CONCURRENT AND PARALLEL PROGRAMMING

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Syllabus - CST 303

- Concurrent versus sequential programming.
- Concurrent programming constructs and race condition.
- Synchronisation primitives.
- Processes and threads.
- Interprocess communication.
- Livelock and deadlocks, starvation, and deadlock prevention.
- Issues and challenges in concurrent programming paradigm and current trends.

Syllabus - CST 303

- Parallel algorithms – sorting, ranking, searching, traversals, prefix sum etc.
- Parallel programming paradigms – Data parallel, Task parallel, Shared memory and message passing,
- Parallel Architectures, GPGPU, pthreads, STM, OpenMP
- OpenCL, Cilk++, Intel TBB, CUDA
- Heterogeneous Computing: C++AMP, OpenCL

References

- Principles of Concurrent and Distributed Programming by Ben-Ari (Prentice-Hall International)
- Concurrent Programming: Principles and Practice by Greg Andrews (Addison Wesley)
- Synchronization Algorithms and Concurrent Programming by Gadi Taubenfeld (Pearson)

References

- Introduction to Parallel Computing by Ananth Grama, et al (Pearson)
- Programming Massively Parallel Processors - A Hands-on Approach by David B. Kirk (Morgan Kaufmann)
- Parallel Algorithms by Joseph JaJa (Addison Wesley)
- CUDA Programming by Shane Cook (Morgan Kaufmann)
- Heterogeneous Computing with OpenCL by Benedict Gaster, et al (Morgan Kaufmann)

Approach

- Concurrent Programming (POSIX Threads)
- Synchronization Primitives
- Interprocess Communication
- Livelock and Deadlocks
- Parallel Programming Paradigms
  - Message Passing (MPI), Shared Memory (OpenMP)
- Parallel Architectures GPGPU
- Nvidia CUDA, AMD OpenCL, Cilk++, Intel TBB
- Parallel Algorithms
- Heterogeneous Computing

Weightage – Theory

- Mid Term 30
- End Term 50
- Quiz / Assignment 20

Concurrent versus Parallel

- **Concurrency** is when two tasks can start, run, and complete in overlapping time periods.
- **Parallelism** is when tasks literally run at the same time, eg. on a multicore processor.

- **Concurrency:** A condition that exists when at least two threads are making progress.
- **Parallelism:** A condition that arises when at least two threads are executing simultaneously.

Concurrent versus Parallel

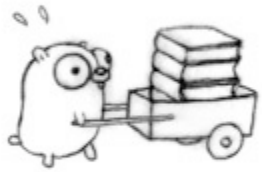
- **Concurrency:** When multiple tasks performed simultaneously with shared resources
- **Parallelism:** when single task divided into multiple simple independent tasks which can be performed simultaneously

- **Concurrency:** Programming as the composition of independently executing processes.
- **Parallelism:** Programming as the simultaneous execution of (possibly related) computations.

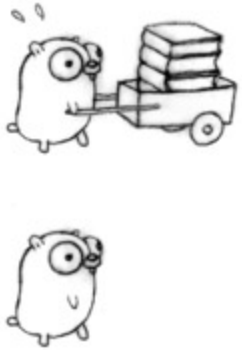
Concurrent versus Parallel

- Sequential
- Concurrent
- Parallel
- Concurrent But Not Parallel
- Parallel But Not Concurrent
- Concurrent and Parallel

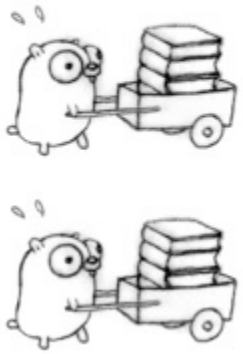
Problem !



Solution ?

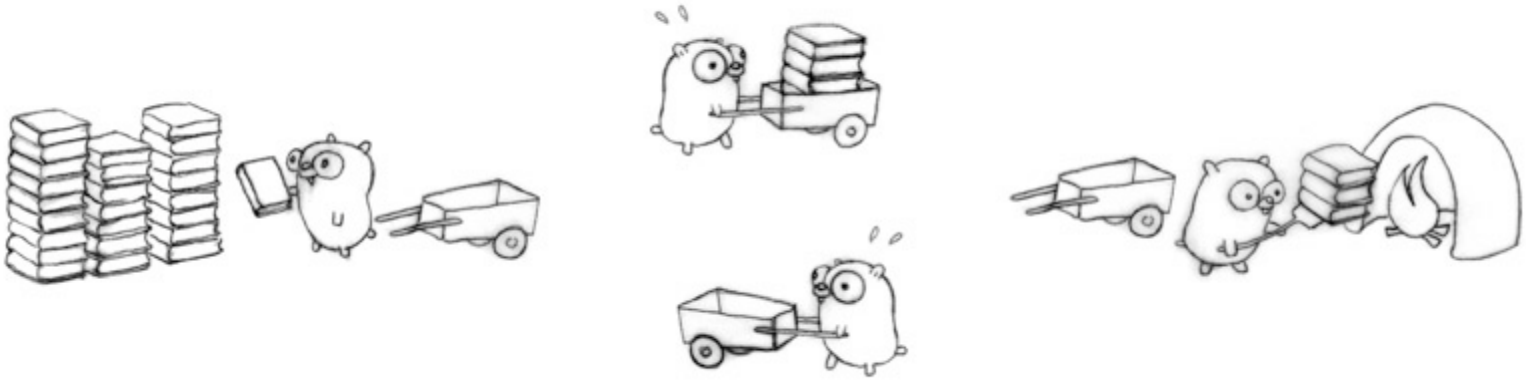


Parallel ?

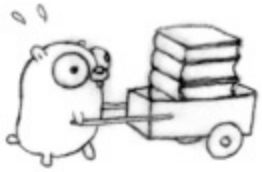


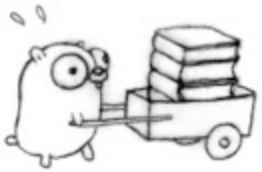
Concurrent ?

More Concurrent ?

