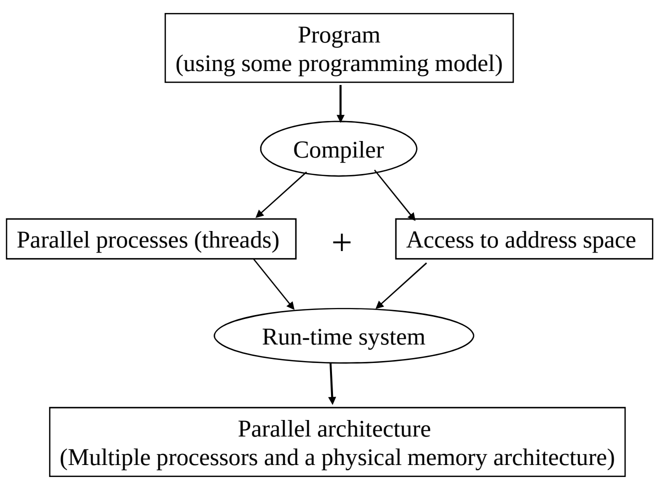
PARALLEL SOFTWARE

Programming parallel computing systems



Note the decoupling between the programming model and the physical architecture – For instance, a parallel program can run on a single processor!!!.

Two schools for programming parallel systems:

- Automatic detection of parallelism in serial programs and automatic distribution of data and computation.
- User specified parallelism (data distribution, computation distribution, or both).

Writing parallel programs:

1. Divide the work among the processes/threads such that
   (a) each process/thread gets roughly the same amount of work
   (b) communication is minimized.
2. Arrange for the processes/threads to synchronize.
3. Arrange for communication among processes/threads.

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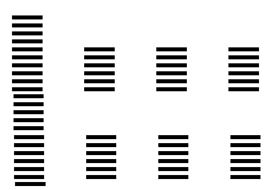
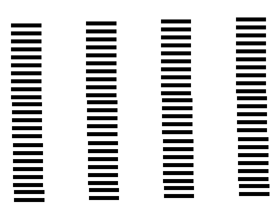
Parallel Programming Models (control threads - processes).

1) Start with one control thread, and create other threads when needed

Examples: Pthreads (explicit thread creation) and OpenMP (implicit thread creation).



2) Start with multiple control threads – usually multiple copies of the same program (SPMD – single program, multiple data).



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Parallel Programming Models (scope of variables).

1) Variables declared shared among threads or processes – any process can read/write to these variables.

Problems with race conditions???

2) Variables declared private to a process or thread

To make the value of a private variable available to other processes, one has to either exchange messages, or copy the value to a shared variable.

A programming model can combine private and shared variables, as well as allow message passing.

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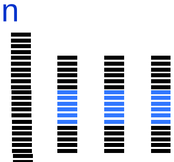
Thread creation strategies

- On demand, Dynamic thread creation
  - Master thread waits for work, forks new threads, and when threads are done, they terminate
  - Efficient use of resources, but thread creation and termination is time consuming.



- Static thread creation
  - Pool of threads created and are allocated work, but do not terminate until cleanup.
  - Better performance, but potential waste of system resources.

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Example - Pthreads

```
int main(int argc, char *argv) {
double A[100]  ;    /* global, shared variable*/
int i ;
…
for (i = 0; i < 4 ; i++)  pthread_create( … , DoStuff, int i ) ;
…   /* execution continues in parallel with 4 copies of DoStuff*/
…
for (i = 0; i < 4 ; i++)  pthread_join (… , DoStuff, …) ;
…
}

void DoStuff (int threadID) {
int  k ;  /* k is a local variable – each instance of DoStuff has a copy*/
…       /* do stuff in parallel with main */
for (k = threadID*25 ; k < (threadID+1)*25 ; k++) … do something with
    A[k] …
…
}
```

The five threads can be executed on separate CPUs or time_shared on one CPU

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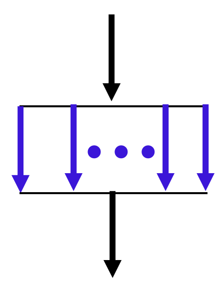
Example - OpenMP

```
int main(){
print("Start\n");
…   /* serial code */
#pragma omp parallel {
   …
   printf("Hello World\n");
   …
 }
…     /* resume serial code */
 printf("Done\n");
}
```



