Chapter 7

Load Balancing and Termination Detection

Load balancing – used to distribute computations fairly across processors in order to obtain the highest possible execution speed.

related issue:

Termination detection – detecting when a computation has been completed. More difficult when the computation is distributed.

divide a problem into P procs, executing in ||

each process performs a known amount of work

no discussion on the effects of types/speeds of procs

some procs complete their task before others and become idle

ideally: all procs operate as much as possible, for similar amounts of time

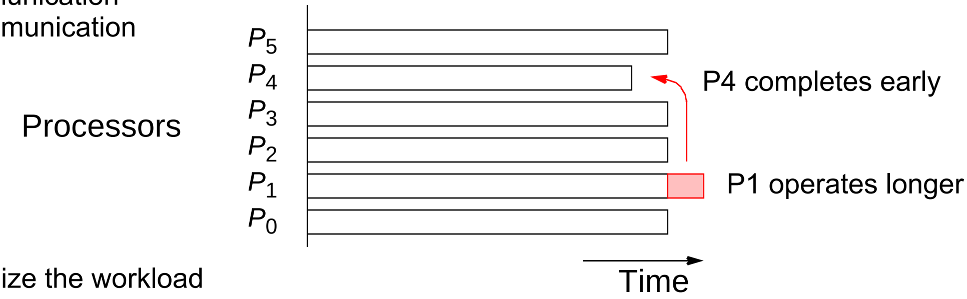
achieving the goal of spreading tasks evenly across the procs: LB

Load balancing

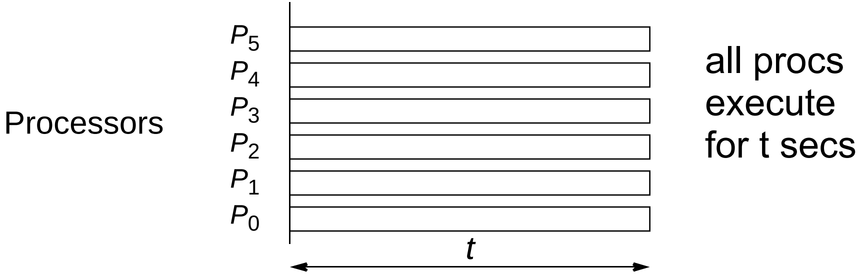
2 categorizations:

(a) with communication
(b) w/out communication

ideally: equalize the workload



(a) Imperfect load balancing leading to increased execution time total



(b) Perfect load balancing

Static Load Balancing

is attempted:

Before the execution of any process. Some potential static load-balancing techniques:

- *Round robin algorithm* — passes out tasks in sequential order of processes coming back to the first when all processes have been given a task
- *Randomized algorithms* — selects processes at random to take tasks
- *Recursive bisection* — recursively divides the problem into subproblems of equal computational effort while minimizing message passing
- *Simulated annealing* — an optimization technique
- *Genetic algorithm* — another optimization technique, described in Chapter 13

Static Load Balancing

Balance load prior to the execution. Various static load-balancing algorithms. There is no poly-time algorithm to solve this problem.

--> heuristics

Several fundamental flaws with static load balancing even if a mathematical solution exists:

- Very difficult to estimate accurately the execution times of various parts of a program without actually executing the parts. --> scheduling these parts is bound to be inaccurate
- Communication delays that vary under different circumstances --> difficult to incorporate in static LB
- Some problems have an indeterminate number of steps to reach their solution. EX: search algorithms: typically traverse a graph

Dynamic Load Balancing

Vary load during the execution of the processes.

All previous factors are taken into account by making the division of load dependent upon the execution of the parts as they are being executed.

Does incur an additional overhead during execution, but it is much more effective than static load balancing

we will focus on dynamic LB and Termination Detection (how a computation comes to an end)

Processes and Processors

Computation will be divided into *work* or *tasks* to be performed, and processes perform these tasks. Processes are mapped onto processors.

Since our objective is to keep the processors busy, we are interested in the activity of the processors.

However, often map a single process onto each processor, so will use the terms *process* and *processor* somewhat interchangeably.

Dynamic Load Balancing

attempted during execution

Can be classified as:

- Centralized
- Decentralized

tasks are allocated to procs during execution of a program

Centralized dynamic load balancing

Tasks handed out from a centralized location. Master-slave structure.

master process controls each of a set of slave processes directly

Decentralized dynamic load balancing

Tasks are passed between arbitrary processes.

A collection of worker processes operate upon the problem and interact among themselves, finally reporting to a single process.

A worker process may receive tasks from other worker processes and may send tasks to other worker processes (to complete or pass on at their discretion).

Centralized Dynamic Load Balancing

Master process(or) holds the collection of tasks to be performed.

Tasks are sent to the slave processes. When a slave process completes one task, it requests another task from the master process. This mechanicm, is the essential part of the work-pool approach

--> Julia sets, Mandelbrot Set, Fractals

Terms used : *work pool*, *replicated worker*, *processor farm*.

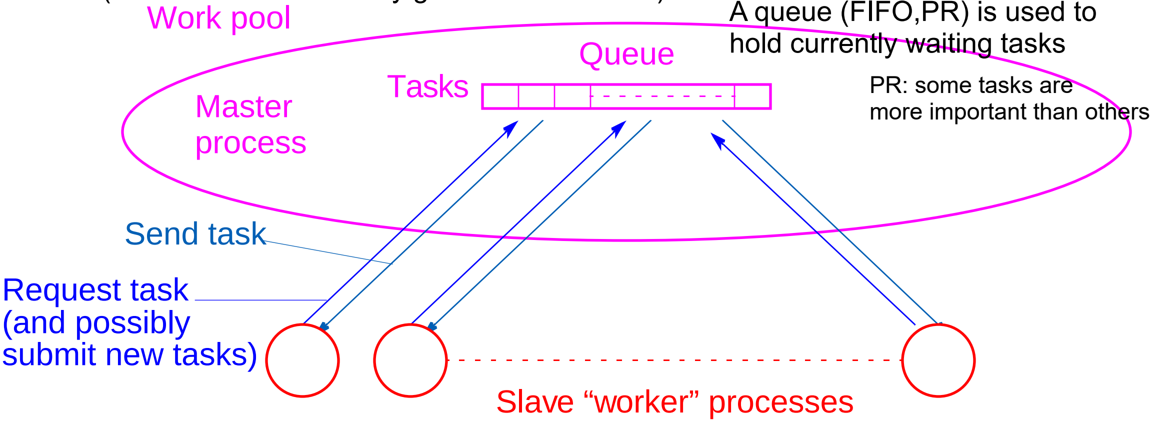
all slaves are the same
we can also have
specialized slaves