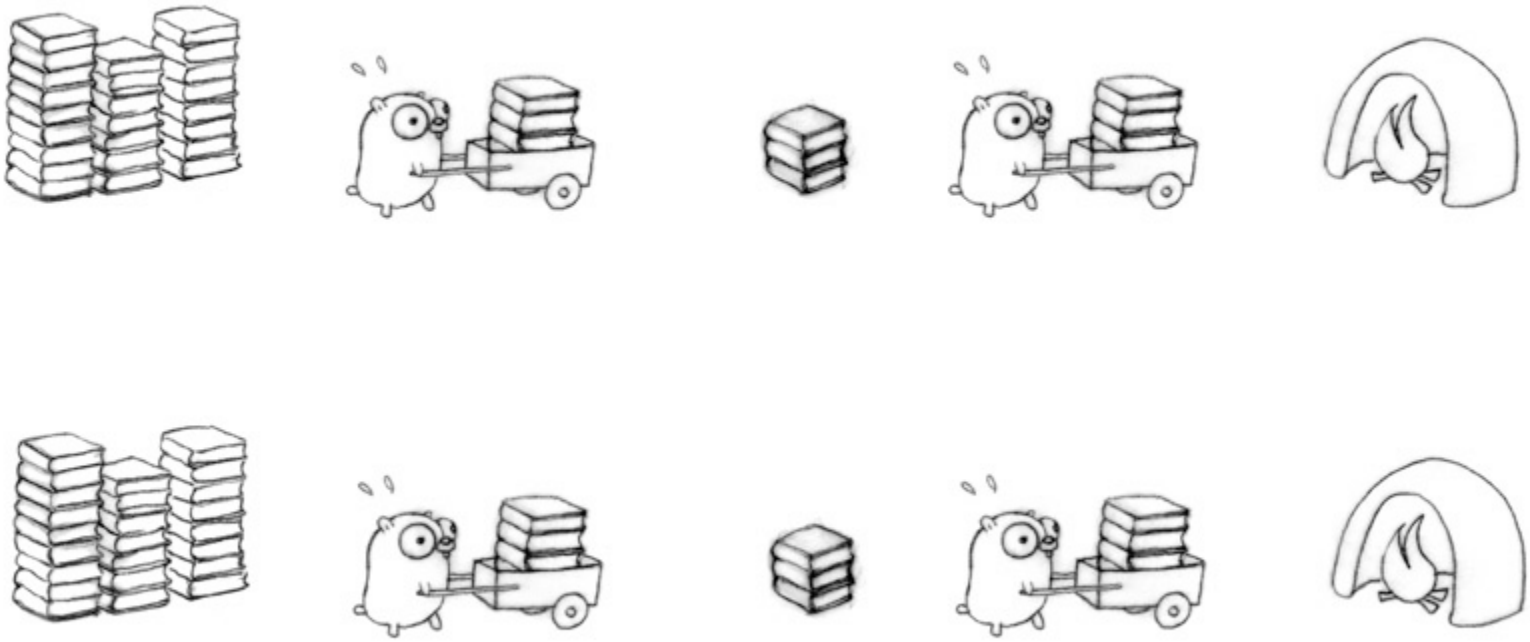


Parallel ?

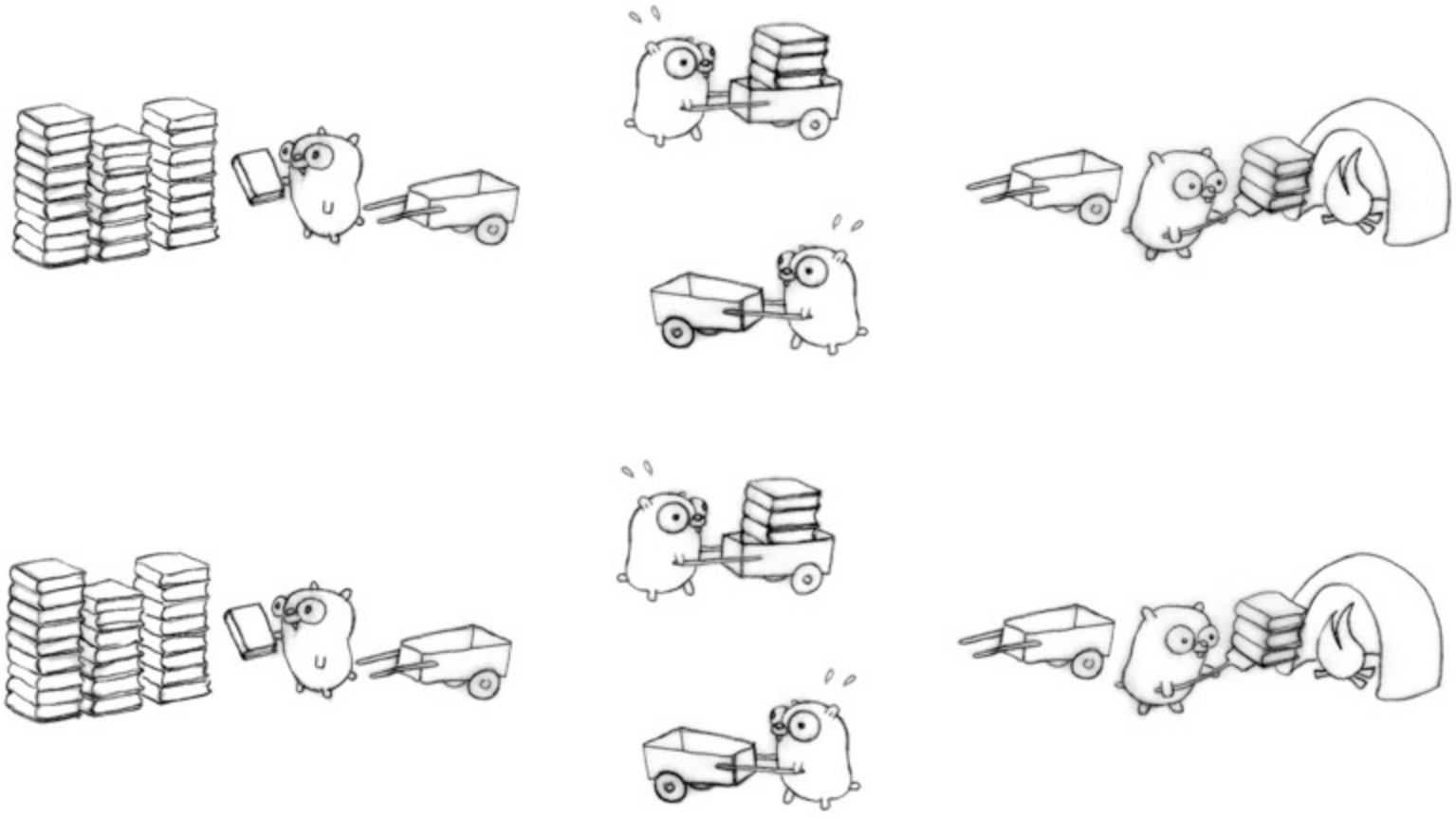




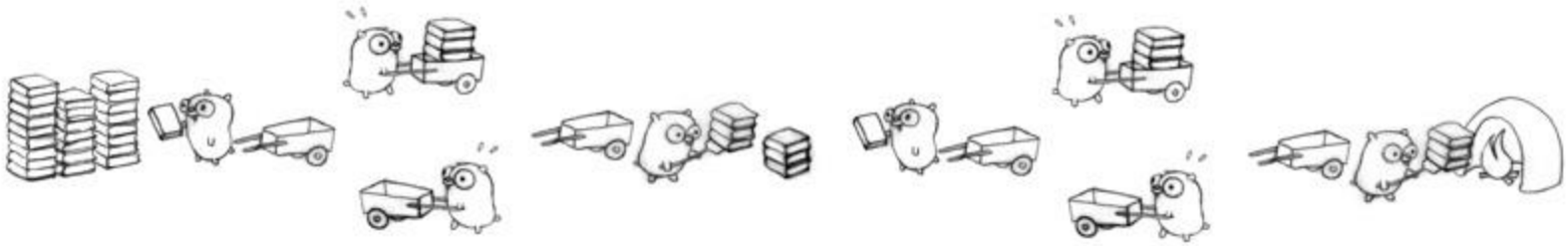
Concurrent or Parallel ?



