Lecture 26: Parallelism in the Real World, Design of 15-210, and Concurrency

Lecturer: Umut A. Acar

Why Parallelism?

- Desire to solve larger more important problems.
  - One machine/processor insufficient
  - Multiple machines needed.
  - Possible because problems often decompose.
- Examples:
  - Scientific computing: massive computations
  - Internet: massive data, many queries
  - Big data

Cray-1 (1976): the world's most expensive love seat

Data Center: Hundred's of thousands of computers

Since 2005: Multicore computers

AMD Opteron (sixteen-core) Model 6274

by AMD

(1 customer review)

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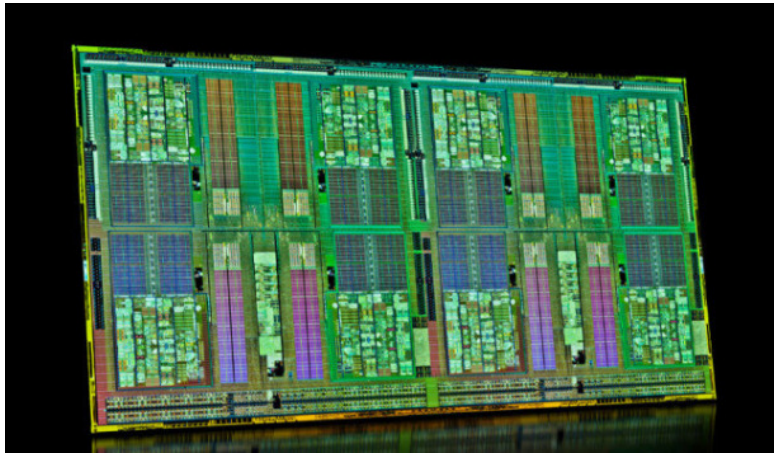
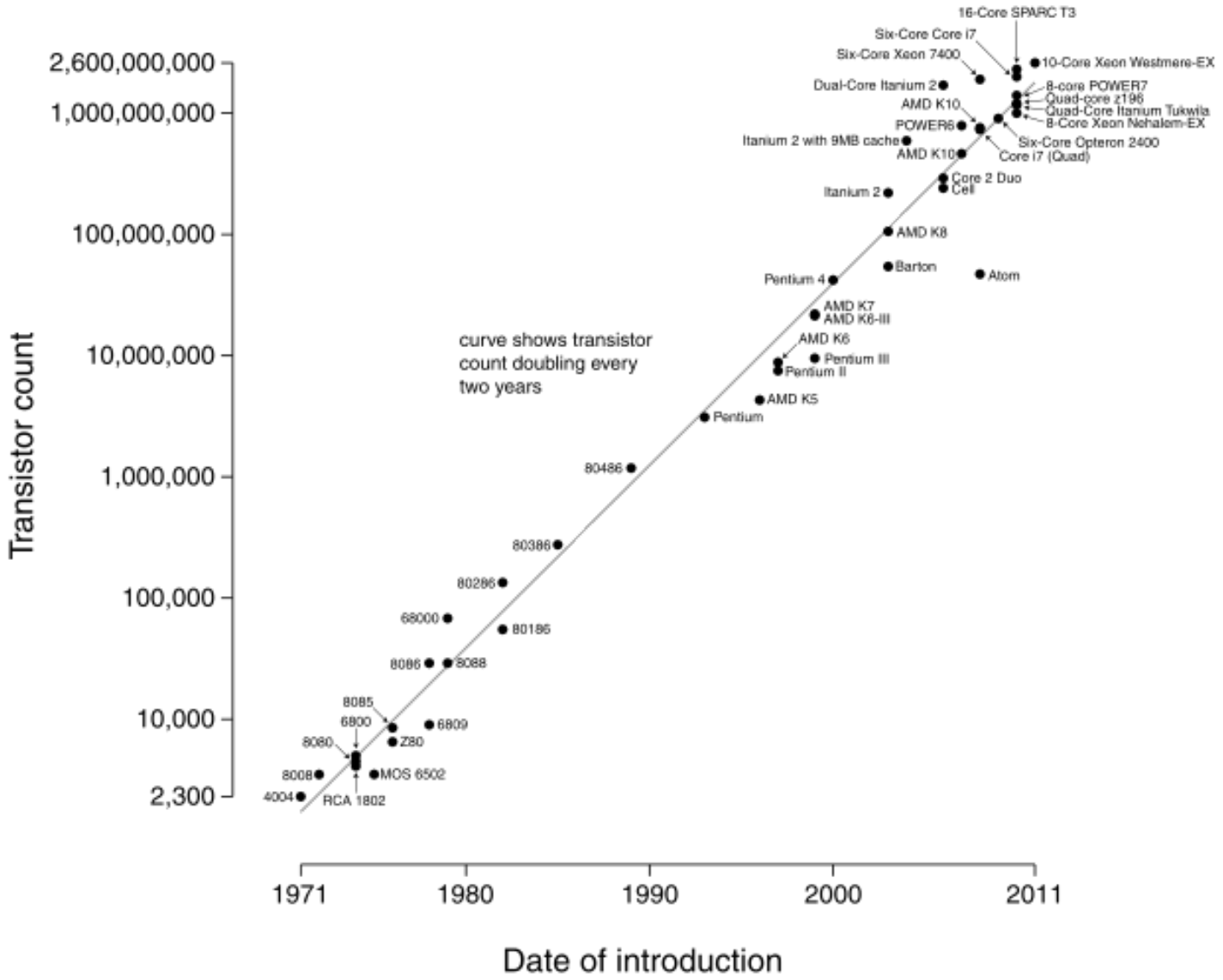
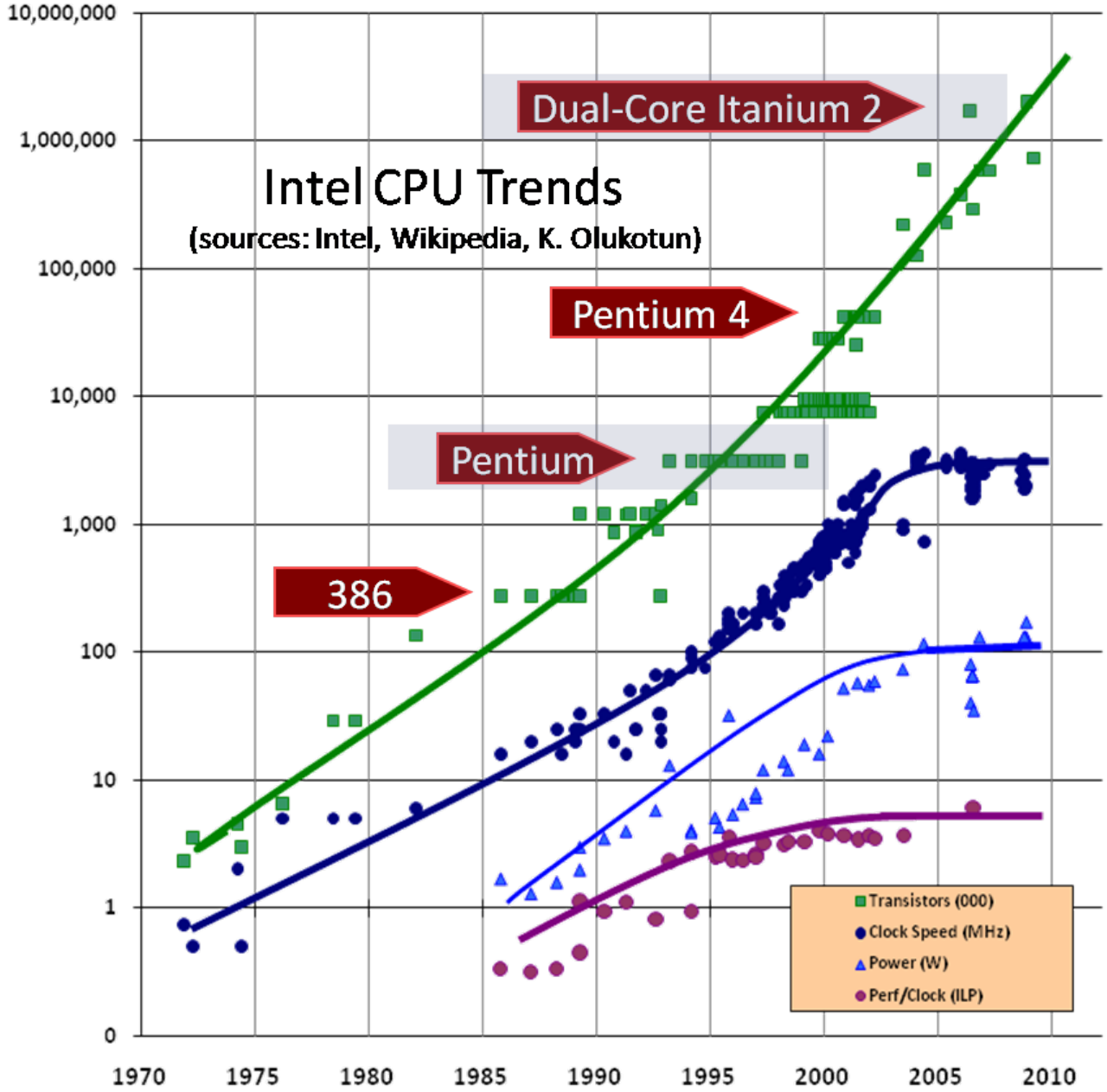
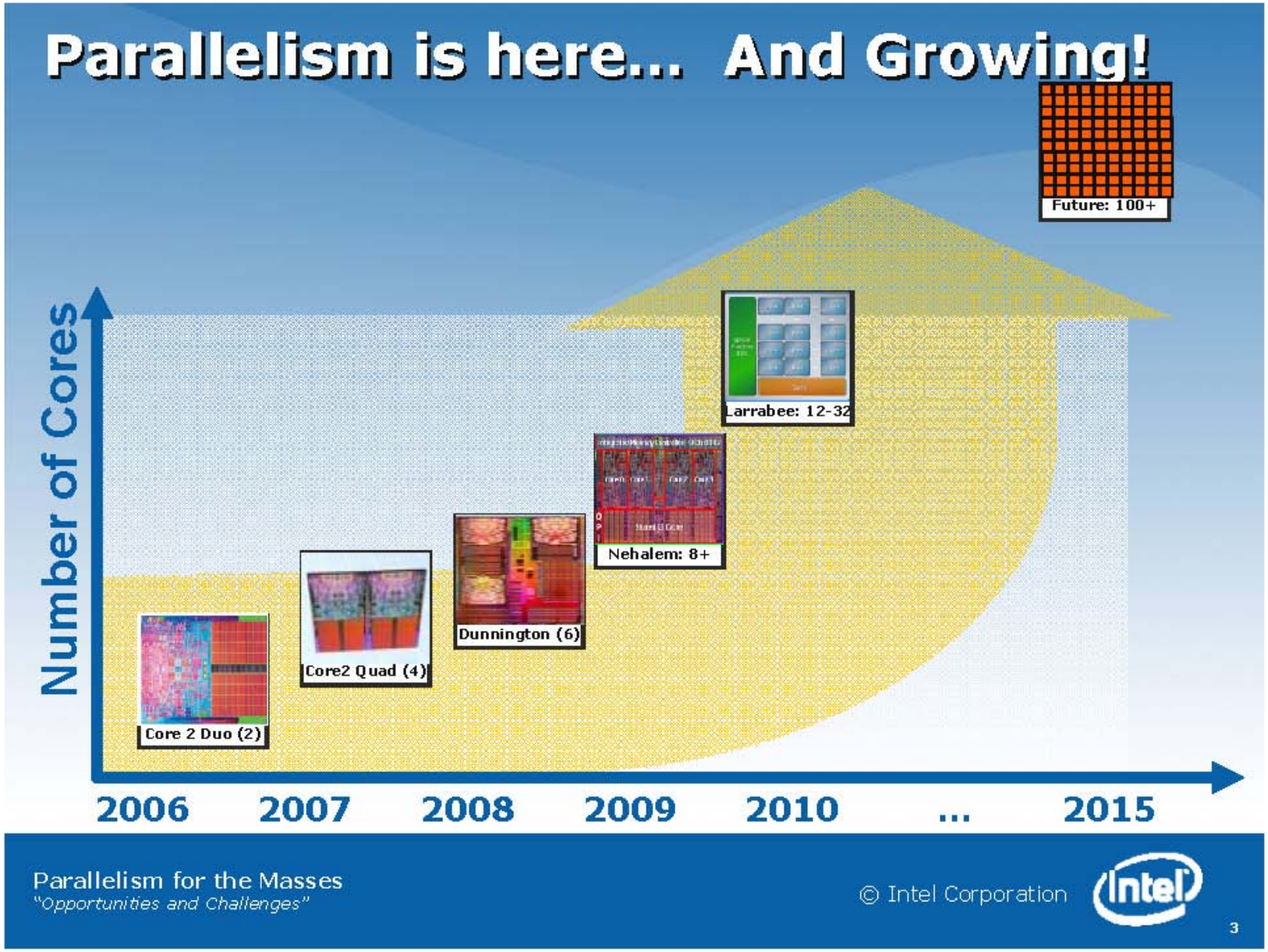


