FIT3143

LECTURE WEEK 1

INTRODUCTION TO PARALLEL COMPUTING

Overview

1. Parallel computing concept and applications
2. Parallel computing models
3. Distributed computing
4. Parallel computing performance
5. Parallel vs. distributed vs. asynchronous computing

Associated learning outcomes

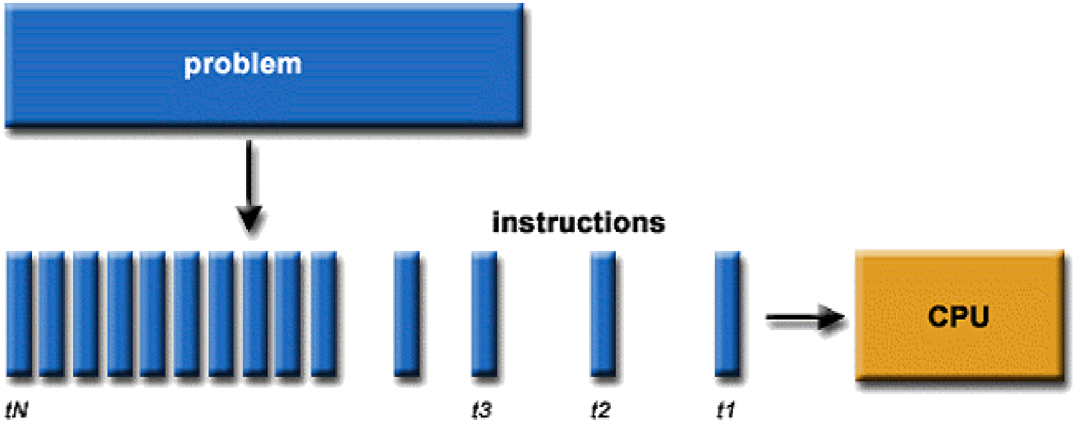
- Explain the fundamental principles of parallel computing architectures and algorithms (LO1)
- Analyze and evaluate the performance of parallel algorithms (LO4)

1. Parallel computing concept and applications

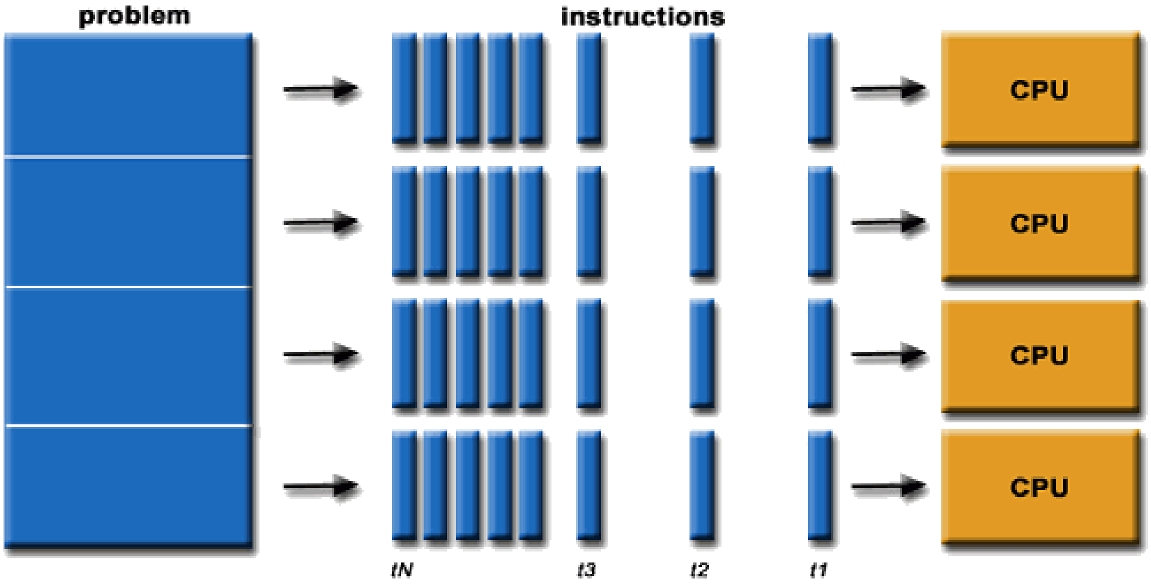
Definitions

A parallel computer is simply a single computer with multiple internal processors, or a group of multiple computers interconnected to form a coherent high-performance computing platform.

Parallel programming is programming multiple computers, or computers with multiple internal processors, to solve a problem at a greater computational speed than is possible with a single computer.



Serial Computing



Parallel Computing

Adapted from https://computing.llnl.gov/tutorials/parallel_comp/

The demand for computational speed

There is a continual demand for greater computational speed from a computer system than is currently possible.

Areas requiring great computational speed include **numerical modeling** and **simulation of scientific and engineering problems**.

Computations must be completed within a “**reasonable**” time period.

Grand challenge problems

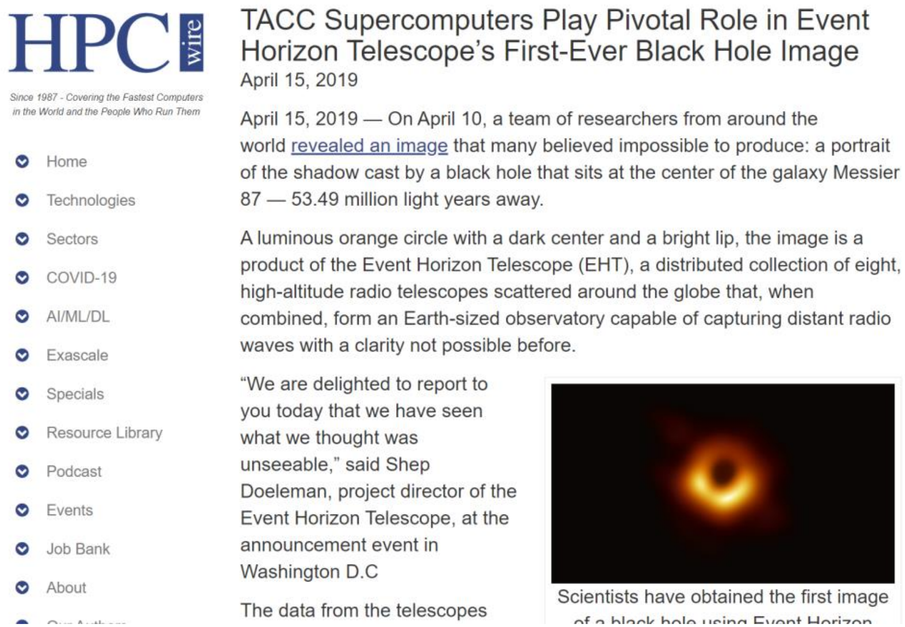
A **grand challenge problem** is one that cannot be solved in a reasonable amount of time with today’s computers.

For example, an execution time of 10 years is usually unacceptable.

Examples:

- Modeling large DNA structures
- Global weather forecasting
- Modeling motion of astronomical bodies

Computationally challenging problems



HPC wire

Since 1987 - Covering the Fastest Computers in the World and the People Who Run Them

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TACC Supercomputers Play Pivotal Role in Event Horizon Telescope's First-Ever Black Hole Image

April 15, 2019

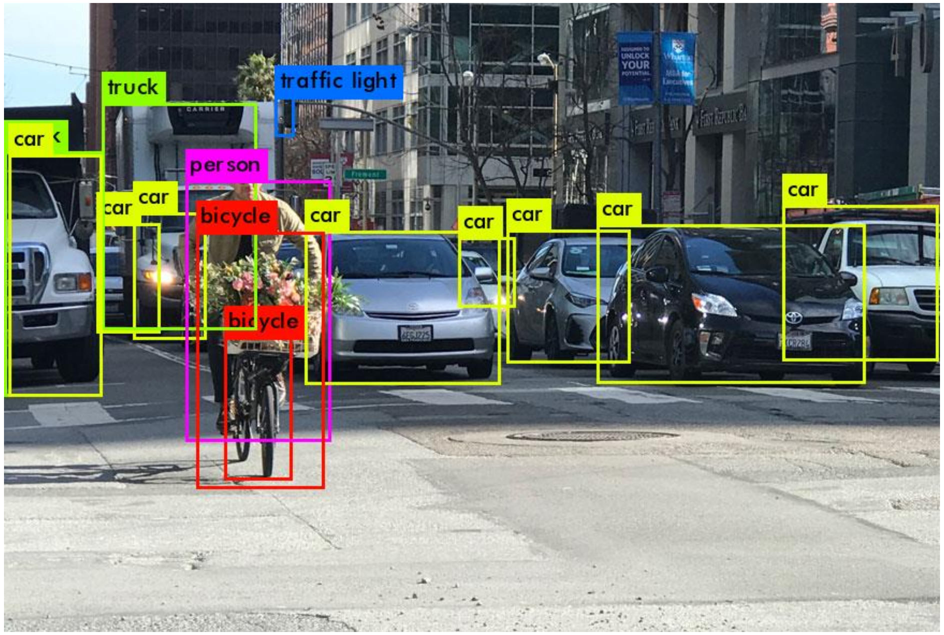
April 15, 2019 — On April 10, a team of researchers from around the world revealed an image that many believed impossible to produce: a portrait of the shadow cast by a black hole that sits at the center of the galaxy Messier 87 — 53.49 million light years away.

A luminous orange circle with a dark center and a bright lip, the image is a product of the Event Horizon Telescope (EHT), a distributed collection of eight, high-altitude radio telescopes scattered around the globe that, when combined, form an Earth-sized observatory capable of capturing distant radio waves with a clarity not possible before.

"We are delighted to report to you today that we have seen what we thought was unseeable," said Shep Doeleman, project director of the Event Horizon Telescope, at the announcement event in Washington D.C

Scientists have obtained the first image of a black hole using Event Horizon

The data from the telescopes



Reasons for not using existing serial machines

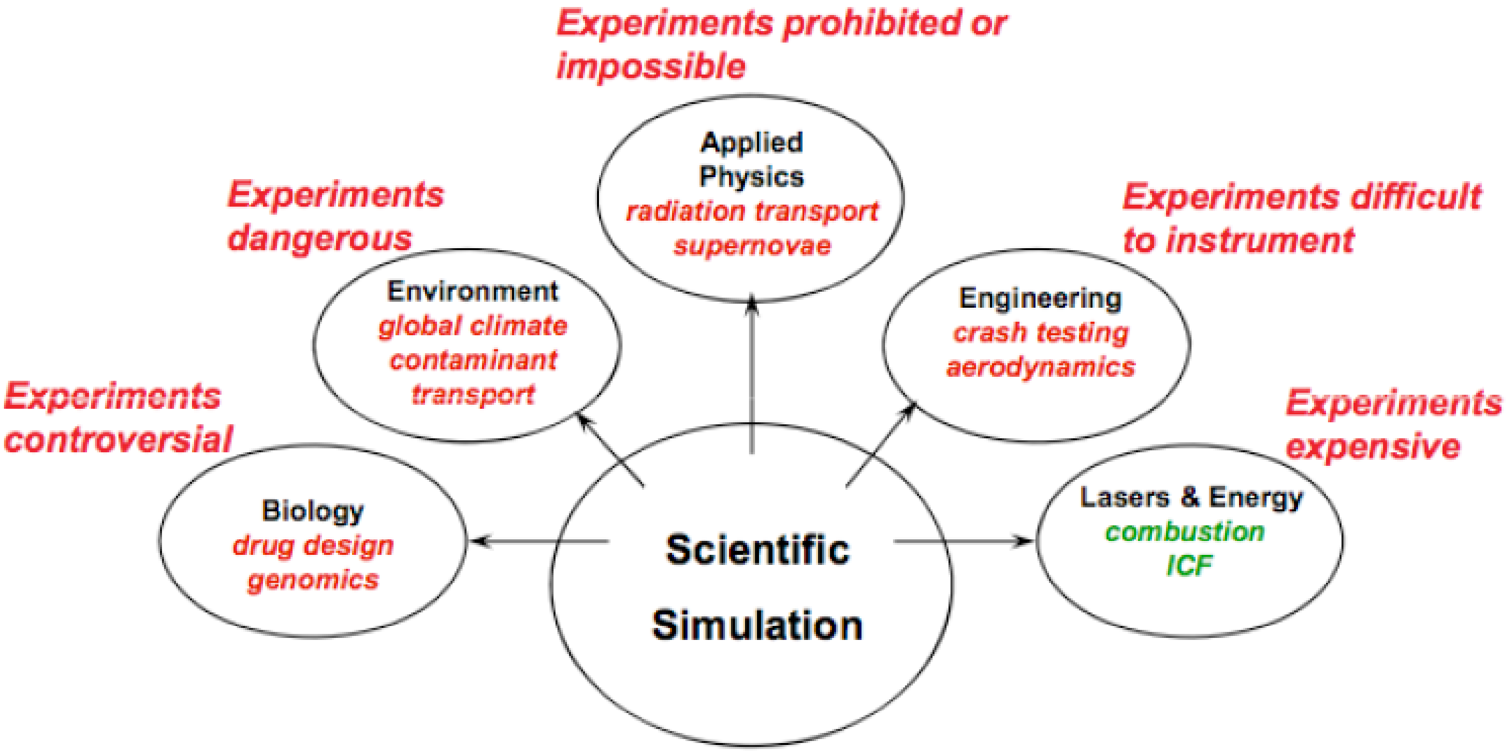
- May not be able to reach the solution **within a reasonable amount of time** if using a single Von Neumann machine.