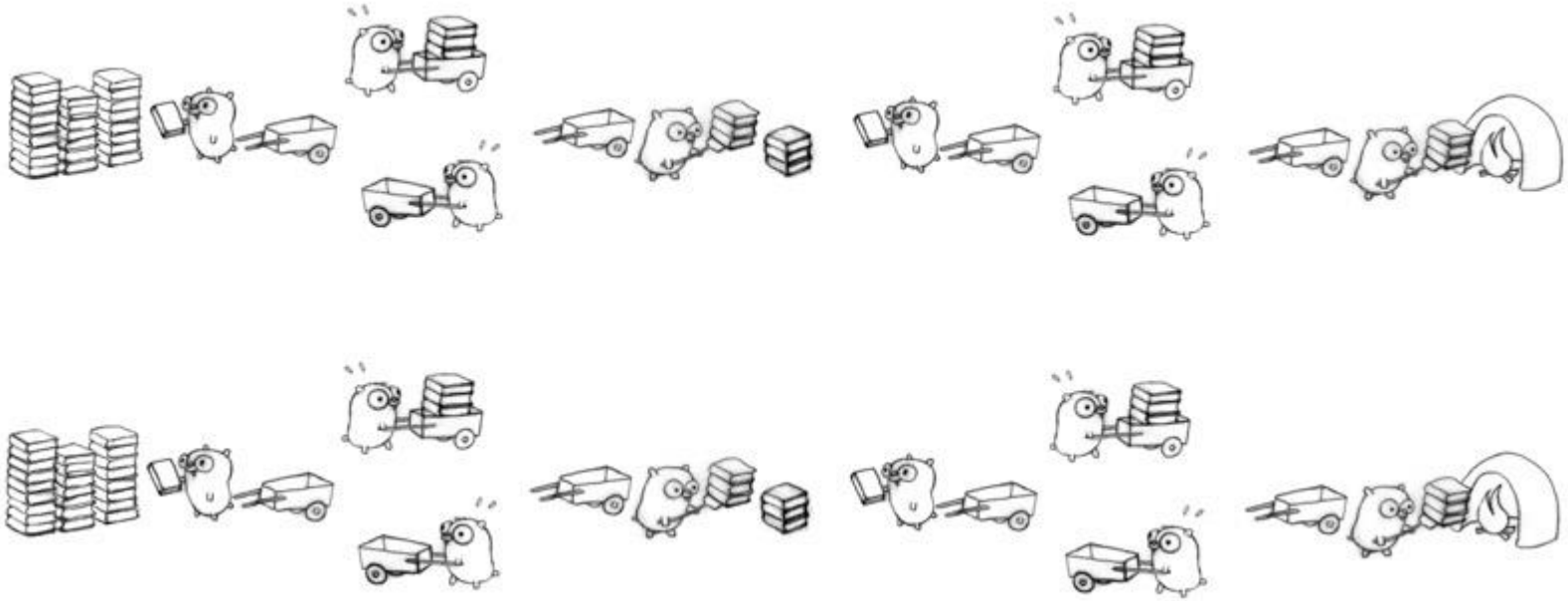
Concurrent or Parallel ?



Multi Gopher + Staging Pile



Full Optimization



CONCURRENT PROGRAMMING

CONCEPTS & NOTATIONS

Three Issues

- How to express concurrent execution
- How processes communicate
- How processes synchronize

Concurrent Programs

- Sequential program specifies sequential execution of a list of statements
- Execution of the program is called a process
- Concurrent program specifies two or more sequential programs that may be executed concurrently as parallel processes

Concurrent Programs

- Concurrent program can be:
  - Executed either by allowing processes to share one or more processes – multiprogramming
  - Executed by running each process on its own processor
    - multiprocessing if the processors share common memory as in multiprocessor
    - distributed processing if processors are connected by a communication network

Process Interaction

- Concurrently executing processors must communicate and synchronize in order to cooperate
- Communication allows execution of one process to influence execution of another
- Interprocess communication can be done
  - Use of shared variables
  - By message passing

Synchronization

- Necessary when processes communicate
- Synchronization is a set of constraints on the ordering of events
- Programmer employs a synchronization mechanism to delay execution of a process in order to satisfy such constraints

Concurrent Execution

- fork
- join
- cobegin
- call
- resume
- process

Sync Prim – Shared Variables

- Busy Waiting
- Semaphores
  - Binary
  - Counting
- Conditional Critical Regions- mutual exclusion condition
- Monitors

Sync Prim – Message Passing

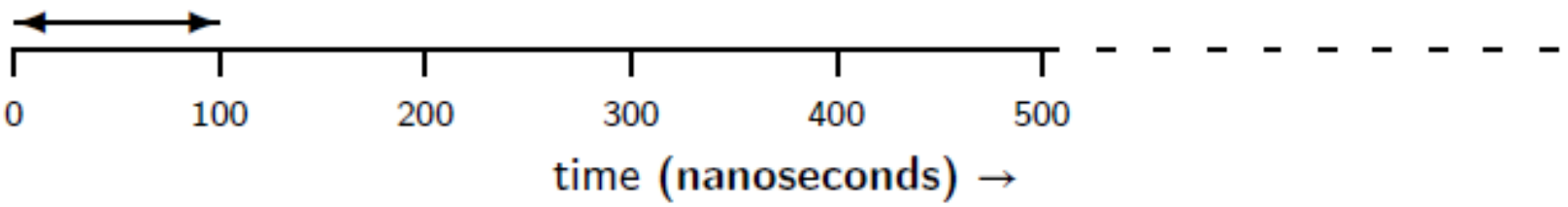
- Specifying channels of Communication
  - send
  - receive
  - blocking
  - non blocking
  - asynchronous message
  - buffered
  - send no-wait

Concurrent versus Parallel

- Concurrent program is a set of sequential programs that can be executed in parallel
- Parallel program is used for systems in which executions of several programs overlap in time by running them on separate processors
- Concurrency can be used to denote potential parallelism – execution may, but need not overlap

