# Leftover

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# Parallel Computer Architecture

Shared-memory
Distributed-memory

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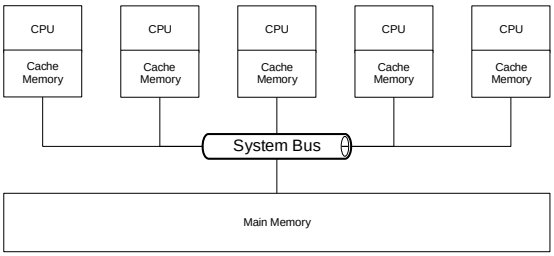
## Shared-Memory Parallel Computer

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## Shared-Memory Parallel Computer

- Shared Memory
  - Programming through threading
  - Multiple processors share a pool of memory
  - Problems: *cache coherence*
  - UMA vs. NUMA architecture
- Pros:
  - Easier to program (probably)
- Cons:
  - Performance may surfer if the memory is located on distant machines
  - Limited scalability

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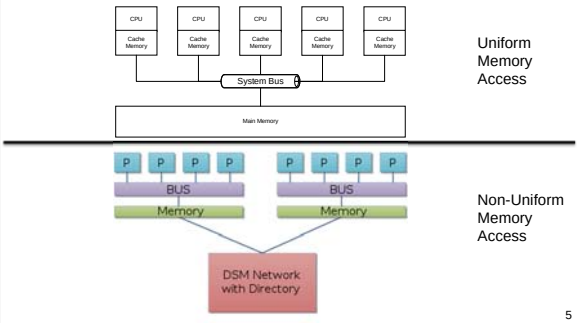
## UMA vs. NUMA

http://en.wikipedia.org/wiki/Uniform_Memory_Access




Uniform Memory Access

Non-Uniform Memory Access

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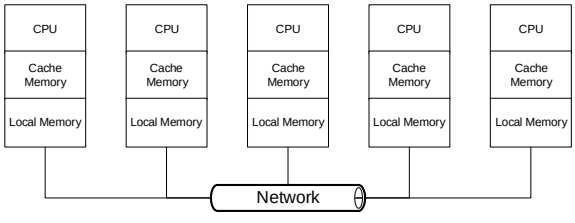
http://en.wikipedia.org/wiki/Non-Uniform_Memory_Access

## Distributed-Memory Parallel Computer

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## Distributed-Memory Parallel Computer

- Distributed Memory
  - Programming through processes
  - Explicit message passing
  - Networking
- Pros:
  - Tighter control on message passing
- Cons:
  - Harder to program
- **Modern supercomputers are hybrids!**

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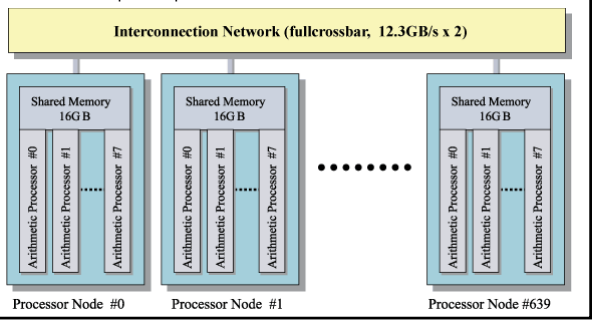
## Earth Simulator

http://www.es.jamstec.go.jp/esc/eng/index.html
the fastest supercomputer in the world from 2002 to 2004




## Beowulf Cluster

- Is a form of parallel computer
- Thomas Sterling, Donald Becker, … (1994)
- Emphasize the use of **COTS**
  - COTS: Components-Off-The-Shelf
  - Intel, AMD processors
  - Gigabit Ethernet (1000Mbps)
  - Linux
- A dedicated facility for parallel processing
  - Non-dedicated: NOW (Network Of Workstations)
- Performance/Price ratio is significantly higher than traditional supercomputers!

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## Lecture 2

Misc Topics in
C/C++ Programming

## Topics

- Source code optimization
- Command Line Arguments
- Dynamic memory allocation and memory layout
- Pre-processor Directives

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## Source Code Optimization

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## Data Type Consideration

- Integer
  - unsigned:
    - Division and remainders
    - Loop counters
    - Array indexing
  - signed:
    - Integer to float conversion
- In function prototypes
  - Use const as much as possible
    - By the way, what is a constant pointer ?