Moore's Law


Microprocessor Transistor Counts 1971-2011 & Moore's Law
Transistor count
2,600,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
2,300
curve shows transistor count doubling every two years
16-Core SPARC T3
Six-Core Core i7
Six-Core Xeon 7400
10-Core Xeon Westmere-EX
Dual-Core Itanium 2
8-core POWER7
AMD K10
Quad-core z196
Quad-Core Itanium Tukwila
POWER6
8-Core Xeon Nehalem-EX
Itanium 2 with 9MB cache
Six-Core Opteron 2400
AMD K10
Core i7 (Quad)
Core 2 Duo
Cell
Itanium 2
AMD K8
Barton
Atom
Pentium 4
AMD K7
AMD K6-III
AMD K6
Pentium III
Pentium II
AMD K5
Pentium
80486
80386
80286
68000
80186
8086
8088
8085
6800
6809
8080
Z80
8008
MOS 6502
4004
RCA 1802
1971
1980
1990
2000
2011
Date of introduction

Moore's Law and Performance





Andrew Chien, 2008

64 core blade servers ($6K) (shared memory)

AMD Opteron (sixteen-core) Model 6274

by AMD

(1 customer review)

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Samsung Galaxy S IV to feature Exynos 28nm quad-core processor?

Written by Andre Yoskowitz @ 01 Nov 2012 18:02

It has been a few weeks but there is a new rumor regarding the upcoming Samsung Galaxy S IV.

According to reports, Samsung will pack next year's flagship device with its "Adonis" Exynos processor, a quad-core ARM 15 beast that uses efficient 28nm tech.

Samsung is supposedly still testing the application processor, but mass production is scheduled for the Q1 2013 barring any delays.

Circa November 2012

Samsung Galaxy S IV is now Official: Octa-Core CPU, 5″ Full HD Display & 13MP Camera

Follow: Phones GT-I9500 Samsung Display Samsung Exynos Samsung Galaxy S IV Samsung Mobile Unpacked 2013

Samsung has just announced the Samsung Galaxy S4 at their Mobile Unpacked Event 2013 Episode 1 in New York, USA. The Galaxy S4 features a stunning 4.99″ Full HD (1920×1080) SuperAMOED display. With a 441 ppi pixel density, your eyes won't be able to distinguish the pixels, which ensures excellent visual comfort. Even though the Galaxy S4 has a large display and a massive battery of 2,600 MAh, it's only 7.9mm thick. Samsung's latest flagship device is PACKED with powerful components, consisting of Samsung's latest Exynos 5 Octa-Core (5410) CPU based on ARM's big.LITTLE technology with Quad Cortex-

Intel Has a 48-Core Chip for Smartphones and Tablets

By Wolfgang Gruener OCTOBER 31, 2012 9:20 AM - Source: Computerworld

Intel has developed a prototype of a 48-core processor for smartphones. Before you ask: No, you can't buy a 48-core smartphone next year.

