COMP 322: Fundamentals of Parallel Programming

Lecture 1: The What and Why of Parallel Programming

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Scope of Course

- Fundamentals of parallel programming
  - Task creation and termination, computation graphs, scheduling theory, futures, forall parallel loops, barrier synchronization (phasers), isolation & mutual exclusion, task affinity, bounded buffers, data flow, threads, GUI applications, data races, deadlock, memory models
- Introduction to parallel algorithms
- Habanero-Java (HJ) language, developed in the Habanero Multicore Software Research project at Rice
- Abstract executable performance model for HJ programs
- Java Concurrency
- Written assignments
- Programming assignments
  - Abstract metrics
  - Real parallel systems (8-core Intel, Rice SUG@R system)
- Beyond HJ and Java: introduction to CUDA and MPI

Acknowledgments for Today's Lecture

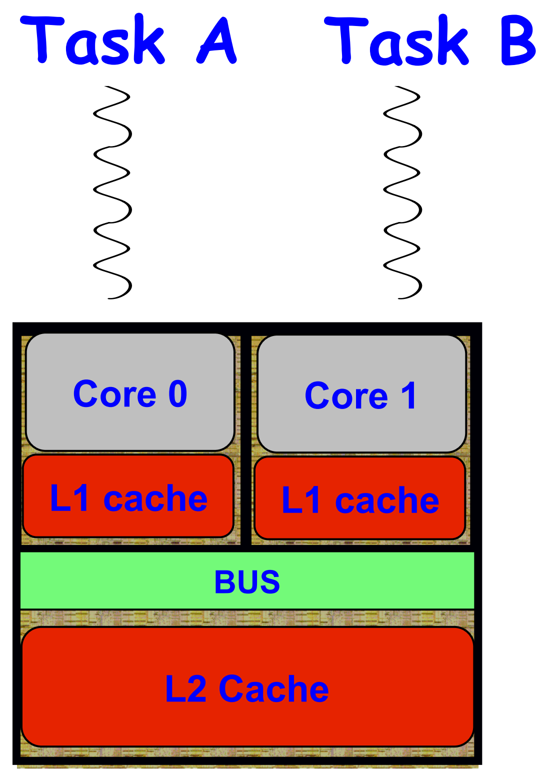
- CS 194 course on "Parallel Programming for Multicore" taught by Prof. Kathy Yelick, UC Berkeley, Fall 2007
  - http://www.cs.berkeley.edu/~yelick/cs194f07/
- COMP 322 Lecture 1 handout

What is Parallel Computing?

- Parallel computing: using multiple processors in parallel to solve problems more quickly than with a single processor, or with less energy
- Examples of parallel machines
  - A computer Cluster that contains multiple PCs with local memories combined together with a high speed network
  - A Symmetric Multi-Processor (SMP) that contains multiple processor chips connected to a single shared memory system
  - A Chip Multi-Processor (CMP) contains multiple processors (called cores) on a single chip, also called Multi-Core Computers
- The main motivation for parallel execution historically came from the desire for improved performance
  - Computation is the third pillar of scientific endeavor, in addition to Theory and Experimentation
- But parallel execution has also now become a ubiquitous necessity due to power constraints, as we will see

What is Parallel Programming?

- Specification of operations that can be executed in parallel
- A parallel program is decomposed into sequential subcomputations called *tasks*
- Parallel programming constructs define task creation, termination, and interaction