Centralized work pool

(1) w-p technique applies to divide-and-conquer pbs (binary search, quicksort, FFT)

(2) w-p technique applies to pbs with different-size tasks (send larger tasks first, so that slaves completing smaller talks do not stay idle, waiting for large task to finish)

(3) w-p technique applies when #tasks changes during execution (execution of a task may generate new tasks)



Work pool

A queue (FIFO,PR) is used to hold currently waiting tasks

Queue

Tasks

PR: some tasks are more important than others

Master process

Send task

Request task (and possibly submit new tasks)

Slave “worker” processes

Master process can keep info on current best quality solution

Termination

stop the computation when a solution has been found

In centralized dynamic LB,

Computation terminates when:

it is simple for the master process to recognize when to terminate:

- The task queue is empty and every slave is idle and
- Every process has made a request for another task without any new tasks being generated

Not sufficient to terminate when task queue empty if one or more processes are still running if a running process may provide new tasks for task queue. (Unless the pb does not generate new tasks during execution)

in some applications:
(1) a slave proc can detect termination locally (e.g. item found)
(2) all slave procs must reach a local termination condition

Decentralized Dynamic Load Balancing

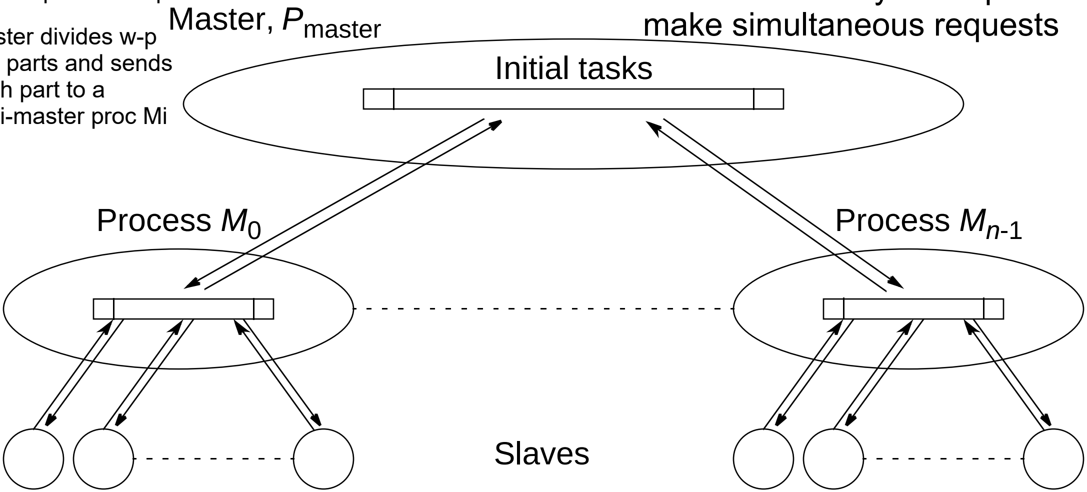
Distributed Work Pool

disadvantage of centralized w-p:
master process can issue one task at a time
and respond to requests one at a time

distribute the w-p into more than 1 sites

bottleneck: many slave procs
make simultaneous requests

master divides w-p
into parts and sends
each part to a
mini-master proc Mi

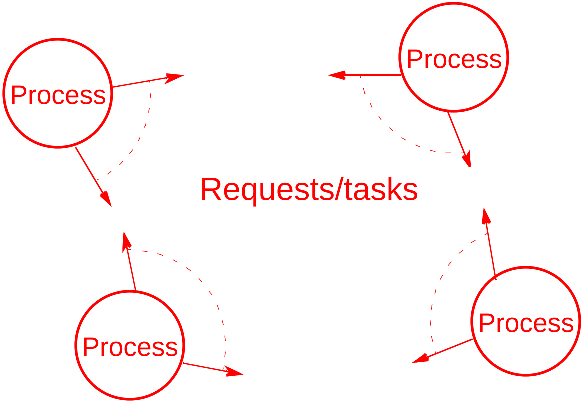


each mini-master:
(1) controls a group of slaves
(2) finds a local optimum and passes it on to master. master selects best solution

Fully Distributed Work Pool

Once workload is distributed, with the procs having generated their own tasks, there is the possibility for

Processes to execute tasks from each other



Two Task Transfer Mechanisms

(1) Receiver-Initiated Method

A process requests tasks from other processes it selects.

Typically, a process would request tasks from other processes when it has few or no tasks to perform.

Method has been shown to work well at high system load.

Unfortunately, it can be expensive to determine process loads.

(2) Sender-Initiated Method

A process sends tasks to other processes it selects.

Typically, a process with a heavy load passes out some of its tasks to others that are willing to accept them.

Method has been shown to work well for light overall system loads.

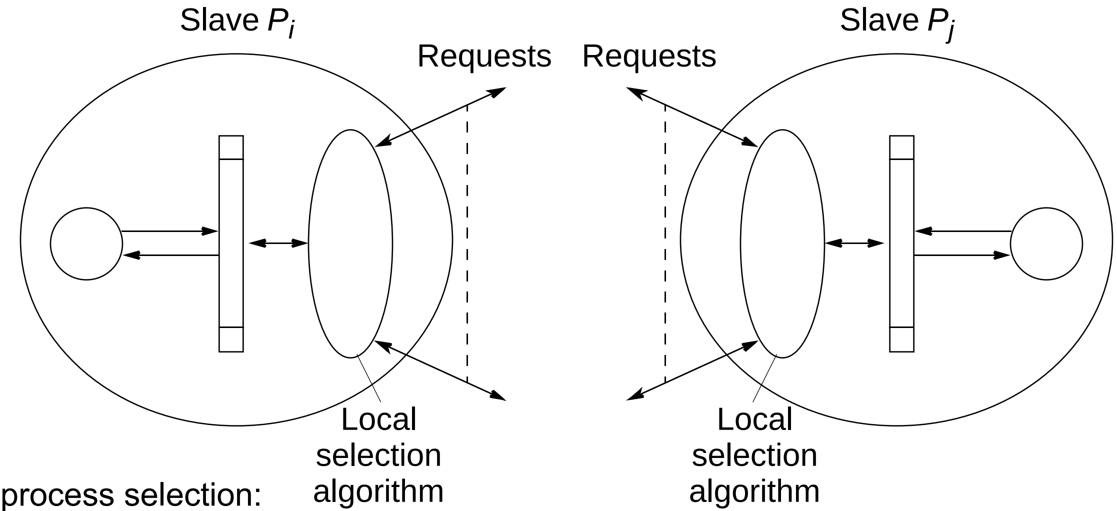
Another option is to have a mixture of both methods.