Parallel Hardware

- Many forms of parallelism
  - Supercomputers: large scale, shared memory
  - Clusters and data centers: large-scale, distributed memory
  - Multicores: tightly coupled, smaller scale

- Parallelism is important in the real world.

Key Challenge: Software (How to Write Parallel Code?)

- At a high-level, it is a two step process:
  - Design a work-efficient, low-span parallel algorithm
  - Implement it on the target hardware
- In reality: each system required different code because programming systems are immature
  - Huge effort to generate efficient parallel code.
    - Example: Quicksort in MPI is 1700 lines of code, and about the same in CUDA
  - Implement one parallel algorithm: a whole thesis.

Teaching Challenge: How to Teach Parallelism

- Education must prepare for the "real world" and research.
- Essential to teach parallel algorithm design.
- But many different models of parallelism.
- Inadequate parallel systems make practical work gruesome. Practically impractical in the context of an undergraduate course.

15-210 Approach

Enable parallel thinking by raising abstraction level

I. **Parallel thinking:** Applicable to many machine models and programming languages

II. **Reason** about correctness and efficiency of algorithms and data structures.

Parallel Thinking

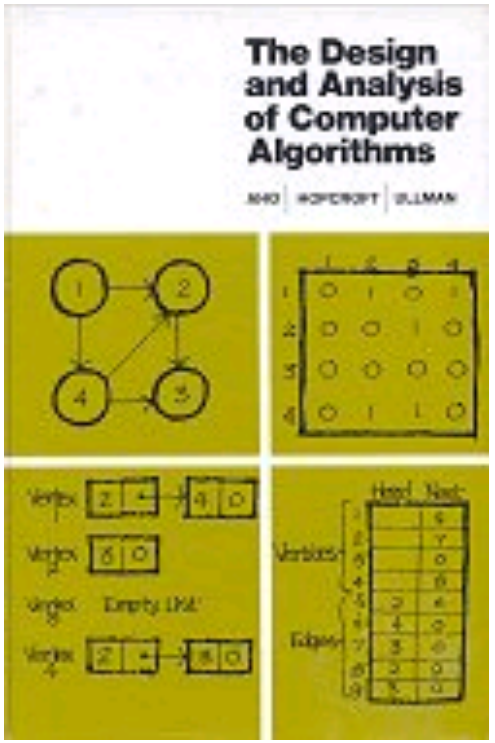
- Recognizing true dependences: unteach sequential programming.

- Parallel algorithm-design techniques
  - Operations on aggregates: map/reduce/scan
  - Divide & conquer, contraction
  - Viewing computation as DAG

- Cost model based on work and span

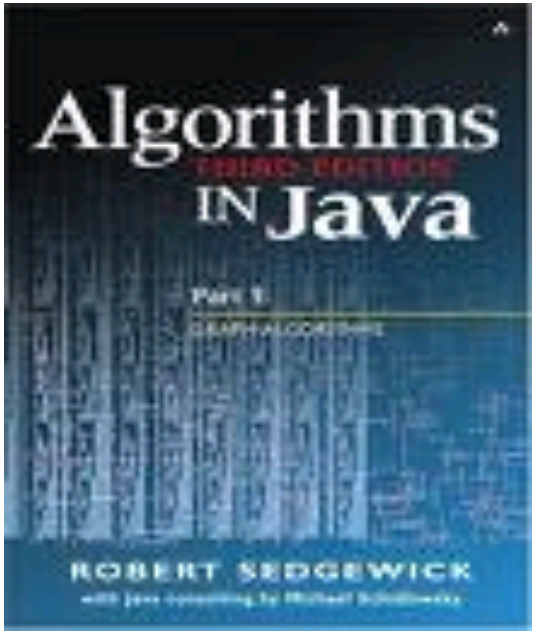
Quicksort from Aho-Hopcroft-Ullman (1974)

procedure QUICKSORT(**S**):
  if S contains at most one element **then return S**
  else
    begin
    choose an element **a** randomly from **S**;
    let S_1, S_2 and S_3 be the sequences of
        elements in **S** less than, equal to,
        and greater than **a**, respectively;
    return (QUICKSORT(S_1) followed by S_2
      followed by QUICKSORT(S_3))
end