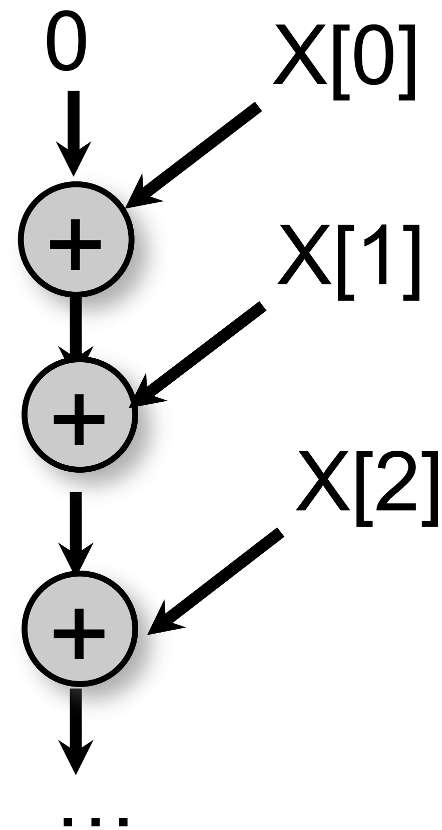


Schematic of a Dual-core Processor

Example of a Sequential Program: Computing the sum of array elements

```
int sum = 0;
for (int i=0 ; i < X.length ; i++ )
    sum += X[i];
```

Computation Graph



Observations:

- The decision to sum up the elements from left to right was arbitrary
- The *computation graph* shows that all operations must be executed sequentially

Async and Finish Statements for Task Creation and Termination

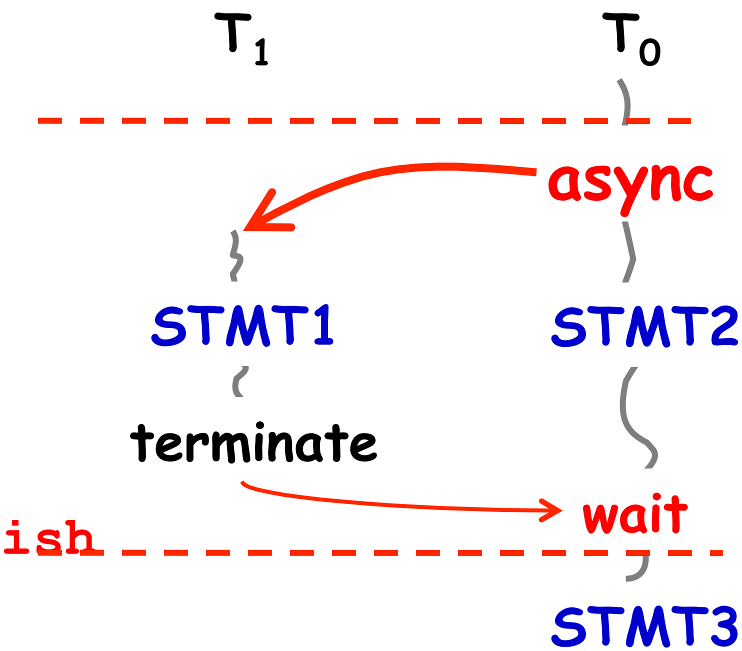
async S

- Creates a new child task that executes statement S
- Parent task immediately continues to statement following the async

finish S

- Execute S, but wait until *all* (transitively) spawned asyncs in S's scope have terminated.
- Implicit finish between start and end of main program

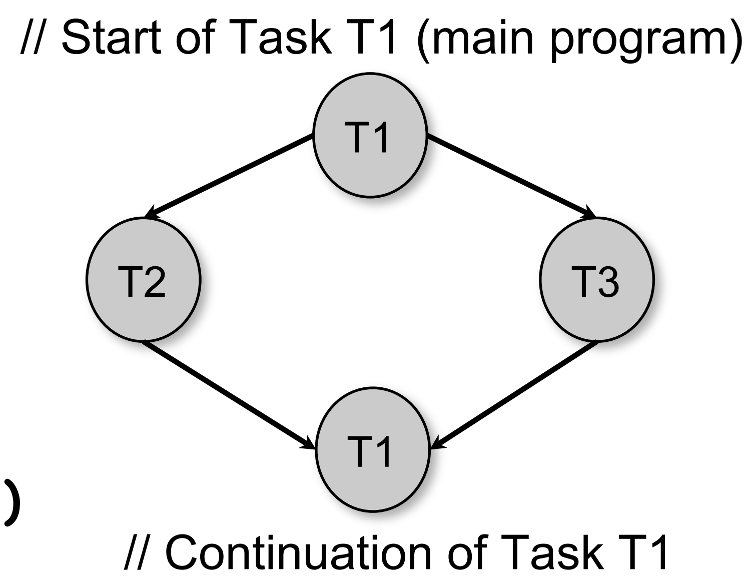
```
//Task T0(Parent)
finish {    //Begin finish
  async
    STMT1; //T1(Child)
  //Continuation
  STMT2;    //T0
} //Continuation //End finish
STMT3;      //T0
```



