Linda

Developed at Yale University by D. Gelernter, N. Carriero et al.

Goal: simple language-and machine-independent model for parallel programming

Model can be embedded in host language

- C/Linda
- Modula-2/Linda
- Prolog/Linda
- Lisp/Linda
- Fortran/Linda

Linda's Programming Model

Sequential constructs

- Same as in base language

Parallelism

- Sequential processes

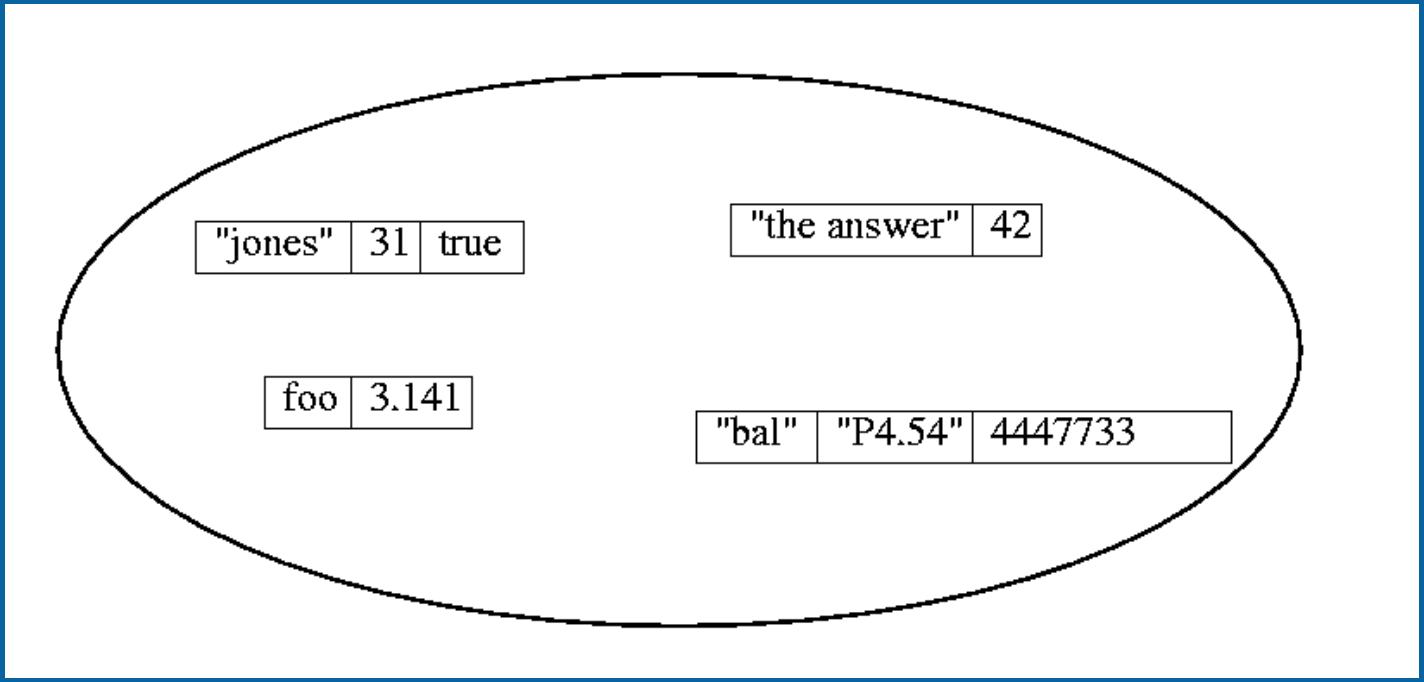
Communication

- Tuple Space

Linda's Tuple Space

Tuple Space

- box with tuples (records)
- shared among all processes
- addresses associatively (by contents)



Tuple Space operations

Atomic operations on Tuple Space (TS)

OUT	adds a tuple to TS
READ	reads a tuple (blocking)
IN	reads and deletes a tuple

Each operation provides a mixture of

- actual parameters (values)
- formal parameters (typed variables)

Example

```
age: integer;
married: boolean;

OUT("jones", 31, true)
READ("jones", ? &age, ? &married)
IN("smith", ? &age, false)
```

Atomicity

Tuples cannot be modified while they are in TS

Modifying a tuple:

```
IN("smith", ? &age,  ? &married) /* delete tuple */
OUT("smith", age+1,  married)    /* increment age */
```

The assignment is atomic

Concurrent READ or IN will block while tuple is away

Distributed Data Structures in Linda

Data structure that can be accessed simultaneously by different processes

Correct synchronization due to atomic TS operations

Contrast with *centralized manager* approach, where each processor encapsulates local data