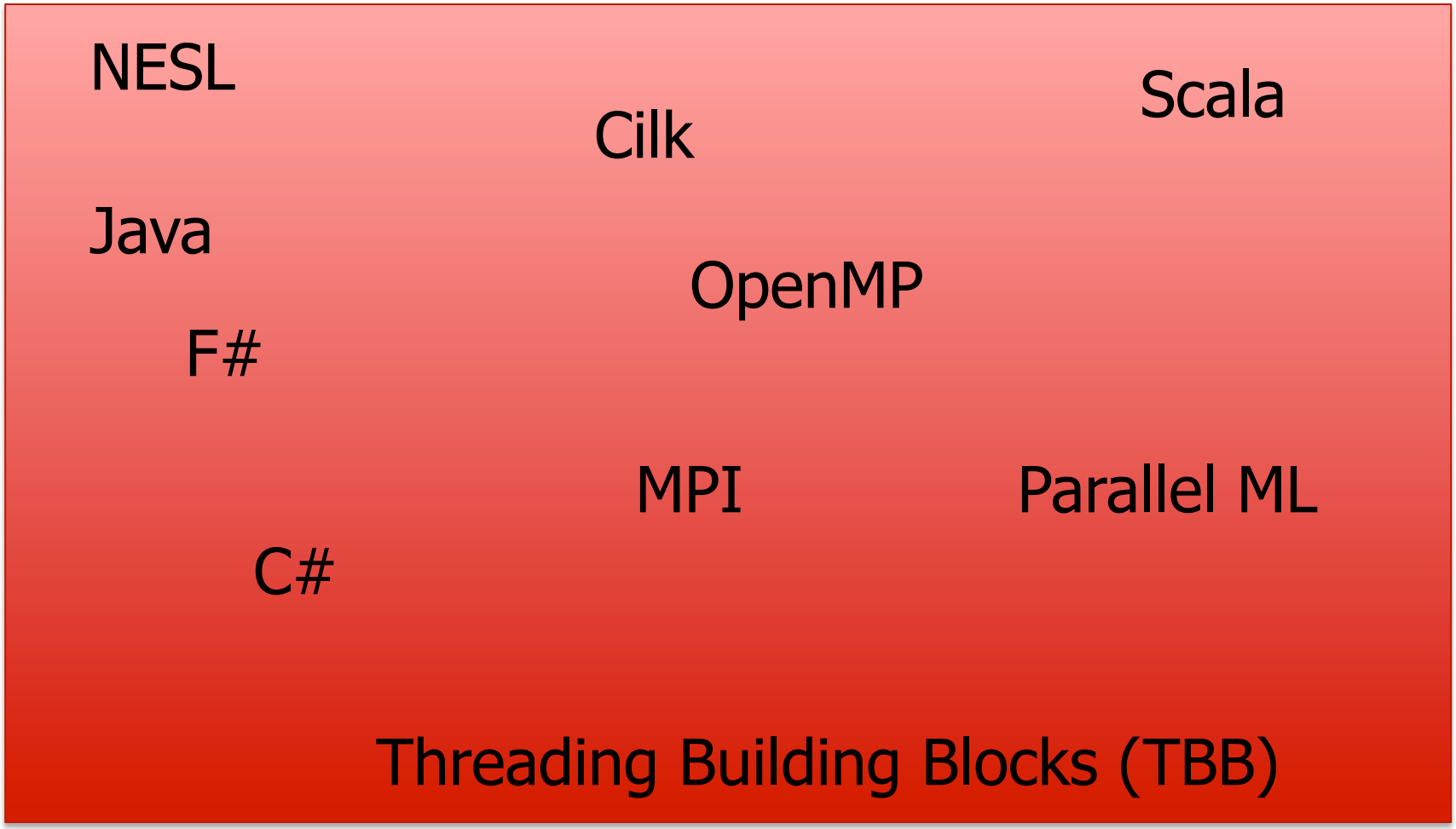


Quicksort from Sedgewick (2003)