Unfortunately, it can be expensive to determine process loads.

In very heavy system loads, load balancing can also be difficult to achieve because of the lack of available processes.

Decentralized selection algorithm requesting tasks between slaves

LB in the context of receiver-initiated method: strategies:
(1) procs organized in a ring, requesting tasks from NN
(2) procs organized in hypercube, requesting tasks from directly interconnected procs



process selection:
(1) suppose there is no interconnection network
(2) then all procs are equal candidates for requests
(3) each process has its own selection algorithm

Process Selection

Algorithms for selecting a process:

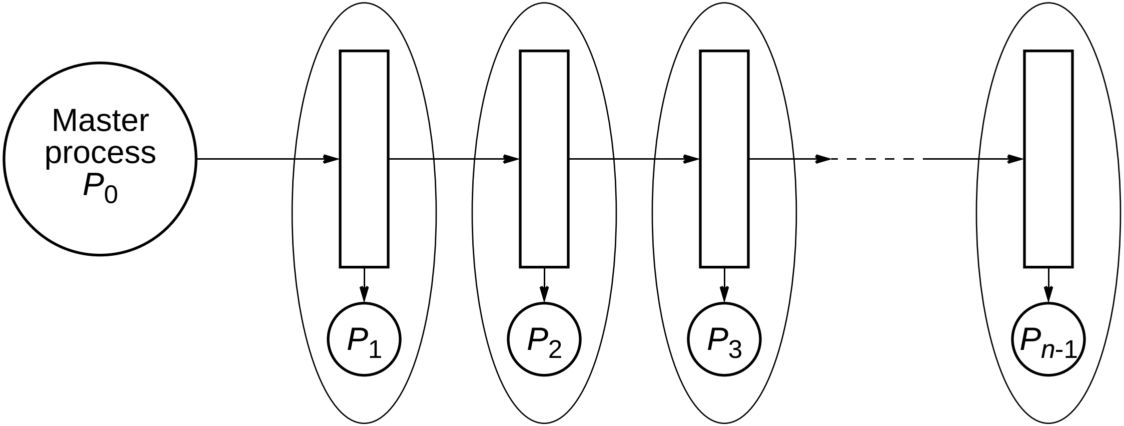
Round robin algorithm – process P_i requests tasks from process P_x, where x is given by a counter that is incremented after each request, using modulo n arithmetic (n processes), excluding $x = i$.

EX: n=8, x takes values 0,1,2,3,4,5,6,7,0,1,2,3,4, ... process does not select itself (x=i), one more increment

Random polling algorithm – process P_i requests tasks from process P_x, where x is a number that is selected randomly between 0 and $n - 1$ (excluding i).

random number generators ...

Load Balancing Using a Line Structure



Master process (P_0) feeds queue with tasks at one end, and tasks are shifted down queue.

When a process, P_i ($1 \leq i < n$), detects a task at its input from queue and process is idle, it takes task from queue.

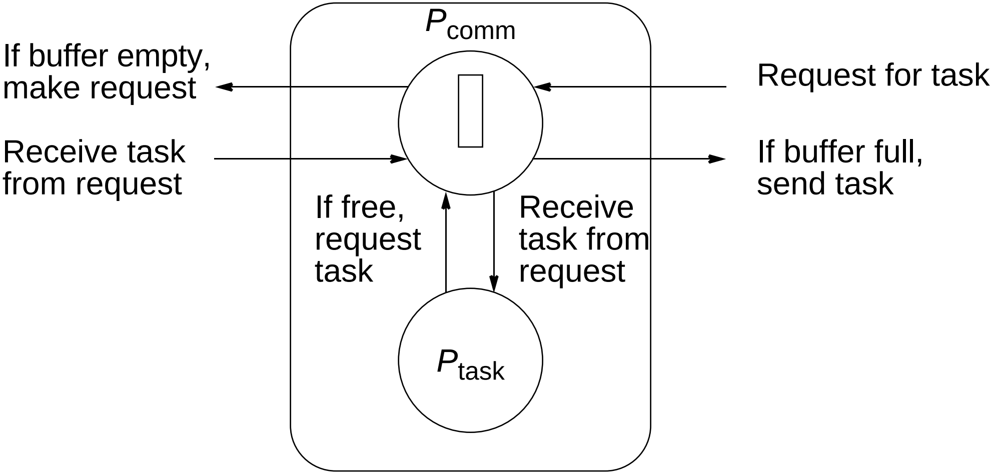
Then tasks to left shuffle down queue so that space held by task is filled. A new task is inserted into e left side end of queue.

Eventually, all processes have a task and queue filled with new tasks. High- priority or larger tasks could be placed in queue first.

