Parallel and distributed computing

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Contents

1 Architectures

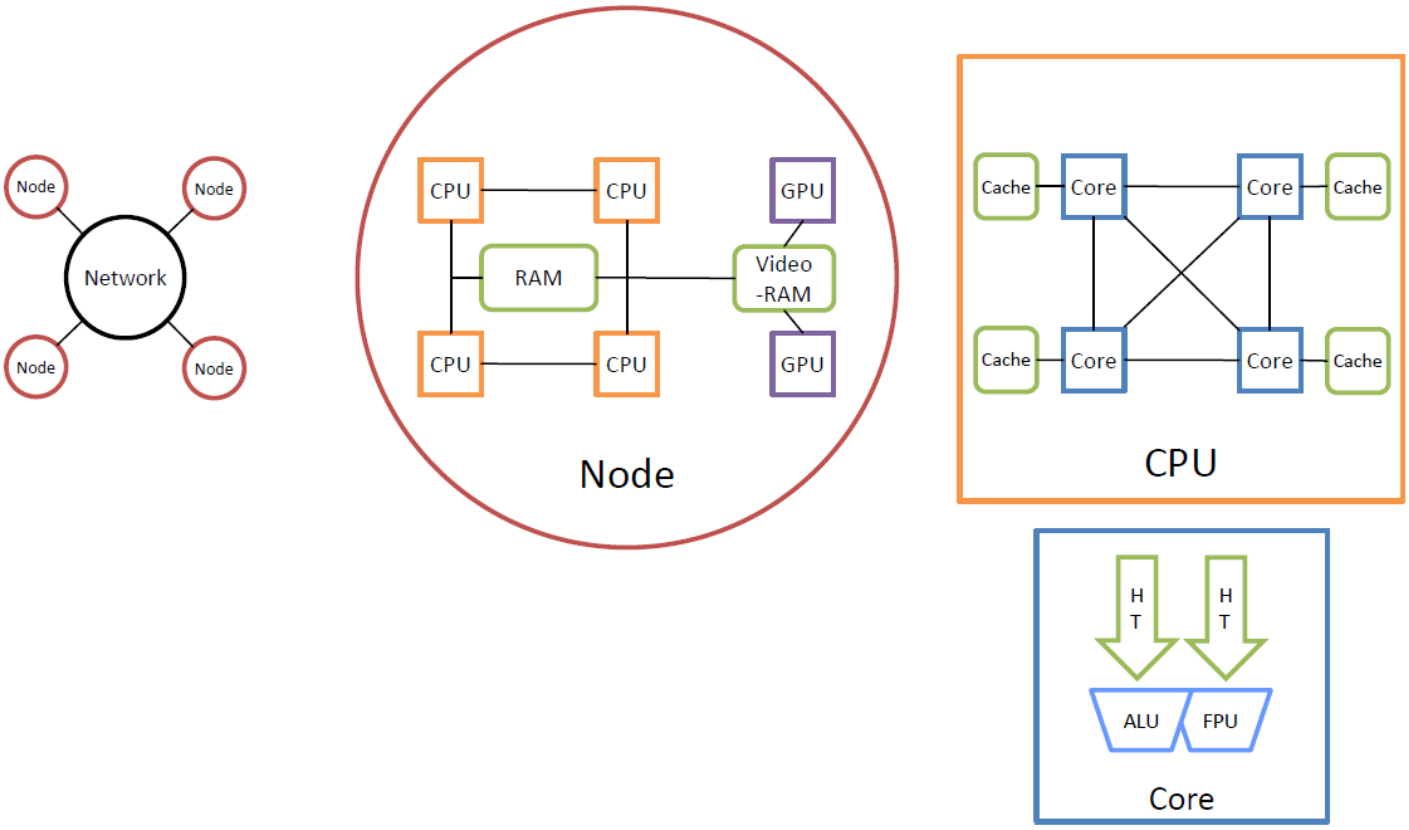


Figure 1: Parallel machine model (cluster)

1.1 Implicit vs. explicit parallelism

- Implicit Parallelism
  - processors have multiple functional units and execute multiple instructions in the same cycle
  - the precise way these instructions are selected and executed provides impressive diversity in Architectures
    - **pipelining**
    - **superscalar execution**
    - **very long instruction word processors**
- Explicit Parallelism
  - an explicitly parallel program must specify concurrency (**control structure**) and interaction (**communicatio model**) between concurrent subtasks

1.2 Parallel programming models

1.2.1 Overview of Programming models

- Programming models
  - provide support for expressing concurrency and synchronization
- Process based models
  - assume that all data associated with a process is private, by default, unless otherwise specified
- Lightweight processes and Threads

  - assume that all memory is global (bounded by process boundaries)
  - memory protection between threads of the same process is not necessary
  - support much faster memory access than processes with explicitly allocated shared memory
- Parallel programming language with syntax to specify parallelism
  - Examples: Ada, SR, Occam (no longer common)
- Directive based programming models
  - extend the threaded model by facilitating creation and synchronization of threads
  - Examples: Open MP, Linda, POP-C++

1.2.2 Parallel Machine Model

- PRAM
  - a natural extension of the Random Access Machine (RAM) serial architecture
  - consists of p processors and a global memory of unbounded size that is uniformly accessible to all processors
  - procesors share a common clock but may execute different instructions in each cycle
- Handling of simultaneous memory accesses
  - Exclusive-read, exclusive-write (EREW)
  - Concurrecnt-read, exclusive-write (CREW)
  - Exclusive-read, concurrent-write (ERCW)
  - Concurrent-read, concurrent-write (CRCW)

What does concurrent write mean?

Common: write only if all values are identical.

Arbitrary: write the data from a randomly selected processor.

Priority: follow a predetermined priority order.

Sum: write the sum of all data items.

1.3 Different grains of parallelism

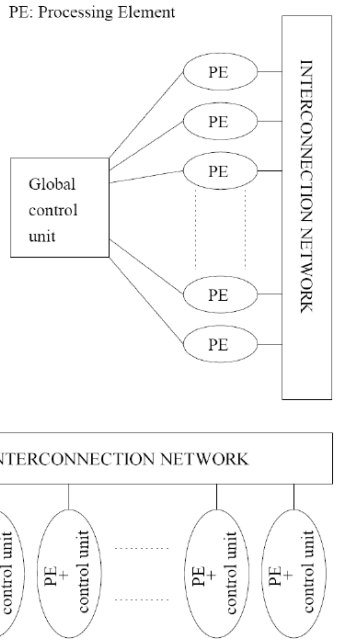
- Granularity: the ratio of computation to communication
  - periods of computation are separated from periods of communication by synchronization events
  - constrained by the inherent characteristics of the used algorithms
  - the parallel programmer must select the right granularity to benefit from the underlying platform
- Chunking
  - determining the amount of data to assign to each task (chunk or grain size)
- Which Granularity will lead to best performance?
  - depends on the algorithm and the used hardware environment
  - general rule: increase grain size if the communication overhead is too large

1.3.1 Trade-offs associated with chunk size

- Fine-grained parallelism
  - low arithmetic intensity
  - may not have enough work to hide long-duration asynchronous communication
  - facilitates load balancing by providing a larger number of more manageable (i.e. smaller) work units
  - too fine granularity can produce slower parallel implementation than the serial execution (too much overhead required for communication)
- Coarse-grained parallelism
  - high arithmetic intensity
  - complete applications can serve as the grain of parallelism
  - more difficult to load balance efficiently

1.4 Control structure of parallel platforms

- SIMD: Single Instruction stream, Multiple Data stream
  - there is a single control unit that dispatches the same instruction to various processors (that work on different data)
  - data parallelization
- MIMD: Multiple Instruction stream, Multiple Data stream
  - each processor has its own control unit
  - each processor can execute different instructions on different data items



1.4.1 SIMD Computers

- Hardware requirements
  - SIMD computers require less HW than MIMD computers (only one control unit)
  - SIMD computers require less memory (only one copy of the program is stored)
- Current implementations
  - Graphics Processing Units (GPUs)
  - Digital Signal Processors (DSPs) are widely used in cameras and sound equipments
  - Co-processing units in Intel CPUs: SSEx, AVX-512
- Software requirements
  - SIMD relies on the regular structure of computations (such as those in image and video processing or in deep learning)
  - it is often necessary to selectively turn off operations on certain data items

