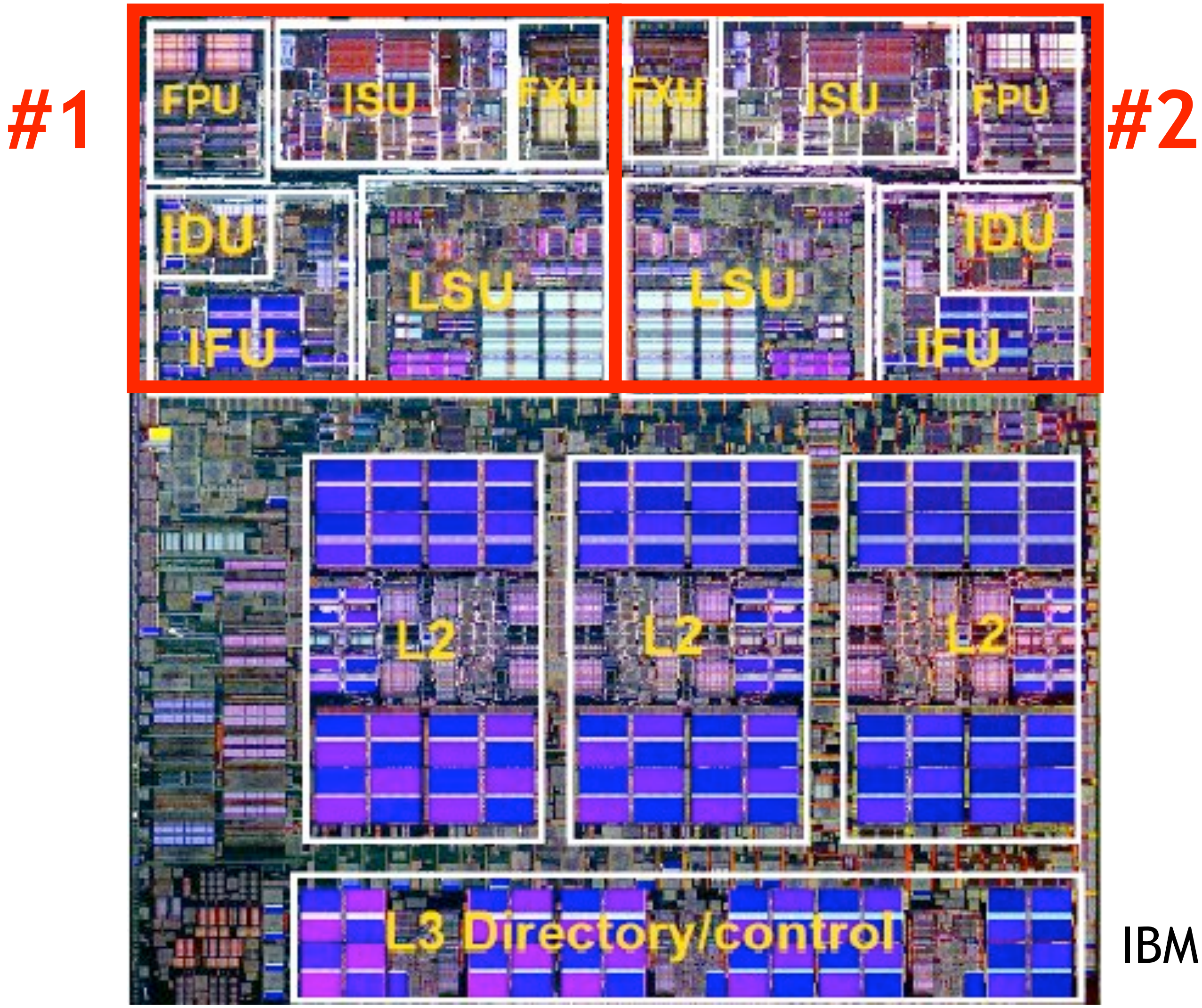
Announcements

- Homework 4 out today
- Dec 7th is the last day you can turn in Lab 4 and HW4, so plan ahead.