Shifting Actions

could be orchestrated by using messages between adjacent processes:

- For left and right communication
- For the current task


P_{comm}
If buffer empty, make request
Request for task
Receive task from request
If buffer full, send task
If free, request task
Receive task from request
P_{task}

Code Using Time Sharing Between Communication and Computation

Master process (P_0)

```
for (i = 0; i < no_tasks; i++) {
   recv(P1, request_tag);       /* request for task */
   send(&task, Pi, task_tag);   /* send tasks into queue */
}
recv(P1, request_tag);          /* request for task */
send(&empty, Pi, task_tag);     /* end of tasks */
```

Process P_i $(1 < i < n)$

```
if (buffer == empty) {
    send(Pi-1, request_tag);    /* request new task */
    recv(&buffer, Pi-1, task_tag);/* task from left proc */
}
if ((buffer == full) && (!busy)) {/* get next task */
    task = buffer;              /* get task*/
    buffer = empty;             /* set buffer empty */
    busy = TRUE;                /* set process busy */
}
nrecv(Pi+1, request_tag, request);/* check msg from right */
if (request && (buffer == full)) {
    send(&buffer, Pi+1);        /* shift task forward */
    buffer = empty;
}
if (busy) {                     /* continue on current task */
    Do some work on task.
    If task finished, set busy to false.
}
```

Nonblocking `nrecv()` necessary to check for a request being received from right.

Nonblocking Receive Routines

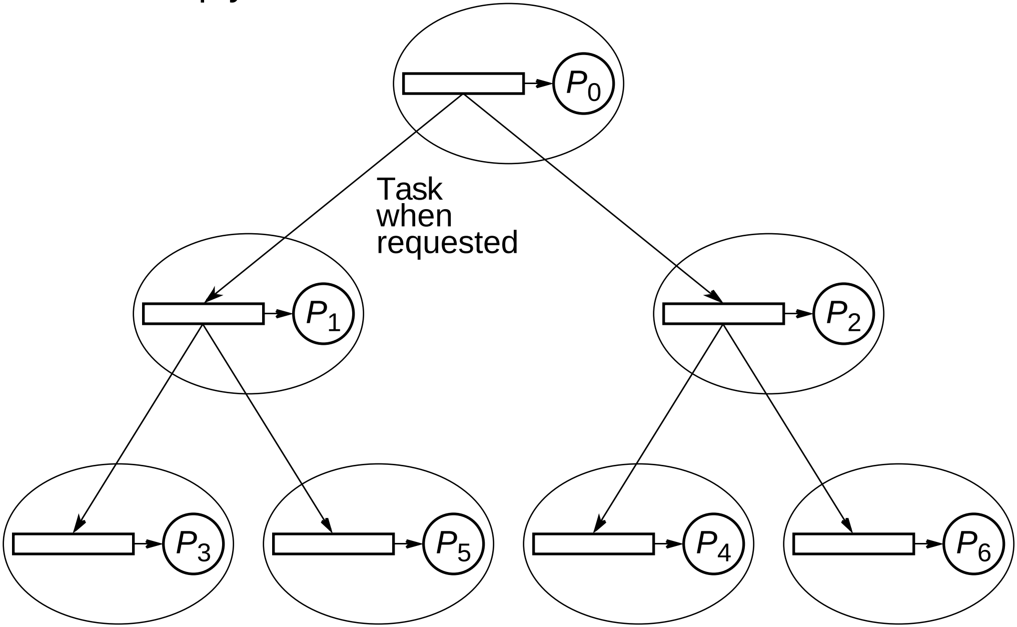
MPI

Nonblocking receive, **`MPI_Irecv()`**, returns a request “handle,” which is used in subsequent completion routines to wait for the message or to establish whether the message has actually been received at that point (**`MPI_Wait()`** and **`MPI_Test()`**, respectively).

In effect, the nonblocking receive, **`MPI_Irecv()`**, posts a request for message and returns immediately.

Load balancing using a tree

Tasks passed from node into one of the two nodes below it when node buffer empty.



Distributed Termination Detection Algorithms

Termination Conditions

At time *t* requires the following conditions to be satisfied:

- Application-specific local termination conditions exist throughout the collection of processes, at time *t*.
- There are no messages in transit between processes at time *t*.

Subtle difference between these termination conditions and those given for a centralized load-balancing system is having to take into account messages in transit.

Second condition necessary because a message in transit might restart a terminated process. More difficult to recognize. Time for messages to travel between processes not known in advance.

One very general distributed termination algortithm

Each process in one of two states:

1. Inactive - without any task to perform
2. Active

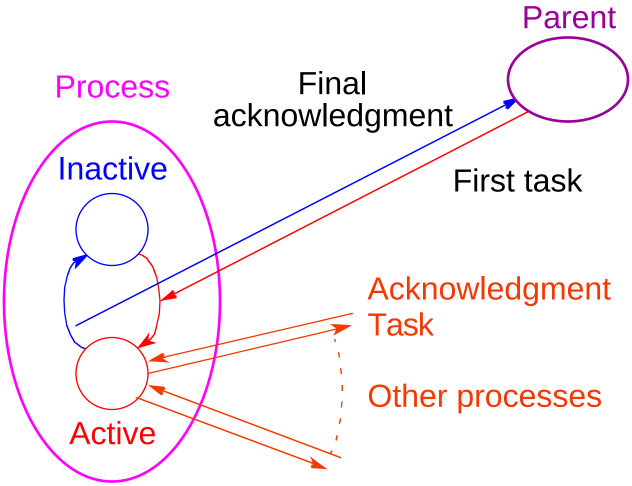
Process that sent task to make a process enter the active state becomes its "parent."

When process receives a task, it immediately sends an acknowledgment message, except if the process it receives the task from is its parent process. Only sends an acknowledgment message to its parent when it is ready to become inactive, i.e. when

- Its local termination condition exists (all tasks are completed, *and*
- It has transmitted all its acknowledgments for tasks it has received, *and*
- It has received all its acknowledgments for tasks it has sent out.

A process must become inactive before its parent process. When first process becomes idle, the computation can terminate.

Termination using message acknowledgments



Other termination algorthms in textbook.

Ring Termination Algorithms

Single-pass ring termination algorithm

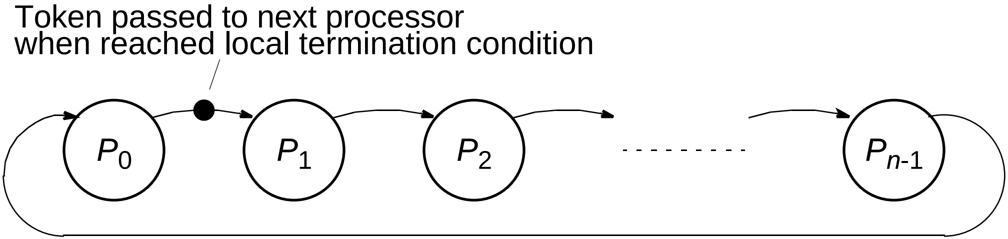
1. When P_0 has terminated, it generates a token that is passed to P_1.