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## Constant pointer

```
#include <iostream>
using namespace std;

int main() {
   const int *a;
   int p[] = {1, 2, 3};
   int q[] = {4, 5, 6};
   int i;

   a = p;
   for(i=0;i<3;i++) {
        cout << a[i];
        a[i] = 0;
   }
   a = q;
   for(i=0;i<3;i++) {
        cout << a[i];
        a[i] = 0;
   }
   return 0;
}
```

Which line above will cause a compilation error?

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## Array Access and Loop Optimization

- Loop jamming / Loop fusion
- Loop fission / Loop distribution
- Move invariants out of loops
  - Loop un-switching
- Loop peeling
- Loop interchange
- Loop unrolling
- Loop unrolling and sum reduction

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## Loop Jamming / Loop Fusion

```
for(i=0;i<N;i++) {
  b[i] += 1;
}
for(i=0;i<N;i++) {
  y += b[i];
}
```

```
for(i=0;i<N;i++) {
  b[i] += 1;
  y += b[i];
}
```

Pentiun D930, icpc -O2, N=10000000
Separated: 0.133132 secs.
Fused: 0.116919 secs.

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## Loop Fission / Loop Distribution

```
for(i=0;i<N;i++) {
  x += b[i];
  y += c[i];
}
```

```
for(i=0;i<N;i++)
  x += b[i];
for(i=0;i<N;i++)
  y += c[i];
```

Pentiun D930, icpc -O2, N=1000000
Fused: 1.3226511 secs.
Separated: 0.00791911 secs.

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## Move invariants out of loops If() - Loop unswitching

```
for(i=0;i<N;i++) {
  for(j=0;j<N;j++) {
    if(a[i] > 100.0) b[i] = a[i] - 3.7;
    x = x + a[j] + b[i];
  }
}
```

```
for(i=0;i<N;i++) {
  if(a[i] > 100.0) b[i] = a[i] - 3.7;
  for(j=0;j<N;j++) {
    x = x + a[j] + b[i];
  }
}
```

Pentiun D930, icpc -O2, N=10000
Inside: 0.256424 secs.
Outside: 0.203336 secs.

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## Move invariants out of loops
## If() - Loop unswitching

```
for(i=0;i<N;i++) {
   x[i] = x[i] + y[i];
   if(w) z[i]=0.0;
 }
```

Pentiun D930, icpc -O2, N=1000000
Before: 0.022519 secs.
After : 0.021649 secs.

```
if(w) {
   for(i=0;i<N;i++) {
     x[i] = x[i] + y[i];
     z[i]=0.0;
   }
 }
 else {
   for(i=0;i<N;i++) {
     x[i] = x[i] + y[i];
   }
 }
```



## Move invariants out of loops
## Math operations

```
for(i=0;i<N;i++) {
  a[i] = 0.0;
  for(j=0;j<N;j++) {
    a[i] += b[j] * d[j] * c[i];
  }
}
```

3x7 + 4x7 + 5x7 + ... + 99x7

Pentiun D930, icpc -O2, N=10000
Inside: 0.274137 secs.
Outside: 0.200256 secs.

```
for(i=0;i<N;i++) {
  a[i] = 0.0;
  for(j=0;j<N;j++) {
    a[i] += b[j] * d[j];
  }
  a[i] *= c[i];
}
```

(3+4+5+ .... +99 )x7



## Loop Peeling

```
j = N-1;
for(i=0;i<N;i++) {
  b[i] = (a[i] + a[j]) * 0.5;
  j = i;
}
```

3 4 5 6 7
b5 3.5 4.5 5.5 6.5

```
b[0] = (a[0] + a[N-1]) * 0.5;
for(i=1;i<N;i++) {
  b[i] = (a[i] + a[i-1]) * 0.5;
}
```

Pentiun D930, icpc -O2, N=1000000
Before: 0.011461 secs.
After : 0.011407 secs.



## Loop Interchange
### Stride minimization

```
for(i=0;i<N;i++) {
  for(j=0;j<N;j++) {
    c[i][j] += a[i][j] + b[i][j];
  }
}
```

```
for(j=0;j<N;j++) {
  for(i=0;i<N;i++) {
    c[i][j] += a[i][j] + b[i][j];
  }
}
```

Pentiun D930, icpc -O2, N=300
Stride 1: 0.001437 secs.
Stride N: 0.002837 secs.