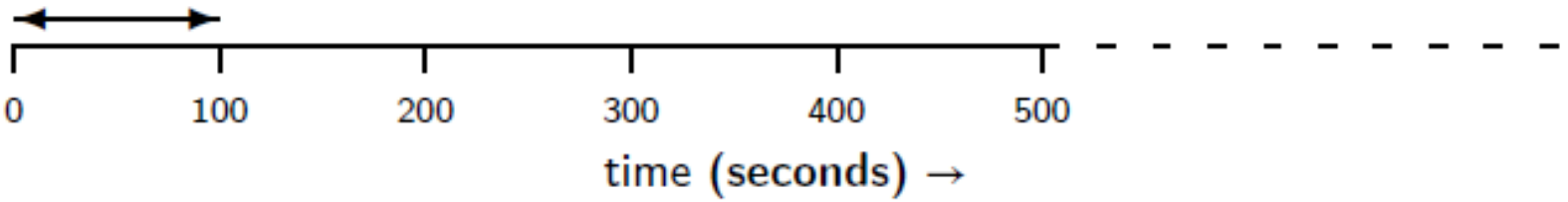
Concurrency as Abstract Parallelism

- Clock speed of CPU of a PC is of the order of magnitude of one GHz (one billion times a second)
- Every nano second, the clock ticks and the processor performs some operation



Concurrency as Abstract Parallelism

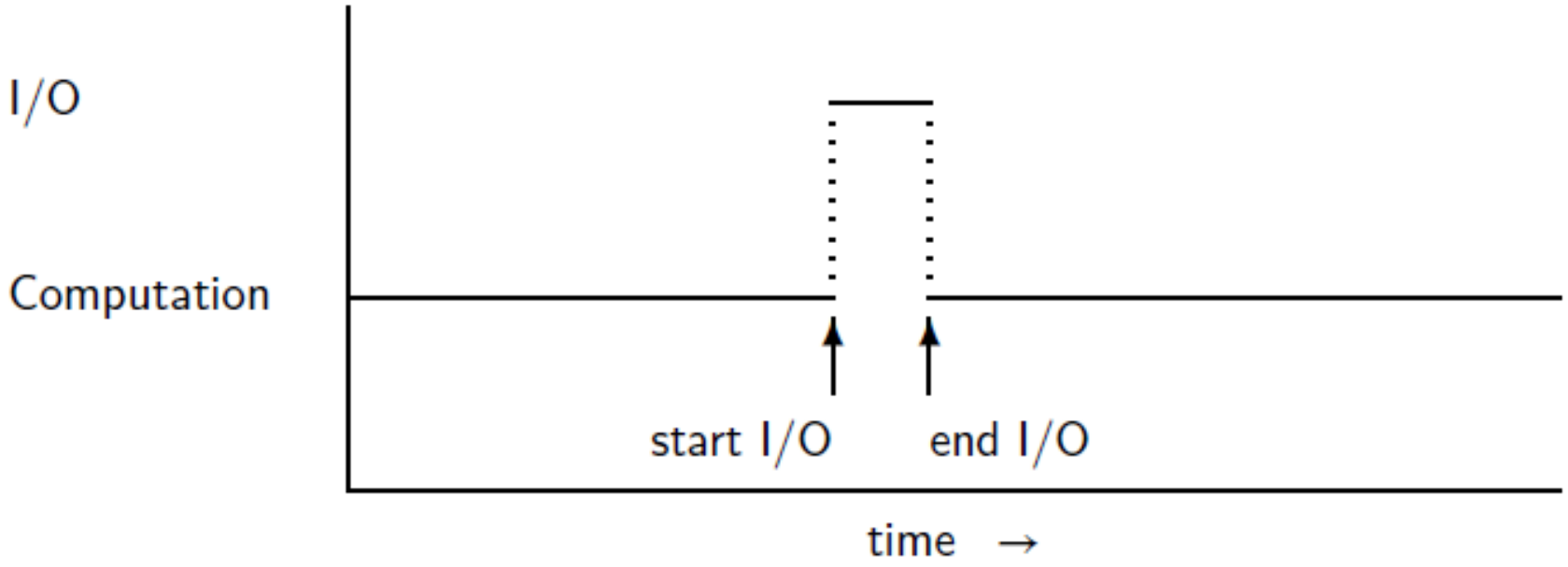
- If we are processing characters by hand, we do not consciously perform operations on the scale of nanoseconds
- Tremendous gap between human and electronic devices led to OS which allow I/O operations in parallel with computation



Concurrency as Abstract Parallelism

- On a single CPU, processing required for each character typed cannot really be done in parallel
- A fraction of micro second can be stolen from the other computation to process the character
- Degradation is not noticeable even if the overhead of switching between the two computations is included
- I/O processing is performed as the result of an interrupt and is a separate process executed concurrently with a process doing another computation

Concurrency as Abstract Parallelism



Multitasking

- Simple generalization of overlapping the computation with that of another computation
- Kernel of all modern OS does *multitasking*
- Scheduler program is run by the OS to determine which process should be allowed to run for the next interval of time
- Time-slicing is implemented where computations are periodically interrupted to allow a fair sharing of resources of CPU

Multitasking

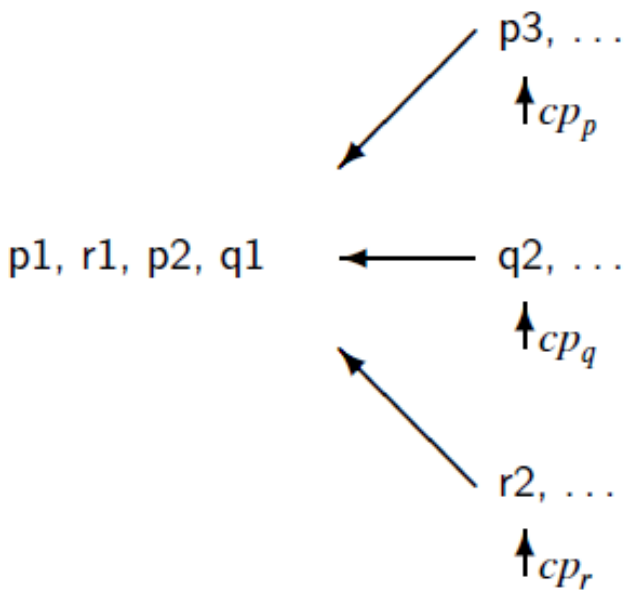
- Programming languages support *multi threading* - multitasking within programs
- Threads enable the programmer to write concurrent computations within a single program
- Process runs in its own address space managed by the OS
- Thread runs within the address space of a single process which may be managed by a multithreaded kernel within the process

Interleaving of Atomic Statements

- *Concurrent program* consists of a finite set of sequential processes
- The processes are written using a finite set of *atomic statements*
- Execution of a concurrent program proceeds by executing a sequence of atomic statements obtained by *arbitrarily interleaving* the atomic statements from the processes
- *Computation* is an execution sequence that can occur as a result of the interleaving