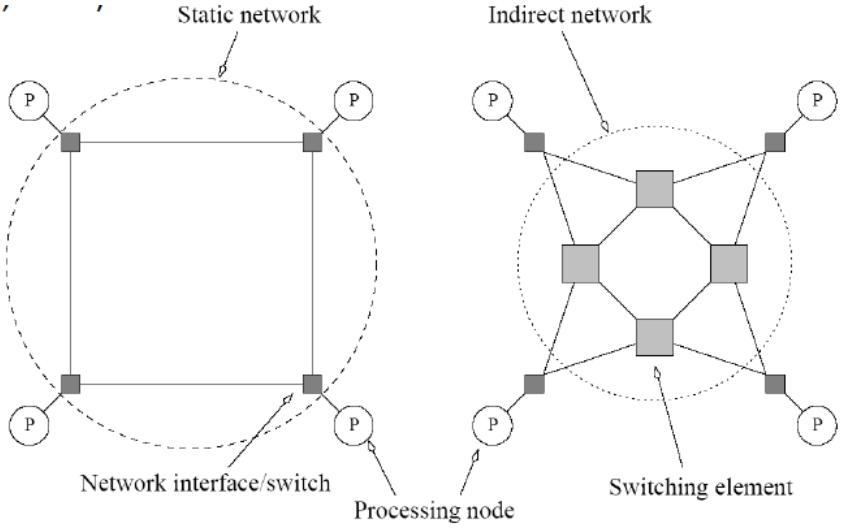
1.4.2 MIMD Computers

- Single Program Multiple Data (SPMD)
  - a simple variant of MIMD executes the same program on different processors
  - SPMD and MIMD are closely related in terms of programming flexibility and underlying architectural support
  - a single program consisting of several programs in a large switch block with conditions specified by the task identifiers is equivalent to the MIMD model
- Current MIMD implementations
  - SPARC servers, multiprocessor PCs, NASA Beowulf inspired workstation clusters
- Key advantages of workstation clusters
  - high performance workstations and PCs available at low cost
  - latest processors can easily be incorporated into the system as they become available
  - existing software can be used or modified

1.5 Communication models of parallel platforms

- Shared-Address-Space Platforms (Multiprocessors)
  - part (or all) of the memory is accessible to all processors
  - processors interact by modifying data objects stored in this shared-address-space
  - uniform or non-uniform memory access time (UMA vs. NUMA)
- Message Passing Platforms (Multicomputers)
  - comprise of a set of processors and their own (exclusive) memory
  - instances come naturally from clustered workstations (distributed systems) and non-shared-address-space multi-computers
  - are programmed using sending messages (variants of send and receive primitives)
  - libraries such as MPI (1990's) provide such primitives

1.6 Interconnection networks



- Interconnection Networks for Parallel Computers
  - carry data between processors and to memory
  - are made of switches and links (wires, fiber)
  - are classified as static or dynamic
    - static (direct) networks consist of point-to-point communication links among processing nodes
    - dynamic (indirect) networks are built using switches and communication links
- Network Topologies
  - a variety of network topologies have been proposed and implemented
  - tradeoff performance for cost
  - two basic categories: physical and logical topologies
  - commercial machines often implement hybrids of multiple topologies

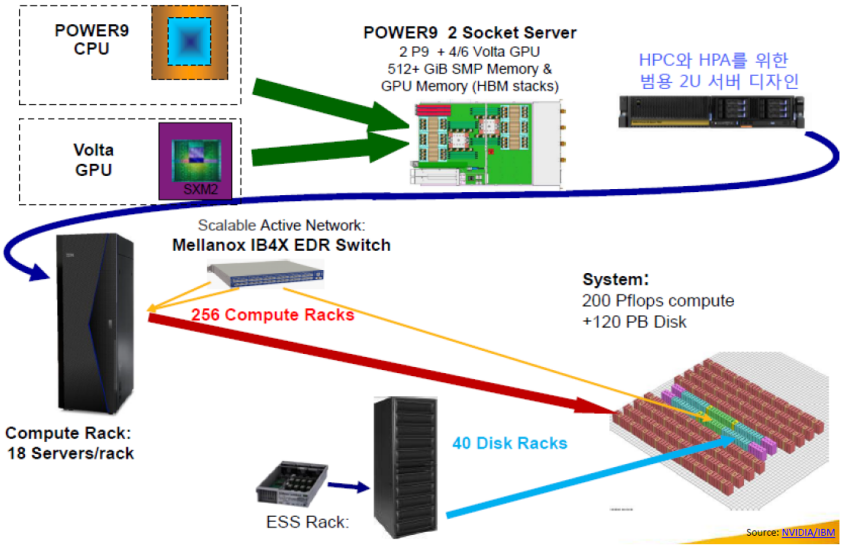
1.6.1 Interconnection Network for HPC

- Infiniband
  - a computer-networking communications standard used in HPC that features very high throughput and very low latency
  - it is used for data interconnect both among and within computers
  - it is also utilized as either a direct, or switched interconnect between servers and storage systems, as well as an interonnect between storage systems
  - it is designed to be scalable and uses a switched fabric network topology

Year	FDR 2011	EDR 2014	HDR 2017	NDR 2020	XDR 2023
Throughput, per 1x [Gbit/s]	13.64	25	50	100	250
Speed for 4x links [Gbit/s]	54.54	100	200	400	1000
Speed for 12x links [Gbit/s]	163.64	300	600	1200	3000
Latency [μs]	0.7	0.5	0.5	tbd	tbd

- PCI Express Version 4
  - a high-speed serial computer expansion bus standard
  - has numerous improvements over the older standards
    - higher maximum system bus throughput
    - lower I/O pin count and smaller physical footprint
  - has been drafted with final specifications expected in 2017
  - throughput:
    - x1: 1.969 GByte/s
    - x16: 31.508 GByte/s
  - external cabling: Thunderbolt
- NVIDIA NVLink
  - is a high-bandwidth, energy-efficient interconnect
  - enables ultra-fast communication between the CPU and GPU, and between GPU
  - throughput:
    - version 1 (used in NVIDIA Pascal): x1: 20 GByte/s, x4: 80 GByte/s
    - version 2 (used in IBM Power9 chip, NVIDIA Volta GPUs): x1: 25 GByte/s, x8: 200 GByte/s

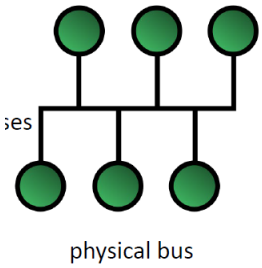
1.6.2 Data-Centric IT Environments

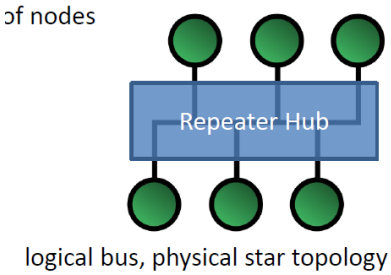


1.7 Network topologies

1.7.1 Network Topologies: Bus

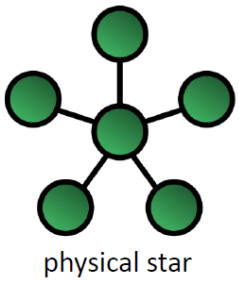
- Principle and Properties
  - some of the simplest and earliest parallel machines used buses
  - all processors access a common bus for exchanging data
  - the distance between any two nodes is $O(1)$ in a bus
- Bottleneck
  - the bandwidth of the shared bus is a major bottleneck
  - typical bus-based machines are limited to dozens of nodes
- Examples
  - WLAN zone (logical bus topology)
  - PCI bus (physical bus topology)