## Loop Interchange
### Exercise

```
for(i=0;i<NUM;i++)
  for(j=0;j<NUM;j++)
    for(k=0;k<NUM;k++)
      c[i][j] =c[i][j] + a[i][k] * b[k][j];
```

T T

| | ijk | ikj | jik | jki | kij | kji |
|---|---|---|---|---|---|---|
| a | | 1 0 | 1 | | N 0 | N |
| b | | N 1 | N | | 0 1 | 0 |
| c | | 0 1 | 0 | | N 1 | N |



## Loop Unrolling

```
for(i=0;i<N;i++)
  for(j=0;j<N;j++)
    for(k=0;k<4;k++)
      a[i][j] += b[k][i] * c[k][j];
```

```
for(i=0;i<N;i++) {
  for(j=0;j<N;j++) {
    a[i][j] += b[0][i] * c[0][j];
    a[i][j] += b[1][i] * c[1][j];
    a[i][j] += b[2][i] * c[2][j];
    a[i][j] += b[3][i] * c[3][j];
  }
}
```

Pentiun D930, icpc -O2 -unroll0, N=2000
Before: 2.07285 secs.
After : 0.069612 secs.

## Loop Unrolling and Sum Reduction

```
for(i=0;i<N;i++)
  for(j=0;j<N;j++)
    for(k=0;k<4;k++)
      a += b[k][i] * c[k][j];
```

```
for(i=0;i<N;i++) {
  for(j=0;j<N;j++) {
    a += b[0][i] * c[0][j];
    a += b[1][i] * c[1][j];
    a += b[2][i] * c[2][j];
    a += b[3][i] * c[3][j];
  }
}
```

Pentiun D930, icpc -O2 -unroll0, N=2000
Before: 1.99077 secs.
After : 0.039288 secs.



## Loop Unrolling and Sum Reduction

```
for(i=0;i<N;i++) {
  for(j=0;j<N;j++) {
    a1 += b[0][i] * c[0][j];
    a2 += b[1][i] * c[1][j];
    a3 += b[2][i] * c[2][j];
    a4 += b[3][i] * c[3][j];
  }
}
a = a1 + a2 + a3 + a4;
```

Pentiun D930, icpc -O2 –unroll0, N=2000
Before: 1.99077 secs.
After : 0.039288 secs.
Further: 0.029734 secs.



## Write Efficient Code

- Contiguous memory access helps to improve code efficiency. (why?)
- Loop unrolling & SIMD instructions (e.g. MMX, SSE, 3DNOW, …) can be used to help vector operations.
- Modern compilers (gcc, Intel compiler) can do loop unrolling automatically for you.
  - icc/icpc *-O2 -unroll -axP* yourcode.cpp
  - gcc/g++ *-O2 -funroll-loops -march=p4 -msse3* yourcode.cpp
- Compiler flags (red text above) can make a huge different in terms of both computational efficiency and sometimes results.
- Use assembly language to gain ultimate control on the instruction flow to processors.



## Matrix operations

- For operations involve matrices, each element may be referenced more than once, thus provides better chance for optimizing memory access pattern (reuse the data that is already in cache memory)
- Even if elements (either vector or matrix) are referenced only once, how the memory is accessed still dictates the performance.
  - We must pay attention to the 2-D data layout in memory.
- As modern computers has blocking memory access (lecture one, cache-line: one memory request returns a block of memory), we need to work on adjacent entries first.



## Dynamic Memory Allocation and Memory Layout



## Dynamic Memory Allocation

- Array: A data structure consisting of a group of elements that are accessed by indexing. In most programming languages each element has the same data type and the array occupies a contiguous area of storage.
- Arrays are declared with a fixed size
  - `int a[5], b[10];`
  - `char c[]="12345";`
- Auto variables use stack memory, thus their sizes are limited!
- Dynamic variables use memory space from “heap”, and their sizes are limited only by the available memory from OS (physical + virtual)
- Program often deals with unknown size of data set. Thus, we need to use dynamic memory management.



http://en.wikipedia.org/wiki/Array

# Dynamic 1-D Array

```
int n;

cout << "Enter size: ";
cin >> n;

int *a = new int[n];
for(int i=0;i<n;i++) {
    a[i]=i;
}

delete []a;
```

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/home/course/Lecture02/01.cpp