Interleaving of Atomic Statements

- Computations are also called *scenarios*
- During a computation, the *control pointer* of a process indicates the next statement that can be executed by that process



p1→q1→p2→q2,

p1→q1→q2→p2,

p1→p2→q1→q2,

q1→p1→q2→p2,

q1→p1→p2→q2,

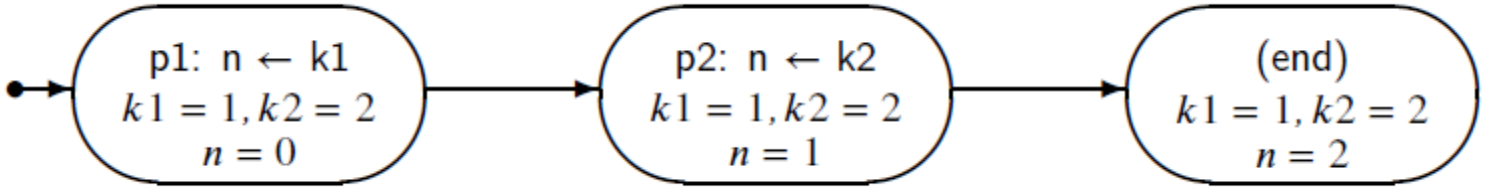
q1→q2→p1→p2.

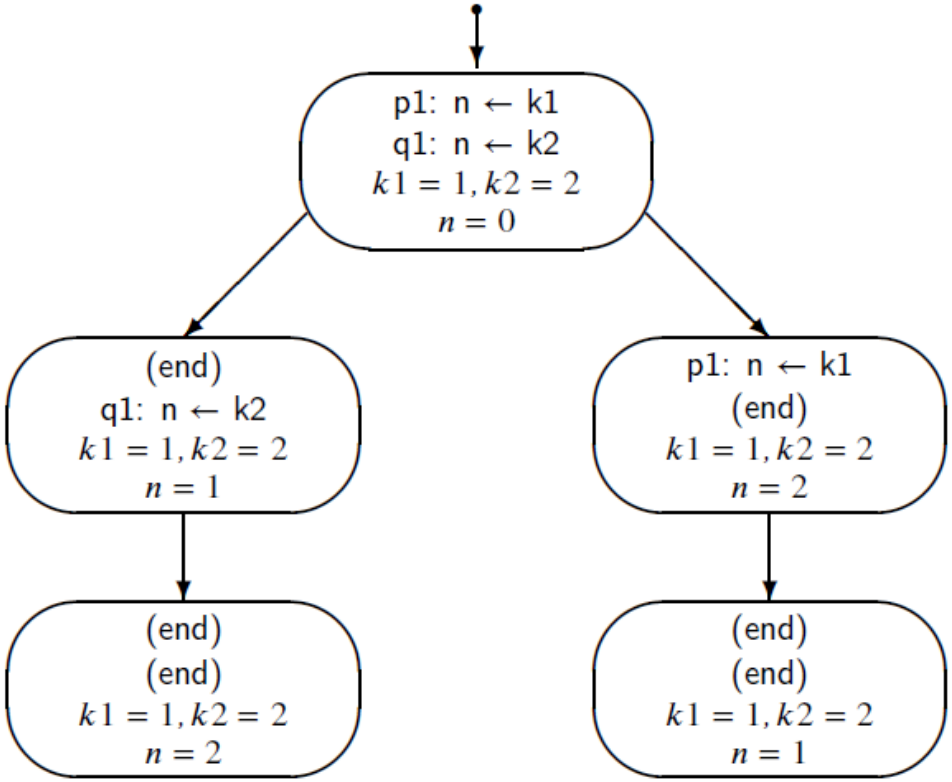
Concurrent and Serial Program

Algorithm 2.1: Trivial concurrent program	
integer n ← 0	
p	**q**
integer k1 ← 1	integer k2 ← 2
p1: n ← k1	q1: n ← k2

Algorithm 2.2: Trivial sequential program
integer n ← 0
integer k1 ← 1
integer k2 ← 2
p1: n ← k1
p2: n ← k2

State Representation





State and Transition

- The *state* of a concurrent algorithm is a tuple consisting of one element for each process that is a label from that process, and one element for each global or local variable that is a value whose type is the same as type of the variable
- Let s_1 and s_2 be two states, then there is a *transition* between s_1 and s_2 if executing a statement in state s_1 changes the state to s_2

State Diagram

- A *state diagram* is a graph defined inductively.
- The initial state diagram consists a single node labeled with the initial state.
- If state s_1 labels a node in the state diagram, and if there is a transition from s_1 to s_2, then there is a node labeled s_2 in the state diagram and a directed edge from s_1 to s_2
- For each state, there is only one node labeled with that state
- Set of reachable states is the set of states in a state diagram

Scenario

- Scenario is defined by a sequence of states
- Use tables of scenarios instead of diagrams
- List the sequence of states, columns for control pointers are labeled with processes and columns for variable values with the variable names

Process p	Process q	n	k1	k2
p1: n←k1	q1: n←k2	0	1	2
(end)	**q1: n←k2**	1	1	2
(end)	(end)	2	1	2

Scenario

- In a state, there may be more than one statement that can be executed
- Bold font is used for denoting the statement that was executed to get to the state in the following row
- Rows represent states
- If a statement executed is an assignment statement, the new value that is assigned to the variable is a component of the next state in the scenario, which is found in the next row.

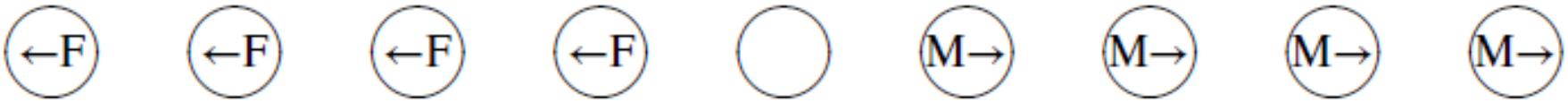
Justification of the Abstraction

- Coordination between computers cannot be done at the level of individual instructions
- There is not enough time to coordinate individual instructions of more than one CPU
- Execution of a concurrent program is considered to be carried out by a global entity who at each step selects the process from which the next statement will be executed
- The interleaving of processes is arbitrary
- This abstraction is justified for various possible architectures

