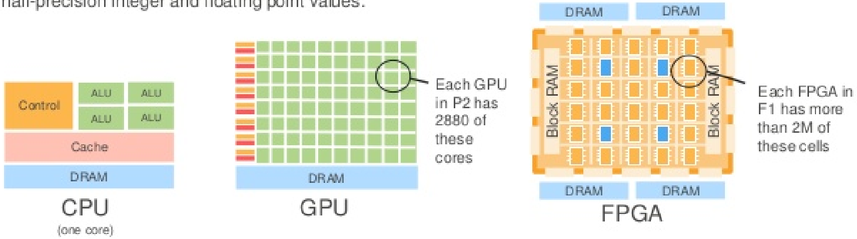

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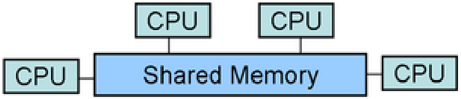
- CPU & GPU: Traditional von Neumann architecture with instruction interpretation overheads
- FPGA: Directly program **circuits**!

Shared-Memory & Distributed-Memory

Shared-memory



Distributed-memory

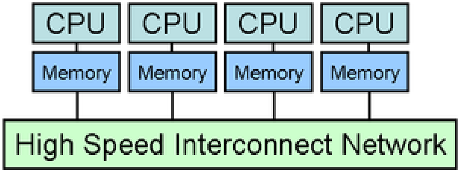


Fig source: Parallel Computing: Introduction to MPI

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Shared-Memory Parallelism

Check your CPU

See how many CPU cores do you have

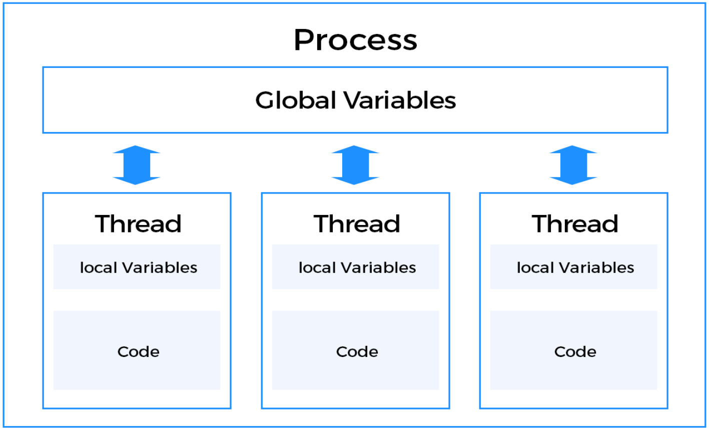
- Windows: Open the task manager
- Linux: `lscpu`

2.1

Multi-threads

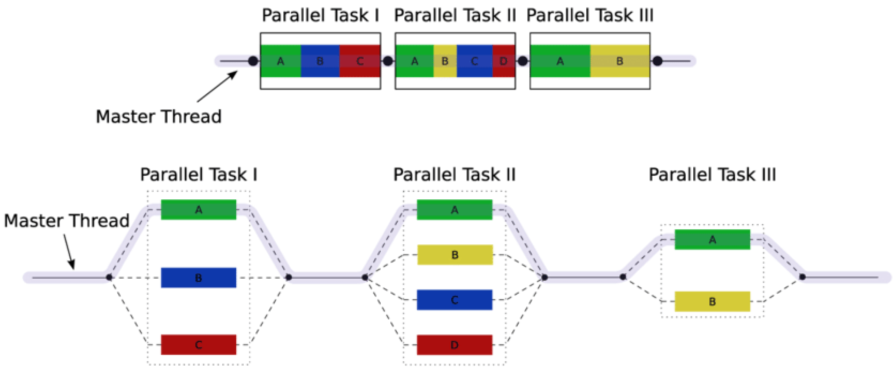
Process & Thread

Check `top`. Commonly, one program is a process.



