Lecture 25 (Mon & Wed 12/01 & 03/2008)

- HW #4 (optional) – Due Fri Dec 5 during class
- Lab #4 Hardware – Due Fri Dec 5 at 5pm

- **Today**: Parallelism!

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Pipelining vs. Parallel processing

- In both cases, multiple "things" processed by multiple "functional units"

  Pipelining: each thing is broken into a **sequence of pieces**, where each piece is handled by a **different** (specialized) functional unit

  Parallel processing: each thing is processed **entirely** by a single functional unit

- We will briefly introduce the key ideas behind parallel processing
  - instruction level parallelism
  - thread-level parallelism

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Exploiting Parallelism

- Of the computing problems for which performance is important, many have inherent parallelism
- Best example: computer games
  - Graphics, physics, sound, AI etc. can be done separately
  - Furthermore, there is often parallelism within each of these:
    - Each pixel on the screen's color can be computed independently
    - Non-contacting objects can be updated/simulated independently
    - Artificial intelligence of non-human entities done independently
- Another example: Google queries
  - Every query is independent
  - Google is read-only!!

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Parallelism at the Instruction Level

```
add $2 <- $3, $4
or $2 <- $2, $4
lw $6 <- 0($4)
addi $7 <- $6, 0x5
sub $8 <- $8, $4
```

Dependences?
RAW
WAW
WAR

When can we reorder instructions?

When should we reorder instructions?

```
add $2 <- $3, $4
or $5 <- $2, $4
lw $6 <- 0($4)
sub $8 <- $8, $4
addi $7 <- $6, 0x5
```

Surperscalar Processors:
Multiple instructions executing in parallel at *same* stage

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Data Dependences

Flow dependence - RAW. Read-After-Write. A "true" dependence. Read a value after it has been written into a variable.

Anti-dependence - WAR. Write-After-Read. Write a new value into a variable after the old value has been read.

Output dependence - WAW. Write-After-Write. Write a new value into a variable and then later on write another value into the same variable.

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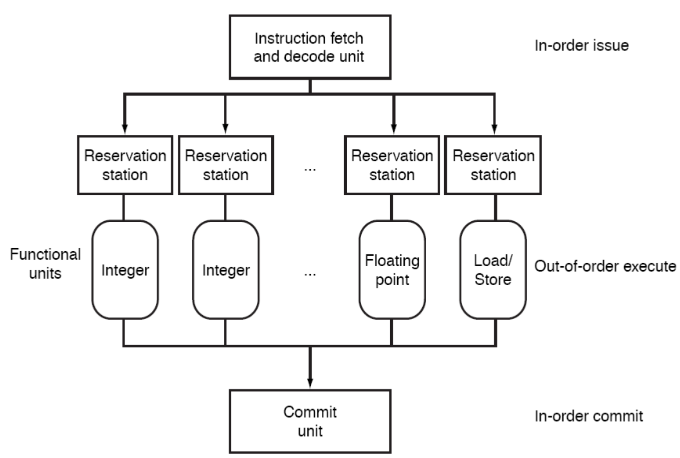
O o O Execution Hardware



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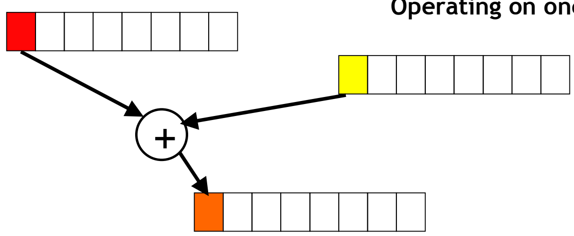
Exploiting Parallelism at the Data Level

- Consider adding together two arrays:

```
void
array_add(int A[], int B[], int C[], int length) {
  int i;
  for (i = 0 ; i < length ; ++ i) {
   C[i] = A[i] + B[i];
  }
}
```

Operating on one element at a time



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Exploiting Parallelism at the Data Level

- Consider adding together two arrays:

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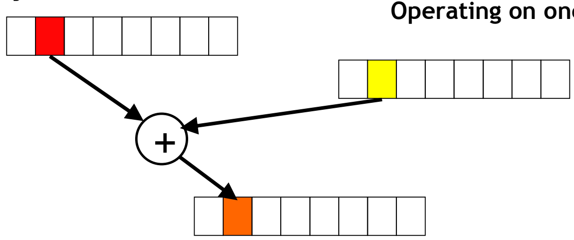
Operating on one element at a time



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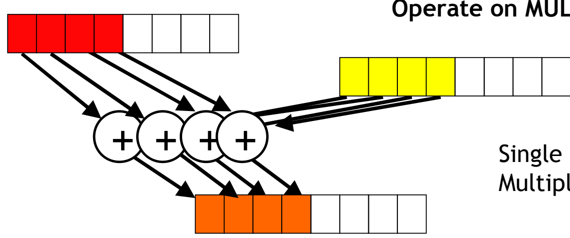
Exploiting Parallelism at the Data Level (SIMD)

- Consider adding together two arrays:

```
void
array_add(int A[], int B[], int C[], int length) {
  int i;
  for (i = 0 ; i < length ; ++ i) {
   C[i] = A[i] + B[i];
  }
}
```

Operate on MULTIPLE elements



Single Instruction,
Multiple Data (**SIMD**)

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Intel SSE/SSE2 as an example of SIMD

- Added new 128 bit registers (XMM0 – XMM7), each can store
  - — 4 single precision FP values (SSE) 4 * 32b
  - — 2 double precision FP values (SSE2) 2 * 64b
  - — 16 byte values (SSE2) 16 * 8b
  - — 8 word values (SSE2) 8 * 16b
  - — 4 double word values (SSE2) 4 * 32b
  - — 1 128-bit integer value (SSE2) 1 * 128b

	4.0 (32 bits)	4.0 (32 bits)	3.5 (32 bits)	-2.0 (32 bits)
+	-1.5 (32 bits)	2.0 (32 bits)	1.7 (32 bits)	2.3 (32 bits)
	2.5 (32 bits)	6.0 (32 bits)	5.2 (32 bits)	0.3 (32 bits)

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Is it always that easy?

- Not always… a more challenging example:

```
unsigned
sum_array(unsigned *array, int length) {
  int total = 0;
  for (int i = 0 ; i < length ; ++ i) {
         total += array[i];
  }
  return total;
}
```

- Is there parallelism here?

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We first need to restructure the code

```
unsigned
sum_array2(unsigned *array, int length) {
  unsigned total, i;
  unsigned temp[4] = {0, 0, 0, 0};
  for (i = 0 ; i < length & ~0x3 ; i += 4) {
    temp[0] += array[i];
    temp[1] += array[i+1];
    temp[2] += array[i+2];
    temp[3] += array[i+3];
  }
  total = temp[0] + temp[1] + temp[2] + temp[3];
  for ( ; i < length ; ++ i) {
    total += array[i];
  }
  return total;
}
```

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Then we can write SIMD code for the hot part

```
unsigned
sum_array2(unsigned *array, int length) {
  unsigned total, i;
  unsigned temp[4] = {0, 0, 0, 0};
  for (i = 0 ; i < length & ~0x3 ; i += 4) {
    temp[0] += array[i];
    temp[1] += array[i+1];
    temp[2] += array[i+2];
    temp[3] += array[i+3];
  }
  total = temp[0] + temp[1] + temp[2] + temp[3];
  for ( ; i < length ; ++ i) {
    total += array[i];
  }
  return total;
}
```

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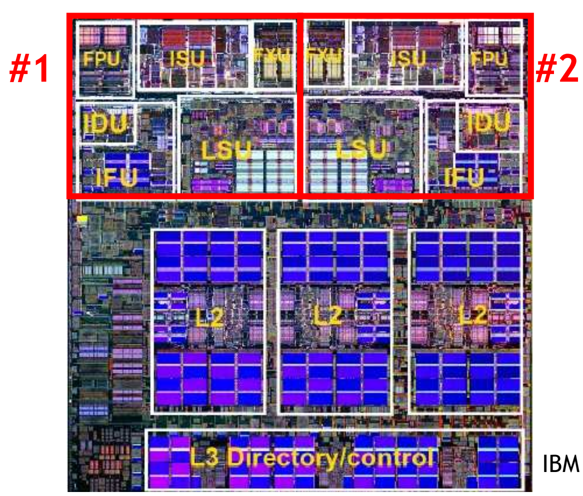
Thread level parallelism: Multi-Core Processors