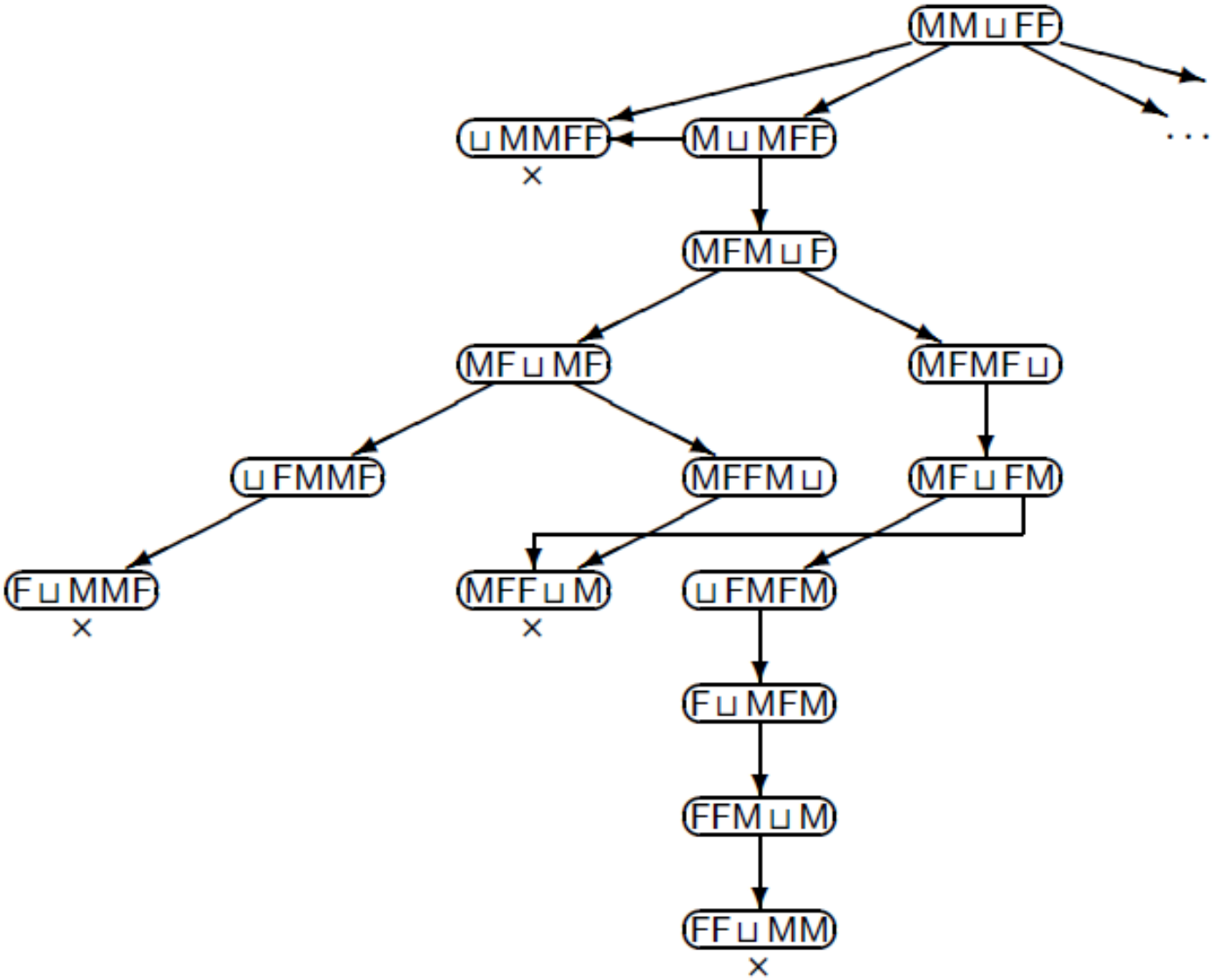
State Diagram for the Frog Puzzle

State Diagram for the Frog Puzzle

State Diagram for the Frog Puzzle



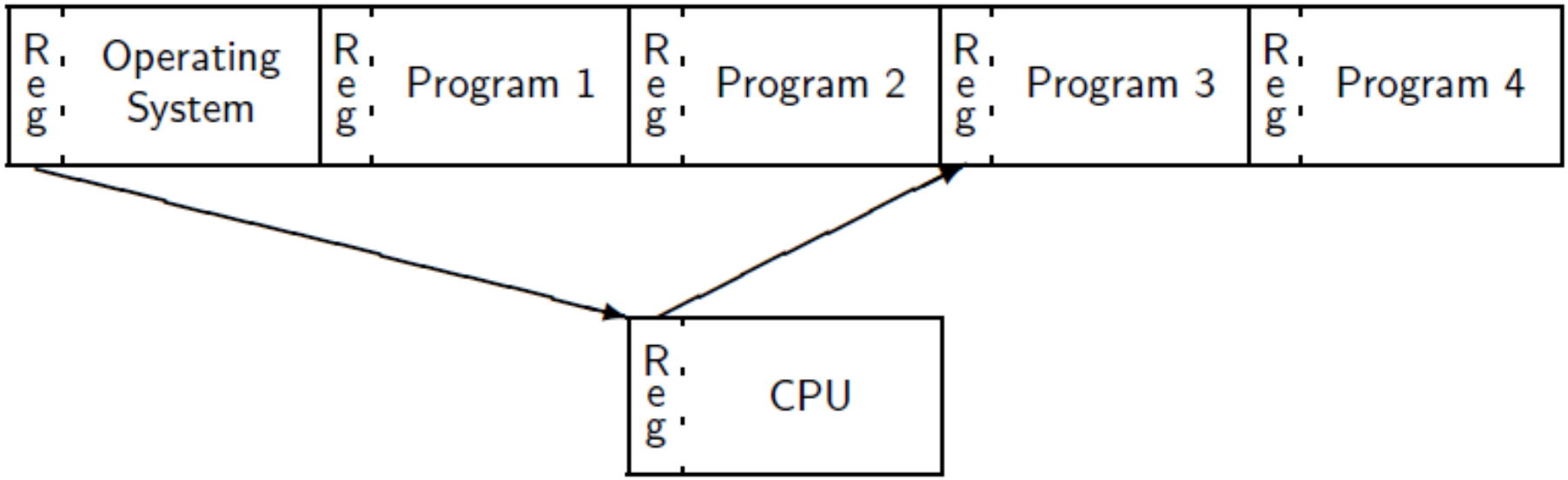
State Diagram for the Frog Puzzle



Multitasking Systems

- Selection of next instruction to execute is carried out by the CPU and the OS
- Interrupts from I/O devices or interrupt timers will cause execution to be interrupted
- *Interrupt handler* will be executed and upon its completion, the OS scheduler is invoked to select a new process
- This mechanism is called *context switch*