Replicated Workers Parallelism

Popular programming style, also called *task-farming*

Collection of P identical workers, one per CPU

Worker repeatedly gets work and executes it

In Linda, work is represented by distributed data structure in TS

Advantages Replicated Workers

Scales transparently – can use any number of workers

Eliminates context switching

Automatic load balancing

Example: Matrix Multiplication ($C = A \times B$)

Source matrices:

```
("A", 1, A's first row)
("A", 2, A's second row)
...
("B", 1, B's first column)
("B", 2, B's second column)
```

Job distribution: index of next element of C to compute

```
("Next", 1)
```

Matrix Multiplication (Cnt'd)

Result matrix:

```
("C", 1, 1, C[1,1])
...
("C", N, N, C[N,N])
```

Code for Workers

```
repeat
    in("Next", ? &NextElem);
    if NextElem < N*N then
        out("Next", NextElem + 1)
    i = (NextElem - 1)/N + 1
    j = (NextElem - 1)%N + 1

    read("A", i, ? &row)
    read("B", j, ? &col)
    out("C", i, j, DotProduct(row, col))
end
```

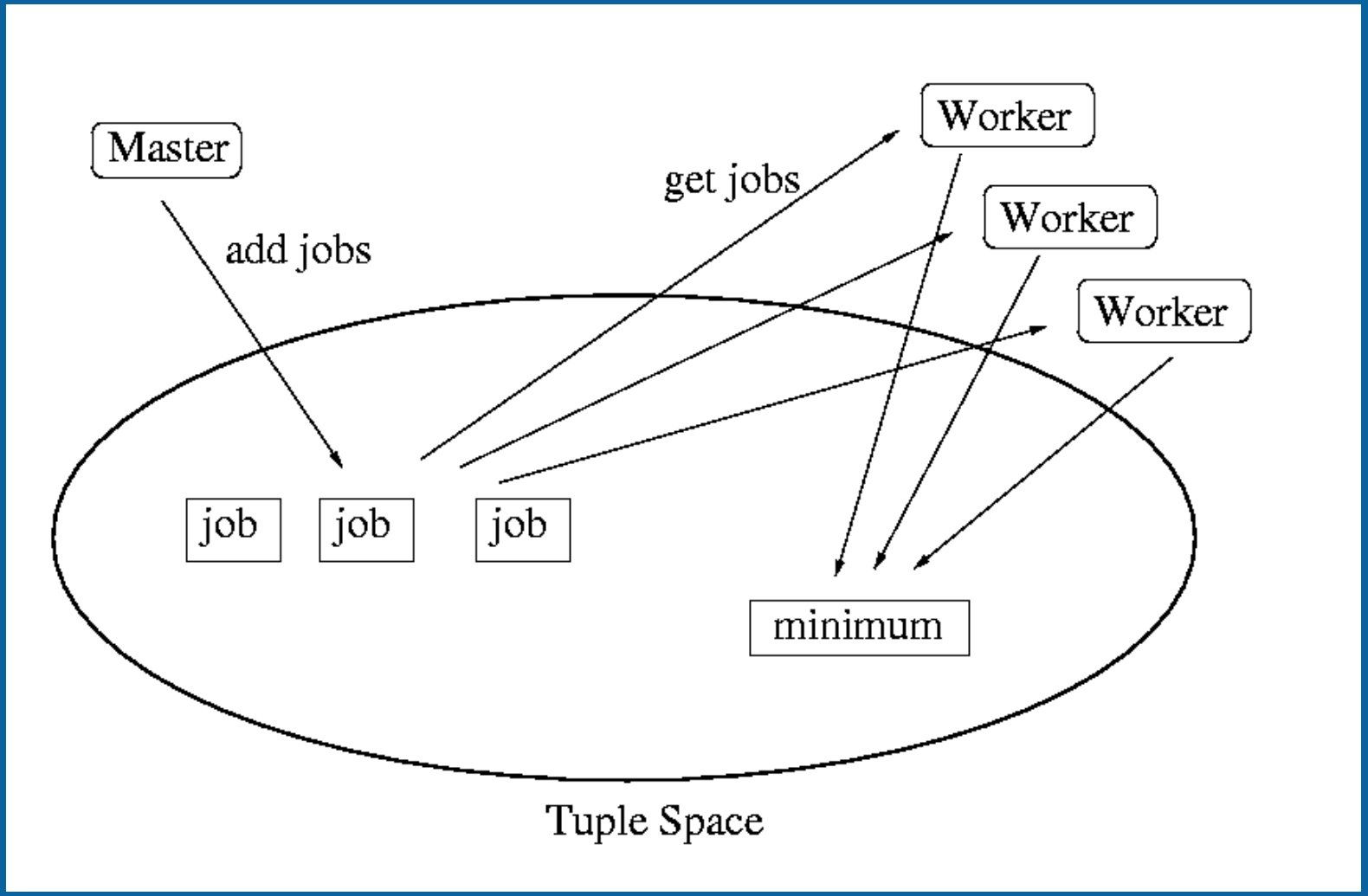
Example 2: Traveling Salesman Problem

Use replicated workers parallelism

- A master process generates work
- The workers execute the work
- Work is stored in a FIFO job-queue