- Two (or more) complete processors, fabricated on the same silicon chip
- Execute instructions from two (or more) programs/threads at same time



IBM Power5

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Multi-Cores are Everywhere

Intel Core Duo in new Macs: 2 x86 processors on same chip

XBox360: 3 PowerPC cores

Sony Playstation 3: Cell processor, an asymmetric multi-core with 9 cores (1 general-purpose, 8 special purpose SIMD processors)

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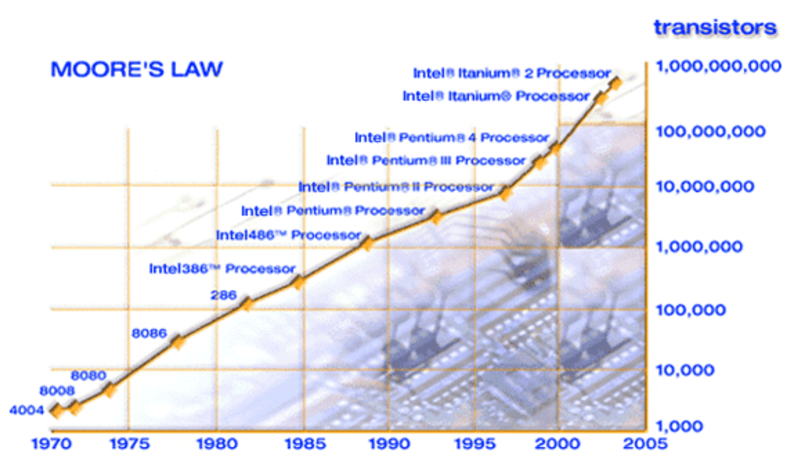
Why Multi-cores Now?

- Number of transistors we can put on a chip growing exponentially…



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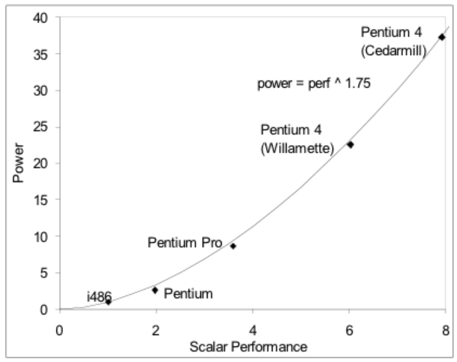
… and performance growing too…



- But power is growing even faster!!
  - Power has become limiting factor in current chips

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What is a Thread?

- What does Shared Memory imply?
- Machine model

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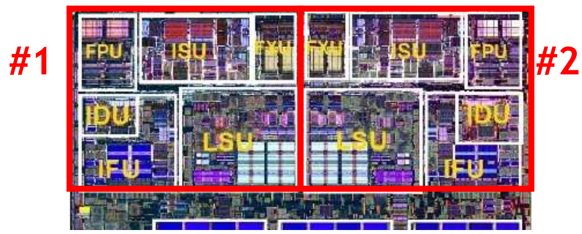
As programmers, do we care?

- What happens if we run a program on a multi-core?

```
void
array_add(int A[], int B[], int C[], int length) {
  int i;
  for (i = 0 ; i < length ; ++i) {
   C[i] = A[i] + B[i];
  }
}
```



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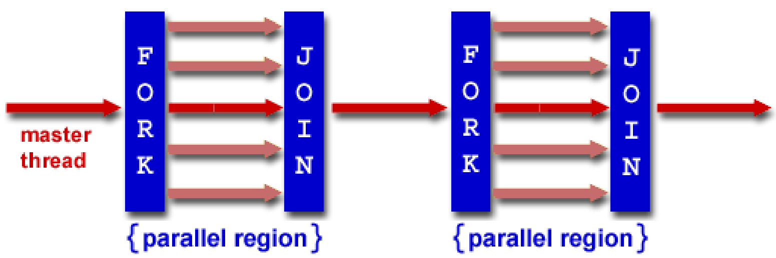
What if we want a program to run on both processors?