Multitasking Systems

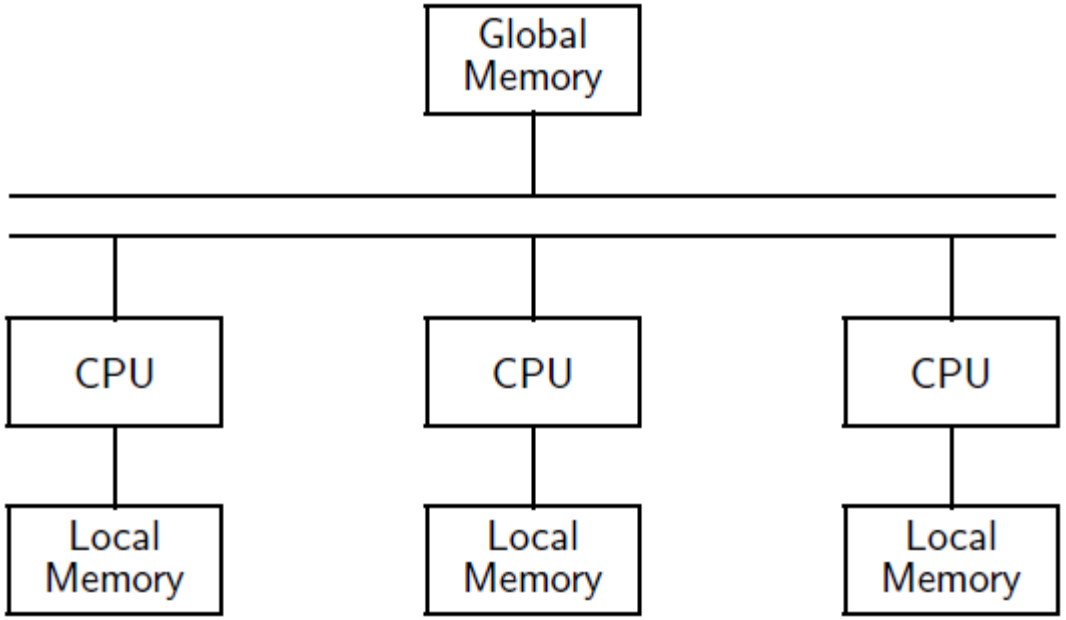


Multitasking Systems

- When execution is interrupted, all the registers (computation, control and others) are saved in a predefined area in the program's memory
- Register contents required to execute the interrupt handler are loaded into the CPU
- After interrupt is processed, the symmetric context switch is performed storing the interrupt handler registers and loading program registers
- OS scheduler decides to perform the context switch with another program and not the one that was interrupted

Multiprocessor Computers

- Computer with more than one CPU
- Memory is physically divided into banks
- *Local* memory (accessed by one CPU) and *Global* memory (accessed by all CPUs)

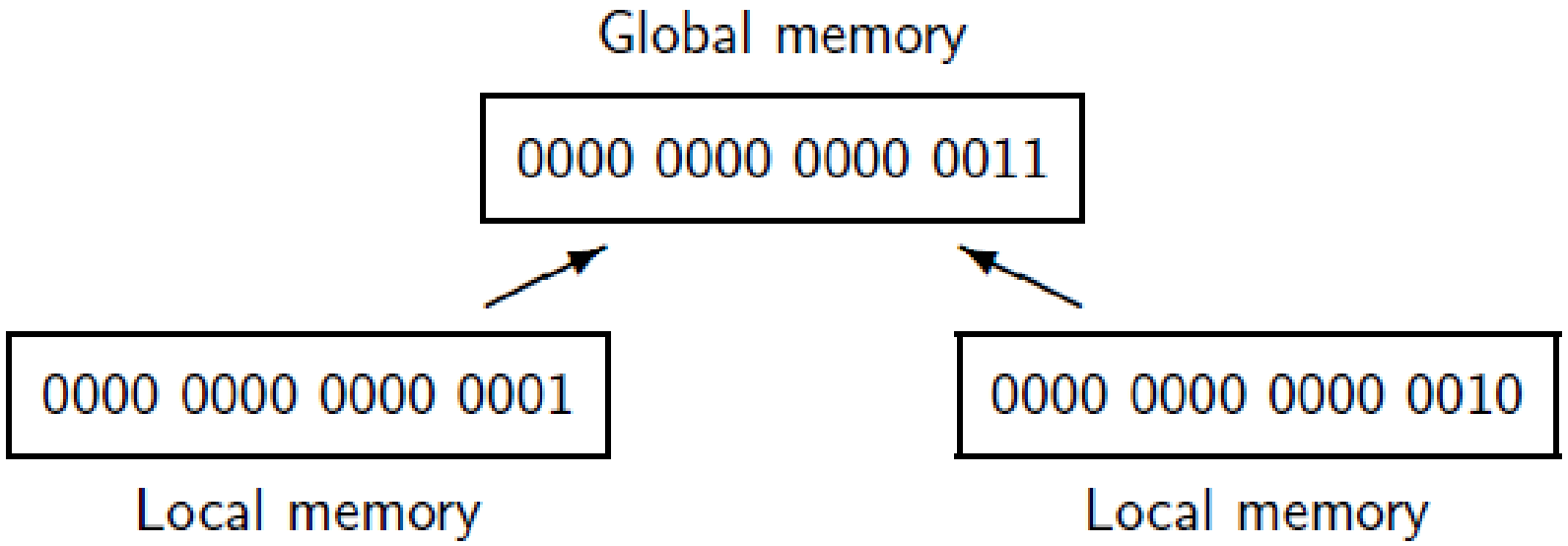


Multiprocessor Computers

- If sufficient CPUs are present, each process has its own CPU
- Interleaving is no longer real as each CPU is executing instructions independently
- As long as there is no *contention* and two CPUs do not attempt to access the same resource (say global memory)
- Computations defined by interleaving will be indistinguishable from parallel execution
- With contention there is a potential problem

Multiprocessor Computers

- If two processes try to read or write to a cell simultaneously so that the operations overlap