- The **limits** imposed by both:
  - ➢ Physical constraints such as the speed of light
  - ➢ Cost of designing and manufacturing new chips.
    - - Current speed of chips - may reach a few billion Hz but will not grow enormously beyond that.

Reasons for using parallel machines

- With parallelism, much greater speeds can be achieved. The fastest computer in the world has a peak speed of about 415,530 Teraflops (https://top500.org/lists/top500/2020/06/). (flops: floating point instructions)
- The **enormous size** of the problems that are being investigated. These problems fall in many domains of **science, engineering**, and **economics**.
- To solve these problems requires carrying out huge numbers of computations, such as 10^{12}, 10^{14}, 10^{16} or even more. This number of computations cannot be done by any existing serial machine but is feasible to attack using parallel processing.

Why is Parallel Computing Important?



Source: Vivek Sarkar, Rice University, 2008

Some Particularly Challenging Computations

- **Science**
  - Global climate modelling
  - Biology: genomics; protein folding; drug design
  - Astrophysical modelling
  - Computational Chemistry
  - Computational Material Sciences and Nanosciences
- **Engineering**
  - Semiconductor design
  - Earthquake and structural modelling, remote sensing
  - Computation fluid dynamics (airplane design) & Combustion (engine design)
  - Simulation
  - Deep learning
  - Game design
  - Telecommunications (e.g. Network monitoring & optimization)
  - Autonomous systems
- **Business**
  - Financial derivatives and economic modelling
  - Transaction processing, web services and search engines
  - Analytics
- **Defense**
  - Nuclear weapons -- test by simulations
  - Cryptography

Source: Vivek Sarkar, Rice University, 2008

Why Parallelism is now necessary for Mainstream Computing?

- In single core processor, the performance of the processor will not gain much simply by the increasing operating frequency:
  - **Memory wall**

    The processor was incapable of optimizing the performance by increasing the operating frequency as the actual cause is the increasing gap between the CPU and memory throughput (data transfer rate).
  - **ILP (Instruction Level Parallelism) wall**

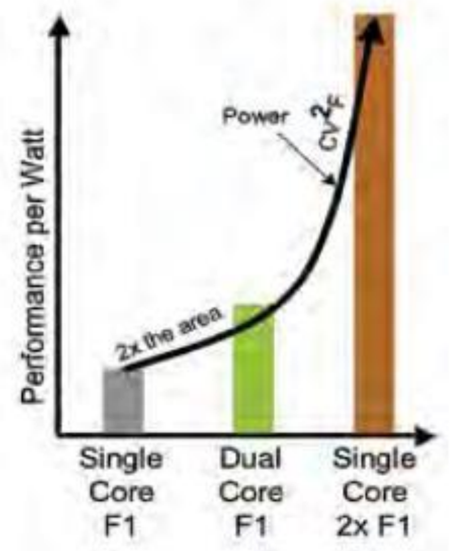
    Difficulty in full parallel instruction processing.
  - **Power wall**

    Power consumption doubled following the doubling of operating frequency.

    Faster clock speeds require higher input voltages.

    Every transistor leaks a small amount of current

    1% clock increase results in a 3% power increase.

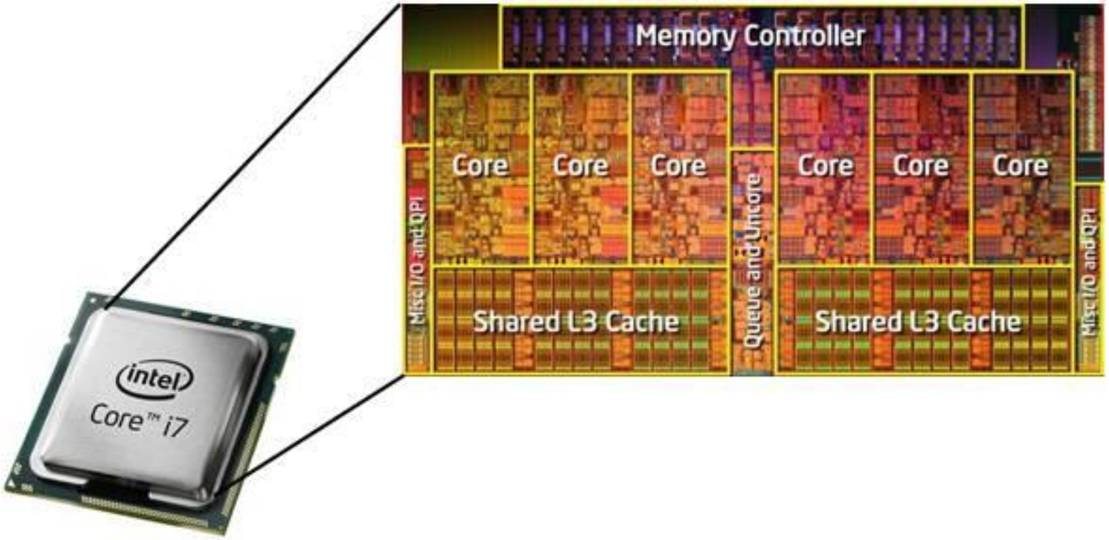


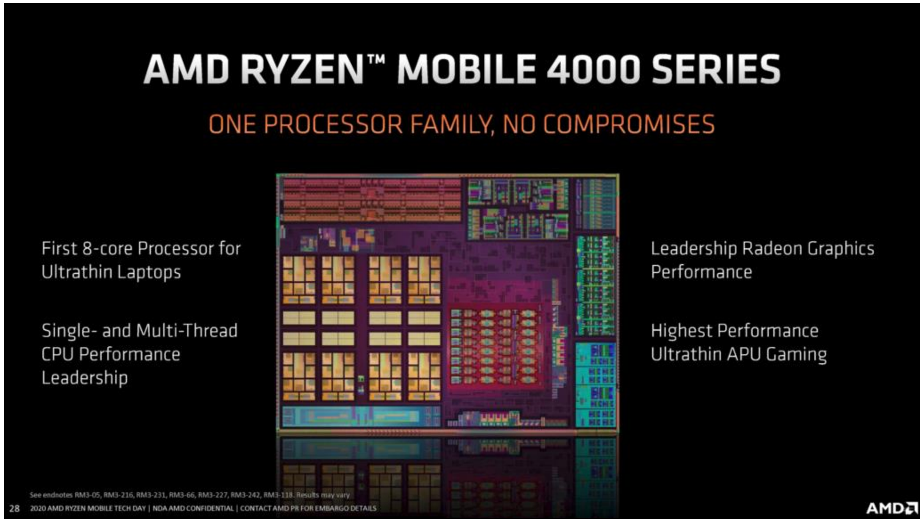
Types of parallelism

- **Bit level parallelism**
  - Parallelism achieved by doubling word size
- **Instruction level parallelism**
  - Superscalar processor with multiple executing units and out of order execution.
- **Data level parallelism**
  - Each processor performs the same task on different pieces of distributed data
- **Task level parallelism**
  - Each processor executes a different thread (or process) on the same or different data

Classes of parallel computers

Multi core processor





AMD RYZEN™ MOBILE 4000 SERIES

ONE PROCESSOR FAMILY, NO COMPROMISES

First 8-core Processor for Ultrathin Laptops

Single- and Multi-Thread CPU Performance Leadership

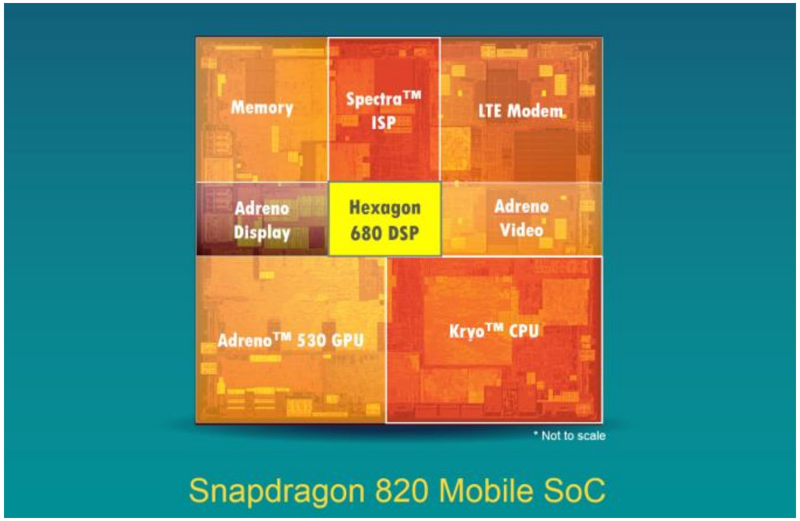
Leadership Radeon Graphics Performance

Highest Performance Ultrathin APU Gaming

See endnotes RM3-05, RM3-216, RM3-231, RM3-66, RM3-227, RM3-242, RM3-118. Results may vary