- We have to explicitly tell the machine exactly how to do this
  - This is called parallel programming or concurrent programming
- There are many parallel/concurrent programming models
  - We will look at a relatively simple one: **fork-join parallelism**
  - In CSE 451, you learn about threads and explicit synchronization



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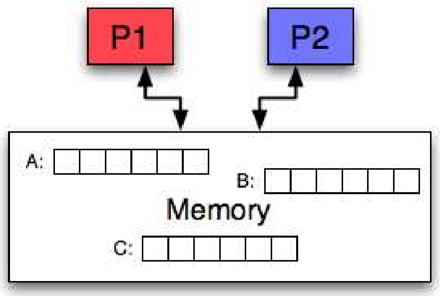
Fork/Join Logical Example

1. Fork N-1 threads
2. Break work into N pieces (and do it)
3. Join (N-1) threads

```
void
array_add(int A[], int B[], int C[], int length) {
  cpu_num = fork(N-1);
  int i;
  for (i = cpu_num ; i < length ; i += N) {
    C[i] = A[i] + B[i];
  }
  join();
}
```

How good is this with caches?

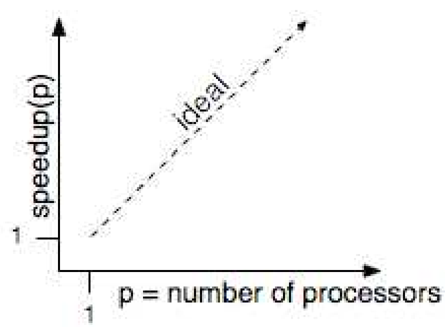


How does this help performance?

- Parallel **speedup** measures improvement from parallelization:

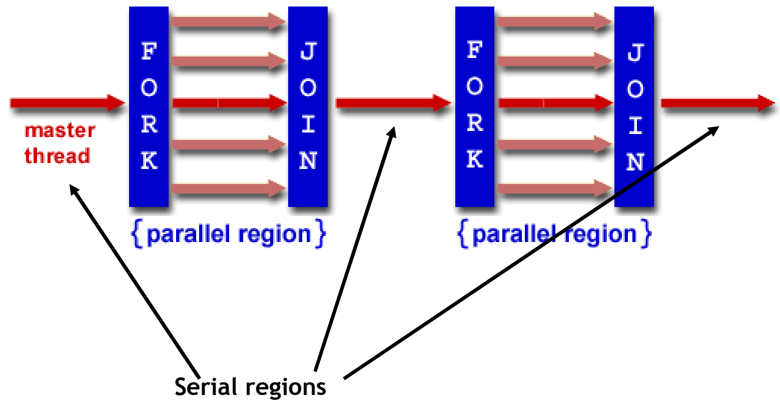
speedup(**p**) = $\frac{\text{time for best serial version}}{\text{time for version with } \mathbf{p} \text{ processors}}$

- What can we realistically expect?



Reason #1: Amdahl's Law

- In general, the whole computation is not (easily) parallelizable



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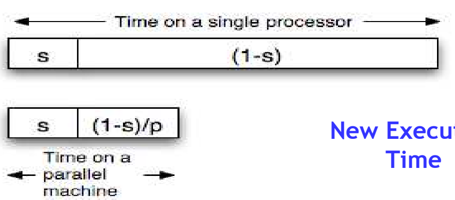
Reason #1: Amdahl's Law

- Suppose a program takes 1 unit of time to execute serially
- A fraction of the program, **s**, is inherently serial (unparallelizable)



New Execution Time $= \frac{1-s}{P} + s$

- For example, consider a program that, when executing on one processor, spends 10% of its time in a non-parallelizable region. How much faster will this program run on a 3-processor system?

New Execution Time $= \frac{.9T}{3} + .1T =$ **Speedup =**

- What is the maximum speedup from parallelization?