The user can control the number of parallel threads by setting the environment variable setenv OMP_NUM_THTREADS 4

% Result of execution
Start
Hello World
Hello World
Hello World
Hello World
Done

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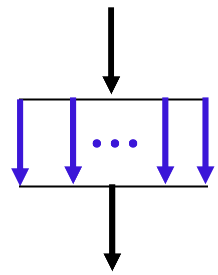
Example - OpenMP

```
#define n 1000
int main(){
int i, a[n], b[n], c[n] ;
…
…
#pragma omp for shared(a,b,c), private(i)
 { for (i = 0; i < n ; i++)
    c[i] = a[i] + b[i] ;
  }  /* end of parallel section */

…     /* resume serial code */
…
}
```



The loop will be automatically broken down into smaller loops and each small loop will be given to one thread

Warning: the loop iterations should be independent (no loop carried dependences)

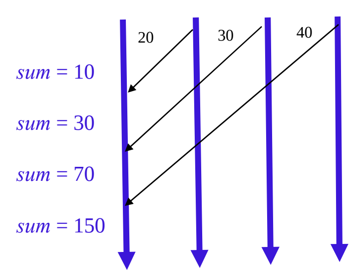
Example – a message passing program

```
int main(){
int x ,sum,  i ;   /* local variables */
…
call a function to get the num_processors ;
…
call a function to get your processorID ;
compute a local value for x;
if (processorID > 0)
    send the value of x to processor 0 ;
else {
    sum = x ;
    for (i = 1; i < num_processors ; i++)
    { receive  a value from processor i ;
       add that value to sum
    }
  } ;

…
}
```

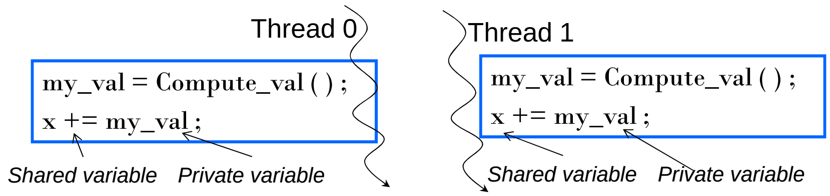
In SPMD, the number of processes (threads) is specified before execution starts

processID =	0	1	2	3
x =	10	20	40	80



sum = 150 ?? ?? ??

Avoiding race conditions



- To guarantee correctness, use critical sections
- Enforce mutual exclusion
- Can use mutual exclusion lock (mutex, or simply lock)

```
my_val = Compute_val ( ) ;
Lock(&add_my_val_lock ) ;
x += my_val ;
Unlock(&add_my_val_lock ) ;
```


Busy-waiting to enforce order

/* Initially, ok_for_1 = 0 */

```
my_val = Compute_val ( my_rank ) ;
if ( my_rank == 1)
   while ( ! ok_for_1 ) ;  /* Busy−wait loop */
x += my_val ;  /* Critical section */
if ( my_rank == 0)
   ok_for_1 = true ;  /* Let thread 1 update x */
```

How do you extend this method to more than two threads?

Input and Output

- Only one thread/process should access *stdin*.
- All processes/threads may access *stdout*, but it is clearer if only one process/thread accesses *stdout*.
- Debug output should always include the rank or id of the process/thread that's generating the output
- Only a single process/thread will attempt to access any single file other than *stdin*, *stdout*

PERFORMANCE

Speedup, S, and Efficiency, E.