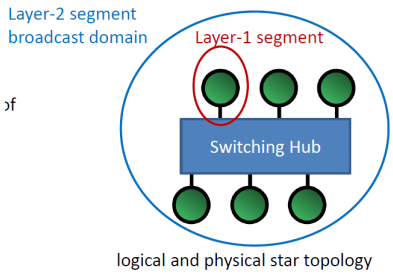




1.7.2 Network Topologies: Star

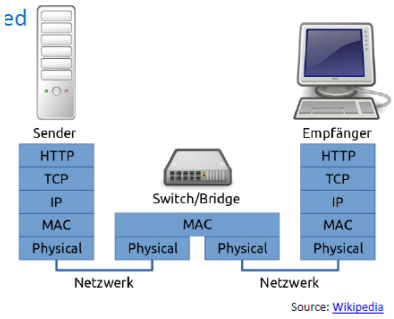
- Principle and Properties
  - every node is connected only to a common node at the center
  - distance between any pair of node is $O(1)$
- Bottleneck
  - the central node
- Example
  - today's Ethernet based LANs with bridging hub (Bridge) or switching hub (Switch) as the center of the start topology





Network Infrastructure: Switchung Hub

- Principle and Properties
  - frame forwarding depends on learned physical device-addresses (MAC) per port (Layer-2 switching)
  - non-blocking: several input-output connections can be used in parallel without blocking
  - store-and-forward
    - the switch buffers and verifies each frame before forwarding it
    - a frame is received in its entirety before it is forwarded
    - error checking can be done before forwarding
  - cut-through
    - the switch starts forwarding after the frame's destination address is received
    - when the outgoing port is busy at the time, the switch falls back to store-and-forward operation
    - there is no error checking with this method

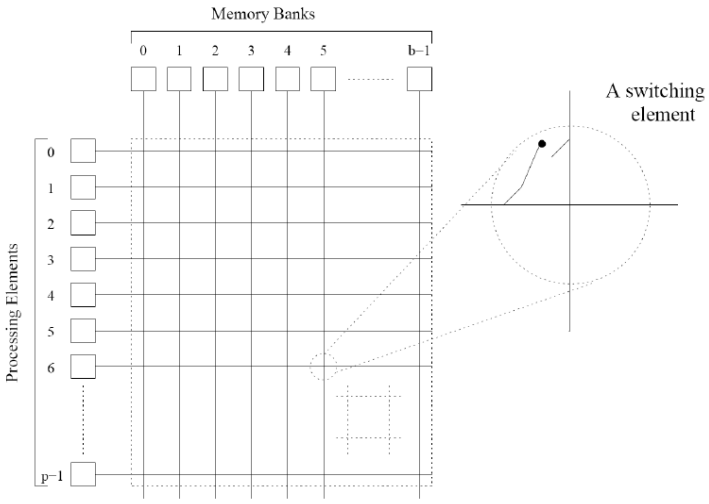


Switching Hub: Advanced Features

- Spanning Tree Protocol → Shortest Path Bridging
  - classic bridges may also interconnect using a spanning tree protocol that disables links so that the resulting local area network is a tree without loops
  - in contrast to routers, spanning tree bridges must have topologies with only one active path between two points
  - IEEE 802.1aq allows all paths to be active with multiple equal cost paths
    - provides much larger layer 2 topologies (up to 16 million compared to the 4096 VLANs limit)
    - improves the use of the **mesh topologies** through increased bandwidth and redundancy between all devices by allowing traffic to load share across all paths of a mesh network
- IEEE 802
  - is a family of IEEE standards dealing with local area networks and metropolitan area networkds
  - services and protocols specified in IEEE 802 map to the lower two layers (Data Link and Physical) of the sevel-layer OSI networking reference model
  - small subset of the working groups
    - 802.1: higher layer LAN protocols (bridging)
    - 802.1D: Spanning Tree Protocol (forwarding stopped while the spanning tree re-converged)
    - 802.1s: Multiple Spanning Tree Protocol
    - 802.1w: Rapid Spanning Tree Protocol
    - 802.1aq: Shortest Path Bridging (SPB) (incorporate all the older spanning tree protocols)

1.7.3 Network Topologies: Crossbar

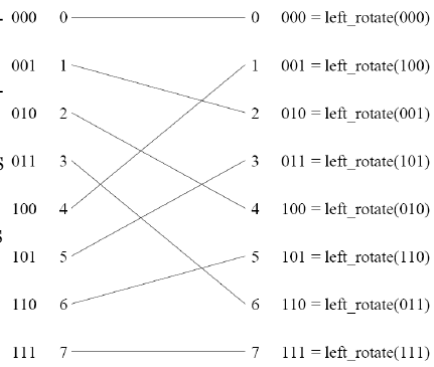
- Principle and Properties
  - a crossbar network uses an $p \cdot b$ grid of switches to connect p inputs to b outputs in a non-blocking manner
- Bottleneck
  - the cost of a crossbar of p processors grows as $O(p^2)$ → difficult to scale for large values of p
- Usage
  - in non-blocking switches
  - between L2- and L2-caches



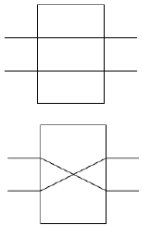
1.7.4 Network Topologies: Multistage Network

- Scalability
  - busses have excellent cost scalability, but poor performance scalability
  - crossbars have excellent performance scalability but poor cost scalability
  - multistage interconnects strike a compromise between these extremes
- Example: Omega Network
  - it consists of $log(p)$ stages, where p is the number of inputs/outputs
  - at each stage, input i is connected to output j if:

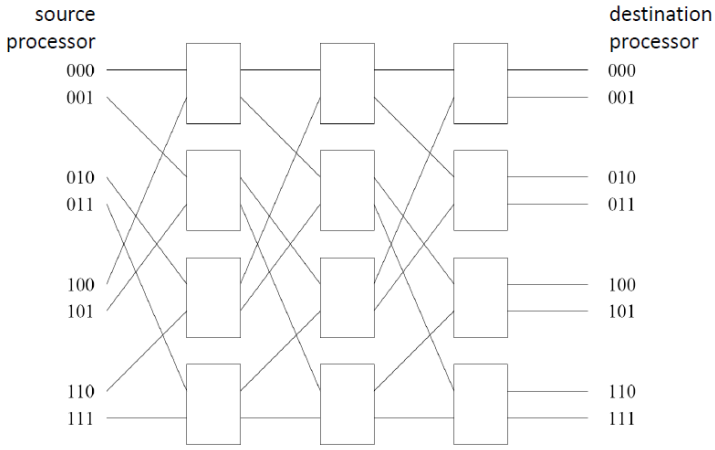
$$j = \begin{cases} 2i, & 0 \leq i \leq p/2 - 1 \\ 2i + 1 - p, & p/2 \leq i \leq p - 1 \end{cases}$$



Omega Network

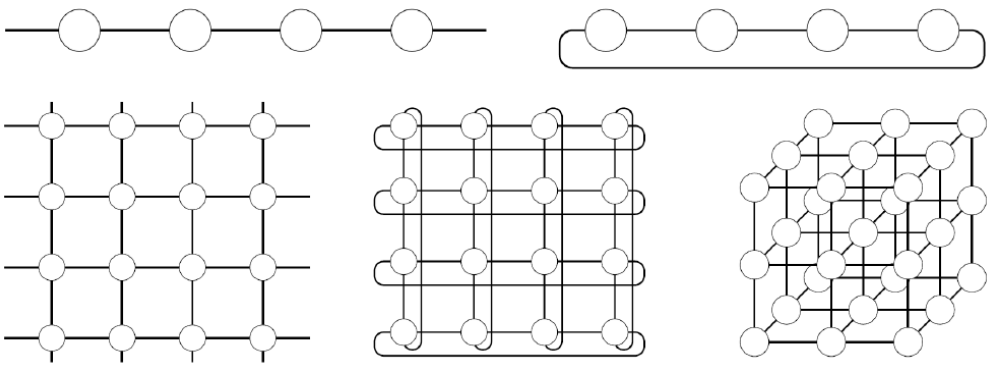


- Principle and Properties
  - the perfect shuffle patterns are connected using 2x2 switches
  - the switches operate in two modes: pass-through or cross-over