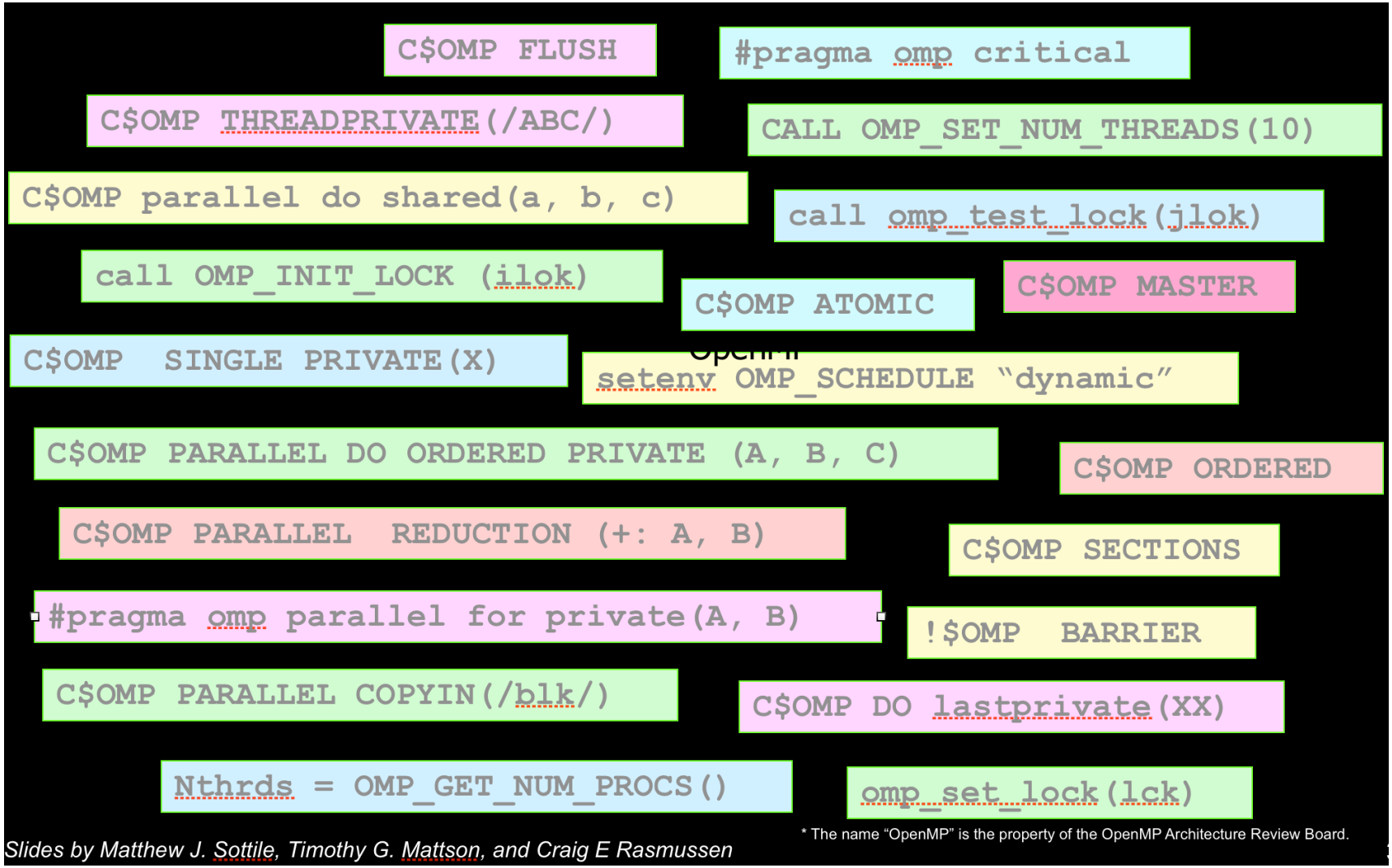
```
public void quickSort(int[] a, int left, int right) {
    int i = left-1;  int j = right;
    if (right <= left) return;
    while (true) {
      while (a[++i] < a[right]);
      while (a[right] < a[--j])
        if (j==left) break;
      if (i >= j) break;
      swap(a,i,j); }
    swap(a, i, right);
    quickSort(a, left, i - 1);
    quickSort(a, i+1, right); }
```