Example of a Parallel Program: Array Sum with two tasks

```
// Start of Task T1 (main program)
sum1 = 0; sum2 = 0;
// Assume that sum1 & sum2 are fields
finish {
  // Compute sum1 (lower half) and sum2
  // (upper half) in parallel
  async for (int i=0; i < X.length/2; i++)
      sum1 += X[i]; // Task T2
  async for (int i=X.length/2; i < X.length; i++)
      sum2 += X[i]; // Task T3
}
//Task T1 waits for Tasks T2 and T3
int sum = sum1 + sum2; // Continuation of Task T1
```

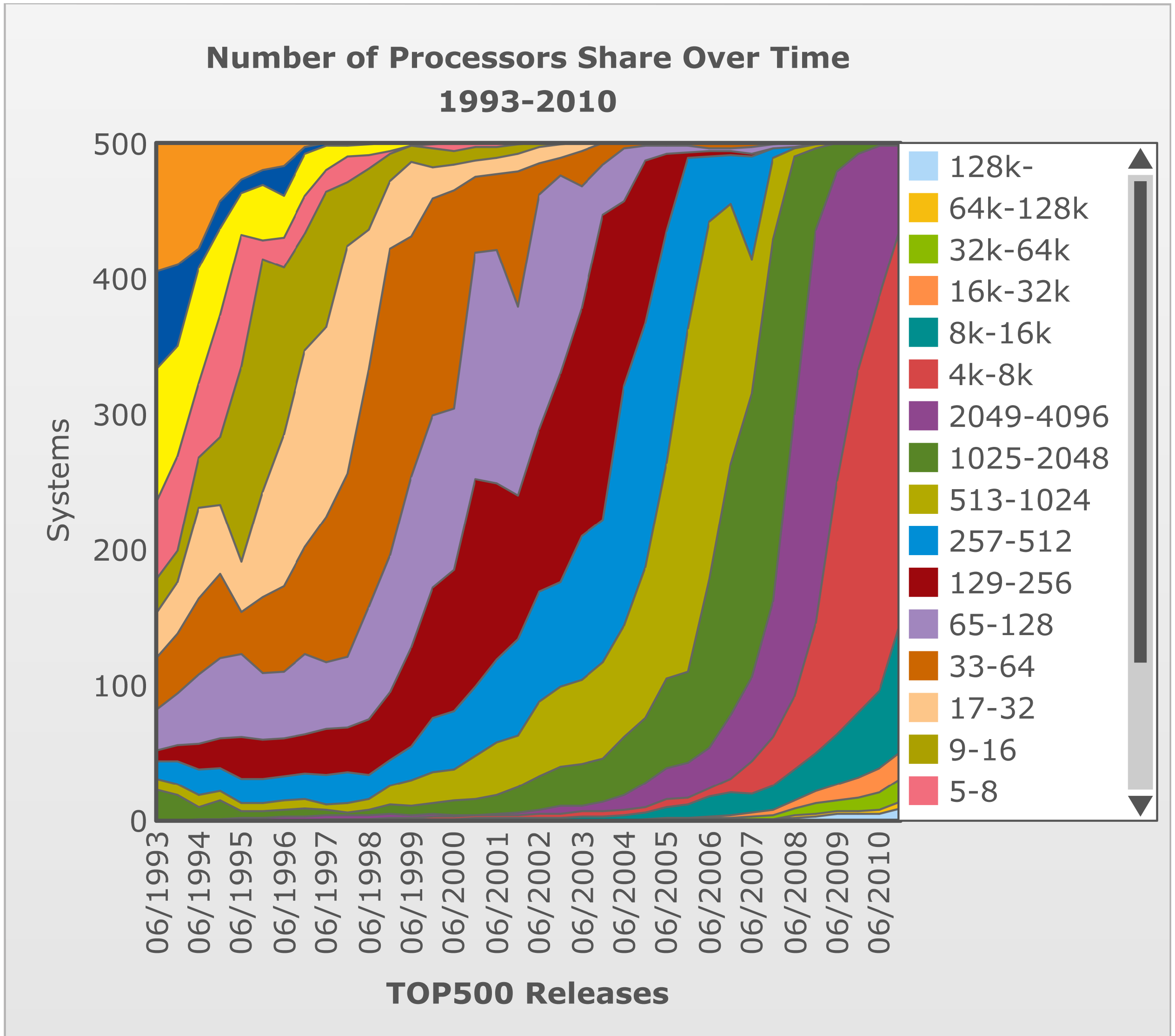
Computation Graph



Why Parallel Computing Now?

- Researchers have been using parallel computing for decades:
  - Mostly used in computational science and engineering