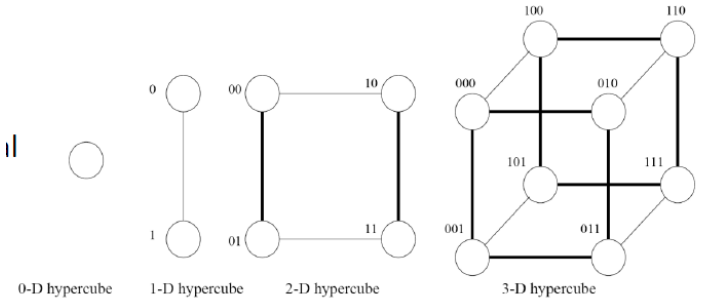
Linear Array, Mesh, and $k-d$ Mesh

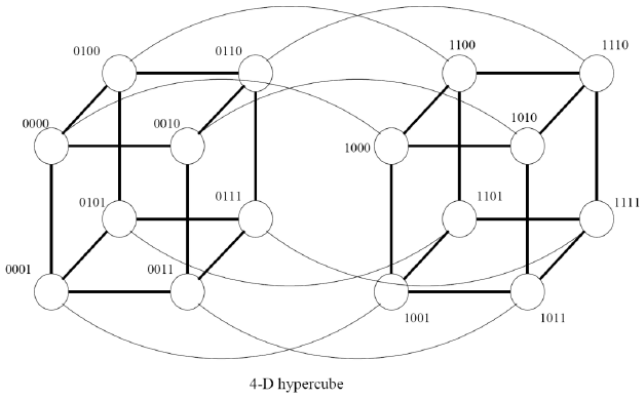
- Principle and Properties
  - in a linear array, each node has two neighbors, one to its left and one to its right
  - if the nodes at either end are connected, we refer to it as a 1-D torus or a ring
  - a generalization to 2 dimensions has nodes with 4 neighbors, to the north, south, east, and west (toroidal mesh)
  - a further generalization to d dimensions has nodes with $2d$ neighbors



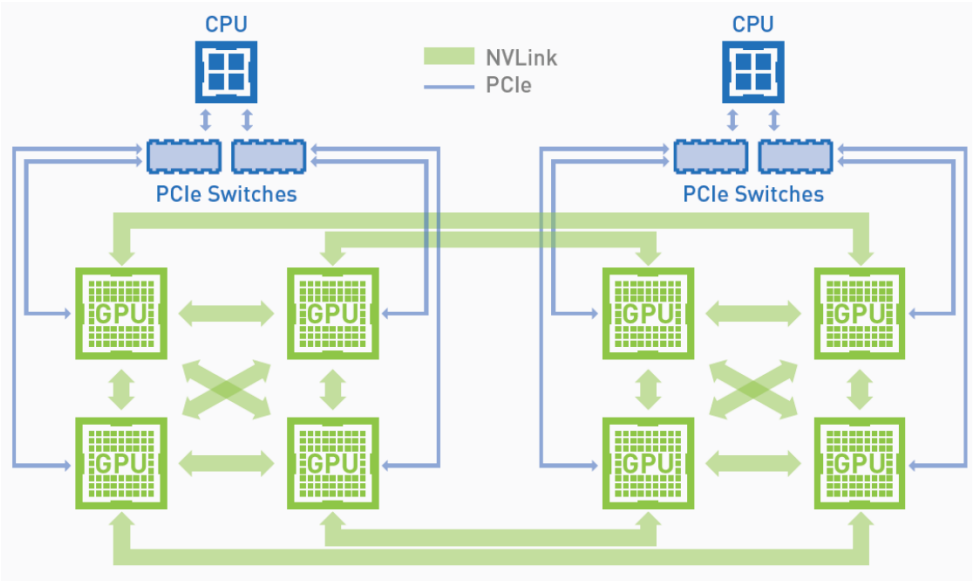
1.7.5 Network Topologies: Hypercube

- Principle and Properties
  - a special case of a d-dimensional mesh is a hypercube
  - $d = log(p)$, where p is the total number of nodes
  - the distance between any two nodes is at most $log(p)$
  - each node has $log(p)$ neighbors
  - the distance between two nodes is given by the number of bit positions at which the two nodes differ



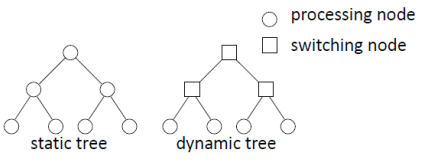


NVIDIA NVLink: Hypercube Mesh Hybrid

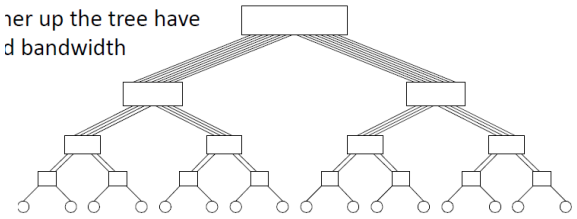


1.7.6 Tree-Based Networks

- Principle and Properties
  - one path between any pair of nodes
    - linear arrays and star-connected networks are special cases of tree networks
  - the distance between any two nodes is no more than $2log(p)$
  - links higher up the tree potentially carry more traffic than those at the lower levels
  - trees can be laid out in 2D with no wire crossings
- Fat-Tree



– links higher-up the tree have increased bandwidth



1.7.7 Evaluating Interconnection Networks

- Diameter
  - the distance between the farthest two nodes in the network
- Channel Bandwidth = channel width x channel rate
  - channel width: number of bits that can be communicated simultaneously over a link
  - channel rate: peak data transfer rate per link
- Cross-Section Bandwidth = bisection width x channel bandwidth
  - bisection width: the minimum number of wires one must cut to divide the network into two equal parts
- Cost
  - the number of links or switches (whichever is asymptotically higher) is a meaningful measure of the cost
  - the ability to layout the network
  - the length of wires
  - ...

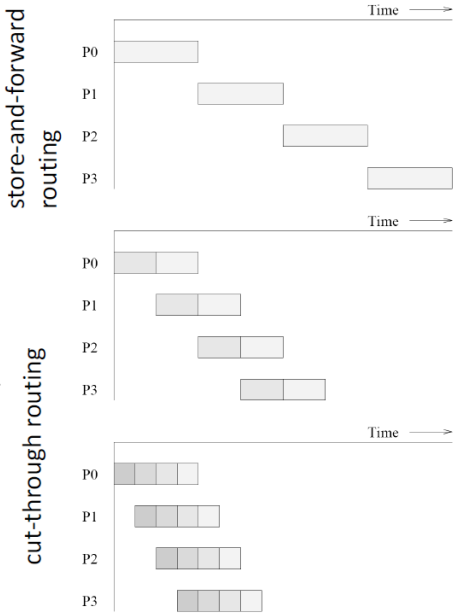
Network	Diameter	Bisection width	Arc connectivity	Cost (No. of links)
Completely-connected	1	$p^2/4$	$p-1$	$p(p-1)/2$
Star	2	*	1	$p-1$
Complete binary tree	$2 \cdot log((p+1)/2)$	1	1	$p-1$
Linear array	$p-1$	1	1	$p-1$
2D Mesh, no wraparound	$2(\sqrt{p}-1)$	$\sqrt{p}$	2	$2(p-\sqrt{p})$
2D wraparound Mesh	$2\lfloor\sqrt{p}/2\rfloor$	$2\sqrt{p}$	4	$2p$
Hypercube	$log(p)$	$p/2$	$log(p)$	$(p \cdot log(p))/2$
Wraparound k-ary d-cube	$d\lfloor k/2\rfloor$	$2k^{d-1}$	$2d$	dp

* depends on the node (switch) in the center, e.g. Crossbar or Omega Network

Network	Diameter	Bisection width	Arc connectivity	Cost (No. of links)
Crossbar	1	p	1	p^2
Omega Network	$log(p)$	$p/2$	2	$p/2$
Dynamic Tree	$2 \cdot log(p)$	1	2	$p-1$

1.8 Communication costs in parallel systems

- Overhead in parallel programs
  - idling
  - contention
  - communication
- Communication costs depend on
  - communication model
  - the network topology
  - data handling and routing (e.g. packet routing, cut-through routing)
  - associated software protocols
  - ...