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Reason #2: Overhead

```
void
array_add(int A[], int B[], int C[], int length) {
   cpu_num = fork(N-1);
  int i;
  for (i = cpu_num ; i < length ; i += N) {
    C[i] = A[i] + B[i];
  }
   join();
}
```

- Forking and joining is not instantaneous
  - Involves communicating between processors
  - May involve calls into the operating system
    - Depends on the implementation

$$\text{New Execution Time} = \frac{1-s}{P} + s + \text{overhead}(P)$$

Programming Explicit Thread-level Parallelism

- As noted previously, the programmer must specify how to parallelize
- But, want path of least effort

- Division of labor between the **Human** and the **Compiler**
  - **Humans: good at expressing parallelism**, bad at bookkeeping
  - **Compilers:** bad at finding parallelism, **good at bookkeeping**

- Want a way to take serial code and say “Do this in parallel!” without:
  - Having to manage the synchronization between processors
  - Having to know a priori how many processors the system has
  - Deciding exactly which processor does what
  - Replicate the private state of each thread

- OpenMP: an industry standard set of compiler extensions
  - Works very well for programs with structured parallelism.

OpenMP

```
void
array_add(int A[], int B[], int C[], int length) {
  int i;
   for (i =0 ; i < length ; i += 1) { // Without OpenMP
    C[i] = A[i] + B[i];
  }
}

void
array_add(int A[], int B[], int C[], int length) {
  int i;
   #pragma omp parallel
  for (i =0 ; i < length ; i += 1) { // With OpenMP
    C[i] = A[i] + B[i];
  }
}
```

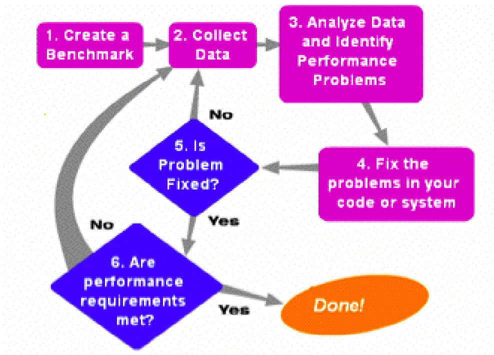
- OpenMP figures out how many threads are available, forks (if necessary), divides the work among them, and then joins after the loop.

OpenMP "hello world" Example

```
#include <omp.h>

main ()  {
int nthreads, tid;

/* Fork a team of threads giving them their own copies of
   variables */
#pragma omp parallel private(tid)
  {
  /* Obtain and print thread id */
  tid = omp_get_thread_num();
  printf("Hello World from thread = %d\n", tid);

  /* Only master thread does this */
  if (tid == 0)
    {
    nthreads = omp_get_num_threads();
    printf("Number of threads = %d\n", nthreads);
    }
  }  /* All threads join master thread and terminate */
}
```

Performance Optimization

- Until you are an expert, first write a working version of the program
- Then, and only then, begin tuning, first collecting data, and iterate
  - Otherwise, you will likely optimize what doesn't matter



"We should forget about small efficiencies, say about 97% of the time: premature optimization is the root of all evil." -- *Sir Tony Hoare*

Summary so Far

- Multi-core is having more than one processor on the same chip.
  - Soon most PCs/servers and game consoles will be multi-core
  - Results from Moore's law and power constraint
- Exploiting multi-core requires parallel programming
  - Automatically extracting parallelism too hard for compiler, in general.
  - But, can have compiler do much of the bookkeeping for us
  - OpenMP
- Fork-Join model of parallelism
  - At parallel region, fork a bunch of threads, do the work in parallel, and then join, continuing with just one thread
  - Expect a speedup of less than P on P processors
    - Amdahl's Law: speedup limited by serial portion of program
    - Overhead: forking and joining are not free

More on Parallelism...