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

Multi-Cores are Everywhere

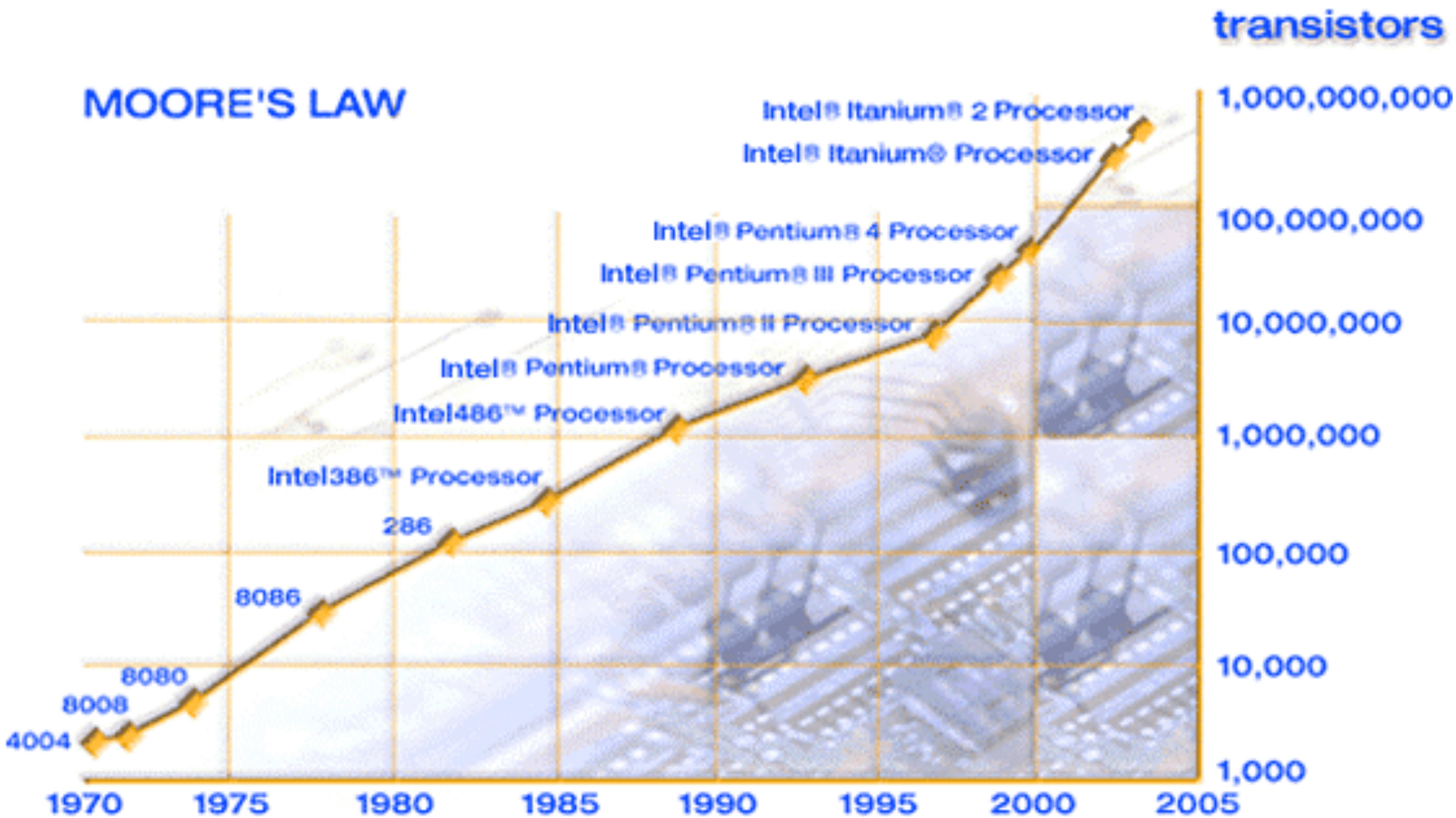
Intel Core Duo in new Macs: 2 x86 processors on same chip

XBox360: 3 PowerPC cores

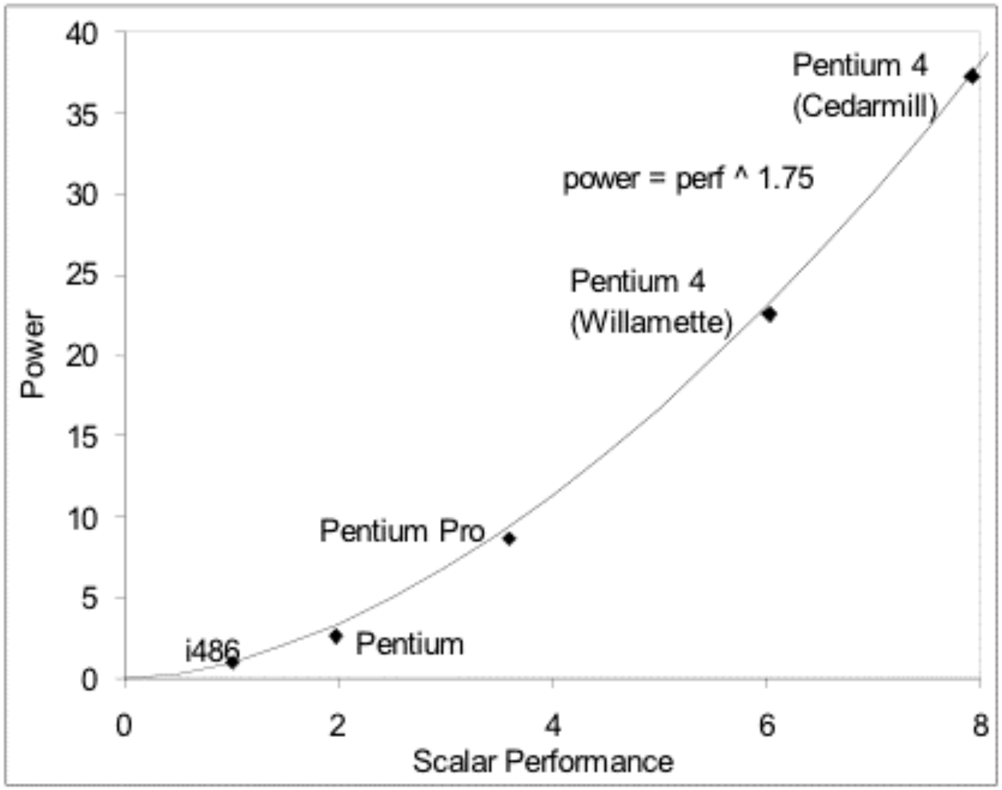
Sony Playstation 3: Cell processor, an asymmetric multi-core with 9 cores (1 general-purpose, 8 special purpose SIMD processors)