1.8.1 Message Passing Costs

- Total time to transfer a message over a network comprises of the following:
  - *Startup time* (t_s): Time spent at sending and receiving nodes (executing the routing algorithm, programming routers, etc.)
  - *Per-hop time* (t_h): This time is a function of number of hops and includes factors such as switch latencies, network delays, etc.
  - *Per-word transfer time* (t_w): This time includes all overheads that are determined by the length of the message. This includes bandwidth of links, error checking and correction, etc.

1.8.2 Cost Model for Communicating Messages

- Communication Costs
  - the cost of communicating a message between two nodes/hops away using cut-through routing is given by
$$t_{\text{comm}} = t_s + l \cdot t_h + m \cdot t_w$$
  - t_h is typically smaller than t_s and t_w, so the second term does not show, when m is large
  - furthermore, it is often not possible to control routing and placement of tasks
- Simplified Cost Model
$$t_{\text{comm}} = t_s + m \cdot t_w$$
- Remarks
  - it is important to note that the original expression for communication time is valid for only uncongested networks
  - if a link takes multiple messages, the corresponding t_w term must be scaled up by the number of messages
  - different communication patterns congest different networks to varying extents

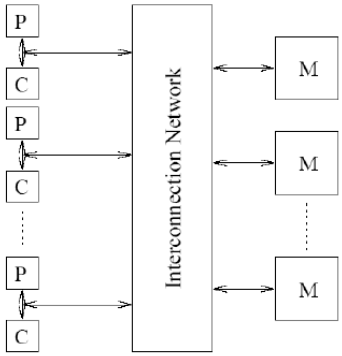
1.8.3 Cost Model for Shared Memory Systems

- Simplified Cost Model (still practical, but accurate cost modeling is more difficult)
  - memory layout is typically determined by the system
  - finite cache sizes can result in cache thrashing

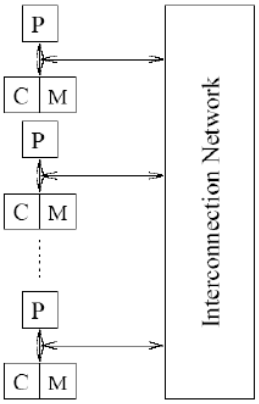
- overheads associated with invalidate and update operations are difficult to quantify
- spatial locality is difficult to model
- pre-fetching can play a role in reducing the overhead associated with data access
- false sharing and contention are difficult to model

2 Shared Memory Systems

2.1 Shared-address-space platforms



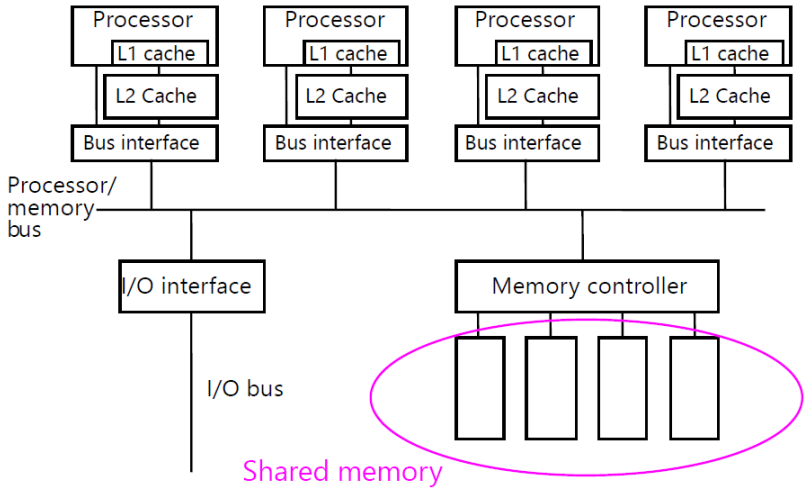
UMA (Uniform-memory-access)
shared-address-space computer with local caches and global memories → all memory access times (except cache) are identical



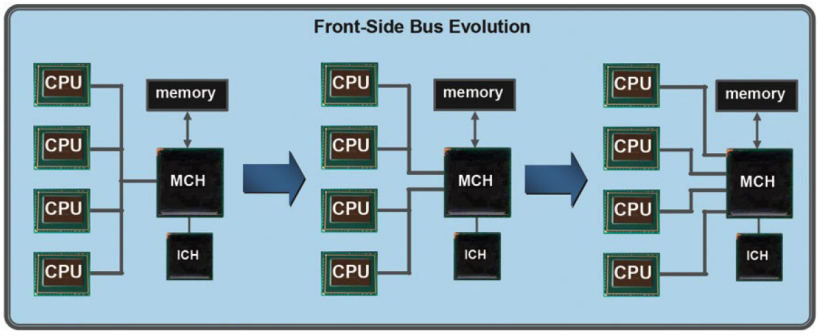
NUMA (Non-uniform-memory-access)
shared-address-space computer with local memory only
→ local memory access times are shorter

2.1.1 UMA Examples

- Intel Front Side Bus Architecture



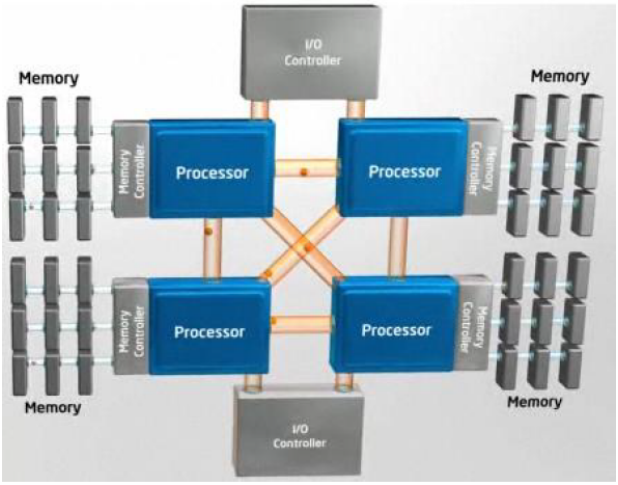
- Intel Pentium Front Side Bus Evolution



Source: Hardware LUXX

2.1.2 NUMA Examples

- Example: Intel Core i7



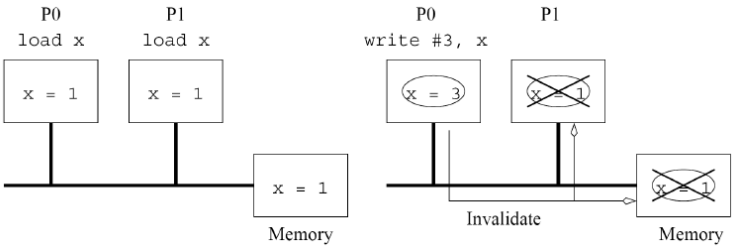
Source: University of Portsmouth

2.2 Cache coherence

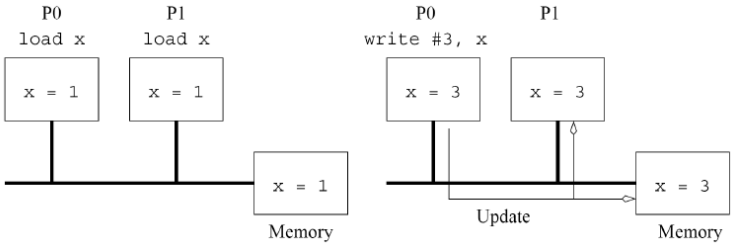
- Cache
  - principle of space and time locality
  - faster memory access
  - additional hardware is required to keep multiple copies of data consistent with each other
- Cache Coherence
  - ensuring that concurrent operations on multiple copies of the same memory word have well-defined semantics
  - this semantic is generally one of serializability
    - there exists some serial order of instruction execution that corresponds to the parallel schedule

2.2.1 Update and Invalidate Protocols

- Scenario
  - when a processor changes the value of its copy of a variable, one of two things must happen:
    - the other copies must be invalidated (invalidate protocol) (write-back)