28 2020 AMD RYZEN MOBILE TECH DAY | NDA AMD CONFIDENTIAL | CONTACT AMD PR FOR EMBARGO DETAILS

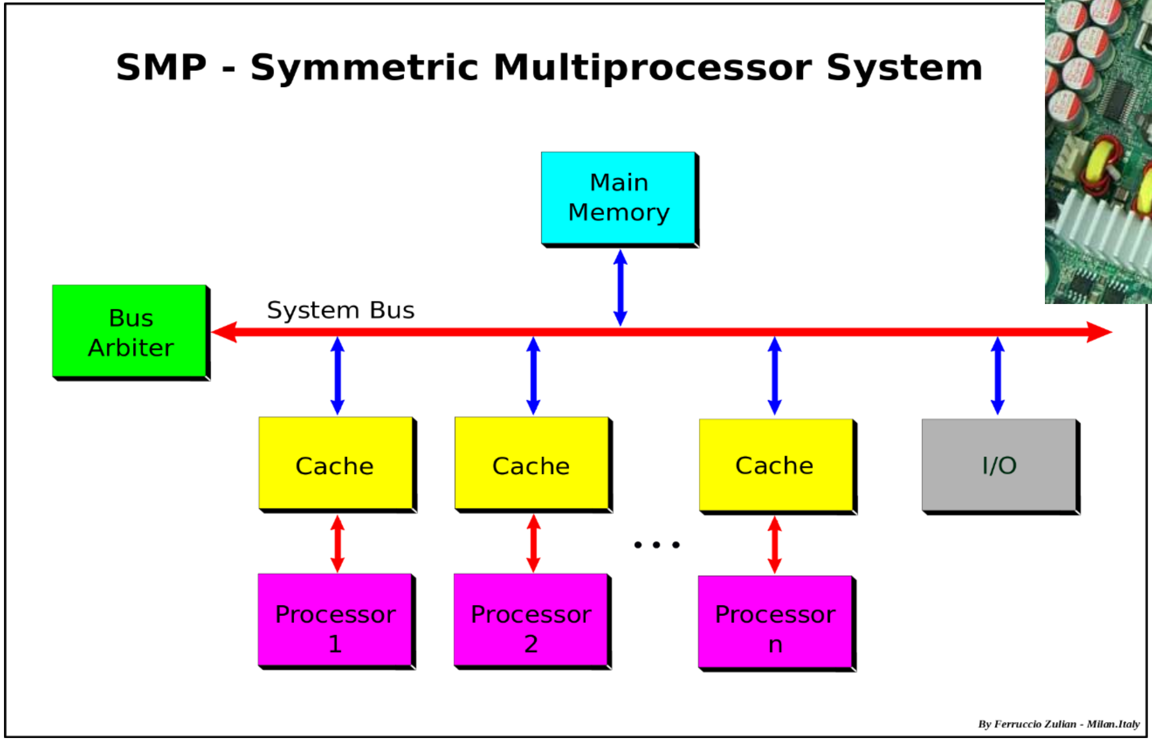
AMD



Snapdragon 820 Mobile SoC

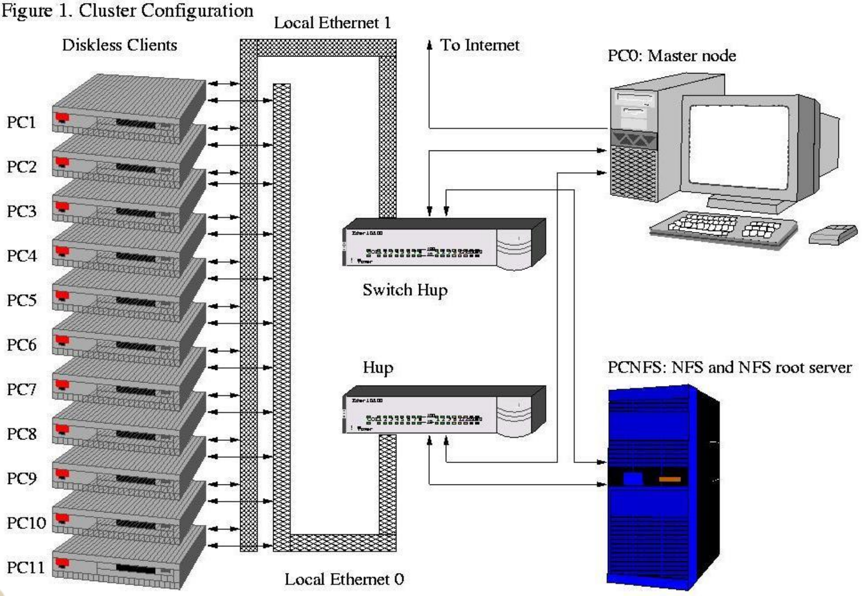
Classes of parallel computers

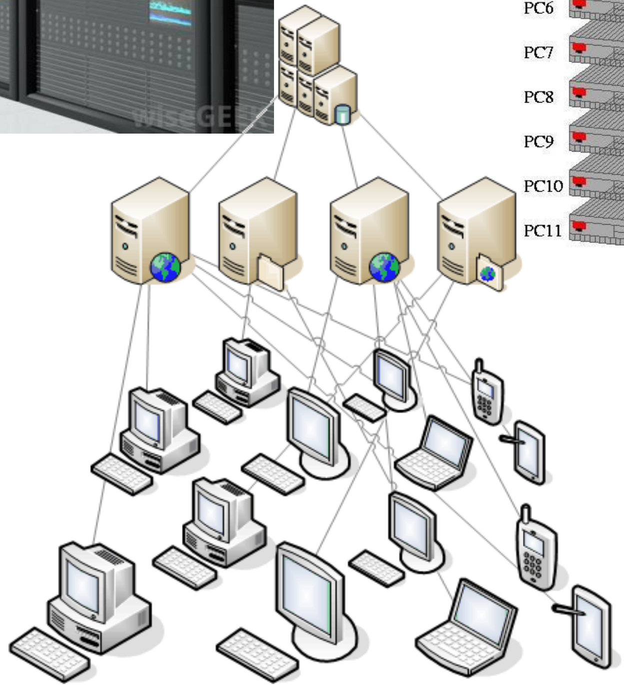
Symmetric multiprocessor



Classes of parallel computers

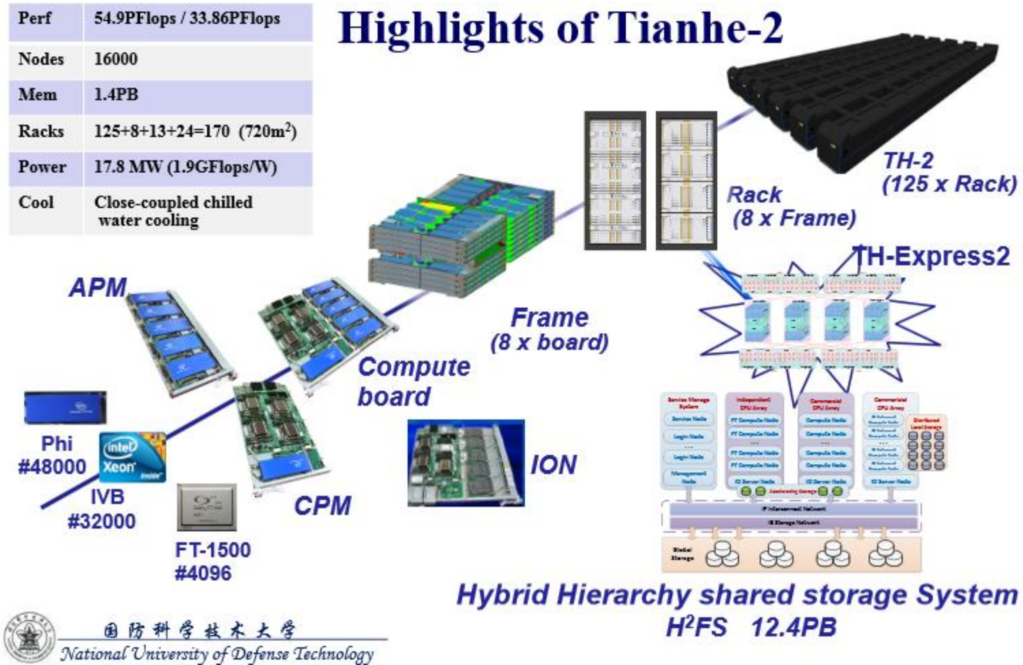
Cluster & Distributed/Grid computing





Classes of parallel computers

Massively parallel computing / supercomputing

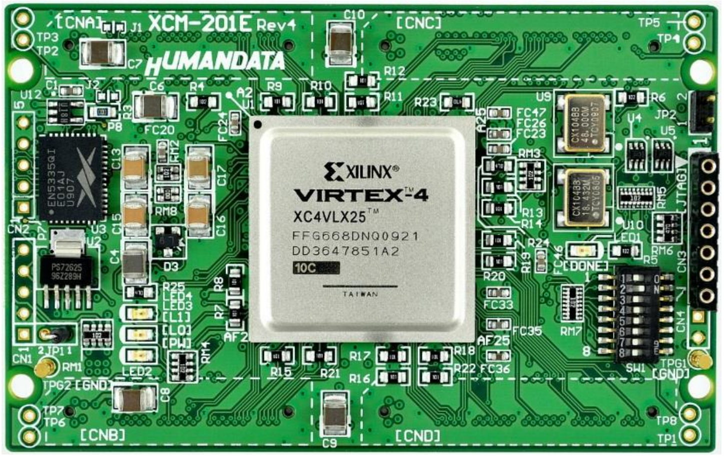


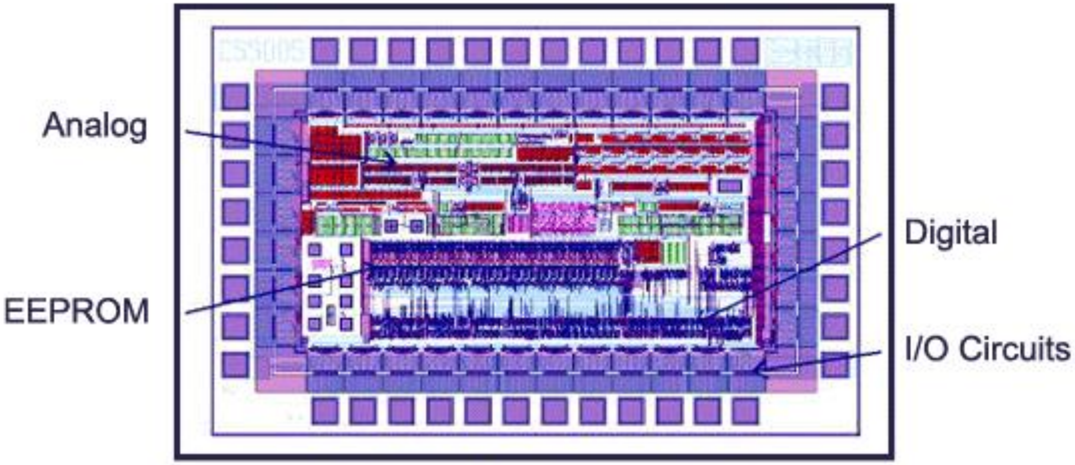
Highlights of Tianhe-2

Perf	54.9PFlops / 33.86PFlops
Nodes	16000
Mem	1.4PB
Racks	125+8+13+24=170 (720m^2)
Power	17.8 MW (1.9GFlops/W)
Cool	Close-coupled chilled water cooling

Classes of parallel computers

Reconfigurable computing (FPGA) & ASIC

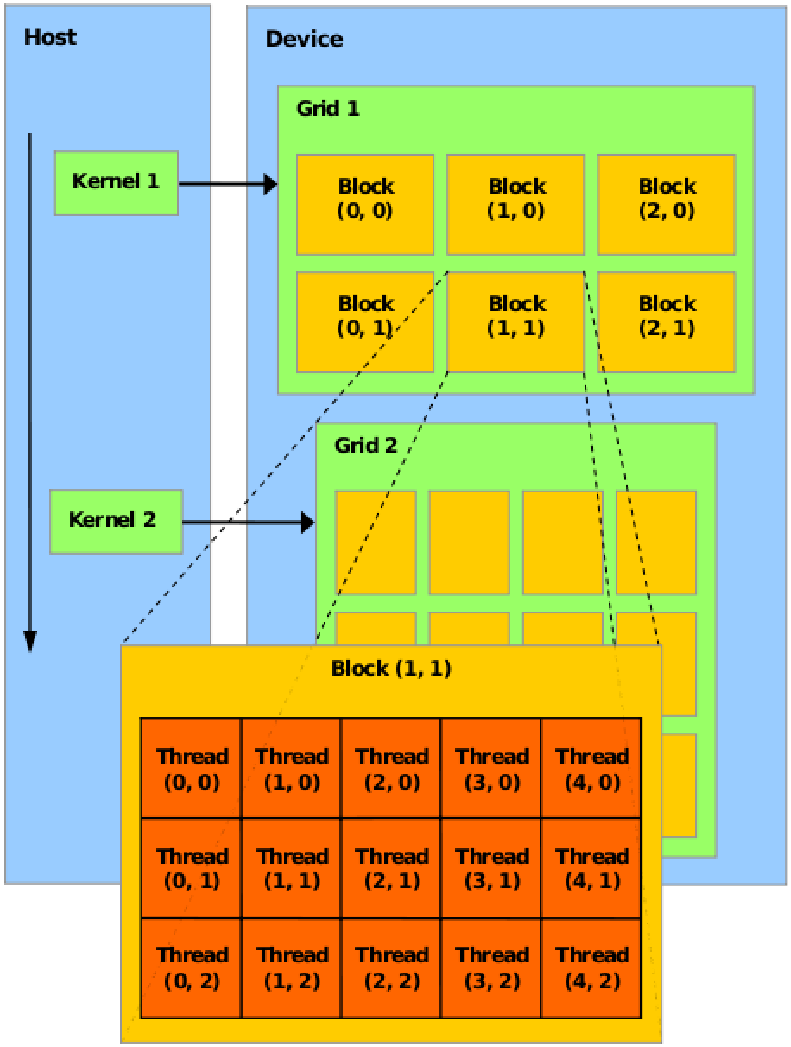




A Typical Mixed Signal ASIC

Classes of parallel computers

General-purpose computing on graphics processing units (GPGPU)



E.g. Embarrassingly parallel computation

An **ideal** parallel computation is one that can be immediately divided into completely independent parts that can be executed simultaneously – this is what is known as an *embarrassingly-parallel computation*, or *job-level parallelism*.