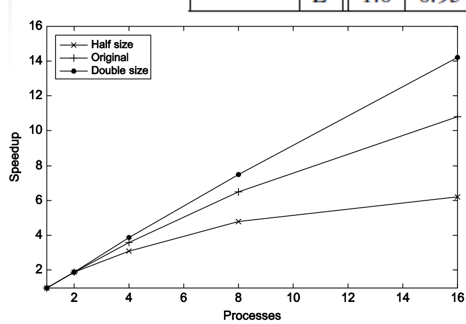
$$S = \frac{T_{serial}}{T_{parallel}}$$

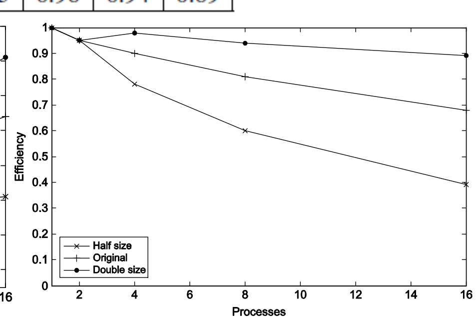
$$E = \frac{S}{p} = \frac{T_{serial}}{p \cdot T_{parallel}}$$

- Number of cores = p
- Serial run-time = T_{serial}
- Parallel run-time = $T_{parallel}$

S and E change with problem sizes

	p	1	2	4	8	16
Half	*S*	1.0	1.9	3.1	4.8	6.2
	E	1.0	0.95	0.78	0.60	0.39
Original	*S*	1.0	1.9	3.6	6.5	10.8
	E	1.0	0.95	0.90	0.81	0.68
Double	*S*	1.0	1.9	3.9	7.5	14.2
	E	1.0	0.95	0.98	0.94	0.89





Amdahl's Law

- Unless virtually all of a serial program is parallelized, the possible speedup is going to be limited — regardless of the number of cores available.

Let α be the fraction of a program that has to be performed serially, then, using p processors, the maximum possible speedup is:

$$S < \frac{1}{\alpha + (1 - f) / p}$$

Hence, even with unlimited number of processors, the speedup cannot be larger than $1 / \alpha$.

Example

- We can parallelize 90% of a serial program.
- Parallelization is "perfect" for any number of cores
- T_{serial} = 20 seconds
- Speed up

$$S = \frac{T_{serial}}{0.9 \times T_{serial} / p + 0.1 \times T_{serial}} = \frac{20}{18 / p + 2}$$

Scalability

- In general, a problem is *scalable* if it can handle ever increasing problem sizes.
- If we increase the number of processes/threads and keep the efficiency fixed without increasing problem size, the problem is *strongly scalable*.
- If we keep the efficiency fixed by increasing the problem size at the same rate as we increase the number of processes/threads, the problem is *weakly scalable*.

Taking Timings

- What is time?
- Start to finish?
- A program segment of interest?
- CPU time?
- Wall clock time?

Taking Timings

```
private double start, finish;
. . .
start = Get_current_time();
/* Code that we want to time */
. . .
finish = Get_current_time();
printf("The elapsed time = %e seconds\n", finish−start);
```

theoretical function

MPI_Wtime

omp_get_wtime

Need to find the maximum across all threads

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PARALLEL PROGRAM DESIGN

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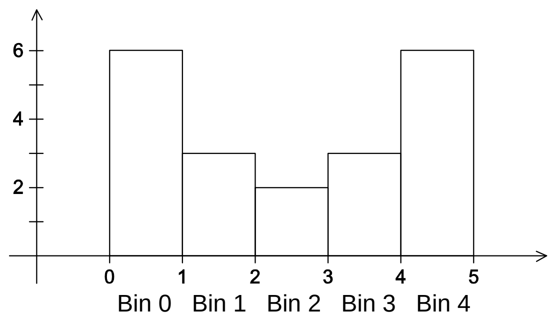
Foster's methodology

1. Partitioning: divide the computation and the data operated on by the computation into small tasks.
2. Communication: determine what communication needs to be carried out among the tasks.
3. Aggregation: combine tasks and communications into larger tasks.
4. Mapping: assign the composite tasks identified in the previous step to processes/threads.

Goal: balance the load and minimize communication.

Example - histogram

- data = 1.3,2.9,0.4,0.3,1.3,4.4,1.7,0.4,3.2,0.3,4.9,2.4,
  3.1,4.4,3.9,0.4,4.2,4.5,4.9,0.9



For each bin, find the number of data elements and the maximum data value.

First two stages of Foster's Methodology