    - the other copies must be updated (update protocol) (write-through)



- Pros and Cons
  - if a processor just reads a value once and does not need it again, an update protocol may generate significant overhead
  - if two processors make interleaved test and updates to a variable, an update protocol is better
  - both protocols suffer from false sharing overheads (two words that are not shared, however, they lie on the same cache line)
- Most current machines use invalidate protocols
  - each copy of a data item is associated with a state (e.g. shared, invalid, or dirty)
    - in shared state, there are multiple valid copies of the data item (therefore, an invalidate would have to be generated on an update)
    - in dirty state, only one copy exists and therefore, no invalidates need to be generated
    - in invalid state, the data copy is invalid, therefore, a read generates a data request (and associated state changes)

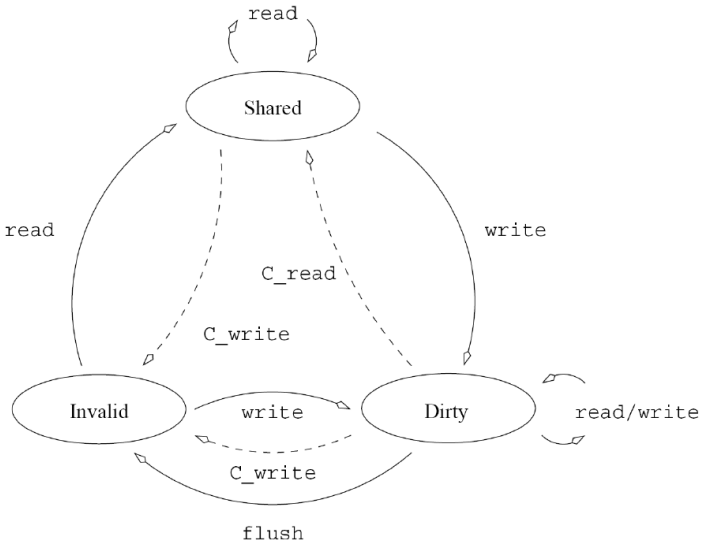


Figure 2: State Diagram of an Invalidate Protocol

2.3 Parallel programming in modern C++

- Explicit Threading
  - data exchange is more apparent
    - this helps in alleviating some of the overheads from data movement, false sharing, and contention
  - provides richer API in the form of condition waits, locks of different types, and increased flexibility for building composite synchronization operations
  - tools and support are easier to find
- Directives Layered on Top of Threads
  - simplify a variety of thread-related tasks
  - a programmer is rid of the tasks of initializing attributes objects, setting up arguments to threads, partitioning iteration spaces, etc.

2.3.1 Thread

- A thread is a single stream of control in the flow of a program. A program like

```
for (row = 0; row < n; row++)
    for (column = 0; column < n; column++)
        c[row][column] = dot_product(get_row(a, row), get_col(b, col));
```

- can be transformed to

```
for (row = 0; row < n; row++)
    for (column = 0; column < n; column++)
        thread([&]) {
            c[row][column] = dot_product(get_row(a, row), get_col(b, col));
        });
```

- In this case, one may think of the thread as an instance of a function that returns before the function has finished executing.

2.4 Threads, Futures, Tasks

2.4.1 C++: Threads and futures

- Thread
  - low-level
  - exchange of data must be synchronized itself
  - uncaught exceptions in the thread function lead to the termination of the entire program
  - thread_local storage class: static/global variables are created for each thread
  - is started automatically in the constructor
- Future
  - asynchronous processing: parallel execution or when calling get()
  - exceptions appear in the parent thread when the result is picked up with get()
  - when leaving the scope of the responsible future, then its destructor ensures a clear and problem-free termination of the asynchronous computation

2.4.2 C++: Threads as the Basis of Parallelism

- Constructor and Executor
  - thread(executable object, parameters of the executable object)
  - Executable object
    - function object (functor)
    - lambda expression
    - pointer to a function
  - the executable object and the parameters are copied by default, so the thread can work on their own data
- Example

```
void printFibs(size_t from,
    size_t to);

struct Image {
    void fill(int r, int g, int
        b);
};
```

```
int main() {
    thread th1(printFibs, 28,
        35);
    Image img;
    thread th2([&img] { img.
        fill(0,1,2); });
    th1.join(); th2.join();
}
```

2.4.3 C++: Futures and async

- Asynchronous Computation
  - parallel or deferred processing
  - async() initiates a computation and returns immediately
  - get() blocks until the result of the computation is available
- Return value of async()
  - future<RT>, where RT is the return type of the asynchronously executed function
- Launch Policy
  - async(launch::async, longComputation) guarantees parallel execution (default)
  - async(launch::deferred, computation) executed when calling get()
- Behind the scenes
  - a future can be produced without calling async(), by first creating a promise (some kind of transmission channel)

C++: Futures Example

```
#include <future>

static size_t fibrec(size_t n) {
    return (n < 2) ? 1 : fibrec(n - 2) + fibrec(n - 1);
}

int main() {
    // asynchronous computation
    auto fut1 = async(launch::async, &fibrec, 35);
    // deferred computation
    auto fut2 = async(launch::deferred, &fibrec, 35);
    cout << fut2.get() << endl;     // waiting for the result of fut2
    cout << fut1.get() << endl;     // waiting for the result of fut1
}
```

What happens if the order of the two calls of get() is changed? → fut2 would only start after fut1 would have finished → serial execution

2.4.4 C++: Packaged Tasks

- Concept
  - a packaged_task wraps a callable element and allows its result to be retrieved asynchronously
  - it is similar to function, but transferring its result automatically to a future object
- Syntax
  - template<class Ret, class ... Args> class packaged_task<Ret(Args...)>;
- Object contains internally two elements

  - a stored task, which is some callable object whose call signature shall take arguments of the types in Args... and return a value of type Ret
  - a shared state, which is able to store the results of calling the stored task (of type Ret) and be accessed asynchronously through a future

C++: Packaged Tasks Example

```
// create task for calling fibrec
// argument of fibrec has to be defined later
packaged_task<size_t(size_t)> task1(&fibrec);
auto f1 = task1.get_future(); // future for getting result

// create task for calling fibrec
// argument of fibrec is bound to 35
packaged_task<size_t(void)> task2(bind(&fibrec, 35));
auto f2 = task2.get_future(); // future for getting result

// call task1 in a parallel thread (move semantic)
thread th(move(task1), 35);
// call task2 in this thread
task2();

// get results
cout << f.get() << endl;
cout << f2.get() << endl;

th.join(); // this thread waits on parallel thread th
```

2.4.5 C++: Synchronization Primitives

- Synchronized data access (read and write) is necessary if at least one of the parallel threads changes common data
- Synchronization Primitives
  - atomic_xyz all accesses are atomic (are not interrupted)
  - atomic_flag atomic bool but lock-free
  - once_flag used in call_once, makes sure that only one of the parallel threads executes the function
  - mutex realizes mutual exclusion
  - recursive_mutex allows a thread computing a recursive function to reenter a critical section
  - lock_guard locks a critical section; very simple usage; the only state is locked
  - unique_lock needs its unique mutex object; handles both states: locked and unlocked
  - condition_variable blocks this thread until signaled (signals or notifications can be sent by other threads)

2.4.6 Serial for- vs. Parallel for-Loop

- Notice
  - a lot of programming languages don't have a special parallel for-loop syntax
  - they use the keyword for in two situations
- Serial for-Loop
  - the loop notation simplifies the programming of a fixed number of repetitive, sequentially ordered steps
    - Example: reading n integers from a sequential file
- Parallel for-Loop

  - the loop notation simplifies the programming of a fixed number of repetitive steps, that can be done in any order
    * Example: for each element of an array proceed the same task

C++: Possible parallel for-each implementation

```
template<typename It>
void parallelForEach(It begin, It end, function<void(typename It::reference)> f) {
    const ptrdiff_t len = end - begin;
    if (len == 0) {
        return;
    } else if (len == 1) {
        f(*begin);
        return;
    }

    const It mid = begin + (ptrdiff_t)(len/2);
    future<void> fut = async(parallelForEach<It>, begin, mid, f);
    try {
        parallelForEach(mid, end, f);
    } catch (...) {
        fut.wait();
        throw;
    }
    fut.get();
}
```