2. When P_i ($1 \leq i < n$) receives token and has already terminated, it passes token onward to P_{i+1}. Otherwise, it waits for its local termination condition and then passes token onward. P_{n-1} passes token to P_0.

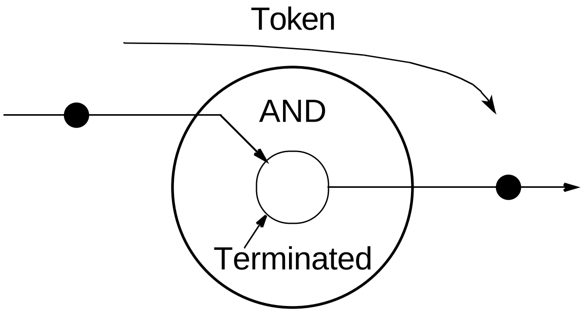
3. When P_0 receives a token, it knows that all processes in the ring have terminated. A message can then be sent to all processes informing them of global termination, if necessary.

Algorithm assumes that a process cannot be reactivated after reaching its local termination condition. Does not apply to work pool problems in which a process can pass a new task to an idle process

Ring termination detection algorithm


Token passed to next processor
when reached local termination condition

Process algorithm for local termination



Dual-Pass Ring Termination Algorithm

Can handle processes being reactivated but requires two passes around the ring.

Reason for reactivation is for process P_i, to pass a task to P_j where $j < i$ and after a token has passed P_j,. If this occurs, the token must recirculate through the ring a second time.

To differentiate these circumstances, tokens colored white or black. Processes are also colored white or black.

Receiving a black token means that global termination may not have occurred andtoken must be recirculated around ring again.

Algorithm is as follows, again starting at P_0:

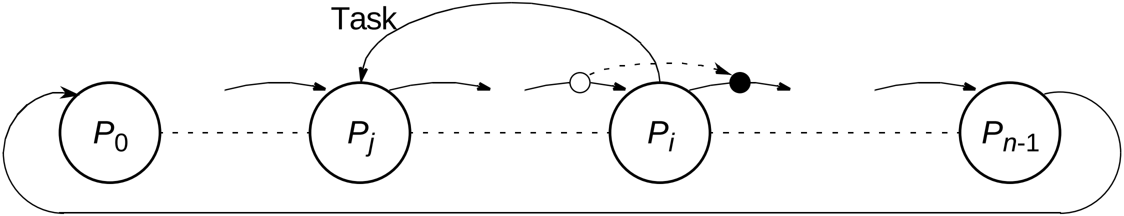
1. P_0 becomes white when terminated and generates white token to P_1.

2. Token passed through ring from one process to next when each process has terminated, but color of token may be changed. If P_i passes a task to P_j where $j < i$ (i.e., before this process in the ring), it becomes a *black process*; otherwise it is a *white process*. A black process will color token black and pass it on. A white process will pass on token in its original color (either black or white). After P_i passed on a token, it becomes a white process. P_{n-1} passes token to P_0.

3. When P_0 receives a black token, it passes on a white token; if it receives a white token, all processes have terminated.

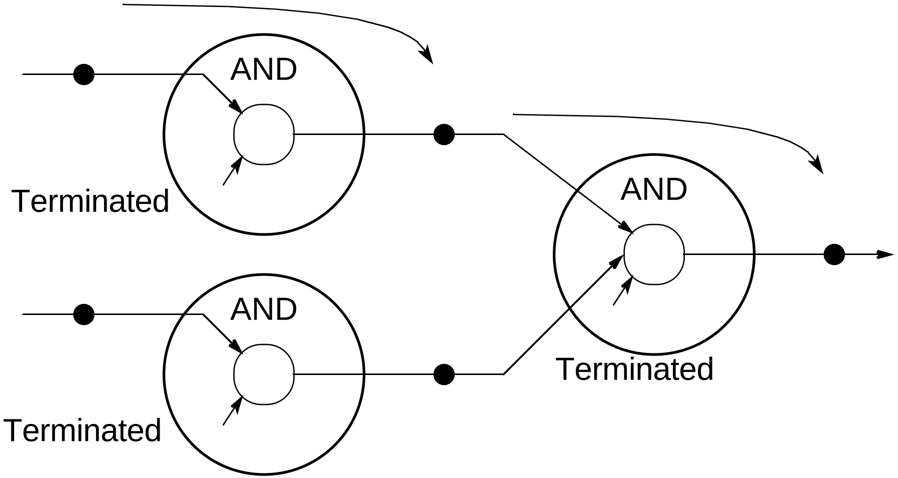
In both ring algorithms, P_0 becomes central point for global termination. Assumes that an acknowledge signal is generated to each request.

Passing task to previous processes



Tree Algorithm

Local actions described can be applied to various structures, notably a tree structure, to indicate that processes up to that point have terminated.



Fixed Energy Distributed Termination Algorithm

A fixed quantity within system, colorfully termed “energy.”

- System starts with all energy being held by the root process.
- Root process passes out portions of energy with tasks to processes making requests for tasks.
- If these processes receive requests for tasks, energy divided further and passed to these processes.
- When a process becomes idle, it passes energy it holds back before requesting a new task.
- A process will not hand back its energy until all energy it handed out returned and combined to total energy held.
- When all energy returned to root and root becomes idle, all processes must be idle and computation can terminate.

Fixed Energy Distributed Termination Algorithm

Significant disadvantage - dividing energy will be of finite precision and adding partial energies may not equate to original energy.

In addition, can only divide energy so far before it becomes essentially zero.

Load balancing/termination detection Example

Shortest Path Problem

Finding the shortest distance between two points on a graph.

It can be stated as follows:

> Given a set of interconnected nodes where the links between the nodes are marked with “weights,” find the path from one specific node to another specific node that has the smallest accumulated weights.

The interconnected nodes can be described by a *graph*.

The nodes are called *vertices*, and the links are called *edges*.

