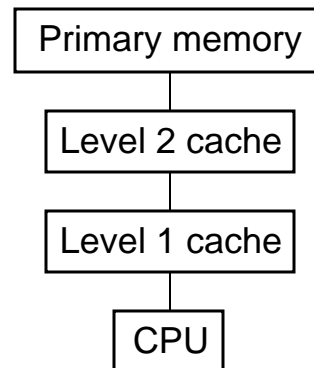


# The Concurrent Computing Landscape

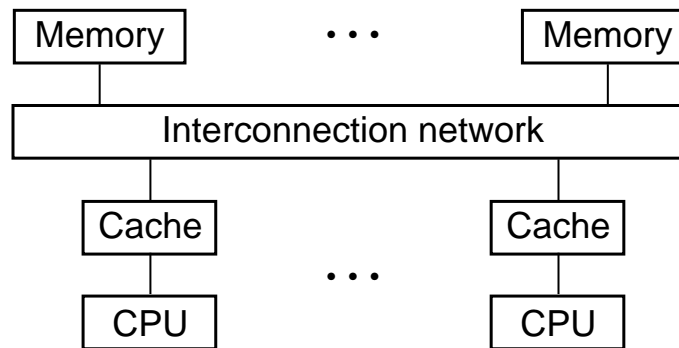
## Andrews Chapter 1



**Figure 1.1** Processors, cache, and memory in a modern machine.

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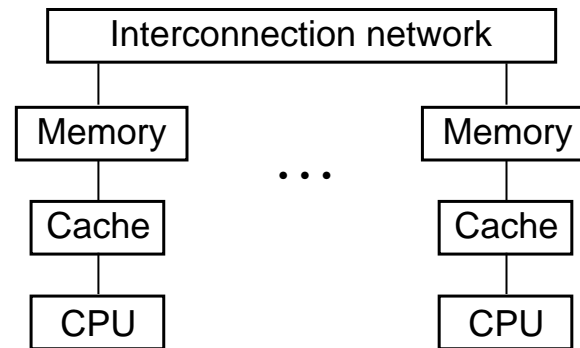
- Temporal locality
- Cache hit
- Cache miss
- Write through cache
- Write back cache
- Cache lines
- Spatial locality



**Figure 1.2** Structure of Shared-Memory Multiprocessors.

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- Cache consistency problem
  - Snooping
- Memory consistency problem
  - Compilers and libraries
- False sharing
  - Padding



**Figure 1.3** Structure of distributed-memory machines.

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- Clusters
- Networks
- Message passing

# Paradigms

- Iterative parallelism
  - Each process is an iterative program. Scientific computation.
- Recursive parallelism
  - Recursive procedure calls are independent.
- Producers and consumers
  - Each process is a filter. Pipelines.
- Clients and servers
  - World Wide Web. Graphics cards.
- Interacting peers
  - Decentralized decision making.

```
double a[n,n], b[n,n], c[n,n];

for [i = 0 to n-1] {
  for [j = 0 to n-1] {
    # compute inner product of a[i,*] and b[* ,j]
    c[i,j] = 0.0;
    for [k = 0 to n-1]
      c[i,j] = c[i,j] + a[i,k]*b[k,j];
  }
}
```

## Sequential Matrix Multiplication

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## Embarrassingly Parallel

- **Read set:** set of variables read by a process
- **Write set:** set of variables written to by a process
- Two operations are **independent** if the write set of each is disjoint from both the read and write sets of the other.

```
co [i = 0 to n-1] { # compute rows in parallel
  for [j = 0 to n-1] {
    c[i,j] = 0.0;
    for [k = 0 to n-1]
      c[i,j] = c[i,j] + a[i,k]*b[k,j];
  }
}
```

Parallel Matrix Multiplication by Rows

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```
co [j = 0 to n-1] { # compute columns in parallel
  for [i = 0 to n-1] {
    c[i,j] = 0.0;
    for [k = 0 to n-1]
      c[i,j] = c[i,j] + a[i,k]*b[k,j];
  }
}
```

## Parallel Matrix Multiplication by Columns

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```
co [i = 0 to n-1, j = 0 to n-1] { # all rows and
  c[i,j] = 0.0;                      # all columns
  for [k = 0 to n-1]
    c[i,j] = c[i,j] + a[i,k]*b[k,j];
}
```