Also need to implement the global bound

TSP in Linda


Master
add jobs
get jobs
Worker
Worker
Worker
job
job
job
minimum
Tuple Space

Global Bound

Use a tuple representing global minimum

Initialize;

```
out("min", maxint)
```

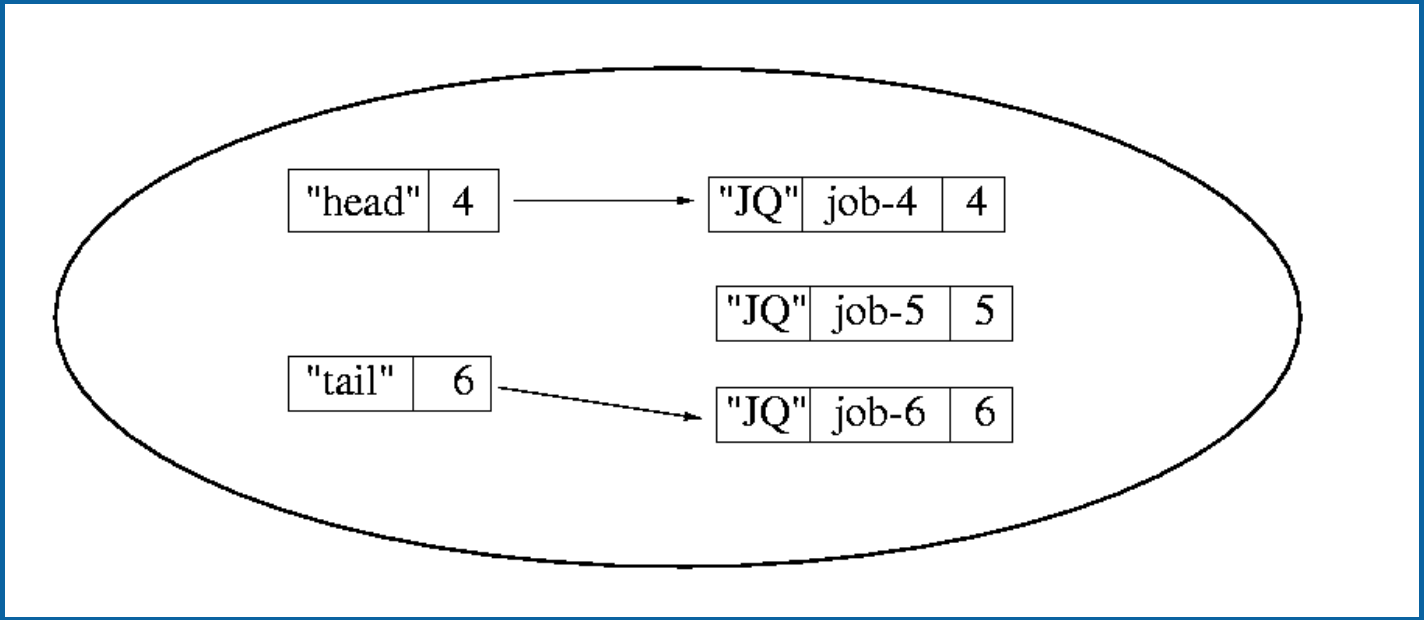
Atomically update minimum with newvalue:

```
in("min", ? & oldvalue);
value = minimum(oldvalue, newvalue)
out("min", value)
```

Read current minimum:

```
read("min", ? &value)
```

Job Queue in Linda



Add a job:

```
in("tail", ? &tail)
out("tail", tail+1)
out("JQ", job, tail+1)
```

Get a job:

```
in("head", ? &head)
out("head", head+1)
in("JQ", ? &job, head)
```

Worker Process

```
int min;
LINDA_BLOCK PATH;

worker()
  int hops, len, head;
  int path[MAXTOWNS];
  PATH.data = path;
  for (;;)
     in("head", ? &head)
     out("head", head+1)
     in("job", ? &hops, ? &len, ? &PATH, head)
     tsp(hops,len,path);    /* sequential TSP */
```