  - Problems too large to solve on one computer; use 100s or 1000s
- There have been higher level courses in parallel computing (COMP 422, COMP 522) at Rice for several years
- Many companies in the 80s/90s "bet" on parallel computing and failed
  - Sequential computers got faster too quickly for there to be a large market for specialized parallel computers
- Why is Rice adding a 300-level undergraduate course on parallel programming now?
  - Because the entire computing industry has bet on parallelism
  - There is a desperate need for all computer scientists and practitioners to be aware of parallelism

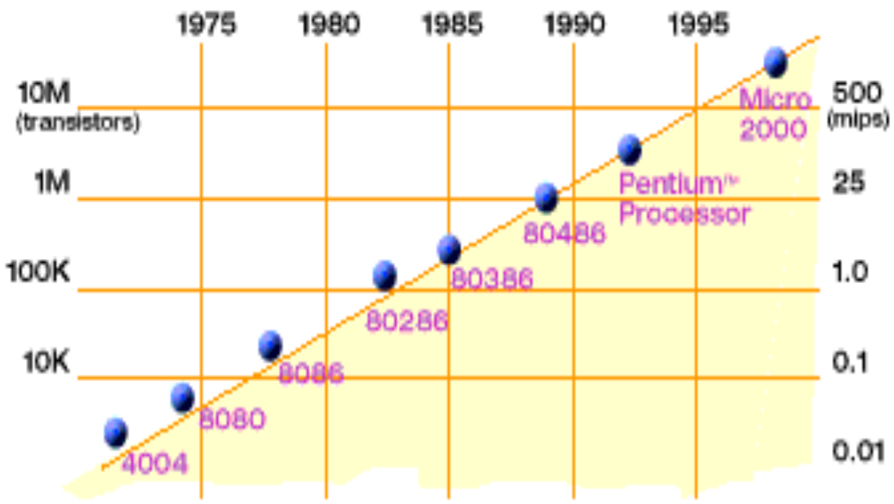
Number of processors used in Top 500 computers from 1993 to 2010