Parallel Matrix Multiplication by Rows and Columns

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```

co [i = 0 to n-1] {      # rows in parallel then
  co [j = 0 to n-1] {    # columns in parallel
    c[i,j] = 0.0;
    for [k = 0 to n-1]
      c[i,j] = c[i,j] + a[i,k]*b[k,j];
  }
}

```

### Parallel Matrix Multiplication Using Nested co Statements

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- Can we parallelize the loop over **k**?

```
process row[i = 0 to n-1] { # rows in parallel
  for [j = 0 to n-1] {
    c[i,j] = 0.0;
    for [k = 0 to n-1]
      c[i,j] = c[i,j] + a[i,k]*b[k,j];
  }
}
```

### Parallel Matrix Multiplication Using a Process Declaration

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- Processes are named.
- Processes cannot be nested.
- Program does not wait for processes to end.

```

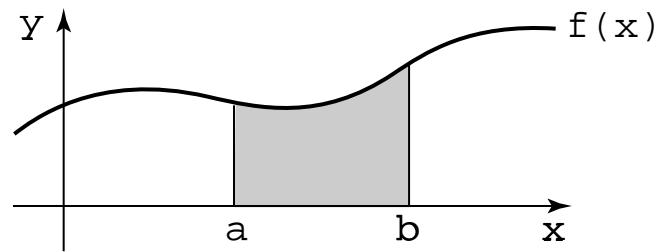
process worker[w = 1 to P] {    # strips in parallel
    int first = (w-1) * n/P;    # first row of strip
    int last = first + n/P - 1; # last row of strip
    for [i = first to last] {
        for [j = 0 to n-1] {
            c[i,j] = 0.0;
            for [k = 0 to n-1]
                c[i,j] = c[i,j] + a[i,k]*b[k,j];
        }
    }
}

```

## Parallel Matrix Multiplication by Strips (Blocks)

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- Useful because we often have only 4 or 8 cores.



**Figure 1.4** The quadrature problem.

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- Find the area under a function.
- Iterative approach:  
Break region into many equal intervals.
- Recursive approach:  
Break region in half, recursion on each half.

```
double fleft = f(a), fright, area = 0.0;
double width = (b-a) / INTERVALS;
for [x = (a + width) to b by width] {
    fright = f(x);
    area = area + (fleft + fright) * width / 2;
    fleft = fright;
}
```

### Iterative Quadrature Program

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- Cannot be parrallelized because of **area**.

```

double quad(double left,right,fleft,fright,lrarea) {
    double mid = (left + right) / 2;
    double fmid = f(mid);
    double larea = (fleft+fmid) * (mid-left) / 2;
    double rarea = (fmid+fright) * (right-mid) / 2;
    if (abs((larea+rarea) - lrarea) > EPSILON) {
        # recurse to integrate both halves
        larea = quad(left, mid, fleft, fmid, larea);
        rarea = quad(mid, right, fmid, fright, rarea);
    }
    return (larea + rarea);
}

```

#### Recursive Procedure for Quadrature Problem

- Only recurse when area changing.  
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- Change the recursion to:

```

co larea = quad(left, mid, fleft, fmid, larea);
// rarea = quad(mid, right, fmid, fright, rarea);
oc

```

- co statements do not end until all branches end.



## **Independent procedure calls**

- If a procedure does not reference global variables and has only value parameters, then every call of the procedure will be independent.
- Functional programming has these features.
- For example, quicksort.

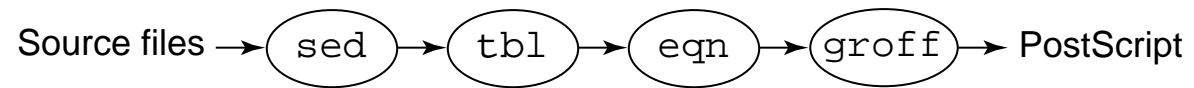
```