In this context, a network is a collection of integrated processors that are communicating and sharing information to speed up the solution to a single task.

Issues

1. How big of a collection?

- *A few very powerful, special purpose computers? (2-64)*
- *Many smaller, standard microprocessors? (100-10,000)*
- *A huge number of simple, one bit processors? (billions, trillions)*

2. What kind of processors?

- *Special purpose?*
- *Standard microprocessors or Simple?*
- *One-bit processors?*

3. How closely integrated is the collection of processors?

http://www.lsbu.ac.uk/oracle/oracle7/server/doc/SPS73/chap3.htm

- ***Tightly coupled**? Designed as a single architecture and a single system.*
- ***Loosely coupled**? Systems that can operate as a single logical system but can also function independently. Not designed as a single architecture.*

4. **How do the processors communicate?**
   - Shared memory?
   - External communications channel?
5. **What type of information is shared?**
   - Data values, inputs, results?
   - Synchronizing information?
6. **Focus on a single task**
   - We will focus more on ***task level parallelism*** rather than *job-level parallelism* or *embarrassingly parallel computation*. This means we're more interested in situations where all the processors work together to speed up the solution of a single task.

Job = Task1 + Task2 + Task3 + …

2. Parallel computing models

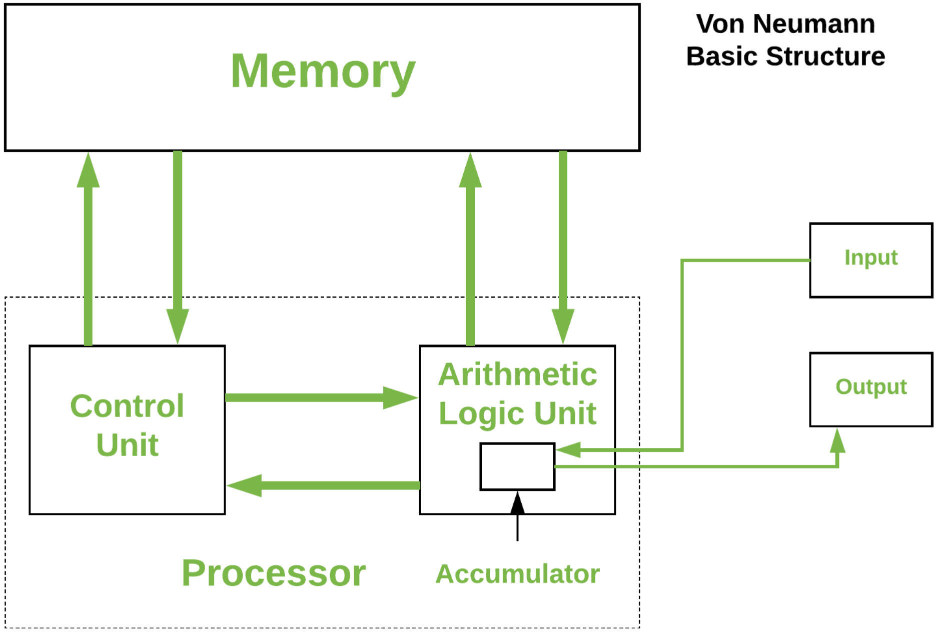
How to classify parallel computers?

Parallel computers can be **classified** by:

- Type and number of processors.
- Interconnection scheme of the processors.
- Communication scheme.
- Input/output operations.

Conventional computer

- Consists of a processor executing a program stored in a (main) memory.



- Each main memory location located by its *address.* Addresses start at 0 and extend to 2^n -1 when there are n bits (binary digits) in the address. (You learned this in COA)

Image link: https://media.geeksforgeeks.org/wp-content/uploads/basic_structure.png

Multi-processor computer architecture

1. **Flynn’s Classification**

2. **Shared memory model**

3. **Distributed memory model**

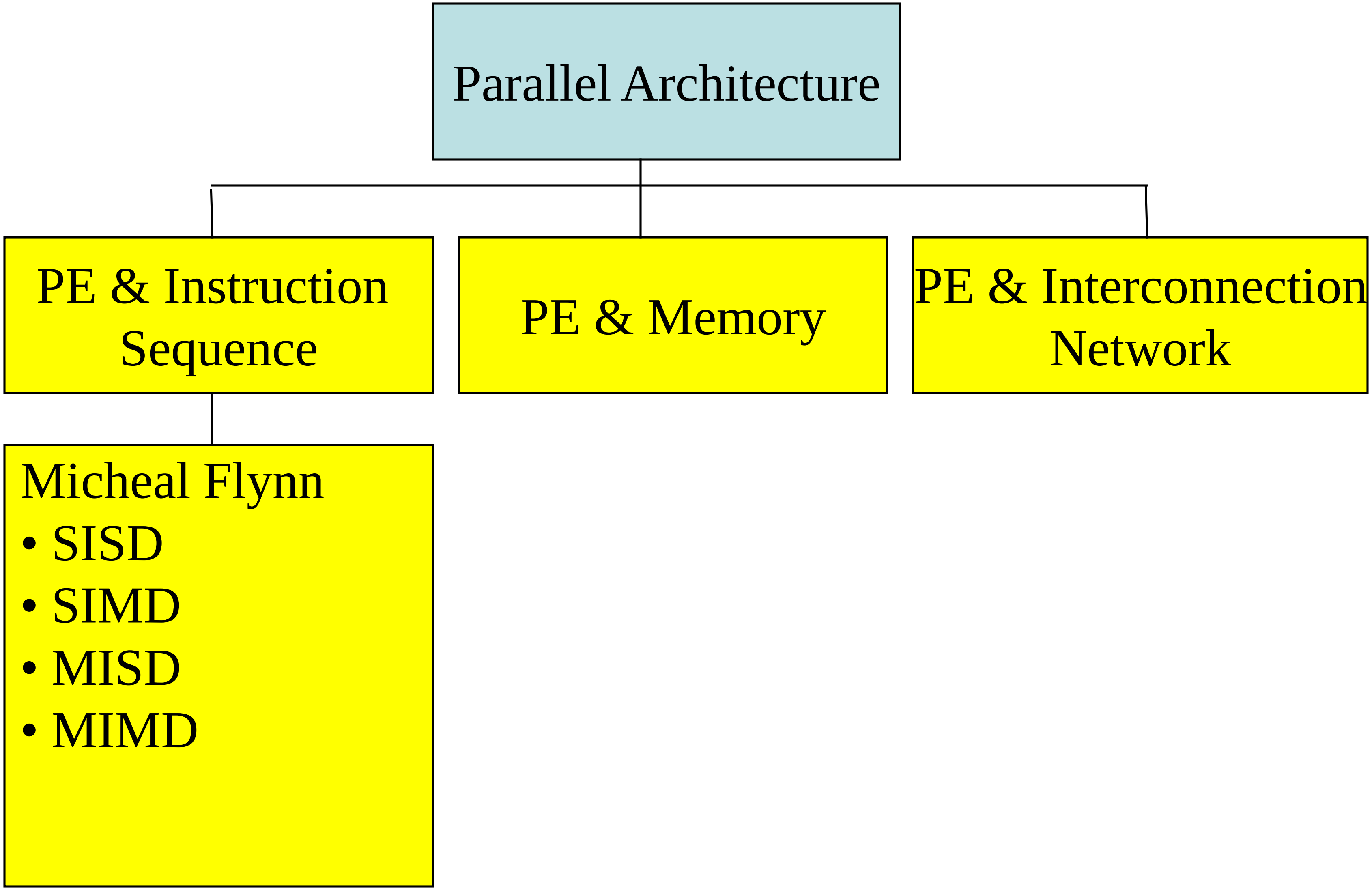
4. **Distributed shared memory model**

Taxonomy (Classification)

A taxonomy of parallel architectures can be built based on three relationships:

1. **Relationship between PE and the instruction sequence executed**
2. **Relationship between PE and the memory**
3. **Relationship between PE and the interconnection network**

PE: Processing Element (CPU)



Parallel Architecture

PE & Instruction Sequence

PE & Memory

PE & Interconnection Network

Micheal Flynn

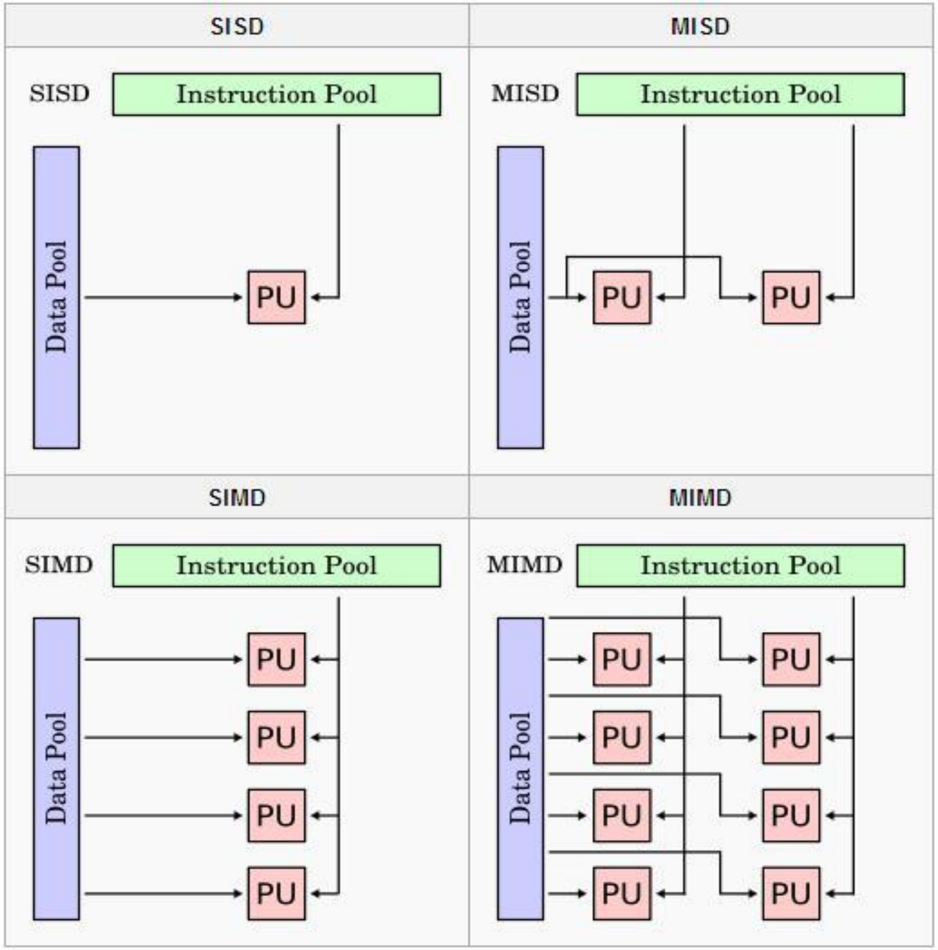
- SISD
- SIMD
- MISD
- MIMD

Flynn taxonomy

Michael Flynn (1966) developed a taxonomy of parallel systems based on the number of independent *instruction and data streams*.