Why Multi-cores Now?

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

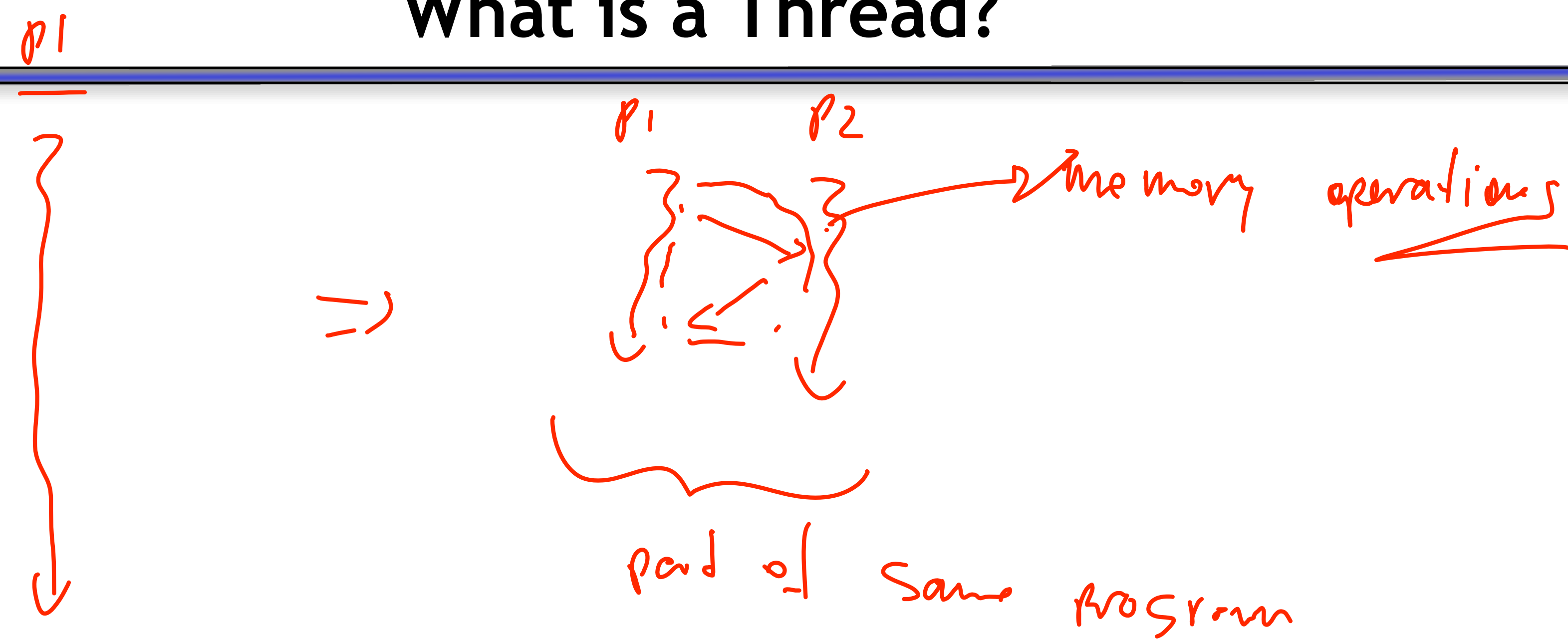


… and performance growing too…

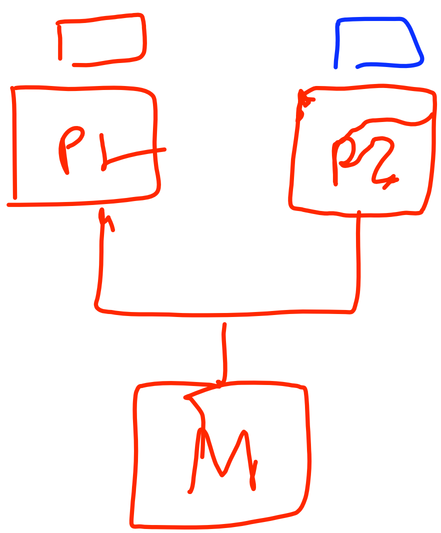


- But power is growing even faster!!
  - Power has become limiting factor in current chips

What is a Thread?