Source:

www.top500.org

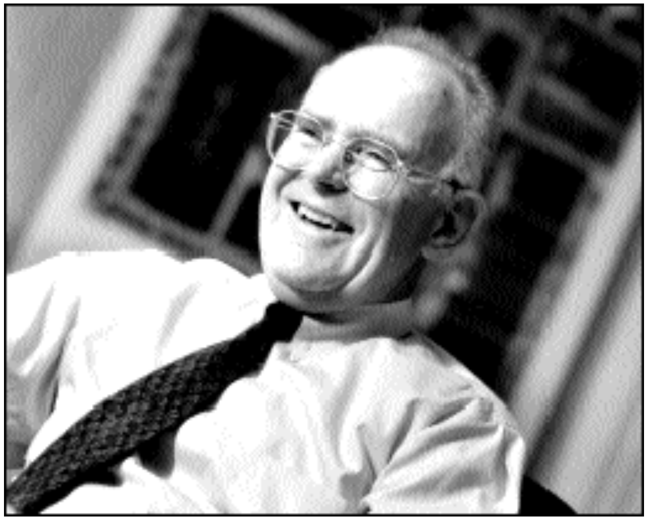
Technology Trends: Microprocessor Capacity



2X transistors/Chip every 1-2 years

Called "Moore's Law"

Microprocessors have become smaller, denser, and more powerful.

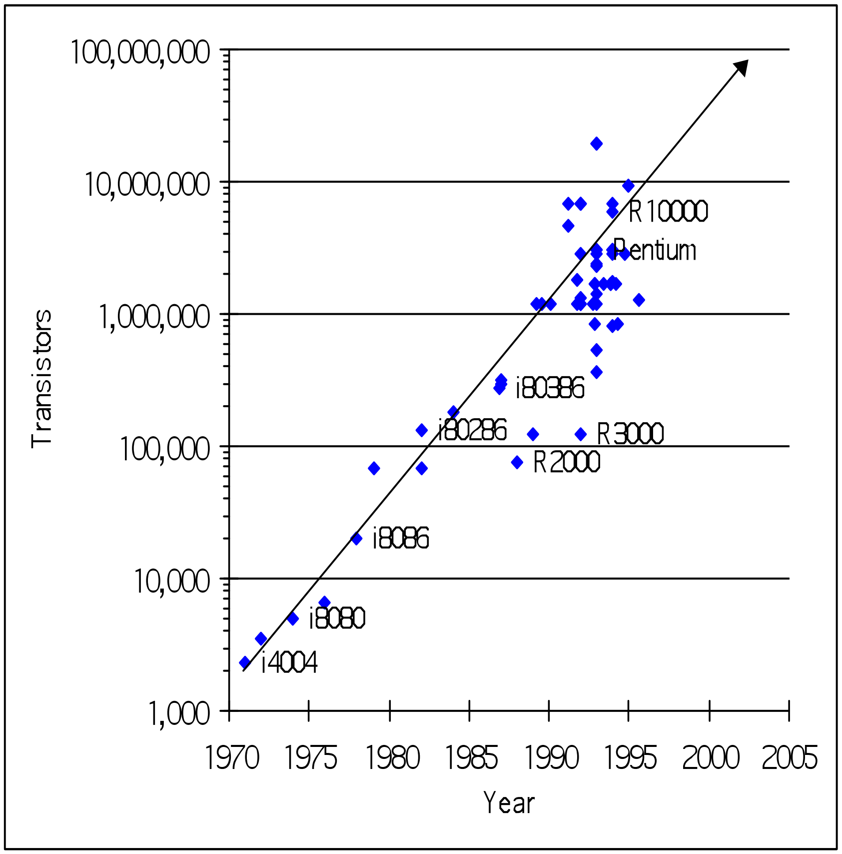


Gordon Moore (co-founder of Intel) predicted in 1965 that the transistor density of semiconductor chips would double roughly every 1-2 years