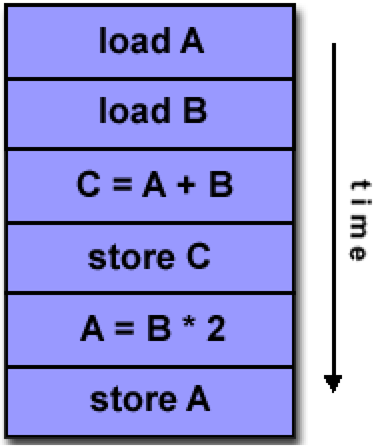
1. ***SISD:*** *Single Instruction Stream- Single Data Stream*
   This is a good conventional sequential Von Neumann machine.
2. ***MISD:*** *Multiple Instruction Stream- Single Data Stream*
3. ***SIMD:*** *Single Instruction Stream- Multiple Data Stream*
4. ***MIMD:*** *Multiple Instruction Stream- Multiple Data Stream*

Flynn’s Classification



Flynn’s Classification

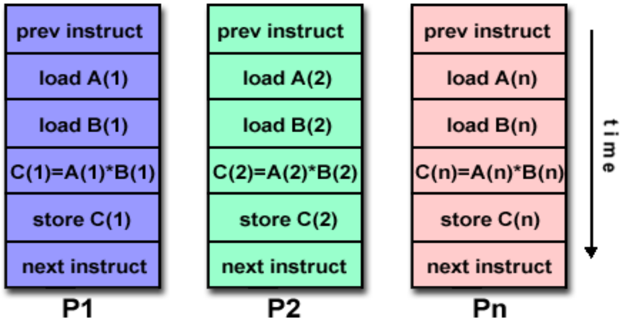
- **Single Instruction, Single Data (SISD):**
  - A serial (non-parallel) computer
  - Single instruction: only one instruction stream is being acted on by the CPU during any one clock cycle
  - Single data: only one data stream is being used as input during any one clock cycle
  - Deterministic execution
  - This is the oldest and until recently, the most prevalent form of computer
  - Examples: most PCs, single CPU workstations and mainframes



Flynn's Classification

Single Instruction, Multiple Data (SIMD):

- A type of parallel computer
- Single instruction: All processing units execute the same instruction at any given clock cycle
- Multiple data: Each processing unit can operate on a different data element
- This type of machine typically has an instruction dispatcher, a very high-bandwidth internal network, and a very large array of very small-capacity instruction units.
- Best suited for specialized problems characterized by a high degree of regularity,such as image processing.
- Synchronous (lockstep) and deterministic execution
- Two varieties: Processor Arrays and Vector Pipelines



- Examples:
  - Processor Arrays: Connection Machine CM-2, Maspar MP-1, MP-2
  - Vector Pipelines: IBM 9000, Cray C90, Fujitsu VP, NEC SX-2, Hitachi S820

Flynn’s Classification

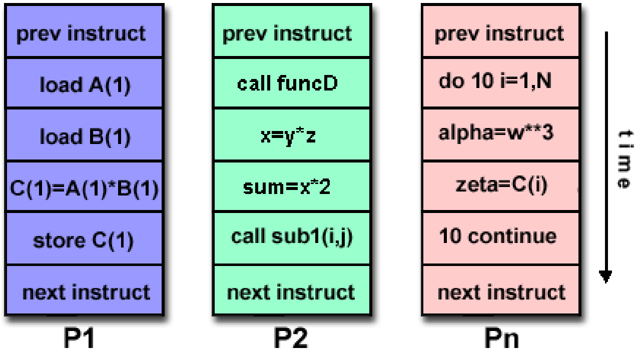
Multiple Instruction, Single Data (MISD):

- A single data stream is fed into multiple processing units.
- Each processing unit operates on data independently via independent instruction streams.
- Few actual examples of this class of parallel computer have ever existed. One is the experimental Carnegie-Mellon computer
- Some conceivable uses might be:
  - multiple frequency filters operating on a single signal stream
  - multiple cryptography algorithms attempting to crack a single coded message.

Flynn’s Classification

Multiple Instruction, Multiple Data (MIMD):

- Currently, the most common type of parallel computer. Most modern computers fall into this category.
- Multiple Instruction: every processor may be executing a different instruction stream
- Multiple Data: every processor may be working with a different data stream
- Execution can be synchronous or asynchronous, deterministic or non-deterministic
- Examples: most current supercomputers, networked parallel computer "grids" and multi-processor SMP computers - including some types of PCs.

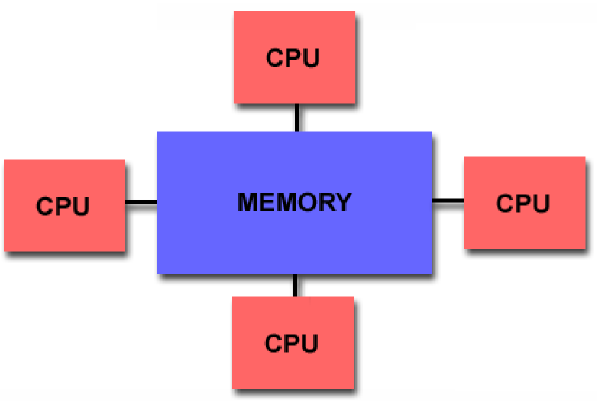


P1	P2	Pn
prev instruct	prev instruct	prev instruct
load A(1)	call funcD	do 10 i=1,N
load B(1)	x=y*z	alpha=w**3
C(1)=A(1)*B(1)	sum=x*2	zeta=C(i)
store C(1)	call sub1(i,j)	10 continue
next instruct	next instruct	next instruct

Parallel Computer Memory Architectures

- Broadly divided into three categories
  - Shared memory
  - Distributed memory
  - Hybrid

Shared Memory

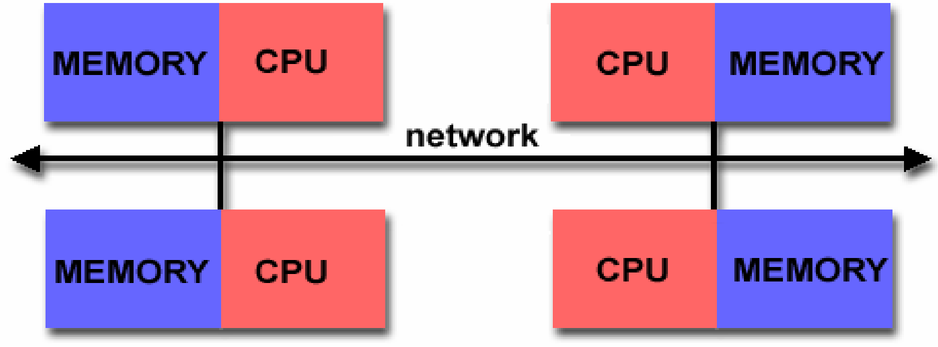


- Shared memory parallel computers vary widely, but generally have in common the ability for all processors to access all memory as global address space.
- Multiple processors can operate independently but share the same memory resources.
- Changes in a memory location effected by one processor are visible to all other processors.
- Shared memory machines can be divided into two main classes based upon memory access times: ***UMA*** and ***NUMA***.

Parallel Computer Memory Architectures

Distributed Memory

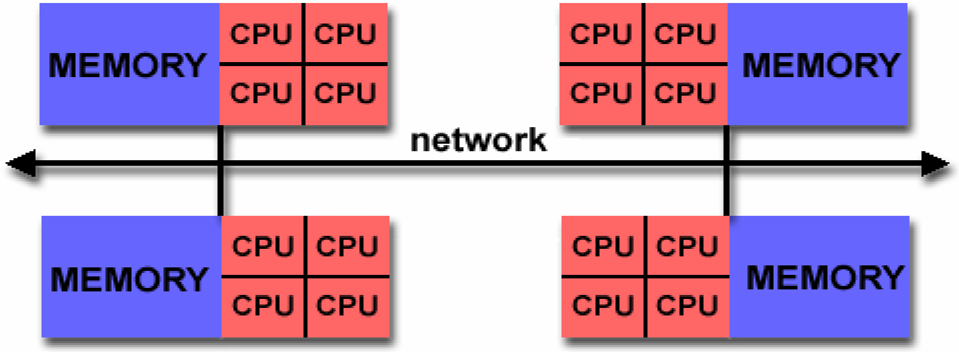
- Distributed memory systems require a communication network to connect inter-processor memory.
- Processors have their own local memory. There is no concept of global address space across all processors.
- Because each processor has its own local memory, it operates independently. Changes it makes to its local memory have no effect on the memory of other processors. Hence, the concept of cache coherency does not apply.
- When a processor needs access to data in another processor, it is usually the task of the programmer to explicitly define how and when data is communicated. Synchronization between tasks is likewise the programmer's responsibility.
- The network "fabric" used for data transfer varies widely, though it can be as simple as Ethernet.



Parallel Computer Memory Architectures

Hybrid

- The largest and fastest computers in the world today employ both shared and distributed memory architectures.
- The shared memory component is usually a cache coherent SMP machine. Processors on a given SMP can address that machine's memory as global.
- The distributed memory component is the networking of multiple SMPs. SMPs know only about their own memory - not the memory on another SMP. Therefore, network communications are required to move data from one SMP to another.
- Current trends seem to indicate that this type of memory architecture will continue to prevail and increase at the high end of computing for the foreseeable future.
- Advantages and Disadvantages: whatever is common to both shared and distributed memory architectures.



Parallel Programming Models

Overview

- There are several parallel programming models in common use:
  - Shared Memory
  - Threads
  - Message Passing
  - Data Parallel
  - Hybrid

- Parallel programming models exist as an abstraction above hardware and memory architectures.

- Although it might not seem apparent, these models are NOT specific to a particular type of machine or memory architecture. In fact, any of these models can (theoretically) be implemented on any underlying hardware.

Single Program Multiple Data (SPMD) structure

- Another programming structure we may use is the **Single Program Multiple Data (SPMD)** structure.
- In this structure, a single source program is written and each processor will execute its personal copy of this program, although independently, and not in synchrony.
- This source program can be constructed so that parts of the program are executed by certain computers and not others depending on the identity of the computer.
- For a **master-slave** structure, the programs could have parts for the master and parts for slaves.

Multiple Program Multiple Data (MPMD) structure

- Within the MIMD classification, each processor will have its own program to execute. This could be described as MPMD.
- In this case, some of the programs to be executed could be copies of the same program.
- Typically only two source programs are written, one for the designated **master processor**, and one for the remaining processors, which are called **slave processors**.

Three ways to create executable code for a shared memory multiprocessor

1. **Parallel Programming Languages**
   - With special parallel programming constructs and statements that allow shared variables and parallel code sections to be declared.
   - Then the compiler is responsible for producing the final executable code.
2. **Threads**
   - Contain regular high-level language code sequences for individual processors. These code sequences can then access shared locations.
3. **Sequential programming**
   - Use a regular sequential programming language and modify the syntax to specify parallelism.