- What does Shared Memory imply?
- Machine model



a = 1

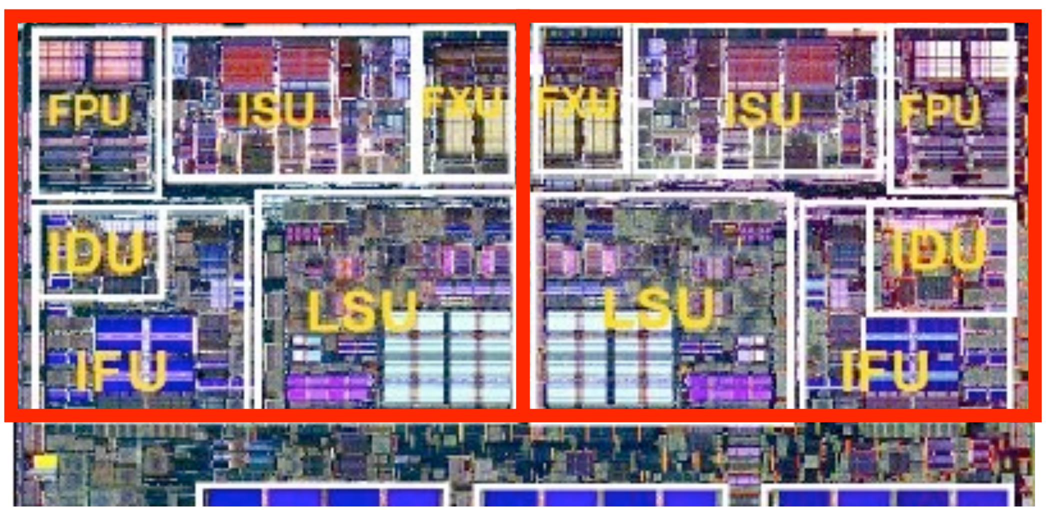
= a (1)