# Dynamic 2-D Array

- How do we dynamically allocate memory space for multi-dimensional arrays?

```
#include <iostream>
using namespace std;
int main() {
        double a[][] = new double[20][10];

        for(int i=0;i<20;i++) {
                for(int j=0;j<10;j++) {
                        a[i][j]=0.0;
                }
        }
        return 0;
}
```

error: declaration of `a' as multidimensional array must have bounds for all dimensions except the first

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/home/course/Lecture02/02.cpp

# Look-alike 2-D Array

```
int m, n;

cout << "\nEnter m and n: ";
cin >> m >> n;

// allocation
double **a = new double* [m];
for(int i=0; i<m; i++) {
  a[i] = new double[n];
}
```

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/home/course/Lecture02/03.cpp

# Look-alike 2-D Array

```
// use
for(int i=0; i<m; i++) {
  for(int j=0; j<n; j++) {
    a[i][j] = i*n+j;
  }
}

// release
for(int i=0; i<m; i++) {
  delete []a[i];
}
delete []a;
```

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/home/course/Lecture02/03.cpp

# Pros and Cons of Look-alike 2-D Array

- Cons
  - Memory is NOT continuous.
  - Increases memory fragmentation.
  - Takes more effort (for OS) to allocate and release memory.
- Pros
  - Familiar looking
  - Less likely to make mistakes except for allocation and de-allocation

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# Simulated 2-D Array

```
int m, n;

cout << "\nEnter m and n (m rows and n columns): ";
cin >> m >> n;

// allocation
double *a = new double [m*n];
```

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/home/course/Lecture02/04.cpp

# Simulated 2-D Array

```
// use
for(int i=0; i<m; i++) {
  for(int j=0; j<n; j++) {
    a[i*n + j] = i*n + j;
  }
}

// release
delete []a;

return 0;
```

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/home/course/Lecture02/04.cpp

# Using Dynamic 2-D Arrays
## Row-Major

- For 2-D arrays, we need to simulate it by managing array indices ourselves and store it in a one-dimensional array.

A[3][2] → A[3*nCol+2]

```
for(i=0;i<3;i++) {
  for(j=0;j<2;j++) {
    a[i][j]=0.0;
  }
}
```

```
for(i=0;i<3;i++) {
  for(j=0;j<2;j++) {
    a[i*nCol+j]=0.0;
  }
}
```

| A[0][0] | A[0][1] | A[0][2] | A[0][3] |
|---|---|---|---|
| A[0] | A[1] | A[2] | A[3] |
| A[1][0] | A[1][1] | A[1][2] | A[1][3] |
| A[4] | A[5] | A[6] | A[7] |
| A[2][0] | A[2][1] | A[2][2] | A[2][3] |
| A[8] | A[9] | A[10] | A[11] |
| A[3][0] | A[3][1] | A[3][2] | A[3][3] |
| A[12] | A[13] | A[14] | A[15] |

# Using Dynamic 2-D Arrays
## Column-Major

- For 2-D arrays, we need to simulate it by managing array indices ourselves and store it in a one-dimensional array.

A[3][2] → A[3+2*nRow]

```
for(j=0;j<2;j++) {
  for(i=0;i<3;i++) {
    a[i][j]=0.0;
  }
}
```

```
for(j=0;j<2;j++) {
  for(i=0;i<3;i++) {
    a[i+j*nRow]=0.0;
  }
}
```

| A[0][0] | A[0][1] | A[0][2] | A[0][3] |
|---|---|---|---|
| A[0] | A[4] | A[8] | A[12] |
| A[1][0] | A[1][1] | A[1][2] | A[1][3] |
| A[1] | A[5] | A[9] | A[13] |
| A[2][0] | A[2][1] | A[2][2] | A[2][3] |
| A[2] | A[6] | A[10] | A[14] |
| A[3][0] | A[3][1] | A[3][2] | A[3][3] |
| A[3] | A[7] | A[11] | A[15] |

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# Pros and Cons of Simulated 2-D Array

- Pros
  - Memory is contiguous.
  - Memory fragmentation is less likely.
  - Easier during memory allocation and de-allocation.
- Cons
  - Need to manually manage array indices.
  - Likely to make mistakes when managing indices

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# Cautions with Dynamic Memory Management