Programming message-passing multicomputer

- **Dividing** the problem into parts that are intended to be executed simultaneously to solve the problem

- Common approach is to use message-passing library routines that are inserted into a conventional sequential program for message passing.

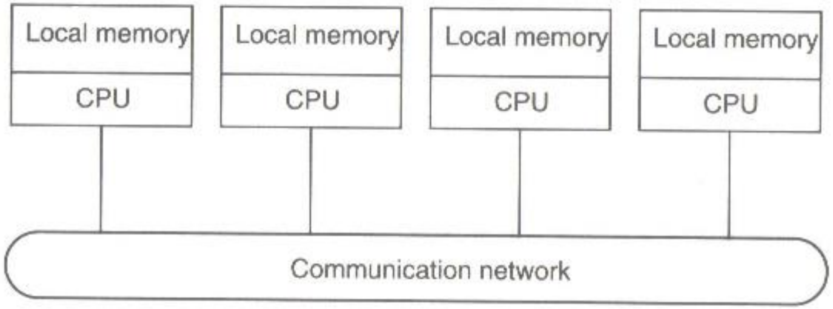
- A problem is divided into a number of concurrent processes that may be executed on a different computer.

- Processes **communicate by sending messages**; this will be the only way to distribute data and results between processes.

3. Distributed computing

DS Introduction

- Loosely coupled systems
  - Processors do not share memory
  - Each processor has its own local memory



Definition of Distributed Systems

- *"A distributed system is a collection of independent computers that appears to its users as a single coherent system."*

- The definition has several important aspects
  - Autonomous components
  - Users (whether people or program) think they are dealing with a single system

- A distributed system is a system in which components located at networked computers communicate and coordinate their actions only by passing messages.

Evolution of Distribution System

- Two advances as the reason for spread of distributed systems

1. Powerful micro-processor:
   - 8-bit, 16-bit, 32-bit, 64-bit
   - x86 family, 68k family, CRAY, SPARC, dual core, multi-core
   - Clock rate: up to 4Ghz

2. Computer network:

   Local Area Network (LAN), Wide Area Network (WAN), MAN, Wireless Network type: Ethernet, Token-bus, Token-ring, Fiber Distributed Data Interface (FDDI), Asynchronous Transfer Mode (ATM), Fast-Ethernet, Gigabit Ethernet, Fiber Channel, Wavelength-Division Multiplex (WDM)

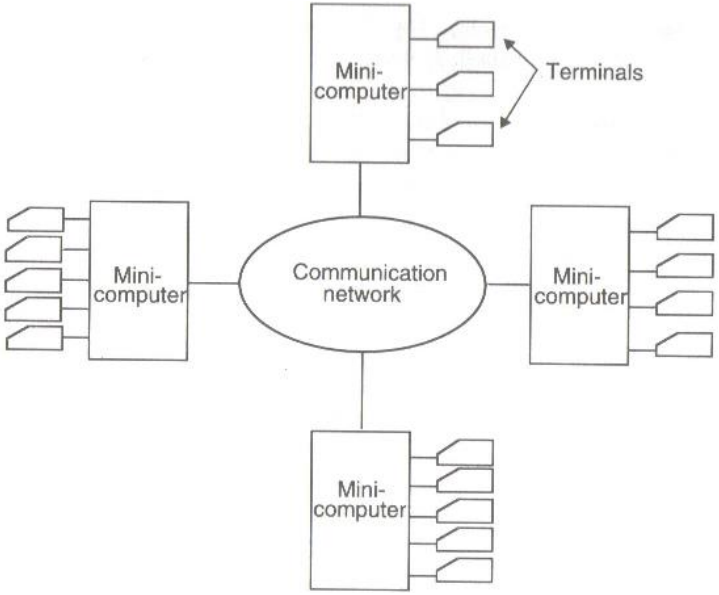
   Transfer rate: 64 kbps up to 1Tbps

Distributed computing system models

- Various models are used for building distributed computing systems.
- These models can be broadly classified into five categories-
  - Minicomputer model
  - Workstation model
  - Workstation-server model
  - Processor-pool model
  - Hybrid model

Distributed computing system models

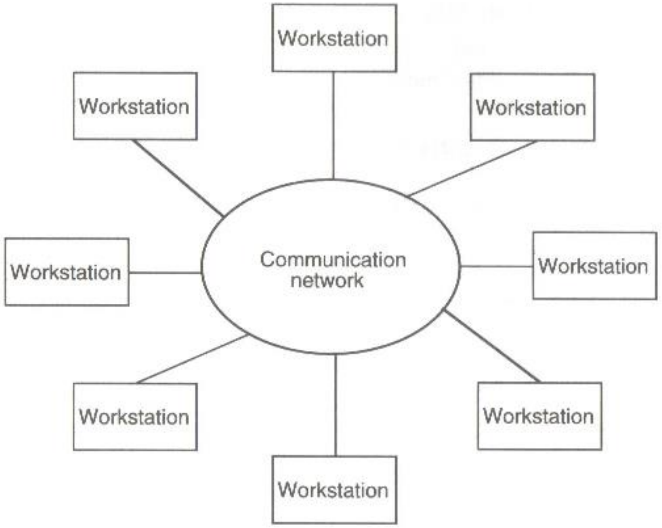
1. Minicomputer model:
   - simple extension of centralized time-sharing systems
   - few minicomputers interconnected by communication network
   - each minicomputer has multiple users simultaneously logged on to it
   - this model may be used when when resource sharing with remote users is desired
   - Example: the early ARPAnet



Distributed computing system models

2. Workstation model:

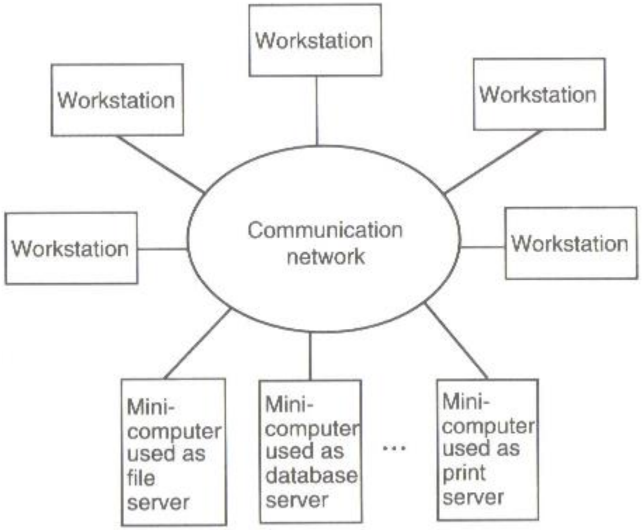
- several workstations interconnected by communication network
- basic idea is to share processor power
- user logs onto home workstation and submits jobs for execution, system might transfer one or more processed to other workstations
- issues must be resolved –
  - how to find an idle workstation
  - how to transfer
  - what happens to a remote process
- Examples- Sprite system, Xerox PARC



Distributed computing system models

3. Workstation-server model

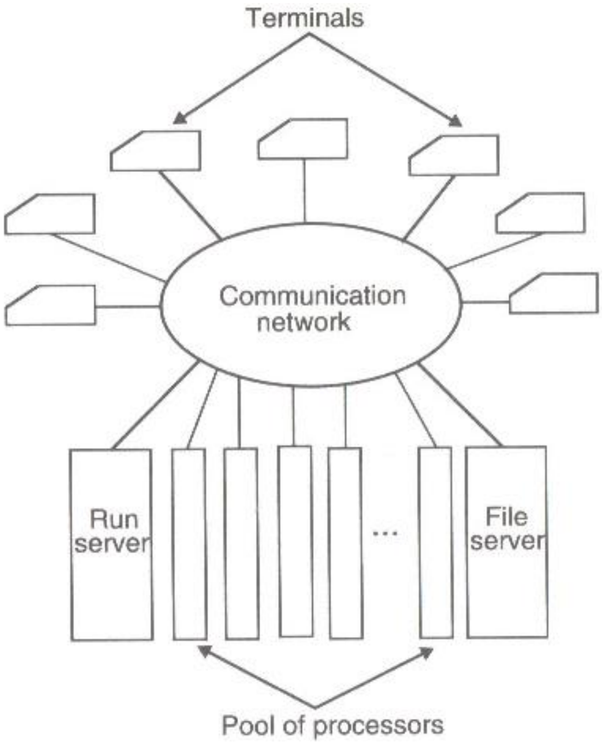
- It consists of a few minicomputers and several workstations (diskless or diskful)
- Minicomputers are used for providing services
- For higher reliability and better scalability multiple servers may be used for a purpose.
- Compare this model with workstation model .
- Example- The V-System


Workstation
Workstation
Workstation
Workstation
Communication network
Workstation
Mini-computer used as file server
Mini-computer used as database server
...
Mini-computer used as print server

Distributed computing system models

4. Processor-pool model

- Base observation –
  sometimes user need NO computing power, but once in a while he needs very large amount of computing power for a short period of time
- Run server manages and allocates the processors to different users
- No concept of a home machine, i.e., a user does not log onto a particular machine but to the system as a whole.
- Offers better utilization of processing power compared to other models.
- Example: Amoeba, Plan9, Cambridge DCS.



Distributed computing system models

5. Hybrid Model

- To combine the advantages of both workstation-server model and processor-pool model a hybrid model may be used
- It is based on the workstation-server model but with addition of a pool of processors
- Expensive!!

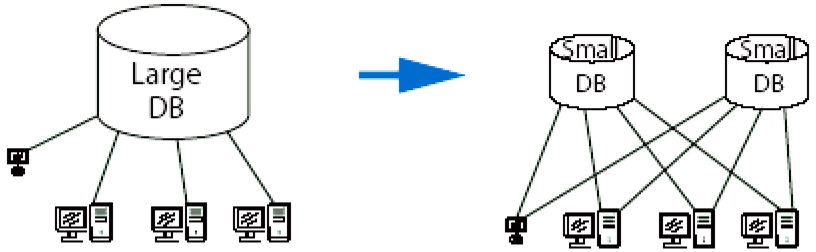
Distribution Model

- There are several distribution models for accessing distributed resources and executing distributed applications as follows.
- File Model - Resources are modeled as files. Remote resources are accessible simply by accessing files.
- Remote Procedure Call Model - Resource accesses are modeled as function calls. Remote resources can be accessed by calling functions.
- Distributed Object Model - Resources are modeled as objects which are a set of data and functions to be performed on the data. Remote resources are accessible simply by accessing an object.

Advantages of Distributed Systems

Economics: Microprocessors offer a better price / performance than mainframes.

Speed: A distributed system may have more total computing power than a mainframe. E.g. one large database may be split into many small databases. In that way, we may improve response time.



Inherent distribution: Some application like banking, inventory systems involve spatially separated machines.

Advantages of Distributed Systems

Reliability: If 5% of the machines are downed, the system as a whole can still survive with a 5% degradation of performance.

Incremental growth: Computing power can be added in small increments

Sharing: Allow many users access to a common database and peripherals.

Communication: Make human-to-human communication easier.

Effective Resource Utilization: Spread the workload over the available machines in the most cost effective way.

Disadvantages of Distributed Systems

- Software: It is harder to develop distributed software than centralized one.
- Networking: The network can saturate or cause other problems.
- Security: Easy access also applies to secret data.

Challenges in Distributed Systems

- Heterogeneity - Within a distributed system, we have variety in networks, computer hardware, operating systems, programming languages, etc.
- Openness - New services are added to distributed systems. To do that, specifications of components, or at least the interfaces to the components, must be published.
- Transparency - One distributed system looks like a single computer by concealing distribution.
- Performance - One of the objectives of distributed systems is achieving high performance out of cheap computers.