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];
  }
}
```

#1

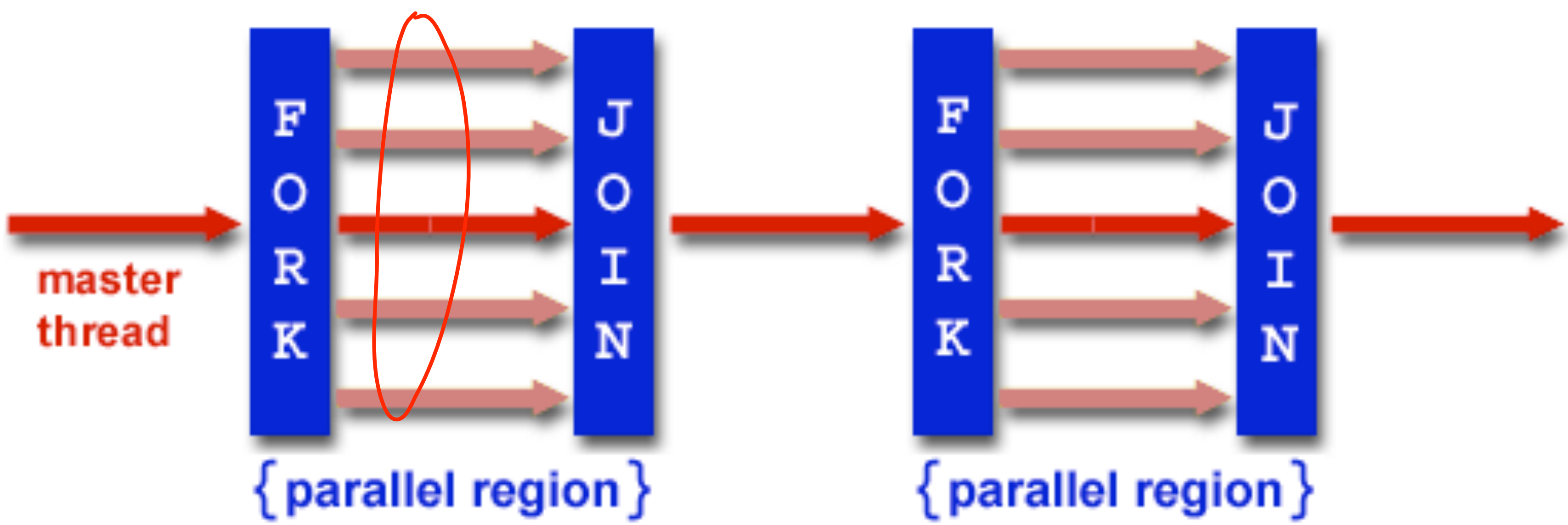


#2

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**
  - Posix threads and explicit synchronization (CSE451?)

See same memory

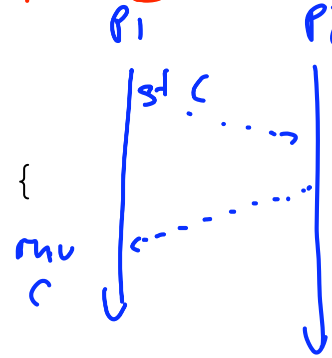


Fork/Join Logical Example

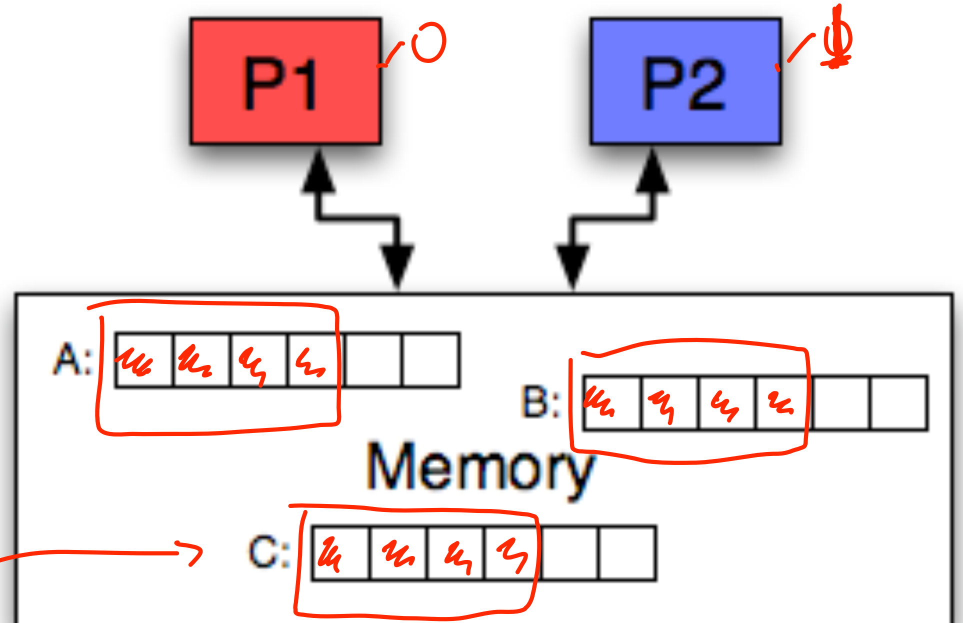
- Fork N-1 threads
- Break work into N pieces (and do it)
- Join (N-1) threads

P1 = 0, 2, 4 . .

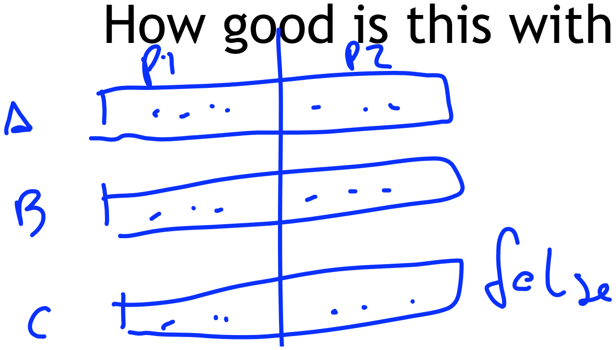
P2 = 1, 3, 5 . .




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



How good is this with caches?

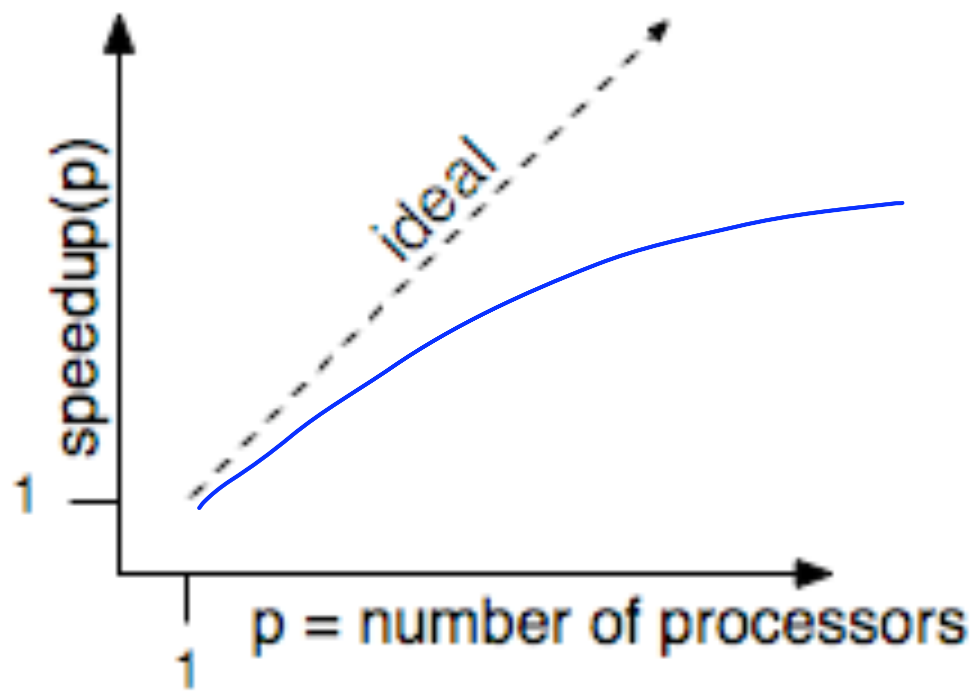


How does this help performance?

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

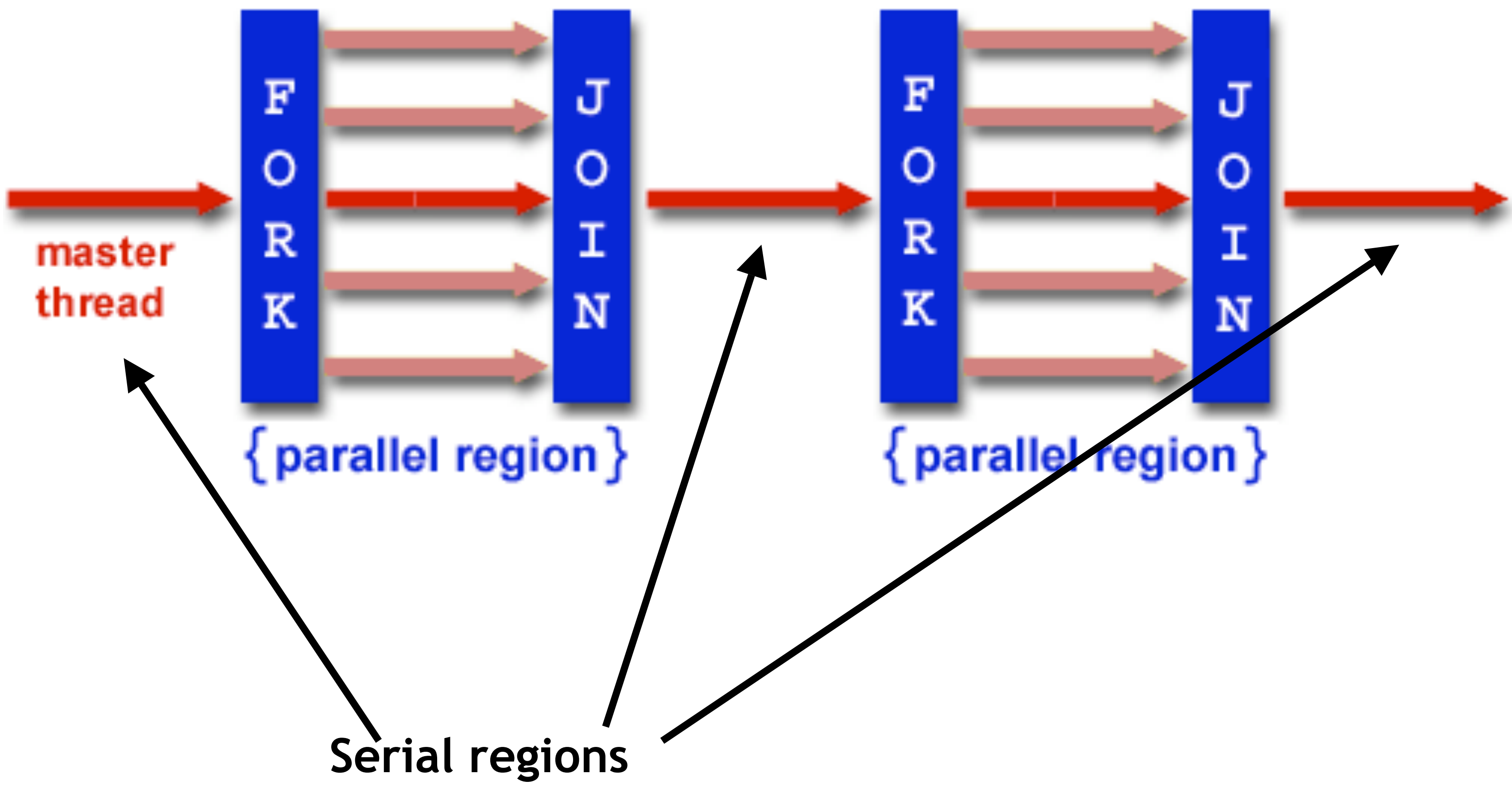