Multi-threading

Fork-Join Model



- Fork: Dispatch tasks to each processor / thread
- Join: Synchronization, wait till all threads are done

pthread

POSIX (Portable Opearing System Interface for Unix)

- `<pthread.h>` is in Linux's system library and can be directly called

```
void *foo(void *arg)
{
    int* id = (int*) arg;
     printf ("My id is %d\n", *id);
}

int main()
{
    pthread_t  id [4];
    for (int i = 0; i < 4; ++i)
        // pass in function pointer and args
        pthread_create(&id[i], NULL,foo,&i);
    for (int i = 0; i < 4; ++i)
        pthread_join (&id[i], NULL);
    for (int i = 0; i < 4; ++i)
        pthread_exit (&id[i]) ;
}
```

Need to add `-lpthread` flag when compiling

C++11 thread

C++11 adds initial support for multi-threading in stl

```
#include <iostream>
#include <thread>
using namespace std;

void exec(int n){
    cout << "My id is" << n << endl;
}

int main(){
    thread myThread[4];
    for (int i = 0; i < 4; ++i)
        myThread[i] = thread(exec,i);
    for (int i = 0; i < 4; ++i)
        myThread[i].join();
}
```

Race Condition

Be careful of the shared data

Thread A	Thread B
···	···
Count++	Count−−
···	···

Thread A		Thread B	
Load	Count	Load	Count
Add	#1	Sub	#1
Store	Count	Store	Count

- Critical section: That part of the program where the shared memory is accessed
- Need to avoid conflicts and make data consistent

Avoid Race Condition

Two basic methods:

- Corse-grained: Lock/mutex
- Fine-grained: Atomic operations

* There are lots of details about synchronization & consistency, please refer to books of OS

Mutex Operations in pthread

<pthread.h>

- `pthread_mutex_init(&mutex1,NULL)`
- `pthread_mutex_destroy(&mutex1)`
- `pthread_mutex_lock(&mutex1)`
- `pthread_mutex_unlock(&mutex1)`

<thread>

- `std::mutex g_display_mutex`
- `std::lock_guard<std::mutex> guard(g_display_mutex)`

Multi-threading in Python

- `threading.Thread`
- `multiprocessing.Process`
- `t1.start()`, `t1.join()`
- Global Interpreter Lock (GIL) limitation → CPython

  An interpreter that uses GIL always allows exactly one thread to execute at a time, even if run on a multi-core processor.

Ref: `https://realpython.com/intro-to-python-threading/`

2.2

OpenMP

OpenMP

OpenMP (Open Multi-Processing): Shared-memory programming model

- Set of parallel commands, library, and routines
- Simplify multi-threading programming
- A spec suitable for different devices from desktop to supercomputer
- gcc has initial support for OpenMP

OpenMP API

`#include <omp.h>` and only need to write compilation directives

```
#pragma omp <directive-name> [clause,...]
```

- `omp_get_thread_num`
- `omp_get/set_num_procs`
- `omp_get/set_num_threads`
- `#pragma omp parallel for`: The most commonly used!
- `#pragma omp ... private (<variable list>)`
- `#pragma omp ... reduction (op:list)`

OpenMP Example (Matrix Multiplication)

```
#pragma omp parallel num_threads(8)
for (int i = 0; i < m; ++i)
  for (int j = 0; j < n; ++j) {
    c[i][j] = 0.0;
    for (int k = 0; k < l; ++k)
      c[i][j] += a[i][j] * b[j][k];
  }
```

Compile with `-fopenmp`

OpenMP Example (Summation)

```
float sum(const float *a, size_t n)
{
    float total = 0.;

    #pragma omp parallel for reduction(+:total)
    for (size_t i = 0; i < n; i++) {
        total += a[i];
    }
    return total;
}
```

2.3

Cilk Plus

Intel Clik Plus

Intel Cilk Plus: A extremely light-weighted parallel framework

- `#include<cilk/cilk.h>`
- gcc 5.0+: `g++ -O3 -fcilkplus -lcilkrts <source>`
- Or compiled by Intel Compiler (icpc) — Better choice!
  - But from icpc 18.0, Intel uses Thread Building Block (TBB)