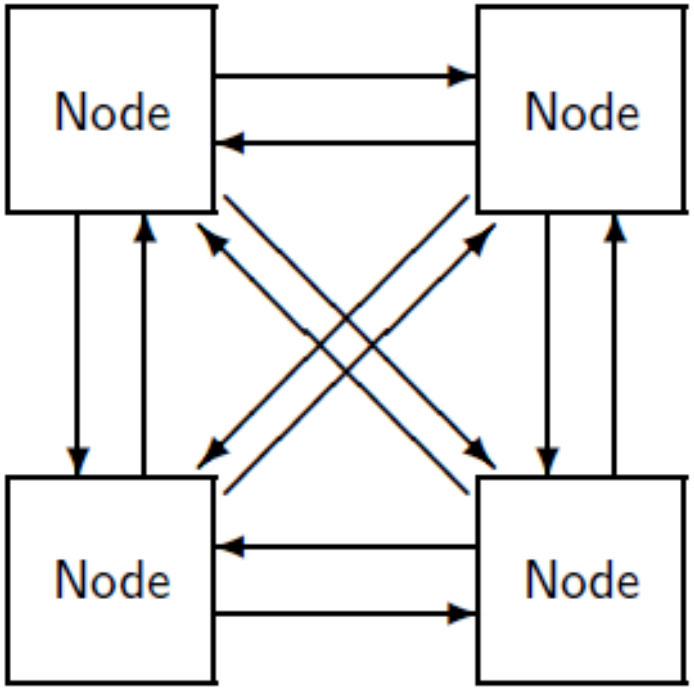
Multiprocessor Computers

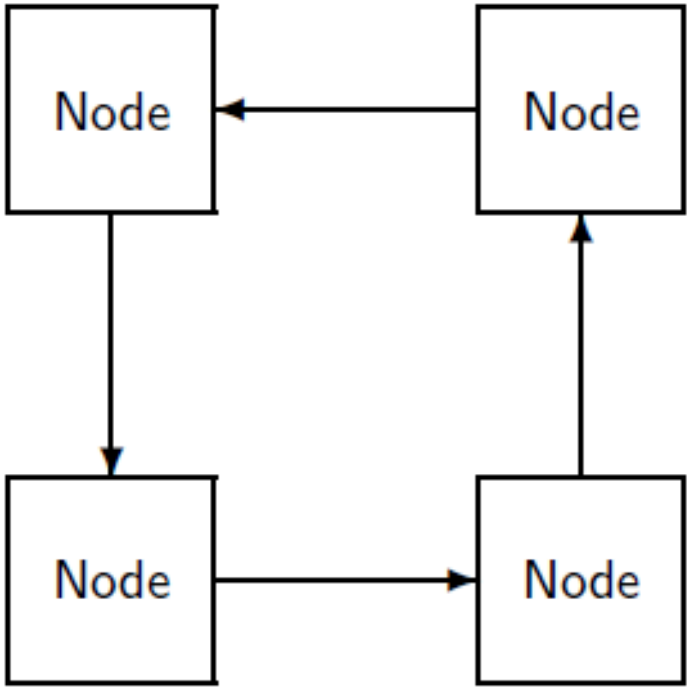
- Interleaving is handled as memory hardware is designed so that one access completes before the other commences
- If two CPUs attempt to read or write the same cell in memory, the result will be same as if the two instructions were executed in either order
- Atomicity and interleaving are performed by the hardware
- Arbitrary interleaving makes more sense as there is no central scheduler, any computation resulting from interleaving may occur

Distributed Systems

- Distributed system is composed of several computers that have no global resources
- They are connected by communication *channels* enabling them to send messages to each other
- Abstraction of interleaving is not applicable
- Each node is either executing one of its statements, sending a message or receiving a message
- Any interleaving of all the events of all the nodes can be used for reasoning
- Interleaving is consistent with the statement sequences of individual node and with the requirement that message be sent before it is received

Distributed Systems





Distributed vs Concurrent

- In concurrent systems, global memory is accessible to all systems
- In distributed systems, nodes may be geographically distant from one another.
- Each node may not send a message *directly* to another node
- We have to consider the *topology* or *connectedness* of the system – fully or ring
- Hardware / software failures catastrophic in CS
- In DS, failures are catastrophic for single nodes, but faulty nodes can be diagnosed and messages can be relayed thro alternate paths

Atomic Statements

- Concurrent programming abstraction has been defined in terms of interleaving of atomic statements
- An atomic statement is executed to completion without the possibility of interleaving statements from another process
- An important property of atomic statements is that if two are executed simultaneously the result is the same as if they had been executed sequentially (in either order)
- It is important to specify the atomic statements precisely as the correctness of the algorithm depends on the specification

Atomic Statements

Algorithm 2.3: Atomic assignment statements	
integer n ← 0	
p	**q**
p1: n ← n + 1	q1: n ← n + 1

Process p	Process q	n
p1: n←n+1	q1: n←n+1	0
(end)	**q1: n←n+1**	1
(end)	(end)	2

Process p	Process q	n
p1: n←n+1	**q1: n←n+1**	0
p1: n←n+1	(end)	1
(end)	(end)	2

Atomic Statements with Global Reference

Algorithm 2.4: Assignment statements with one global reference	
integer n ← 0	
p	**q**
integer temp p1: temp ← n p2: n ← temp + 1	integer temp q1: temp ← n q2: n ← temp + 1

Process p	Process q	n	p.temp	q.temp
p1: temp←n	q1: temp←n	0	?	?
p2: n←temp+1	q1: temp←n	0	0	?
(end)	**q1: temp←n**	1	0	?
(end)	**q2: n←temp+1**	1	0	1
(end)	(end)	2	0	1

Atomic Statements with Global Reference

Algorithm 2.4: Assignment statements with one global reference	
integer n ← 0	
p	**q**
integer temp	integer temp
p1: temp ← n	q1: temp ← n
p2: n ← temp + 1	q2: n ← temp + 1

Process p	Process q	n	p.temp	q.temp
p1: temp←n	q1: temp←n	0	?	?
p2: n←temp+1	**q1: temp←n**	0	0	?
p2: n←temp+1	q2: n←temp+1	0	0	0
(end)	**q2: n←temp+1**	1	0	0
(end)	(end)	1	0	0

Correctness

- In sequential program, running a program with the same input will always give the same result
- In a concurrent program, some scenarios may give correct output while others don’t
- Correctness of sequential programs is defined in terms of computing a final result
- Correctness of concurrent programs is defined in terms of properties of computation
  - There are two properties – *Safety and Liveness*

Correctness

- ***Safety*:** The property must always be true
  - For a safety property P to hold, it must be true that in every state of every computation, P is true
- ***Liveness*:** The property must eventually become true
  - For a liveness property P to hold, it must be true that in every computation, there is some state in which P is true

Correctness

- The challenge of concurrent programs is to ensure that they do useful things, satisfying liveness properties – without violating safety properties
- Safety and liveness are duals of each other – negation of safety property is liveness and v. v
- Safety property will be true if and only if the Liveness property will be false
- Linear Temporal Logic can be used (BTL) to demonstrate correctness

Fairness

- A scenario is (weakly) *fair* if at any state in the scenario, a statement that is continually enabled eventually appears in the scenario
- Does this program halt?

Algorithm 2.5: Stop the loop A	
integer n ← 0 boolean flag ← false	
p	**q**
p1: while flag = false p2: n ← 1 − n	q1: flag ← true q2:

Example

Algorithm 2.9: Concurrent counting algorithm

integer n ← 0

p	q
integer temp	integer temp
p1: do 10 times	q1: do 10 times
p2: temp ← n	q2: temp ← n
p3: n ← temp + 1	q3: n ← temp + 1

C Code

```
int n = 0;

void p() {
  int temp, i;
  for (i = 0; i < 10; i++) {
    temp = n;
    n = temp + 1;
  }
}
```

```
void q() {
  int temp, i;
  for (i = 0; i < 10; i++) {
    temp = n;
    n = temp + 1;
  }
}

void main() {
  cobegin { p(); q(); }
  cout << "The value of n is " << n << "\n";
}
```

Java Code

```
class Count extends Thread {
    static volatile int n = 0;

    public void run() {
      int temp;
      for (int i = 0; i < 10; i++) {
        temp = n;
        n = temp + 1;
      }
    }

    public static void main(String[] args) {
      Count p = new Count();
      Count q = new Count();
      p.start ();
      q.start ();
      try {
        p.join ();
        q.join ();
      }
      catch (InterruptedException e) { }
      System.out.println ("The value of n is " + n);
    }
}
```