$$\text{speedup}(\mathbf{p}) = \frac{\text{time for best serial version}}{\text{time for version with } \mathbf{p} \text{ processors}}$$

- What can we realistically expect?



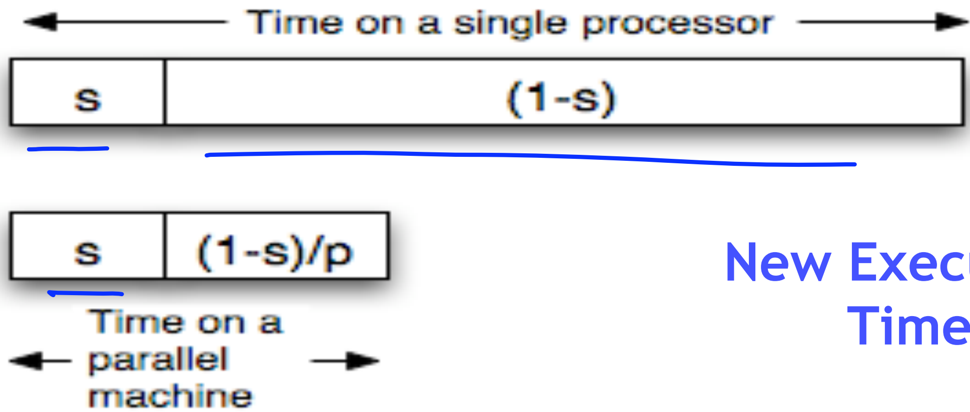
Reason #1: Amdahl's Law

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



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)



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

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

$$\text{New Execution Time} = \frac{.9T}{3} + .1T = 0.3T + 0.1T \qquad \textbf{Speedup} = \frac{1T}{0.4T} = 2$$

- What is the maximum speedup from parallelization?

$$\cancel{\frac{.9T}{\ }} + 0.1T = 0.1T \qquad Sp = \frac{1T}{0.1T} = 10x$$

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();
}
```