C++: Usage of parallelForEach

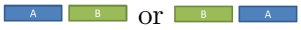
```
static size_t fibrec(size_t n) {
    return (n < 2) ? 1 : fibrec(n - 2) + fibrec(n - 1);
}

int main() {
    int vals[] = {5, 10, 15, 20, 25, 30, 35, 40};
    int size = sizeof(vals)/sizeof(int);

    parallelForEach(vals, vals + size, [](size_t n) {
        cout << fibrec(n) << endl;
    });
    return 0;
}
```

2.4.7 Parallel Algorithms in C++17

- Ordering
  - "sequenced-before" is an asymmetric, transitive, pair-wise relationship between evaluations within the same thread
  - A is sequenced before B

  - if A is not sequenced before B and B is not sequenced before A, then two possibilities exist:
    * evaluations of A and B are **indeterminately sequenced**: they may be performed in any order but may not overlap
      

    * evaluations of A and B are **unsequenced**: they may be performed in any order and may overlap (within a single thread of execution, the compiler may interleave the CPU instructions that comprise A and B)
      

- Execution Policies
  - most algorithms have overloads that accept execution policies:
  - std::execution::seq sequential execution like calling the algorithms without an execution policy
  - std::execution::par execution potentially using multiple threads
    parallel instructions are indeterminately sequenced
    is not allowed to cause data races or to cause dead-locks
  - std::execution::par_unseq execution may be parallelized, vectorized, or migrated across threads
    parallel instructions and ordering in the same thread: unsequenced
    use of blocking synchronization primitives (e.g. mutex) may cause dead-lock
  - std::execution::unseq execution may be vectorized
    ordering in the same thread: unsequenced

Execution Policies and Ordering Examples

```
int a[] = {0, 1};
vector<int> v;
for_each(execution::par, begin(a), end(a), [&](int i) {
    v.push_back(i*2+1);  // Error: data race (vector isn't thread safe)
});

int x = 0;
mutex m;
for_each(execution::par, begin(a), end(a), [&](int) {
    lock_guard<mutex> guard(m);
    ++x;     // Correct, because mutual exclusion is guaranteed
});          // and sequence among parallel lambdas is irrelevant

for_each(execution::par_unseq, begin(a), end(a), [&](int) {
    lock_guard<mutex> guard(m);     // Error: calls m.lock() and several of these
    ++x;                            // calls are unsequenced and can interleave
})
```

2.5 OpenMP

- A Standard for Directive Based Parallel Programming
  - OpenMP is a directive-based API that can be used with
    * FORTRAN
    * C/C++

    for programming shared address space machines
- OpenMP directives provide support for
  - concurrency
  - synchronization
  - data handling

while obviating the need for explicitly setting up
  - mutexes
  - condition variables
  - data scope
  - initialization
- standard specifications: `http://www.openmp.org/specifications`
  - Visual Studio 2019 only supports OpenMP standard 2.0

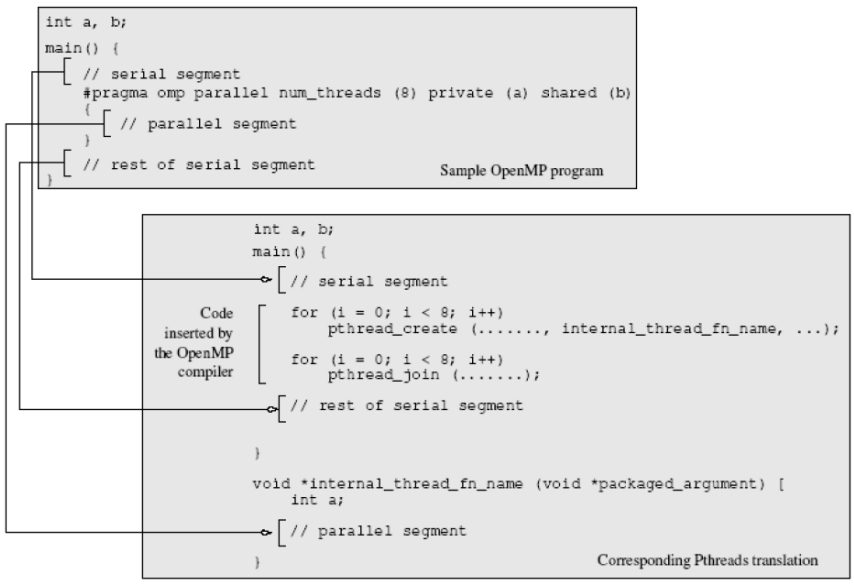
2.5.1 OpenMP Programming Model

- OpenMP in C/C++
  - directives are based on the #pragma compiler directives
  - a directive consists of a directive name followed by clauses
    #pragma omp directive [clause list]
- OpenMP programs
  - execute serially until they encounter the parallel directive, which creates a group of threads

```
#pragma omp parallel [clause list]
/* structured block */
```

  - the main thread that encounters the parallel directive becomes the **master** of this group of threads and is assigned the thread **id 0** within the group
  - at the end of the parallel executed block the main thread waits for all parallel threads (join)

2.6 OpenMP: behind the scene



2.6.1 Clause List in OpenMP

- Clause List specifies
  - Conditional Prallelization
    - the clause if (scalar expr) determines whether the parallel construct results in creation of threads
    - the scalar expression is evaluated at runtim
  - Degree of Concurrency
    - the clause num_threads(integer expr) specifies the number of threads that are created
  - Data Handling
    - the clause private (variable list) indicates variables local to each thread T

    - the clause firstprivate (variable list) is similar to the private, except values of variables are initialized to corresponding values before the parallel directive
    - the clause shared (variable list) indicates that variables are shared across all the threads
- Example

```
#pragma omp parallel if(is_parallel == 1) num_threads(8) \
private(a) shared(b) firstprivate(c)
{
  /* structured block */
}
```

2.6.2 Default Clause in OpenMP

- Syntax
  - default(shared — none)
- Semantic
  - the default clause allows the user to affect the data-sharing attributes of variables
  - omitting this clause is the same as the default(shared)
- default(shared)
  - is equivalent to explicitly listing each currently visible variable in a **shared** clause, unless it is **threadprivate** or **const**-qualified
- default(none)
  - it is usually better style to use default(none) instead of default(shared)
  - requires that at least one of the following must be true for every reference to a variable in the lexical extent of the parallel construct
    - the variable is explicitly listed in a data-sharing attribute clause
    - the variable is declared within the parallel construct
    - the variable is **threadprivate** or has a **const**-qualified type
    - the variable is the loop control variable for a **for**-loop that immediately follows a **for** or **parallel for**-directive, and the variable reference appears inside the loop

2.6.3 Default Clause in OpenMP

- Reduction Clause
  - specifies how multiple local copies of a variable at different threads are combined into a single copy at the master when threads exit
  - the usage is
    reduction (operator: variable list)
  - the variables in the list are implicitly specified as being private to threads
  - the operator can be one of +, *, −, &, |, ˆ, &&, ||
- Example

```
#pragma omp parallel default(none) reduction(+: sum) num_threads(8)
{
  /* compute local sums here */
  sum = ...;
}
/* sum here contains sum of all local instances of sums */
```

2.6.4 OpenMP Programming: Example

```
int main() {
  const int npoints = 10000000;
```

```
  int sum = 0;
  mt19937_64 re; // random engine
  uniform_real_distribution<double> dist;
  #pragma omp parallel default(none) reduction(+: sum) num_threads(8)
  {
    #pragma omp for
    for (int i = 0; i < npoints; i++) {
      if (hypot(dist(re), dist(re)) < 1) sum++
    }
  }
  cout << setprecision(10) << 4.0*sum/npoints << endl;
}
```

2.6.5 OpenMP Directives

Directive	Description
atomic	Specifies that a memory location will be updated atomically.
barrier	Synchronizes all threads in a team; all threads pause at the barrier, until all threads execute the barrier.
critical	Specifies that code is only executed on one thread at a time.
flush	Specifies that all threads have the same view of memory for all shared objects.
for	Causes the work done in a for-loop inside a parallel region to be divided among threads.
master	Specifies that only the master thread should execute a section of the program.
ordered	Specifies that code inside a parallelized for-loop should be executed by multiple threads in parallel.
sections	Identifies code sections to be divided among all threads.
single	Specifies that section of code should be executed on a single thread, not necessarily the master thread.
threadprivate	Specifies that a variable is private to a thread.