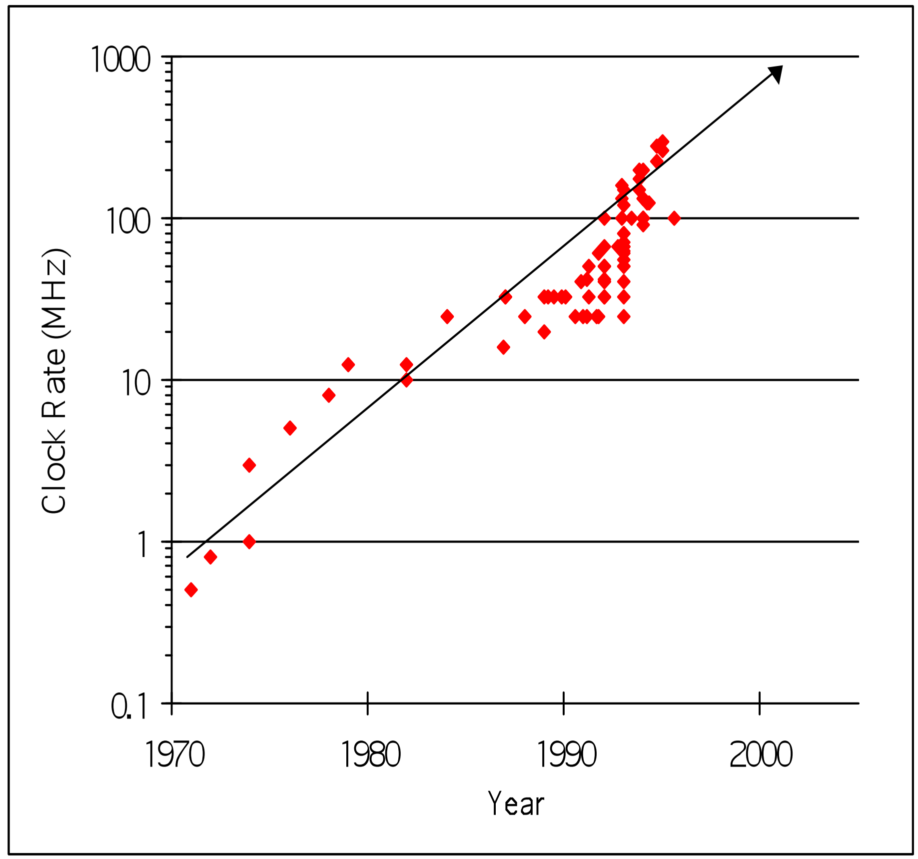
Slide source: Jack Dongarra

Microprocessor Transistors and Clock Rate

Growth in transistors per chip

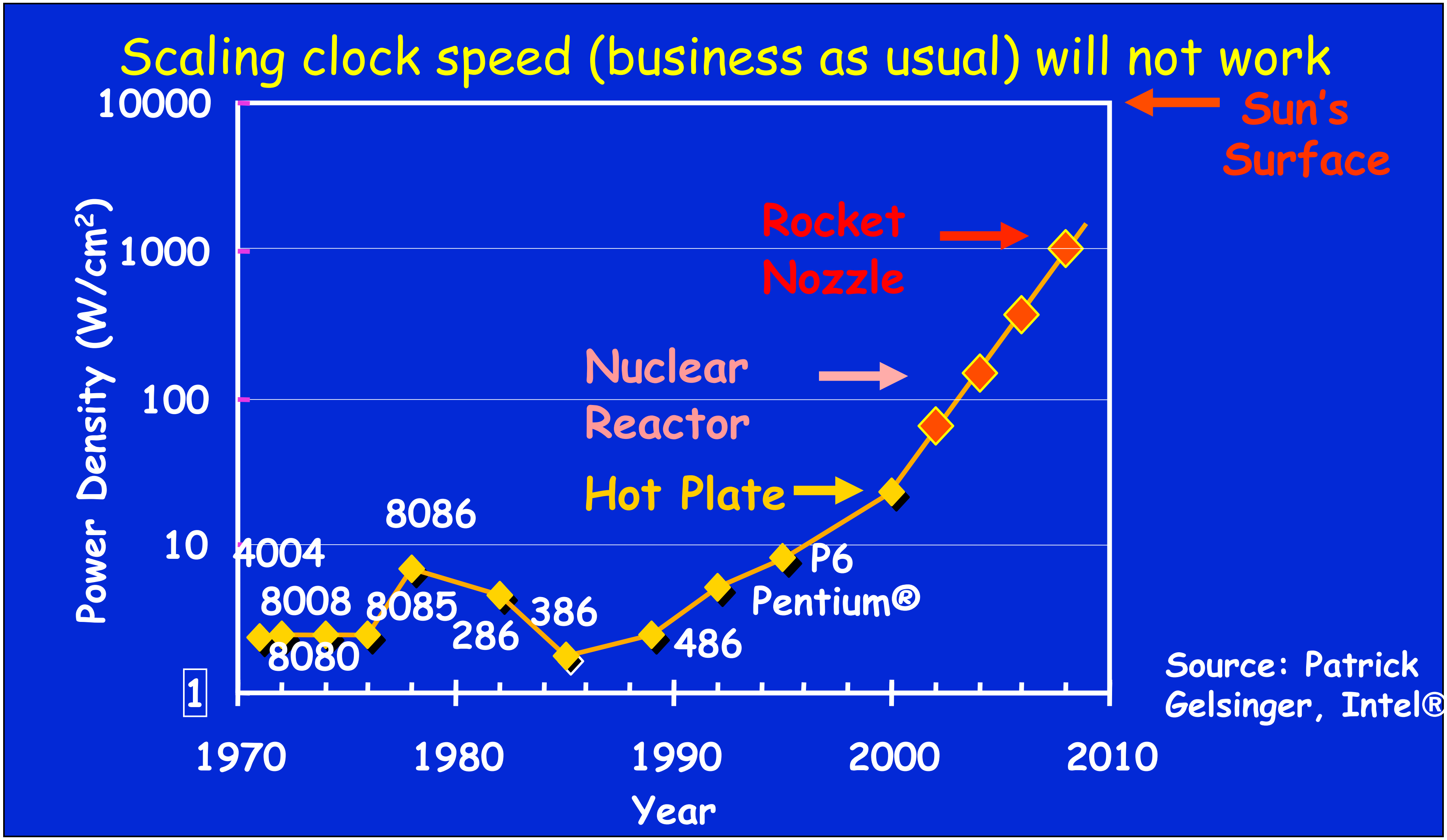


Increase in clock rate



Old view: why bother with parallel programming for increased performance? Just wait a year or two…

Power Wall


Scaling clock speed (business as usual) will not work
10000
1000
100
10
1
Power Density (W/cm2)
Sun's Surface
Rocket Nozzle
Nuclear Reactor
Hot Plate
4004
8008
8080
8085
8086
286
386
486
P6
Pentium®
1970
1980
1990
2000
2010
Year
Source: Patrick Gelsinger, Intel®

Parallelism Saves Power

Power = (Capacitance) * (Voltage)^2 * (Frequency)