double quad(double left,right,fleft,fright,lrarea) {
    double mid = (left + right) / 2;
    double fmid = f(mid);
    double larea = (fleft+fmid) * (mid-left) / 2;
    double rarea = (fmid+fright) * (right-mid) / 2;
    if (abs((larea+rarea) - lrarea) > EPSILON) {
        # recurse to integrate both halves in parallel
        co larea = quad(left, mid, fleft, fmid, larea);
        // rarea = quad(mid, right, fmid, fright, rarea);
        oc
    }
    return (larea + rarea);
}

```

## Recursive Parallel Adaptive Quadrature

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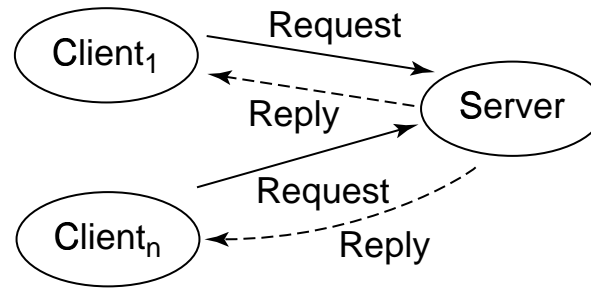


**Figure 1.5** A pipeline of processes.

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```
sed -f Script $* | tbl | eqn | groff Macros -
```

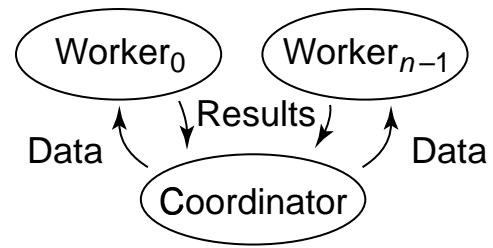
- Producers and consumers.



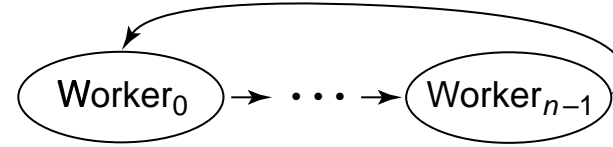
**Figure 1.6** Clients and servers.

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- File servers
- Web pages
- Graphics cards



(a) Coordinator/worker interaction



(b) A circular pipeline

**Figure 1.7** Matrix multiplications using message passing.

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- Interacting peers

```

process worker[i = 0 to n-1] {
    double a[n];      # row i of matrix a
    double b[n,n];    # all of matrix b
    double c[n];      # row i of matrix c
    receive initial values for vector a and matrix b;
    for [j = 0 to n-1] {
        c[j] = 0.0;
        for [k = 0 to n-1]
            c[j] = c[j] + a[k] * b[k,j];
    }
    send result vector c to the coordinator process;
}

process coordinator {
    double a[n,n];    # source matrix a
    double b[n,n];    # source matrix b
    double c[n,n];    # result matrix c
    initialize a and b;
    for [i = 0 to n-1] {
        send row i of a to worker[i];
        send all of b to worker[i];
    }
    for [i = 0 to n-1]
        receive row i of c from worker[i];
    print the results, which are now in matrix c;
}

```

```

process worker[i = 0 to n-1] {
    double a[n];          # row i of matrix a
    double b[n];          # one column of matrix b
    double c[n];          # row i of matrix c
    double sum = 0.0;      # storage for inner products
    int nextCol = i;       # next column of results
    receive row i of matrix a and column i of matrix b;
    # compute  $c[i,i] = a[i,*] \times b[:,i]$ 
    for [k = 0 to n-1]
        sum = sum + a[k] * b[k];
    c[nextCol] = sum;
    # circulate columns and compute rest of  $c[i,*]$ 
    for [j = 1 to n-1] {
        send my column of b to the next worker;
        receive a new column of b from the previous worker;
        sum = 0.0;
        for [k = 0 to n-1]
            sum = sum + a[k] * b[k];
        if (nextCol == 0)
            nextCol = n-1;
        else
            nextCol = nextCol-1;
        c[nextCol] = sum;
    }
    send result vector c to coordinator process;
}

```

Matrix Multiplication Using a Circular Pipeline