Only three keywords

- `cilk_spawn`: fork
- `cilk_sync`: join
- `cilk_for`: `parallel for`

Clik Example (Fibbonacci)

```
int fib(int n)
{
    if (n < 2)
        return n;
    int x = fib(n-1);
    int y = fib(n-2);
    return x + y;
}

int fib(int n)
{
    if (n < 2)
        return n;
    int x = cilk_spawn fib(n-1);
    int y = fib(n-2);
    cilk_sync;
    return x + y;
}
```

Cilk Runtime

The most powerful thing is Cilk runtime deploys **work-stealing** scheduling strategy, which greatly outperforms OpenMP's runtime

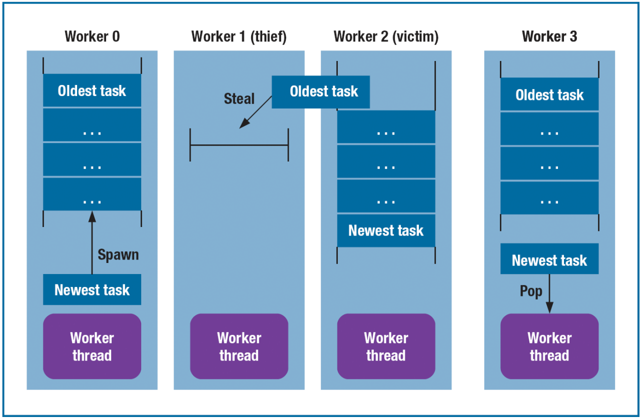


Fig source: Intel TBB

2.4

Finer-grained Parallelism

Parallelism

- Thread-Level Parallelism (TLP)
- Instruction-Level Parallelism (ILP)
    - Pipelining
    - Hyperscalar
    - Very Long Instruction Word (VLIW)
    - Vector processing
    - Out-of-Order (OoO) execution
    - Spectacular execution
- Data-Level Parallelism
    - SIMD (Single Instruction Multiple Data) array processor $\rightarrow$ GPU

* Please refer to Computer Architecture books / CSAPP

SIMD

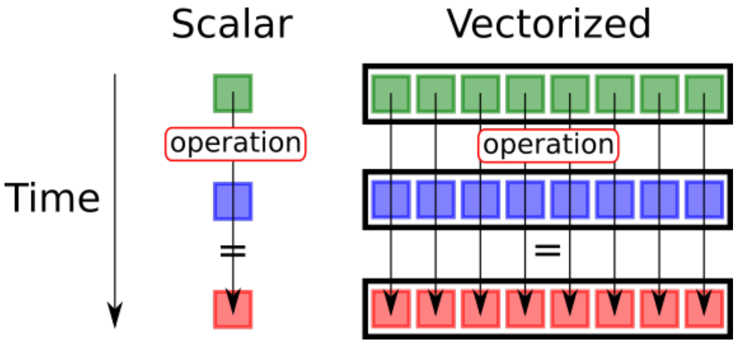


Fig source:
https://lappweb.in2p3.fr/~paubert/ASTERICS_HPC/6-6-1-985.html

Intel CPU SIMD Instruction Set

- MME (Multi Media Extensions): Pentium, 1996
- SSE (Streaming SIMD Extensions): Pentium III, 1999
- AVX (Advanced Vector Extensions): Sandy Bridge 2008
- AVX2: Haswell, 2011

Naming Conventions

`_mm<bit_width>_<name>_<data_type>`

- `<bit_width>`: the return size, 128 - empty, 256 - 256
- `<name>`: describes the operation performed by the intrinsic
- `<data_type>`: the function's primary arguments

Instructions	Description
ps	packed single-precision
pd	packed double-precision
epi8/epi16/epi32/epi64	signed integers
epu8/epu16/epu32/epu64	unsigned integers
si128/si256	unspecified vector
m128/m128i/m128d	input vector types

e.g. `_mm256_srlv_epi64`: 64-bit signed int → 256-bit vector

AVX Example

```c
#include <immintrin.h>
#include <stdio.h>

int main() {

    /* Initialize the two argument vectors */
    __m256 evens = _mm256_set_ps(2.0, 4.0, 6.0, 8.0, 10.0, 12.0, 14.0, 16.0);
    __m256 odds = _mm256_set_ps(1.0, 3.0, 5.0, 7.0, 9.0, 11.0, 13.0, 15.0);

    /* Compute the difference between the two vectors */
    __m256 result = _mm256_sub_ps(evens, odds);

    /* Display the elements of the result vector */
    float* f = (float*) &result; // type conversion
    printf("%f %f %f %f %f %f %f %f\n",
      f[0], f[1], f[2], f[3], f[4], f[5], f[6], f[7]);

    return 0;
}
```

Add `-mavx` flag when compiling

* Be careful that redundant movements reduce performance!