- Avoid frequent dynamic memory allocation!
  - Memory, like disk, can be fragmented.
  - It takes time for OS to find a contiguous memory block that meets the demand.
  - Memory fragments reduce maximum allocable memory.
- Be careful with memory leaks.
  - Allocating memory without releasing them.
  - As computation progresses, the available memory decreases, and it takes longer and longer to find available memory.
  - Not to mention memory swapping!
- *When you see "segmentation fault" or "sig11" when your program executes on Linux/UNIX, they are usually caused by programs using memory space that they are not supposed to use.*

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# Command Line Arguments

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# Command line arguments

- Purpose:
  - An alternative method of getting user-inputs
  - Taking inputs from CLI (command line interface)
    - cp **a.cpp** b.cpp ← a.cpp & b.cpp are arguments
  - Allowing the developed program use in conjunction with other programs, especially with shell scripting languages (bash, Perl, …)
  - Enables program running in batch without user intervention (through scripting)
  - This is especially important for using computer systems with queues.



# Command Line Arguments

/home/course/Lecture02/05.cpp

```
#include <iostream>
using namespace std;

int main(int argc, char **argv) {
    for(int i=0;i<argc;i++) {
        cout << "\nargv[" << i << "]=" << argv[i];
    }
    return 0;
}
```

```
./a.out

argv[0]=./a.out
```

```
./a.out 1 2 3 4 5

argv[0]=./a.out
argv[1]=1
argv[2]=2
argv[3]=3
argv[4]=4
argv[5]=5
```

```
./a.out "Yo-Ming Hsieh" 1 49 B80501049

argv[0]=./a.out
argv[1]=Yo-Ming Hsieh
argv[2]=1
argv[3]=49
argv[4]=B80501049
```



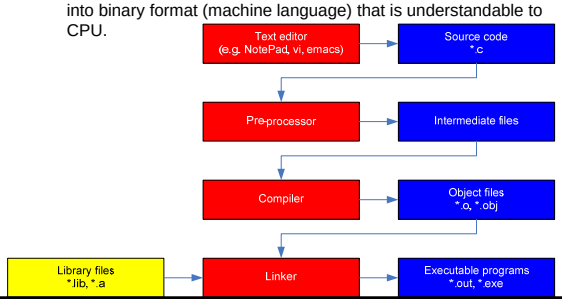
# Pre-processor Directives

#define / #undef macro
#include
conditional compilation



# How executable files are generated

- Compiled
  - Programs written in C language are translated through compiler into binary format (machine language) that is understandable to CPU.




# #define / #undef

- Define a macro with certain “value”, and when source code is pre-processed, the macro/label will be replaced by its value.

/home/course/Lecture02/06.cpp

```
#define N 1000

int main() {
    int a[N][N];

    for(int i=0;i<N;i++) {
        for(int j=0;j<N;j++) {
            a[i][j]=0;
        }
    }
}

#undef N
```

```
int main() {
    int a[1000][1000];

    for(int i=0;i<1000;i++) {
        for(int j=0;j<1000;j++){
            a[i][j]=0;
        }
    }
}
```

# #define / #undef

- Macro can also have arguments, and it looks like functions.

```
#define SQUARE(x) ((x) * (x))
#define MAX(x,y) ((x)>(y)?(x):(y))
#include <iostream>

int main() {
    std::cout << "\n5^2=" << SQUARE(5);
    std::cout << "\nMAX(3,5)=" << MAX(3,5);

    return 0;
}
```

/home/course/Lecture02/07.cpp

```
int main() {
    std::cout << "\n5^2=" << ((5) * (5)) ;
    std::cout << "\nMAX(3,5)=" << ((3)>(5)?(3):(5));

    return 0;
}
```

# #include

- To add the content of other files into the current file at the place of the #include directive before compilation.

**abc.inc**

```
int n=3;
int j=4;
```

```
int main() {
    int n=3;
    int j=4;

    std::cout << "\nn=" << n << ", j=" << j;
    return 0;
}
```

**myProg.c**

```
int main() {
#include "abc.inc"

    std::cout << "\nn=" << n << ", j=" << j;
    return 0;
}
```

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# Conditional Compilation

- #ifdef … #else … #endif
- #ifndef … #else … #endif

/home/course/Lecture02/08.cpp

```
#define BETA
#include <iostream>
int main() {
#ifdef BETA
    std::cout << "\nThis is the beta version";
#else
    std::cout << "\nThis is the full version";
#endif
    return 0;
}
```

```
int main() {
    std::cout << "\nThis is the beta version";
    return 0;
}
```

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# Assignment #2

Due: 3/19/2012

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