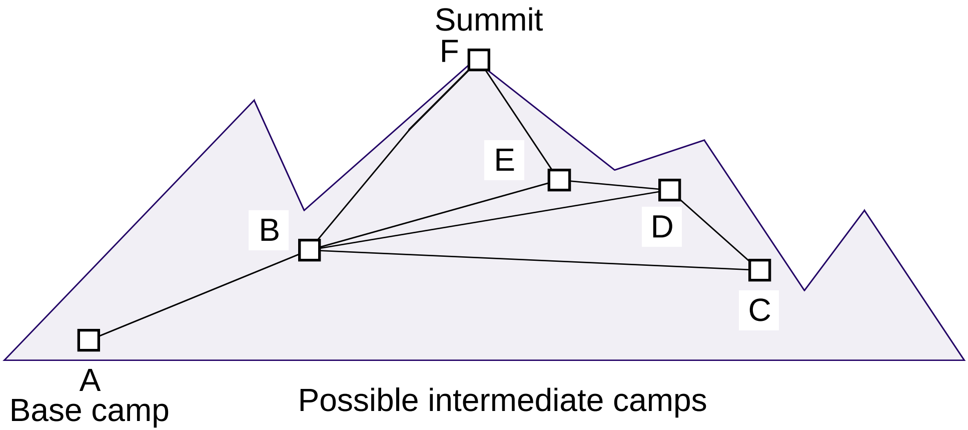
If the edges have implied directions (that is, an edge can only be traversed in one direction, the graph is a *directed graph*.

Graph could be used to find solution to many different problems; eg:

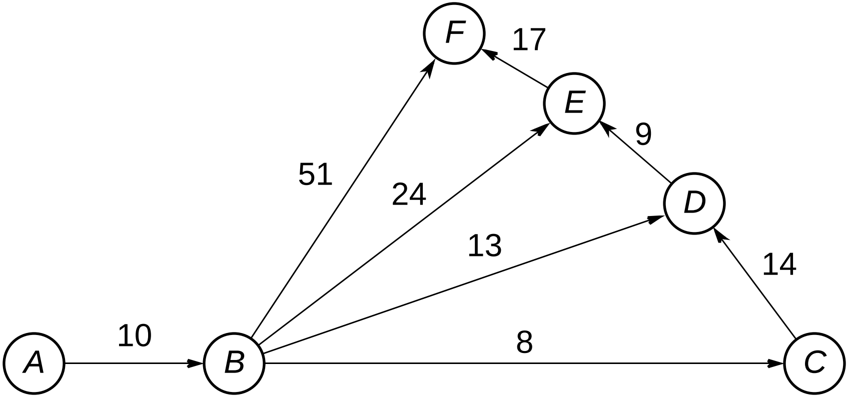
1. Shortest distance between two towns or other points on a map, where the weights represent distance
2. Quickest route to travel, where the weights represent time (the quickest route may not be the shortest route if different modes of travel are available; for example, flying to certain towns)
3. Least expensive way to travel by air, where the weights represent the cost of the flights between cities (the vertices)
4. Best way to climb a mountain given a terrain map with contours
5. Best route through a computer network for minimum message delay (the vertices represent computers, and the weights represent the delay between two computers)
6. Most efficient manufacturing system, where the weights represent hours of work

“The best way to climb a mountain” will be used as an example.

Example: The Best Way to Climb a Mountain



Graph of mountain climb



Weights in graph indicate amount of effort that would be expended in traversing the route between two connected camp sites.

The effort in one direction may be different from the effort in the opposite direction (downhill instead of uphill!). (*directed graph*)

Graph Representation

Two basic ways that a graph can be represented in a program:

1. Adjacency matrix — a two-dimensional array, **a**, in which **`a[i][j]`** holds the weight associated with the edge between vertex *i* and vertex *j* if one exists

2. Adjacency list — for each vertex, a list of vertices directly connected to the vertex by an edge and the corresponding weights associated with the edges

Adjacency matrix used for dense graphs. Adjacency list used for sparse graphs.

Difference based upon space (storage) requirements. Accessing the adjacency list is slower than accessing the adjacency matrix.

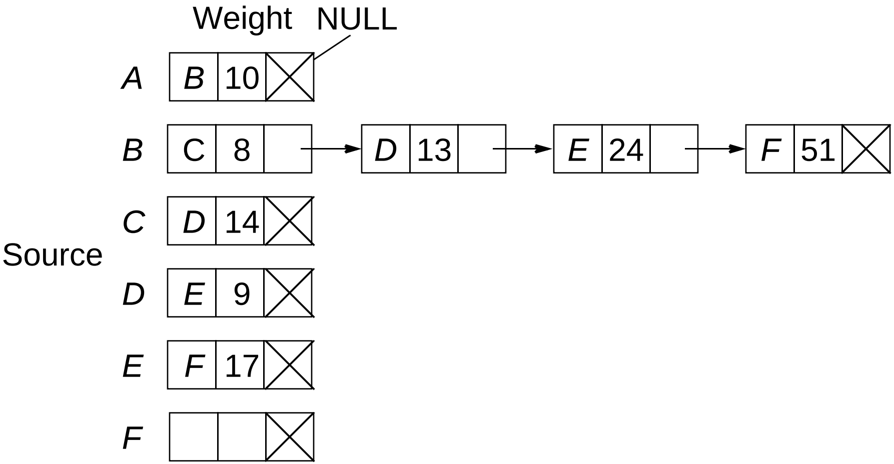
Representing the graph

Destination

Source

	A	*B*	*C*	*D*	*E*	*F*
A	•	10	•	•	•	•
B	•	•	8	13	24	51
C	•	•	•	14	•	•
D	•	•	•	•	9	•
E	•	•	•	•	•	17
F	•	•	•	•	•	•

(a) Adjacency matrix



(b) Adjacency list

Searching a Graph

Two well-known single-source shortest-path algorithms:

- Moore’s single-source shortest-path algorithm (Moore, 1957)
- Dijkstra’s single-source shortest-path algorithm (Dijkstra, 1959)

which are similar.

Moore’s algorithm is chosen because it is more amenable to parallel implementation although it may do more work.

The weights must all be positive values for the algorithm to work.