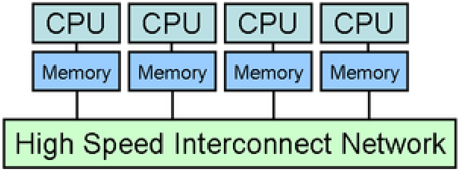
3

Distributed-Memory Parallelism

Message Passing Interface (MPI)

- All the machine execute the **same** program!
- Use condition to judge whether it needs to execute this piece of code
- Need to install MPI compiler
  - `#include<mpi.h>`
  - `mpicc`, `mpic++`
  - `mpirun -np 2 foo : -np 4 bar`

Distributed Memory Model



Each host has a rank

* Tianhe2 with millions of distributed nodes need to explicitly manage communication via MPI

MPI Hello World

```c
#include <mpi.h>

int main(int argc, char* argv[])
{
    int npes, myrank;
    MPI_Init(&argc, &argv);
    MPI_Comm_size(MPI_COMM_WORLD, &npes);
    MPI_Comm_rank(MPI_COMM_WORLD, &myrank);
    printf("From process %d out of %d, Hello World!\n", myrank,
        npes);
    MPI_Finalize();
}
```

Message Passing

Message communication is the central part of MPI

```
MPI_Send(
    void* data,
    int count,
    MPI_Datatype datatype,
    int  destination ,
    int tag,
    MPI_Comm communicator)

MPI_Recv(
    void* data,
    int count,
    MPI_Datatype datatype,
    int source,
    int tag,
    MPI_Comm communicator,
    MPI_Status* status)
```

MPI Example Program (Ping Pong)

```c
int ping_pong_count = 0;
int partner_rank = (world_rank + 1) % 2;
while (ping_pong_count < PING_PONG_LIMIT) {
    if (world_rank == ping_pong_count % 2) {
        // Increment the ping pong count before you send it
        ping_pong_count++;
        MPI_Send(&ping_pong_count, 1, MPI_INT, partner_rank, 0,
                MPI_COMM_WORLD);
        printf("%d sent and incremented ping_pong_count "
               "%d to %d\n", world_rank, ping_pong_count,
               partner_rank);
    } else {
        MPI_Recv(&ping_pong_count, 1, MPI_INT, partner_rank, 0,
                MPI_COMM_WORLD, MPI_STATUS_IGNORE);
        printf("%d received ping_pong_count %d from %d\n",
               world_rank, ping_pong_count, partner_rank);
    }
}
```

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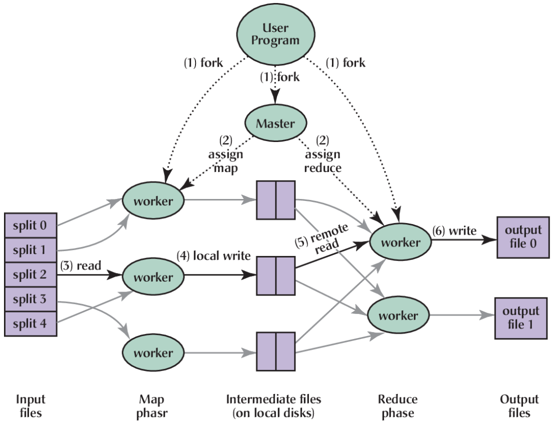
Parallel Computing Frameworks

Frameworks



- MapReduce: Big data programming model → Hadoop
- Spark: Better data management
- Ray: Machine Learning

5

Summary

Summary

- Introduction to parallelism
- Shared-memory: pthreads, OpenMP, Cilk, AVX
- Distributed-memory: MPI
- Parallel computing frameworks: MapReduce