2.7 Concurrent tasks in OpenMP

- The for-directive
  - specifies concurrent iterations
  - is used to split parallel iteration spaces across threads
  - the general form is

```
#pragma omp for [clause list]
/* for loop */
```

  - allowed clauses
    - private
    - firstprivate , lastprivate
    - reduction
    - schedule
    - nowait
    - ordered

- The sections-directive
  - specifies concurrent tasks
  - the general form is

```
#pragma omp sections [clause
    list]
{
  #pragma omp section
    /* structured block 1 */
  #pragma omp section
    /* structured block 2 */
  // ...
}
```

2.7.1 The for Directive

- Schedule Clause

  - deals with the assignment of iterations to threads
  - the general form of the schedule directive is
    schedule(scheduling_class [, parameter])
- four scheduling classes
  - static
    - splits the iteration space into equal chunks of size *parameter* and assigns them to threads in a round-robin fashion
    - when no *parameter* is specified, the iteration space is split into equally sized chunks, one chunk per thread
  - dynamic
    - the iteration space is partitioned into chunks of size *parameter* (default value: 1)
    - these chunks are assigned to threads as they become idle
  - guided
    - the chunk size is reduced exponentially as each chunk is dispatched to a thread
    - the *parameter* specifies the smallest chunk size (default value: 1)
  - runtime
    - the environment variable OMP_SCHEDULE determines at runtime the scheduling class and the chunk size

2.7.2 The schedule Clause: Example

```
/* static scheduling of matrix multiplication loops */
#pragma omp parallel default(none) shared(a, b, c) num_thread(4)
  #pragma omp for schedule(static)
  for (int i = 0; i < 128; i++) {
    for (int j = 0; i < 128; j++) {
      c(i,j) = 0;
      for (int k = 0; k < 128; k++) {
        c(i,j) += a(i, k)*b(k, j);
      }
    }
  }
```

2.7.3 The nowait Clause

- Implicit Barrier
  - at the end of the parallel for-loop all threads join
- Clause nowait
  - often, it is desirable to have a sequence of for-directives within a parallel construct that do not execute an implicit barrier at the end of each for directive
- Example

```
#pragma
{
  #pragma omp for nowait
  for (int i = 0; i < nmax; i++)
    if (isEqual(name, current_list[i])) processCurrName(name);
  #pragma omp for
  for (int i = 0; i < nmax; i++)
    if (isEqual(name, past_list[i])) processPastName(name);
}
```

2.7.4 The sections Directive

- Sections
  - supports non-iterative parallel task assignment using the sections directive
- Example

```
#pragma omp parallel
{
  #pragma omp sections
  {
    #pragma omp section
    {
      taskA();
    }
    #pragma omp section
    {
      taskB();
    }
    #pragma omp section
    {
      taskC();
    }
  }
}
```

2.7.5 Merging Directives

- Remember
  - the **parallel** directive creates the group of threads
  - the for and the sections directive would execute serially (by the master thread) if no parallel directive is specified before
- Merging parallel and for directives

```
#pragma omp parallel shared(n)
{
  #pragma omp for
  for (int i = 0; i < n; i++) {
      // ...
  }
}
```

```
#pragma omp parallel for shared(n)
for (int i = 0; i < n; i++) {
  // ...
}
```

2.7.6 Nesting parallel Directives

- Example

```
#pragma omp parallel for shared(a, b, c) num_threads(4)
for (int i = 0; i < 128; i++) {
  #pragma omp parallel for shared(a, b, c) num_threads(4)
  for (int j = 0; j < 128; j++) {
    c(i,j) = 0;
    #pragma omp parallel for shared(a, b, c) num_threads(4)
    for (int k = 0; k < 128; k++) {
```

```
            c(i,j) += a(i, k)*b(k, j);
        }
      }
    }
```

- Remarks
  - OpenMP does not allow nested for, sections, and single directives that bind to the same parallel directive
  - each for directive brings its own parallel directive, which only generates a logical team of threads on encountering a nested parallel directive
  - the newly generated logical team is still executed by the same thread corresponding to the outer parallel directive
  - to generate a new set of threads, nested parallelism must be enabled by setting the OMP_NESTED environment variable to TRUE

2.8 Synchronization in OpenMP

- Synchronization Constructs
  - #pragma omp barrier
  - #pragma omp single [clause list]
    /* structured block */
  - #pragma omp master
    /* structured block */
  - #pragma omp critical [(name)]
    /* structured block */
  - #pragma omp atomic
    /* memory update instruction */
  - #pragma omp ordered
    /* structured block */
  - #pragma omp flus [(variable list)]

2.8.1 Example: Prefix Sums

```
cumulSum[0] = list[0];
#pragma omp parallel for default(none) shared(cumulSum, list) ordered

for (int i = 1; i < n; i++) {
  // other work
  #pragma omp ordered
  {
    cumulSum[i] = cumulSum[i - 1] + list[i];
  }
}
```

2.8.2 Data Handling in OpenMP

- Which data class should you use when?
  - private
    - a thread initializes and uses a variable and no other thread accesses the data
    - it is better to use a local variable in an omp block
    - if multiple threads manipulate different parts of a large data structure, the programmer should explore ways of breaking it into smaller data structures and making them private to the thread that manipulates them

  - firstprivate
    - a thread repeatedly reads a variable that has been initialized earlier in the program
  - reduction
    - if multiple threads manipulate a single piece of data, one must explore ways of breaking these manipulations into local operations followed by a single global operation (reduction)
  - threadprivate(variable list)
    - all variables in the list are local to each thread and are initialized once before they are accessed in a parallel region
    - these variables persist across different parallel regions provided dynamic adjustment of the number of threads is disabled and the number of threads is the same

2.9 OpenMP library functions

- Thread and Processor Count
  - #include <omp.h
  - void omp_set_num_threads (int num_threads);
  - int omp_get_num_threads();
  - int omp_get_max_threads();
  - int omp_get_thread_num();
  - int omp_get_num_procs();
  - int omp_in_parallel() ;
- Controlling and Monitoring Thread Creation
  - void omp_set_dynamic(int dynamic);
  - int omp_get_dynamic();
  - void omp_set_nested(int nested);
  - int omp_get_nested();
- Mutual Exclusion
  - void omp_init_lock(omp_lock_t *lock);
  - void omp_destroy_lock(omp_lock_t *lock);
  - void omp_set_lock(omp_lock_t *lock);
  - void omp_unset_lock(omp_lock_t *lock);
  - int omp_test_lock(omp_lock_t *lock);

2.9.1 Environment Variables in OpenMP

- Environment Variables
  - OMP_NUM_Threads
    - specifies the default number of threads created upon entering a parallel region
  - OMP_SET_DYNAMIC
    - determines if the number of threads can be dynamically changed
  - OMP_NESTED
    - turns on nested parallelism
  - OMP_SCHEDULE
    - scheduling of for-loops if the clause specifies runtime
- Common Mistakes in OpenMP programs
  - `http://michaelsuess.net/publications/suess_leopold_common_mistakes_06.pdf`

2.9.2 OpenMP Standard

- Version 3.1
  - major change since version 2.5
    - tasks added to execution model
- Version 4.0

  - major changes since version 3.1
    * array syntax extended to support array sections
    * proc_bind clause to support thread affinity policies
    * SIMD contructs to support SIMD parallelism
    * device constructs to support execution of devices (e.g. GPU)
    * user defined reductions
    * depend clause to support task dependencies
- Version 5.1
  - major changes since version 4.5
    * extended memory model to distinguish different types of flush operations
    * support of modern C++20