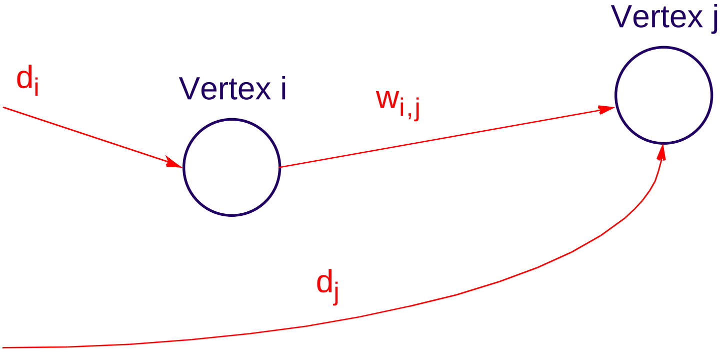
Moore’s Algorithm

Starting with the source vertex, the basic algorithm implemented when vertex *i* is being considered as follows.

Find the distance to vertex *j* through vertex *i* and compare with the current minimum distance to vertex *j*. Change the minimum distance if the distance through vertex *i* is shorter. If d_i is the current minimum distance from the source vertex to vertex *i* and $w_{i,j}$ is the weight of the edge from vertex *i* to vertex *j*:

$$d_j = \min(d_j, d_i + w_{i,j})$$

Moore’s Shortest-path Algorithm



Date Structures

First-in-first-out vertex queue created to hold a list of vertices to examine. Initially, only source vertex is in queue.

Current shortest distance from source vertex to vertex *i* stored in array **`dist[i]`**. At first, none of these distances known and array elements are initialized to infinity.

Code

Suppose **`w[i][j]`** holds the weight of the edge from vertex *i* and vertex *j* (infinity if no edge). The code could be of the form

```
newdist_j = dist[i] + w[i][j];
if (newdist_j < dist[j]) dist[j] = newdist_j;
```

When a shorter distance is found to vertex *j*, vertex *j* is added to the queue (if not already in the queue), which will cause vertex *j* to be examined again - Important aspect of this algorithm, which is not present in Dijkstra's algorithm.

Stages in Searching a Graph

Example

The initial values of the two key data structures are

Vertices to consider

A					

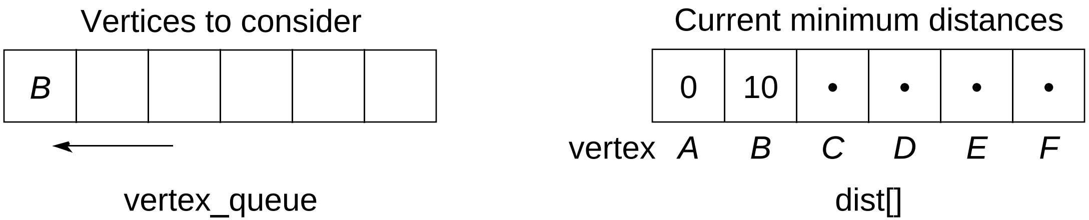
vertex_queue

Current minimum distances

	0	•	•	•	•	•
vertex	*A*	*B*	*C*	*D*	*E*	*F*

dist[]

After examining *A* to



Vertices to consider

B					

vertex_queue

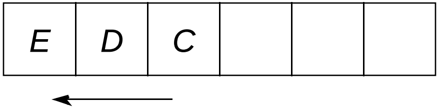
Current minimum distances

vertex	*A*	*B*	*C*	*D*	*E*	*F*
	0	10	•	•	•	•

dist[]

After examining *B* to *F*, *E*, *D*, and *C*::

Vertices to consider



vertex_queue

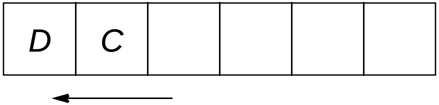
Current minimum distances

vertex	*A*	*B*	*C*	*D*	*E*	*F*
	0	10	18	23	34	61

dist[]

After examining *E* to *F*

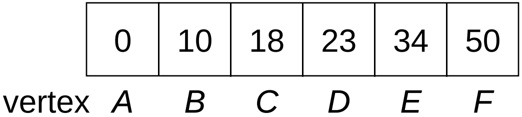
Vertices to consider



D	*C*				

vertex_queue

Current minimum distances

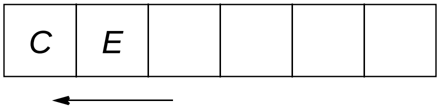


	0	10	18	23	34	50
vertex	*A*	*B*	*C*	*D*	*E*	*F*

dist[]

After examining *D* to *E*:

Vertices to consider



vertex_queue

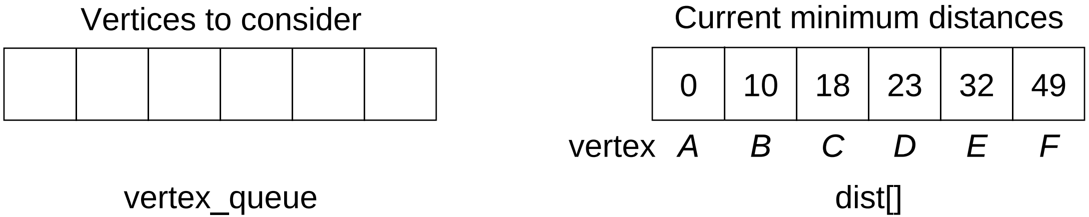
Current minimum distances

	0	10	18	23	32	50
vertex	*A*	*B*	*C*	*D*	*E*	*F*

dist[]

After examining *C* to *D*: No changes.

After examining *E* (again) to *F* :



Vertices to consider

vertex_queue

Current minimum distances

vertex	*A*	*B*	*C*	*D*	*E*	*F*
	0	10	18	23	32	49

dist[]

No more vertices to consider. Have minimum distance from vertex *A* to each of the other vertices, including destination vertex, *F*.

Usually, path required in addition to distance. Then, path stored as distances recorded. Path in our case is *A* → *B* → *D* → *E* → *F*.

Sequential Code

Let **next_vertex()** return the next vertex from the vertex queue or **no_vertex** if none.