Programming Parallel Algorithms



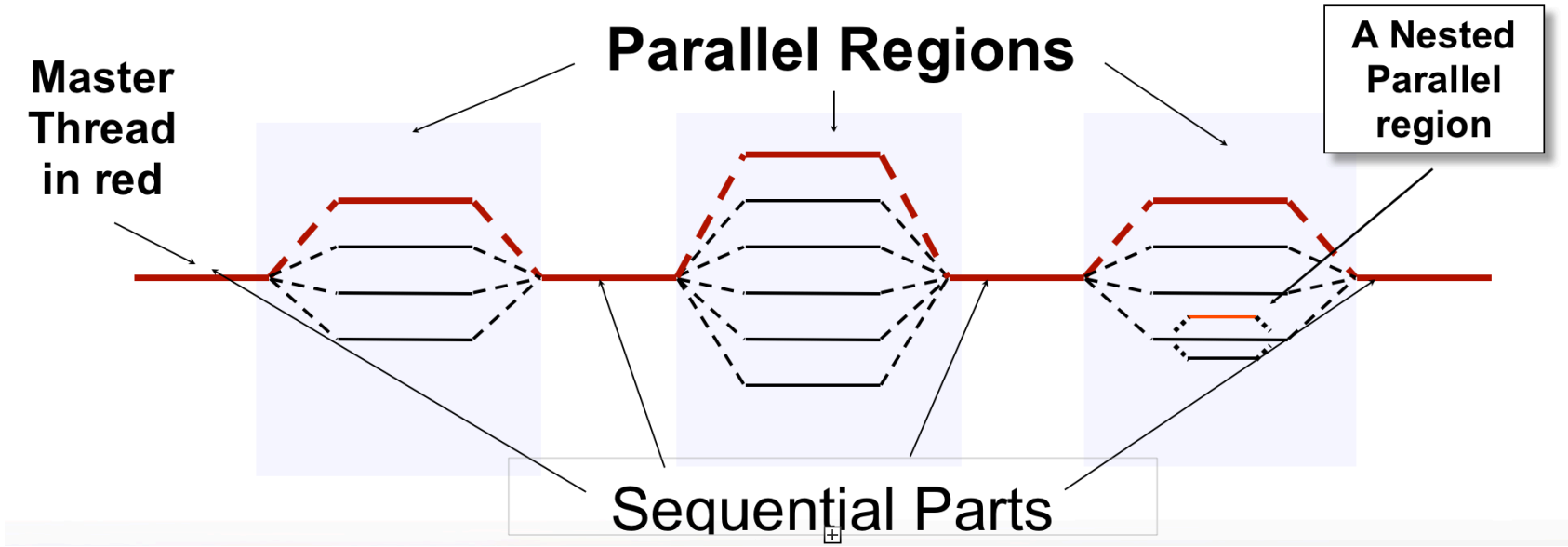
OpenMP Overview



Slides by Matthew J. Sottile, Timothy G. Mattson, and Craig E Rasmussen

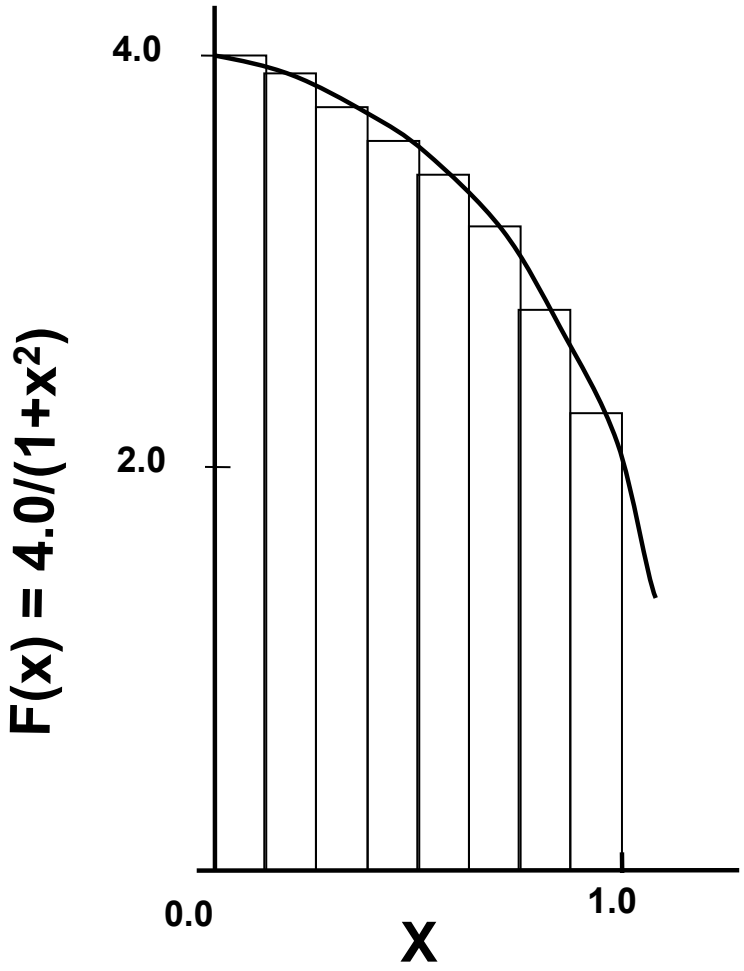
OpenMP Execution Model

- Fork-join parallelism



- Traditionally flat parallelism
- Recently nested parallelism. But not very good.

Example: Numerical Integration



Mathematically, we know that:

$$\int_0^1 \frac{4.0}{(1+x^2)}\,dx = \pi$$

We can approximate the integral as a sum of rectangles:

$$\sum_{i=0}^{N} F(x_i)\Delta x \approx \pi$$

where each rectangle has width Δx and height $F(x_i)$ at the middle of interval i.

The code for Approximating PI

```
static long num_steps = 100000;
double step;
void main ()
{          int i;   double x, pi, sum = 0.0;

           step = 1.0/(double) num_steps;
            x = 0.5 * step;
           for (i=0;i<= num_steps; i++){
                    x+=step;
                    sum += 4.0/(1.0+x*x);
           }
           pi = step * sum;
}
```

The code for Approximating PI

```
#include <omp.h>
static long num_steps = 100000;        double step;
void main ()
{     int i;              double x, pi, sum = 0.0;
      step = 1.0/(double) num_steps;
#pragma omp   parallel    for    private(i, x) reduction(+:sum)
      for (i=0;i<= num_steps; i++){
            x = (i+0.5)*step;
            sum = sum + 4.0/(1.0+x*x);
      }
      pi = step * sum;
}
```

Private clause creates data local to a thread

Reduction used to manage dependencies

Cilk/Cilk++: extending C/C++ with fork-join parallelism for shared-memory systems

Slides by Charles E. Leiserson

Supercomputing Technologies Research Group
Computer Science and Artificial Intelligence Laboratory
Massachusetts Institute of Technology

Cilk Is Simple

- Cilk extends the C language with just a ***handful*** of keywords.
- Every Cilk program has a ***serial semantics***.
- Not only is Cilk fast, it provides ***performance guarantees*** based on performance abstractions.
- Cilk is ***processor-oblivious***.
- Cilk's ***provably good*** runtime system automatically manages low-level aspects of parallel execution, including protocols, load balancing, and scheduling.
- Cilk supports ***speculative*** parallelism.

An Example: Fibonacci

```
int fib (int n) {
if (n<2) return (n);
  else {
    int x,y;
    x = fib(n-1);
    y = fib(n-2);
    return (x+y);
  }
}
```

C elision

Cilk code

```
cilk int fib (int n) {
  if (n<2) return (n);
  else {
    int x,y;
    x = spawn fib(n-1);
    y = spawn fib(n-2);
    sync;
    return (x+y);
  }
}
```

Cilk is a ***faithful*** extension of C. A Cilk program's ***serial elision*** is always a legal implementation of Cilk semantics. Cilk provides *no* new data types.

Basic Cilk Keywords

```
cilk int fib (int n) {
  if (n<2) return (n);
  else {
    int x,y;
    x = spawn fib(n-1);
    y = spawn fib(n-2);
    sync;
    return (x+y);
  }
}
```

Identifies a function as a ***Cilk procedure***, capable of being spawned in parallel.