➔ Power α (Frequency)^3

Baseline example: single 1GHz core with power P

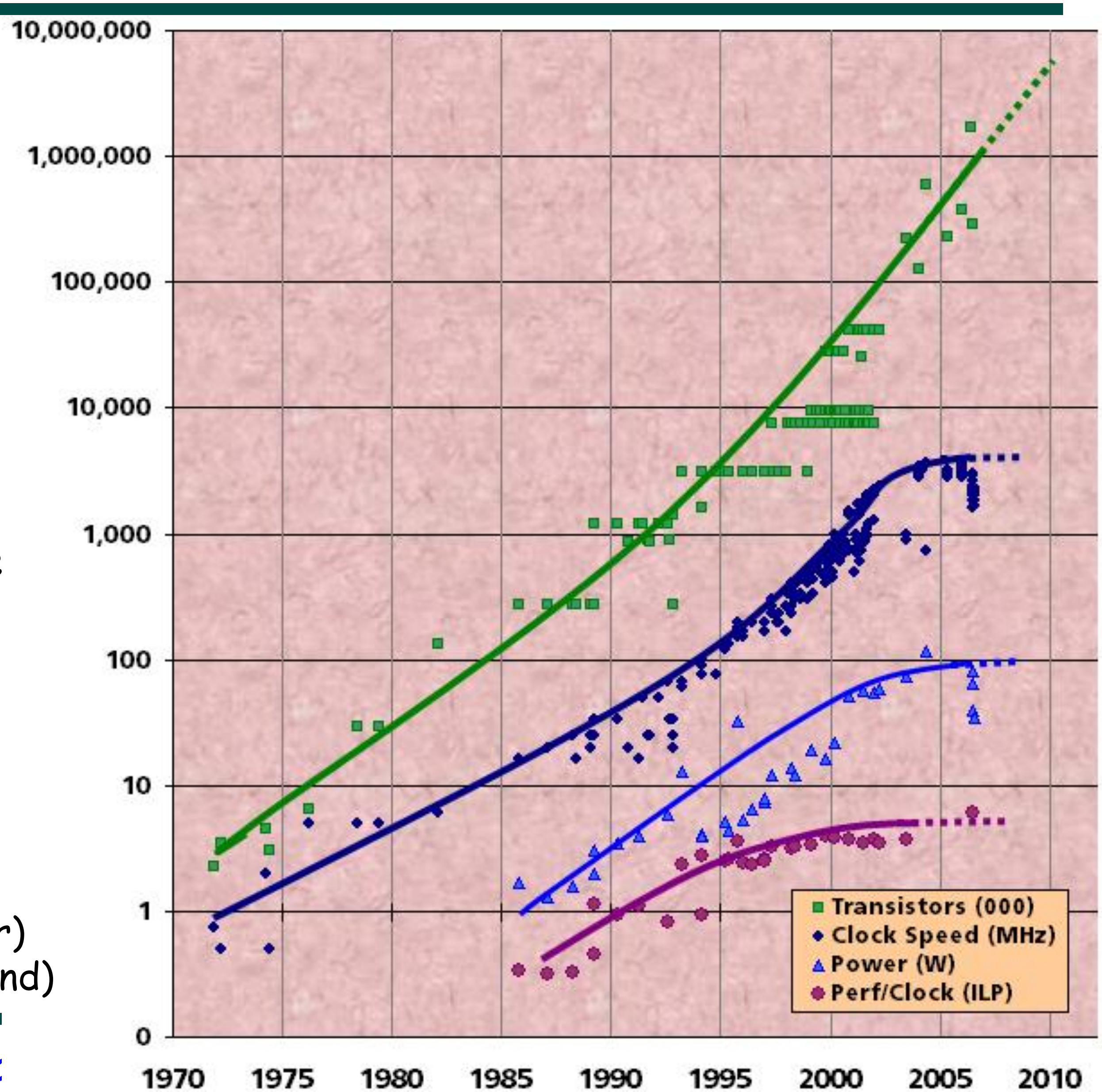
Option A: Increase clock frequency to 2GHz ➔ Power = 8P

Option B: Use 2 cores at 1 GHz each ➔ Power = 2P

- Option B delivers same performance as Option A with 4x less power … provided software can be decomposed to run in parallel!

Revolution is Happening Now

- Chip density is continuing to increase ~2x every 2 years
  - Clock speed is not
  - Number of processor cores may double instead
- There is little instruction-level parallelism (ILP) to be found by hardware
- Parallelism must be exposed to and managed by software



Source: Intel, Microsoft (Sutter) and Stanford (Olukotun, Hammond)

Implications

- These arguments are no long theoretical
- All major processor vendors are producing multicore chips
  - Every machine will soon be a parallel machine
  - All programmers will be parallel programmers???
- Some may eventually be hidden in libraries, compilers, and high level languages
  - But a lot of work is needed to get there
- Big open questions:
  - What will be the killer applications for multicore machines?
  - How should the chips be designed?
  - How will they be programmed?