Challenges in Distributed Systems

- Scalability - A distributed system may include thousands of computers. Whether the system works is the question in that large scale.

- Failure Handling - One distributed system is composed of many components. That results in high probability of having failure in the system.

- Security - Because many stake-holders are involved in a distributed system, the interaction must be authenticated, the data must be concealed from unauthorized users, and so on.

- Concurrency - Many programs run simultaneously in a system and they share resources. They should not interfere with each other

Heterogeneity

A distributed system is composed of a heterogeneous collection of computers

Heterogeneity arises in the following areas-

- networks: Even if the same Internet protocol is used to communicate, the performance parameters may widely vary within the inter-network.
- computer hardware: Internal representation of data is different for different processors.
- operating systems: The interface for exchanging messages is different from one operating system to another.
- programming languages: Characters and data structures are represented differently by different programming languages.
- implementations by different developers: Unless common standards are observed, different implementations cannot communicate.

Openness

- Openness means disclosing information: the usage of services provided by remote computers.
- Open systems are easier to extend and reuse.
- By making services open, servers can be used by various clients.
- The clients which use services provided by other servers can extend the services and again provide services to other clients.
- The openness of distributed systems let us add new services and increase availability of services to different clients.

Transparency

- Transparency means hiding something.

- Transparency is an important issue to realize the single system image which makes systems as easy to use as a single processor system. E.g. WWW we can access whatever information by clicking links without knowing whereabouts of the host.

Classification of Transparency

- Access transparency: Data and resources can be used in a consistent way.

- Location transparency: A user cannot tell where resources are located

- Migration transparency: Resources can move at will without changing their names.

Classification of Transparency

- Replication transparency: A user cannot tell how many copies exist.
- Concurrency transparency: Multiple users can share resources automatically.
- Failure transparency: A user does not notice resource failure.
- Performance transparency: Systems are reconfigured to improve performance as loads vary
- Scaling transparency: Systems can expand in size without changing the system structure and the application programs.

Performance

- Fine-grained parallelism: Small programs are executed in parallel.
  - Large number of messages.
  - Communication overhead decreases the performance gain with parallel processing.
- Coarse-grained parallelism:
  - Long compute-bound programs executed in parallel.
  - Communication overhead is less in this case.

Scalability

- Scalability is the issue whether a distributed system works and the performance increases when more computers are added to the system.

- The followings are potential bottle-necks in very large distributed systems
  - Centralized components: A single mail server for all users.
  - Centralized tables: A single on-line telephone book
  - Centralized algorithms: Routing based on complete information

- Use decentralized algorithms for scalability:
  - No machine has complete information about the system state.
  - Machines make decisions based only on local information.
  - Failure of one machine does not completely invalidate the algorithm.

Reliability

- We have high probability to have faulty components in a distributed system because the system includes large number of components.

- On the other hand, it is theoretically possible to build a distributed system such that if a machine goes down, the other machine takes over the job.

- Reliability has several aspects.
  - **Availability: The fraction of time that the system is available. It can be expressed by the following equation-**

$$R = \frac{usable\_time}{total\_time}$$

  - **Fault tolerance: Distributed systems can hide failures from the users.**

Performance

- Maximum aggregate performance of the system can be measured in terms of Maximum aggregate floating-point operations.

$$P = N*C*F*R$$

- Where P performance in flops, N number of nodes, C number of CPUs, F floating point ops per clock period - FLOP, R clock rate.
- The similar measures with MOP/MIP.

Scalability

- It is computed as

$$S = T(1) / T(N)$$

- Where T(1) is the wall clock time for a program to run on a single processor.
- T(N) is the runtime over N processors.
- A scalability figure close to N means the program scales well.
- Scalability metric helps estimate the optimal number of processors for an application.

Utilization

- It is calculated as,

  $$U = S(N)/N$$

- Values close to unity or 100% are ideally sought.

Summation

- What is a Distributed System?
  - *"A distributed system is a collection of independent computers that appears to its users as a single coherent system."*
- Models of Distributed System?
  - Minicomputer model
  - Workstation model
  - Workstation-server model
  - Processor-pool model
  - Hybrid model
- What are the Strengths and Weaknesses of a Distributed System?
  - S: Reliability, Incremental growth, Resource sharing
  - W: Programming, Reliance on network, Security
- Important characteristics of of a Distributed System?
  - Heterogeneity, Openness, Transparency
- Performance Metrics?

4. Parallel computing performance

Potential for increased computational speed

Process

In all forms of MIMD multiprocessor/multicomputer systems, it is necessary to divide the computations into tasks or processes that can be executed simultaneously.

The size of a process can be described by its granularity, which is related to the number of processors being used.

In coarse granularity, each process contains a large number of sequential instructions and takes substantial time to execute.

In fine granularity, a process might consists of few instructions or perhaps even one instruction.

Medium granularity describes the middle ground.

Sometimes granularity is defined as the size of the computation between communication or synchronization points.

Generally we want to increase the granularity to reduce the cost of process creation and inter-process communication, but of course this will likely reduce the number of concurrent processes and amount of parallelism. A suitable compromise has to be made.

The ratio

$$\frac{Computation}{Communication} = \frac{Computation\,Time}{Communication\,Time} = \frac{t_{comp}}{t_{comm}}$$

can be used as a **granularity metric**.

Speed-Up factor

A measure of relative performance between a multiprocessor system and a single processor system in the ***speed- up factor***, *S(n)*, defined as

$$S(n) = \frac{\text{Execution time using one processor (single processor system)}}{\text{Execution time using a multiprocessor with n processors}}$$

$$= \frac{t_S}{t_P}$$

The factor $S_{(n)}$ gives the increase in speed due to using a multiprocessor

For comparing a parallel solution with a sequential solution, we will use the fastest known sequential algorithm for running on a single processor. The underlying algorithm for a parallel implementation might be (and is usually) different.

The speed up factor can also be cast in terms of computational steps:

The **maximum speedup is n** with n processors (linear speed up).

$$S_{(n)} = \frac{\text{Number of computational steps using one processor}}{\text{Number of parallel computational steps with processors}}$$

Superlinear Speedup

where $S(n) > n$, may be seen on occasion, but usually this is due to using a suboptimal sequential algorithm or some unique feature of the architecture that favors the parallel formation.

One common reason for superlinear speedup is the **extra memory** in the multiprocessor system which can hold more of the problem data at any instant, it leads to less relatively slow disk-memory traffic.

Superlinear speedup can occur in search algorithms.

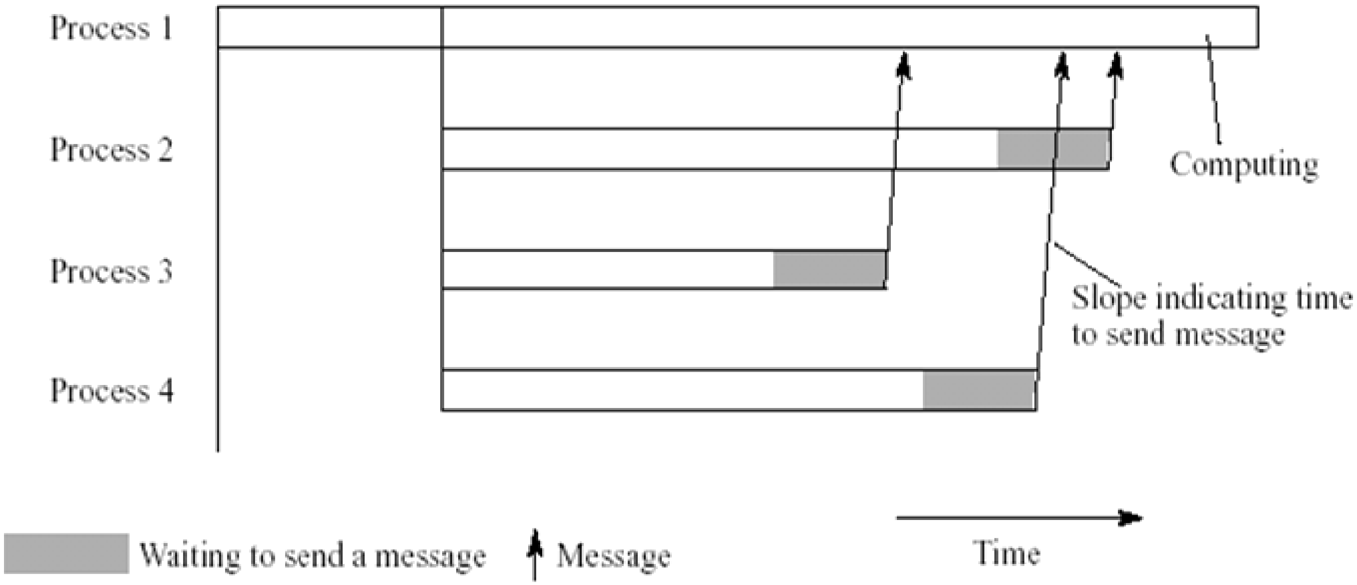
Space-time diagram of a message passing program

It is reasonable to expect that some part of a computation cannot be divided at all into concurrent processes and must be performed serially.

During the initialization period or period before concurrent processes are being setup, only one processor is doing useful work, but for the rest of the computation, additional processors are operating in parallel.

The figure on the next page illustrates a space-time diagram of a message-passing program that has one process on each of four processors. It starts with one process and later others begin to execute and send messages back. In general we would expect periods when processors are idle and are waiting to send their messages.

Space- time diagram of a message- passing program


Process 1
Process 2
Process 3
Process 4
Computing
Slope indicating time to send message
Waiting to send a message
Message
Time

Maximum speed

If the fraction of the computation that cannot be divided into concurrent tasks is f, the time to perform the computation with *p* processors is given by $ft_s + (1\text{-}f)\, t_s/p$ as shown in the next slide.

Illustrated is the case with a single serial part at the beginning of the computation which cannot be parallelized, but the remaining parts could be distributed throughout the computation.

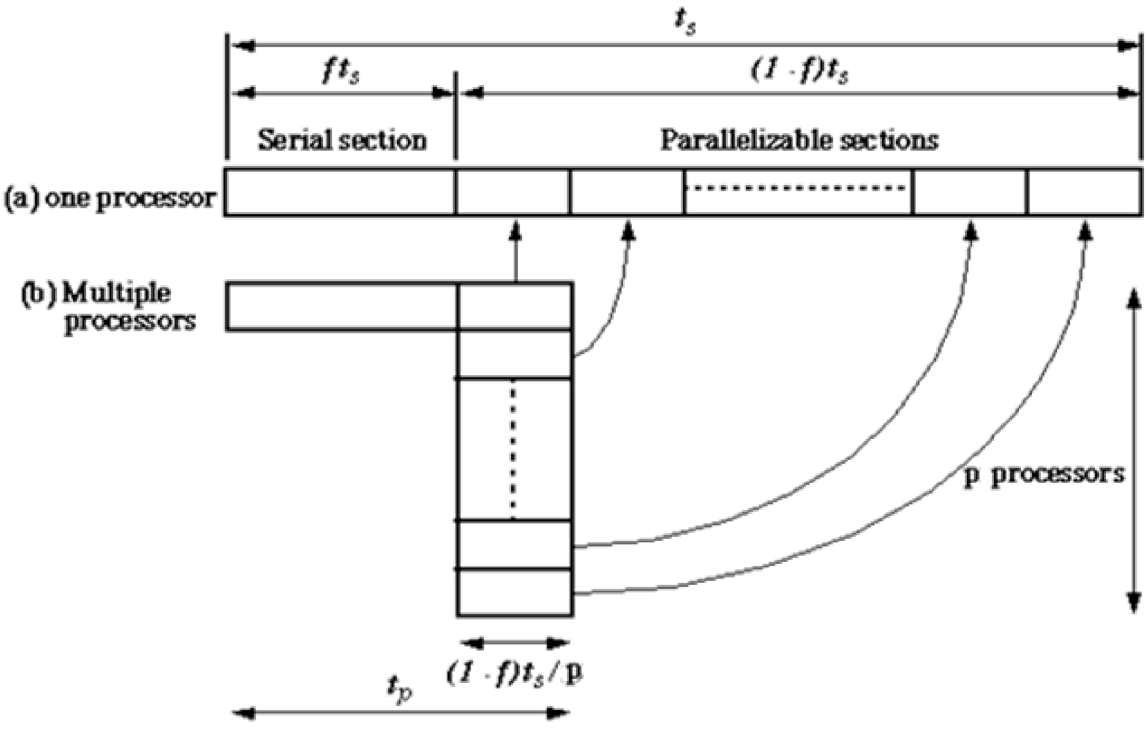
The speed up factor S(p) is given by

$$S(p) = \frac{t_S}{ft_S + (1-f)t_S / p} = \frac{p}{1 + (p-1)f}$$

Number of

This whole thing is t_p

Parallelizing sequential problem-Amdahl’s law



Alternative:

$$\frac{1}{r_s + \frac{r_p}{p}}$$

r_s is the serial ratio (non-parallelizable portion)
r_p is the parallel ratio (parallelizable portion)

p is the number of processors

This equation is known as **Amdahl's law**.