granularity

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

want coarse granularity

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

Programming Explicit Thread-level Parallelism

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

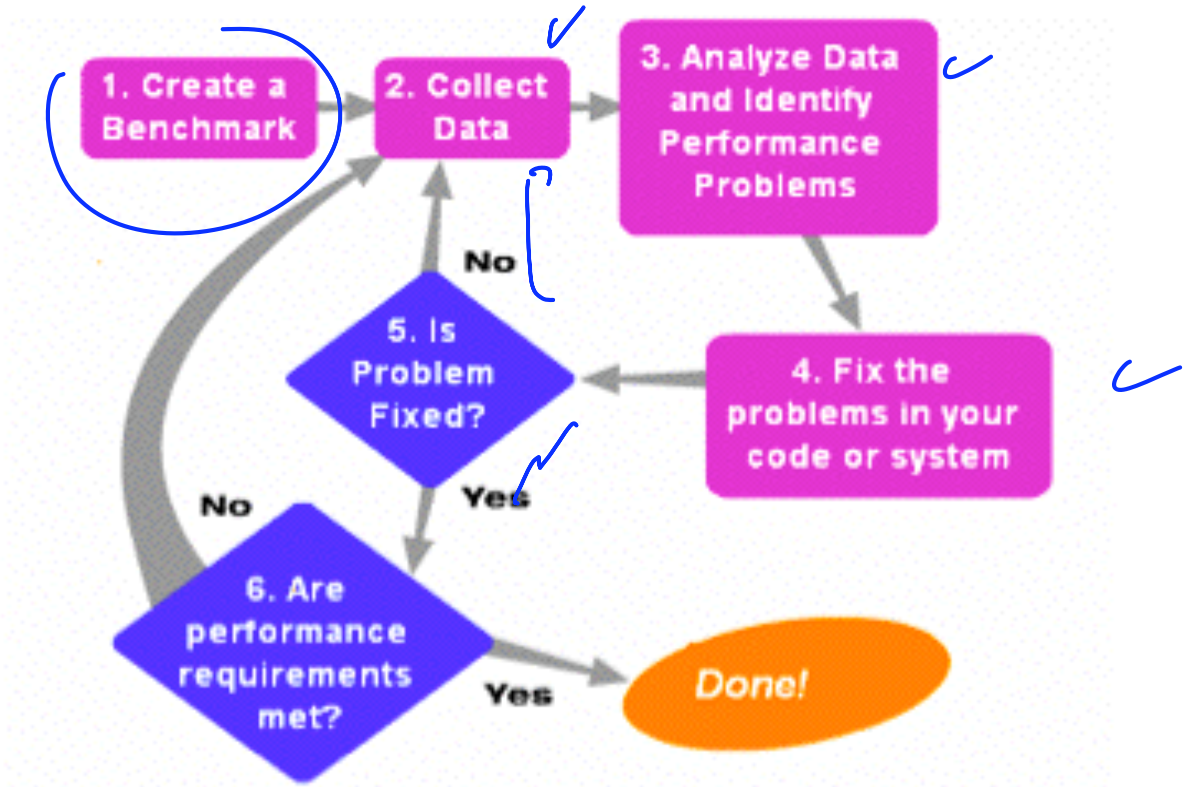
- Division of labor between the **Human** and the **Compiler**
  - **Humans: good at expressing parallelism**, bad at bookkeeping
  - **Compilers:** bad at finding parallelism, **good at bookkeeping**