Assume that adjacency matrix used, named **w[][]**.

```
while ((i = next_vertex()) != no_vertex)  /* while a vertex */
 for (j = 1; j < n; j++)                /* get next edge */
    if (w[i][j] != infinity) {          /* if an edge */
      newdist_j = dist[i] + w[i][j];
      if (newdist_j < dist[j]) {
        dist[j] = newdist_j;
        append_queue(j);        /* add to queue if not there */
      }
    }                           /*no more to consider*/
```

Parallel Implementations

Centralized Work Pool

Centralized work pool holds vertex queue, `vertex_queue[]` as tasks.

Each slave takes vertices from vertex queue and returns new vertices.

Since the structure holding the graph weights is fixed, this structure could be copied into each slave, say a copied adjacency matrix.

Master

```
while (vertex_queue() != empty) {
  recv(PANY, source = Pi);   /* request task from slave */
  v = get_vertex_queue();
  send(&v, Pi);              /* send next vertex and */
  send(&dist, &n, Pi);       /* current dist array */
    .
  recv(&j, &dist[j], PANY, source = Pi);/* new distance */
  append_queue(j, dist[j]);  /* append vertex to queue */
                             /* and update distance array */
};
recv(PANY, source = Pi);     /* request task from slave */
send(Pi, termination_tag);   /* termination message*/
```

Slave (process *i*)

```
send(Pmaster);              /* send request for task */
recv(&v, Pmaster, tag);     /* get vertex number */
if (tag != termination_tag) {
  recv(&dist, &n, Pmaster); /* and dist array */
  for (j = 1; j < n; j++)   /* get next edge */
    if (w[v][j] != infinity) { /* if an edge */
      newdist_j = dist[v] + w[v][j];
      if (newdist_j < dist[j]) {
        dist[j] = newdist_j;
        send(&j, &dist[j], Pmaster); /* add vertex to queue */
      }                       /* send updated distance */
    }
}
```

Decentralized Work Pool

Convenient approach is to assign slave process *i* to search around vertex *i* only and for it to have the vertex queue entry for vertex *i* if this exists in the queue.

The array **`dist[]`** distributed among processes so that process *i* maintains current minimum distance to vertex *i*.

Process also stores adjacency matrix/list for vertex *i*, for the purpose of identifying the edges from vertex *i*.

Search Algorithm

Vertex *A* is the first vertex to search. The process assigned to vertex *A* is activated.

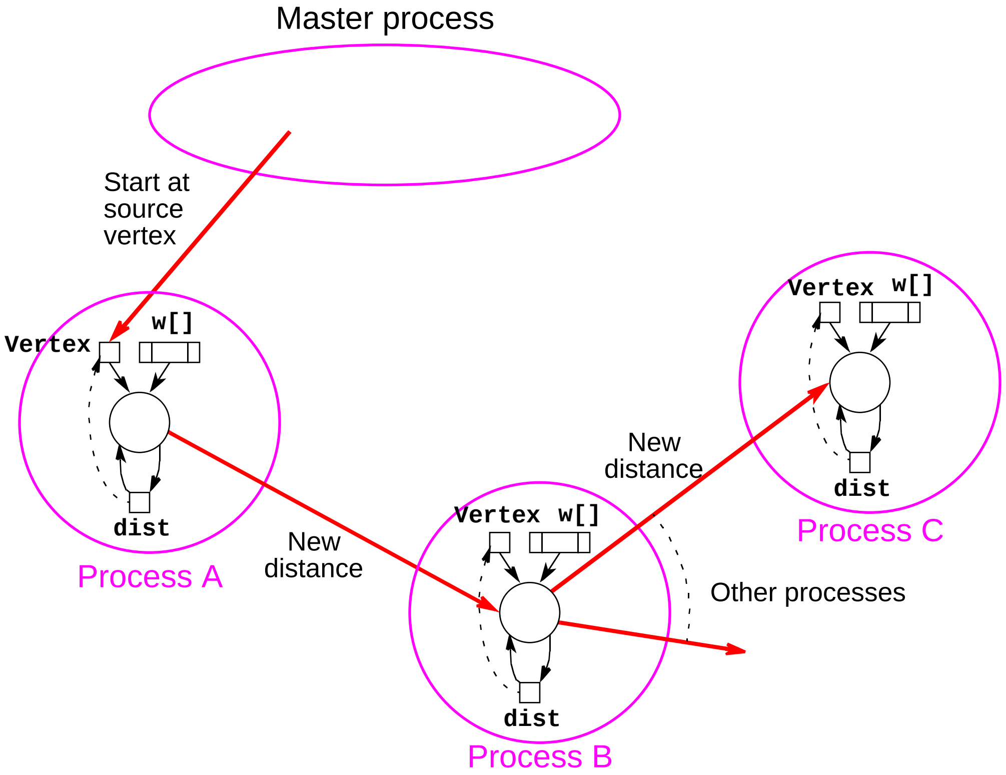
This process will search around its vertex to find distances to connected vertices.

Distance to process *j* will be sent to process *j* for it to compare with its currently stored value and replace if the currently stored value is larger.

In this fashion, all minimum distances will be updated during the search.

If the contents of **`d[i]`** changes, process *i* will be reactivated to search again.

Distributed graph search



Slave (process *i*)

```
recv(newdist, PANY);
if (newdist < dist) {
  dist = newdist;
  vertex_queue = TRUE;      /* add to queue */
} else vertex_queue == FALSE;
if (vertex_queue == TRUE)  /*start searching around vertex*/
  for (j = 1; j < n; j++)   /* get next edge */
    if (w[j] != infinity) {
      d = dist + w[j];
      send(&d, Pj);         /* send distance to proc j */
    }
```

Simplified slave (process *i*)

```
recv(newdist, PANY);
if (newdist < dist)
  dist = newdist;         /* start searching around vertex */
  for (j = 1; j < n; j++) /* get next edge */
    if (w[j] != infinity) {
       d = dist + w[j];
       send(&d, Pj);      /* send distance to proc j */
    }
```

Mechanism necessary to repeat actions and terminate when all processes idle - must cope with messages in transit.

Simplest solution

Use synchronous message passing, in which a process cannot proceed until the destination has received the message.

Process only active after its vertex is placed on queue. Possible for many processes to be inactive, leading to an inefficient solution.

Impractical for a large graph if one vertex is allocated to each processor. Group of vertices could be allocated to each processor.