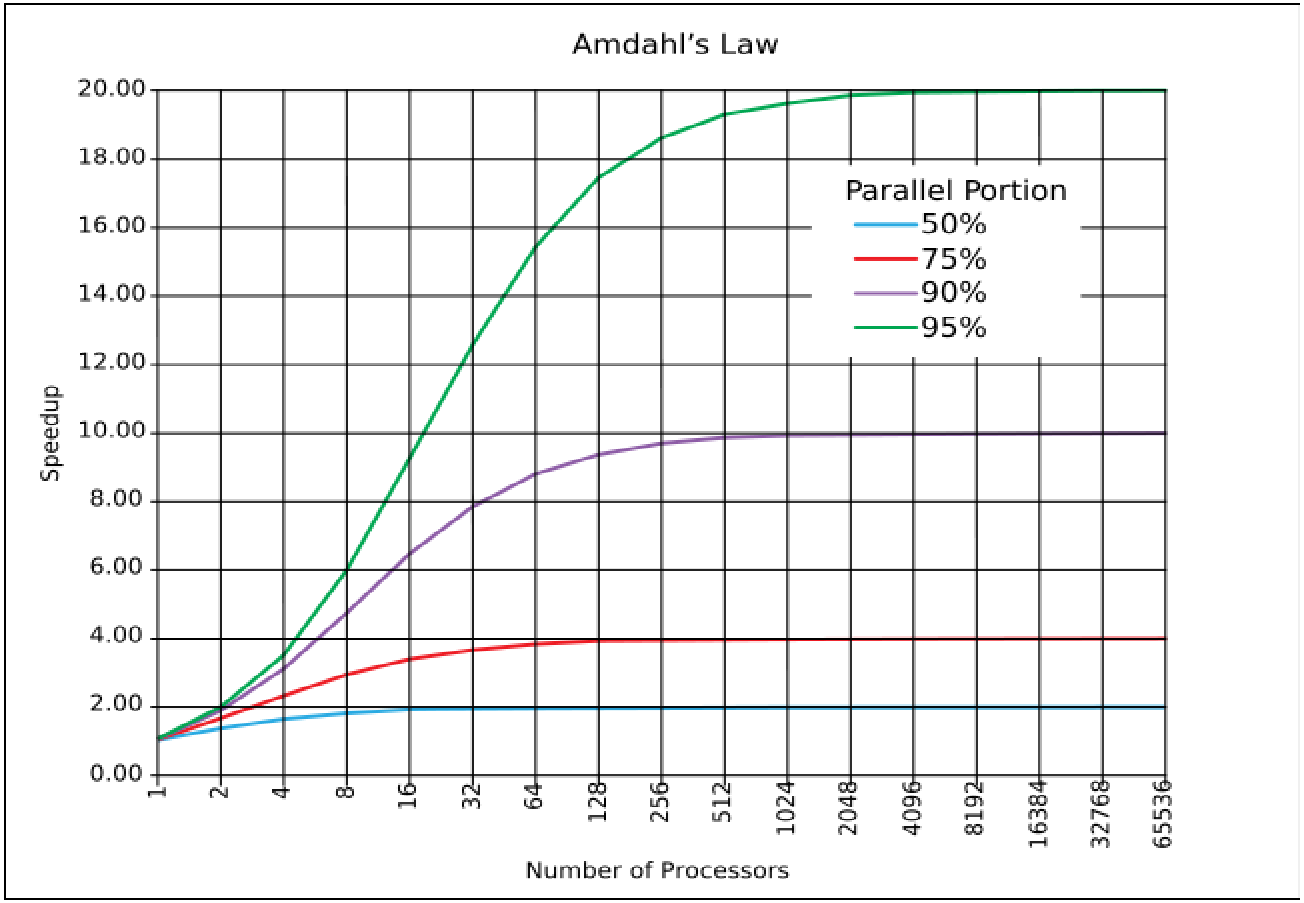
It shows S(n) plotted against number of processors and against f. If a significant increase in speed of computation is to be achieved, the fraction of computation that is executed by concurrent processes needs to be substantial fraction of the overall computation.

Even with infinite number of processors, maximum speedup limited to 1/*f*.

i.e., $S(n) = 1/f$

$n \to \infty$

Amdahl's law


Amdahl’s Law
20.00
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Speedup
1
2
4
8
16
32
64
128
256
512
1024
2048
4096
8192
16384
32768
65536
Number of Processors
Parallel Portion
50%
75%
90%
95%

Efficiency

- Efficiency

$$\text{Efficiency} = \frac{\text{Speedup}}{\text{Processors}} \qquad \varepsilon(n,p) \le \frac{\sigma(n)+\varphi(n)}{p\sigma(n)+\varphi(n)+p\kappa(n,p)}$$

- $0 \le \varepsilon(n,p) \le 1$
- Amdahl's law

$$\psi(n,p) \le \frac{\sigma(n)+\varphi(n)}{\sigma(n)+\varphi(n)/p+\kappa(n,p)}$$

$$\le \frac{\sigma(n)+\varphi(n)}{\sigma(n)+\varphi(n)/p}$$

- Let $f = \sigma(n)/(\sigma(n) + \varphi(n))$; i.e., f is the fraction of the code which is inherently sequential

$$\psi \le \frac{1}{f+(1-f)/p}$$

Examples

- 95% of a program's execution time occurs inside a loop that can be executed in parallel. What is the maximum speedup we should expect from a parallel version of the program executing on 8 CPUs?

$$\psi \le \frac{1}{0.05 + (1 - 0.05)/8} \cong 5.9$$

- 20% of a program's execution time is spent within inherently sequential code. What is the limit to the speedup achievable by a parallel version of the program?

$$\lim_{p \to \infty} \frac{1}{0.2 + (1 - 0.2)/p} = \frac{1}{0.2} = 5$$

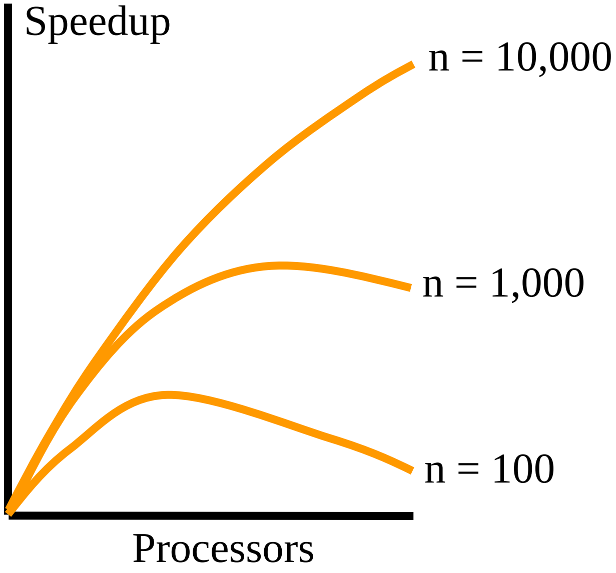
Amdahl's law

Limitations of Amdahl’s Law

- Ignores κ(*n*,*p*) - overestimates speedup
- Assumes f constant, so underestimates speedup achievable

Amdahl Effect

- Typically κ(*n*,*p*) has lower complexity than φ(*n*)/*p*
- As *n* increases, φ(*n*)/*p* dominates κ(*n*,*p*)
- *As n increases, speedup increases*
- *As n increases, sequential fraction f decreases.*



Gustafson’s law

- **Gustafson's Law** (also known as **Gustafson-Barsis' law,** 1988) states that any sufficiently large problem can be efficiently parallelized.

- Gustafson's Law is closely related to Amdahl's law, which gives a limit to the degree to which a program can be sped up due to parallelization.

$$S_s(p) = p + (1 - p)f t_s$$

where *p* is the number of processors, *s* is the speedup, and *f* the non-parallelizable part of the process

- Gustafson's law addresses the shortcomings of Amdahl's law, which cannot scale to match availability of computing power as the machine size increases.

Scaled speedup Factor

- If we fix the parallel execution time t_p and the fraction of the process which cannot be parallelized *f*, we can use Gustafson’s law to figure out the speed-up factor given the number of processors, *p*.
- This is called the *scaled* speedup factor because the t_p is scaled to 1.

$$S_s(p) = \frac{ft_s + (1-f)t_s}{ft_s + (1-f)t_s / p} = \frac{p + (1-p)\,ft_s}{1} = p + (1-p)\,ft_s$$

How the numerator becomes this will be explained on the following slide.

Scaled speedup Factor (cont.)

- The denominator t*p* which we scaled to 1 was
  - $ft_s + (1\text{-}f)t_s/p = 1$
  - $pft_s+(1\text{-}f)t_s = p$
  - $t_s = p + (1\text{-}p)\ ft_s$
- Hence, we get

$$S_s(p) = \frac{ft_s + (1 - f)t_s}{ft_s + (1 - f)t_s / p} = \frac{p + (1 - p)\, ft_s}{1} = p + (1 - p)\, ft_s$$

5. Parallel vs. distributed vs. asynchronous computing

Parallel vs. Distributed computing

S.NO	PARALLEL COMPUTING	DISTRIBUTED COMPUTING
1.	Many operations are performed simultaneously	System components are located at different locations
2.	Single computer is required	Uses multiple computers
3.	Multiple processors perform multiple operations	Multiple computers perform multiple operations
4.	It may have shared or distributed memory	It have only distributed memory
5.	Processors communicate with each other through bus	Computer communicate with each other through message passing.
6.	Improves the system performance	Improves system scalability, fault tolerance and resource sharing capabilities

Source: https://www.geeksforgeeks.org/difference-between-parallel-computing-and-distributed-computing/

Parallel vs. Asynchronous computing

- Both parallel and asynchronous programming models perform similar tasks and functions in modern programming languages.
- However, these models have conceptual differences.
- Asynchronous programming is used to avoid “blocking” within a software application. Example, database queries or network connections are best implemented using asynchronous programming.
- An asynchronous call spins off a thread (e.g. an I/O thread) to complete the target task.
- An asynchronous calls prevents the user interface from the “freeze” effect.

Parallel vs. Asynchronous computing

- As for parallel programming, the main task is segmented into smaller tasks, to be executed by a set of threads within the reach of a common variable pool.
- Parallel programming can also prevent user interface “freeze” effect when running computational expensive tasks on a CPU.
- Key difference: In an asynchronous call, control over threads is limited and is system dependent. In parallel programming, the user has more control over task distribution, based on the number of available logical processors.

Source: http://www.peter-urda.com/2010/10/asynchronous-versus-parallel-programming