TSP

```
tsp(int hops, int len, int path[])
  int e,me;
  rd("minimum",? &min);  /* update min */
  if (len < min)
    if (hops == (NRTOWNS-1))
      in("minimum", ? &min);
      min = minimum(len,min);
      out("minimum",min);
    else
      me = path[hops];
      for (e=0; e < NRTOWNS; e++)
         if (!present(e,hops,path))
            path[hops+1] = e;
            tsp(hops+1,len+distance[me][e], path);
```

Master

```
master(int hops,int len, int path[])
  int e,me;
  if (hops == MAXHOPS)
     PATH.size = hops + 1; PATH.data = path;
     in("tail", ? &tail)
     out("tail", tail+1)
     out("job", hops, len, PATH, tail+1)
  else
     me = path[hops];
     for (e=0; e < NRTOWNS; e++)
      if (!present(e,hops,path))
          path[hops+1] = e;
          master(hops+1, len+distance[me][e], path);
```

Discussion

Communication is *uncoupled* from processes

The model is machine-independent

The model is very simple

Possible efficiency problems

- Associative addressing
- Distribution of tuples

Implementation of Linda

Linda has been implemented on

- Shared-memory multiprocessors (Encore, Sequent, VU Tadpole)
- Distributed-memory machines (S/Net, workstations on Ethernet)

Main problems in the implementation

- Avoid exhaustive search (optimize associative addressing)
- Potential lack of shared memory (optimize communication)

Components of Linda Implementation

Linda preprocessor

- Analyzes all operations on Tuple Space in the program
- Decides how to implement each tuple

Runtime kernel

- Runtime routines for implementing TS operations

Linda Preprocessor

Partition all TS operations in disjoint sets

Tuples produced/consumed by one set cannot be produced/consumed by operations in other sets

```
OUT("hello", 12);
```

will never match

```
IN("hello", 14);      constants don't match
IN("hello", 12, 4);   number of arguments doesn't match
IN("hello", ? &aFloat); types don't match
```

Classify Partitions

Based on usage patterns in *entire* program

Use most efficient data structure

- Queue
- Hash table
- Private hash table
- List

Case-1: Queue

```
OUT("foo", i);
IN("foo", ? &j);
```

First field is always constant $\Rightarrow$ can be removed by the compiler

Second field of IN is always formal $\Rightarrow$ no runtime matching required

Case-2: Hash Tables

```
OUT("vector", i, j);
IN("vector", k, ? &l);
```

First and third field same as in previous example

Second field requires runtime matching

Second field always is actual $\Rightarrow$ use hash table

Case-3: Private Hash Tables

```
OUT("element", i, j);
IN("element", k, ? &j);
RD("element", ? &k, ? &j);
```

Second field is sometimes formal, sometimes actual

If actual $\Rightarrow$ use hashing

If formal $\Rightarrow$ search (private) hash table

Case-4: Exhaustive Search in a List

```
OUT("element", ? &j);
```

Only occurs if OUT has a formal argument $\Rightarrow$ use exhaustive search

Runtime Kernels

Shared-memory kernels

- Store Tuple Space data structures in shared memory
- Protect them with locks

Distributed-memory (network) kernels

- How to represent Tuple Space?
- Several alternatives:

  Hash-based schemes
  Uniform distribution schemes

Hash-based Distributions

Each tuple is stored on a single machine, as determined by a hash function on:

1. search key field (if it exists), or
2. class number

Most interactions involve 3 machines

```
P1: OUT(t);    -> send t to P3
P2: IN(t);     -> get t from P3
```

Uniform Distributions

Network with reliable broadcasting (S/Net)

- broadcast all OUTs $\Rightarrow$ replicate entire Tuple Space
- RD done locally
- IN: find tuple locally, then broadcast

Network without reliable broadcasting (Ethernet)

- OUT is done locally
- To find tuple (IN/RD), repeatedly broadcast

Performance of Tuple Space

Performance is hard to predict, depends on

- Implementation strategy
- Application

Example: global bound in TSP

- Value is read (say) 1,000,000 times and changed 10 times
- Replicated Tuple Space $\Rightarrow$ 10 broadcasts
- Other strategies $\Rightarrow$ 1,000,000 messages

Multiple TS operations needed for 1 logical operation

- Enqueue and dequeue on shared queue each take 3 operations

Conclusions on Linda

+ Very simple model
+ Distributed data structures
+ Can be used with any existing base language
- Tuple space operations are low-level
- Implementation is complicated
- Performance is hard to predict