- 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.

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

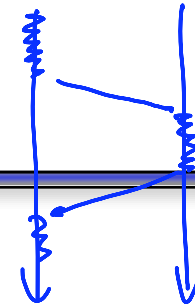


"We should forget about small efficiencies, say about 97% of the time: premature optimization is the root of all evil." -- *Sir Tony Hoare*

Using tools to do instrumentation

- Two GNU tools integrated into the GCC C compiler
- Gprof: The GNU profiler
  - Compile with the `-pg` flag
    - This flag causes gcc to keep track of which pieces of source code correspond to which chunks of object code and links in a profilin signal handler.
  - Run as normal; program requests the operating system to periodicall send it signals; the signal handler records what instruction was executing when the signal was received in a file called `gmon.out`
  - Display results using gprof command
    - Shows how much time is being spent in each function.
    - Shows the calling context (the path of function calls) to the hot spot.

Example gprof output



Each sample counts as 0.01 seconds.

% time	cumulative seconds	self seconds	calls	self s/call	total s/call	name
81.89	4.16	4.16	37913758	0.00	0.00	cache_access
16.14	4.98	0.82	1	0.82	5.08	sim_main
1.38	5.05	0.07	6254582	0.00	0.00	update_way_list
0.59	5.08	0.03	1428644	0.00	0.00	dl1_access_fn
0.00	5.08	0.00	711226	0.00	0.00	dl2_access_fn
0.00	5.08	0.00	256830	0.00	0.00	yylex

Over 80% of time spent in one function

Provides calling context (`main` calls `sim_main` calls `cache_access`) of hot s

index	% time	self	children	called	name
		0.82	4.26	1/1	**main** [2]
[1]	100.0	0.82	4.26	1	**sim_main** [1]
		4.18	0.07	36418454/36484188	**cache_access** <cycle 1> [4
		0.00	0.01	10/10	sys_syscall [9]
		0.00	0.00	2935/2967	mem_translate [16]
		0.00	0.00	2794/2824	mem_newpage [18]

Using tools for instrumentation (cont.)

- Gprof didn't give us information on where in the function we were spending time. (`cache_access` is a big function; still needle in haystack)
- Gcov: the GNU coverage tool
  - Compile/link with the `-fprofile-arcs -ftest-coverage` options
    - Adds code during compilation to add counters to every control flow edge (much like our by hand instrumentation) to compute how frequently each block of code gets executed.
  - Run as normal
  - For each `xyz.c` file an `xyz.gdna` and `xyz.gcno` file are generated
  - Post-process with gcov xyz.c
    - Computes execution frequency of each line of code
    - Marks with ##### any lines not executed
      - Useful for making sure that you tested your whole program

Example gcov output

Code never executed

```
14282656:  540:  if (cp->hsize) {
   #####:  541:      int hindex = CACHE_HASH(cp, tag);
       -:  542:
   #####:  543:      for (blk=cp->sets[set].hash[hindex];
       -:  544:           blk;
       -:  545:           blk=blk->hash_next)
       -:  546:          {
   #####:  547:              if (blk->tag == tag && (blk->status & CACHE_BLK_VALID
   #####:  548:                  goto cache_hit;
       -:  549:      }
       -:  550:  } else {
       -:  551:      /* linear search the way list */
753030193:  552:      for (blk=cp->sets[set].way_head;
       -:  553:           blk;
       -:  554:           blk=blk->way_next)      {
751950759:  555:              if (blk->tag == tag && (blk->status & CACHE_BLK_VALID
738747537:  556:                  goto cache_hit;
       -:  557:      }
       -:  558:  }
```

Loop executed over 50 interations on average (751950759/14282656)

Summary

- 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, ar 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