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Approaches to Parallelism

- Parallel Algorithms
- Parallel Language
- Message passing (low-level)
- Parallelizing compilers

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Parallel Languages

- **Fortran 90** - Array language. Triplet notation for array sections. Operations and intrinsic functions possible on array sections.
- **High Performance Fortran (HPF)** - Similar to Fortran 90, but includes data layout specifications to help the compiler generate efficient code.
- ZPL - array-based language at UW. Compiles into C code (highly portable).
- C* - C extended for parallelism

Object-Oriented

- concurrent Smalltalk,
- threads in Java, Ada, thread libraries for use in C/C++

Functional

- NESL, Multiplisp
- Id & Sisal (more dataflow)

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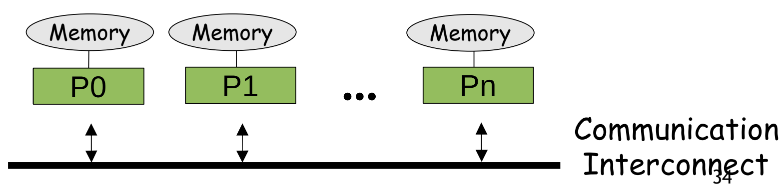
Distributed Memory Architecture

- Each Processor has direct access only to its local memory
- Processors are connected via high-speed interconnect
- Data structures must be distributed
- Data exchange is done via explicit processor-to-processor communication: send/receive messages
- Example Programming Model: Widely used standard: MPI



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Message Passing Interface

MPI is not a language but rather a collection of subroutines and their arguments.

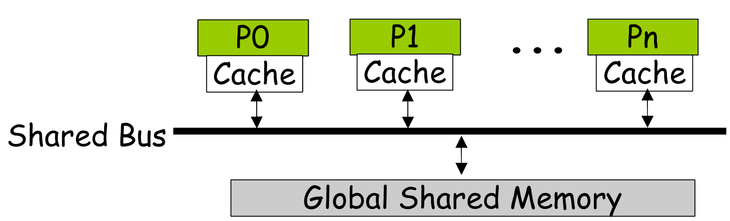
MPI provides:

- Point-to-point communication
- Collective operations
  - Barrier synchronization
  - gather/scatter operations
  - Broadcast, reductions
- Different communication modes
  - Synchronous/asynchronous
  - Blocking/non-blocking
  - Buffered/unbuffered
- C/C++ and Fortran bindings

http://www.mpi-forum.org

Shared Memory Architecture

- Processors have direct access to global memory and I/O through bus or fast switching network
- Cache Coherency Protocol guarantees consistency of memory and I/O accesses
- Each processor also has its own memory (cache)
- Data structures are shared in global address space
- Concurrent access to shared memory must be coordinated
- Example Programming Model: OpenMP



OpenMP

- OpenMP: portable shared memory parallelism
- Higher-level API for writing portable multithreaded applications
- Provides a set of compiler directives and library routines for parallel application programmers
- API bindings for Fortran, C, and C++

http://www.OpenMP.org

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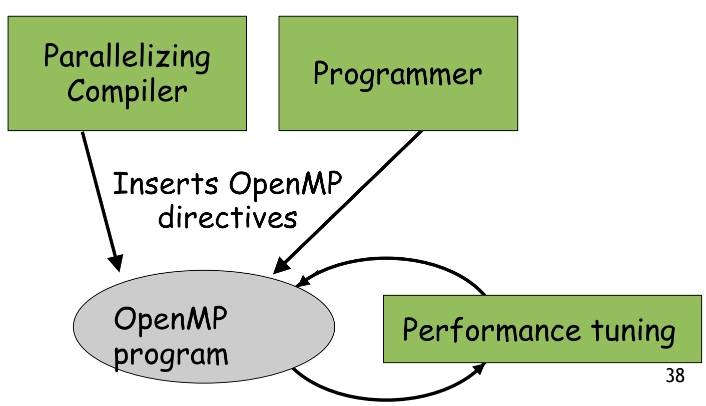
Writing OpenMP Applications

- Program is built with OpenMP-enabled compiler flags
- Programmer explicitly adds OpenMP pragmas
- Fine tuning using OpenMP Profiling and Performance Analysis Tools



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Parallelizing Compilers

Automatically transform a sequential program into a parallel program.

1. Identify loops whose iterations can be executed in parallel.
2. Often done in stages.

Q: Which loops can be run in parallel?

Q: How should we distribute the work/data?

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