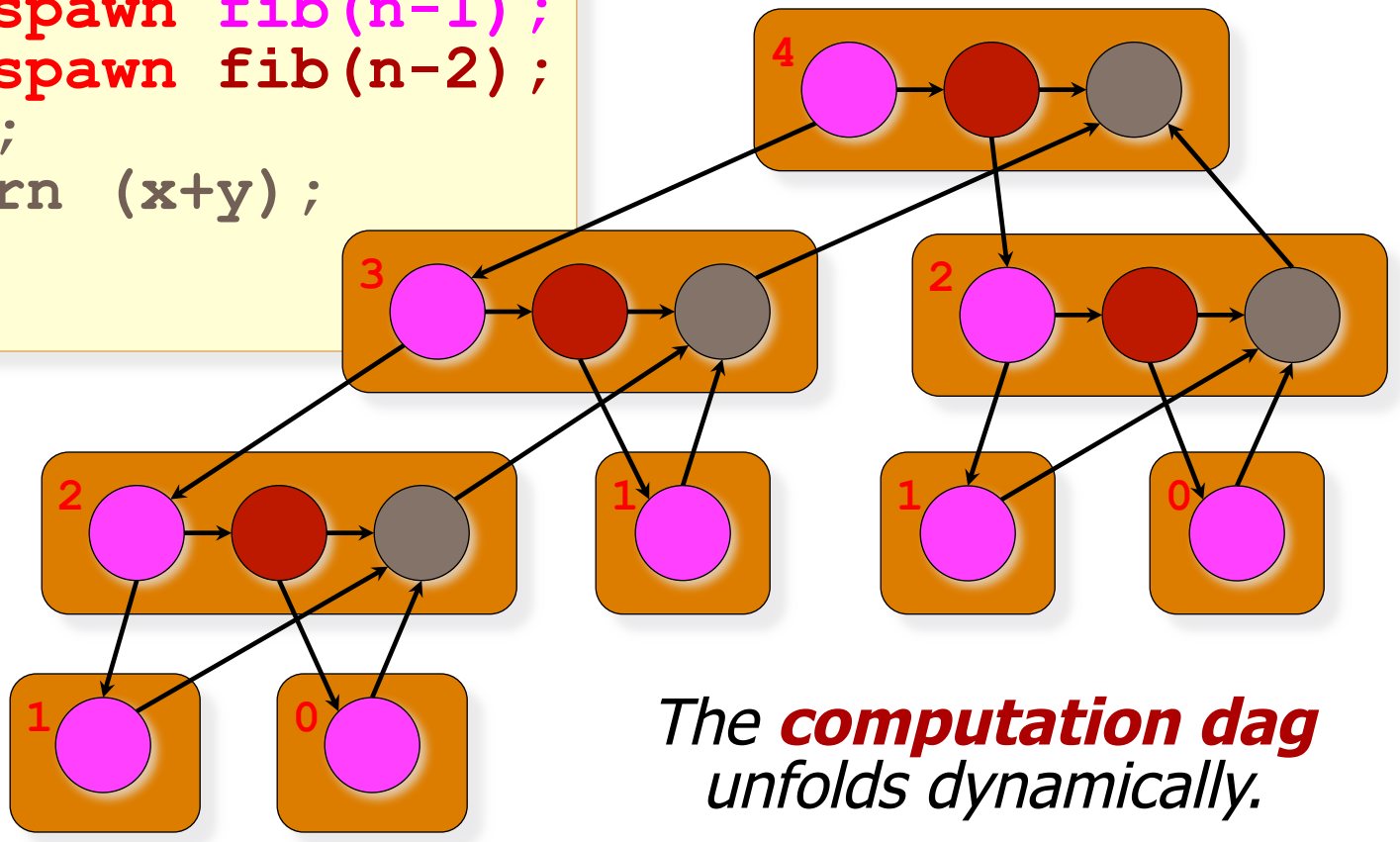
The named ***child*** Cilk procedure can execute in parallel with the ***parent*** caller.

Control cannot pass this point until all spawned children have returned.

Dynamic Multithreading

```
cilk int fib (int n) {
  if (n<2) return (n);
  else {
    int x,y;
    x = spawn fib(n-1);
    y = spawn fib(n-2);
    sync;
    return (x+y);
  }
}
```

Example: `fib(4)`



"Processor oblivious"

*The **computation dag** unfolds dynamically.*

Example: Parallelizing Vector Addition

C

```
void vadd (real *A, real *B, int n){
  int i; for (i=0; i<n; i++) A[i]+=B[i];
}
```

Parallelizing Vector Addition

C

```
void vadd (real *A, real *B, int n){
  int i; for (i=0; i<n; i++) A[i]+=B[i];
}
```

C

```
void vadd (real *A, real *B, int n){
  if (n<=BASE) {
    int i; for (i=0; i<n; i++) A[i]+=B[i];
  } else {
    vadd (A, B, n/2);
    vadd (A+n/2, B+n/2, n-n/2);
  }
}
```

Parallelization strategy:

1. Convert loops to recursion.

Parallelizing Vector Addition

C

```
void vadd (real *A, real *B, int n){
  int i; for (i=0; i<n; i++) A[i]+=B[i];
}
```

Cilk

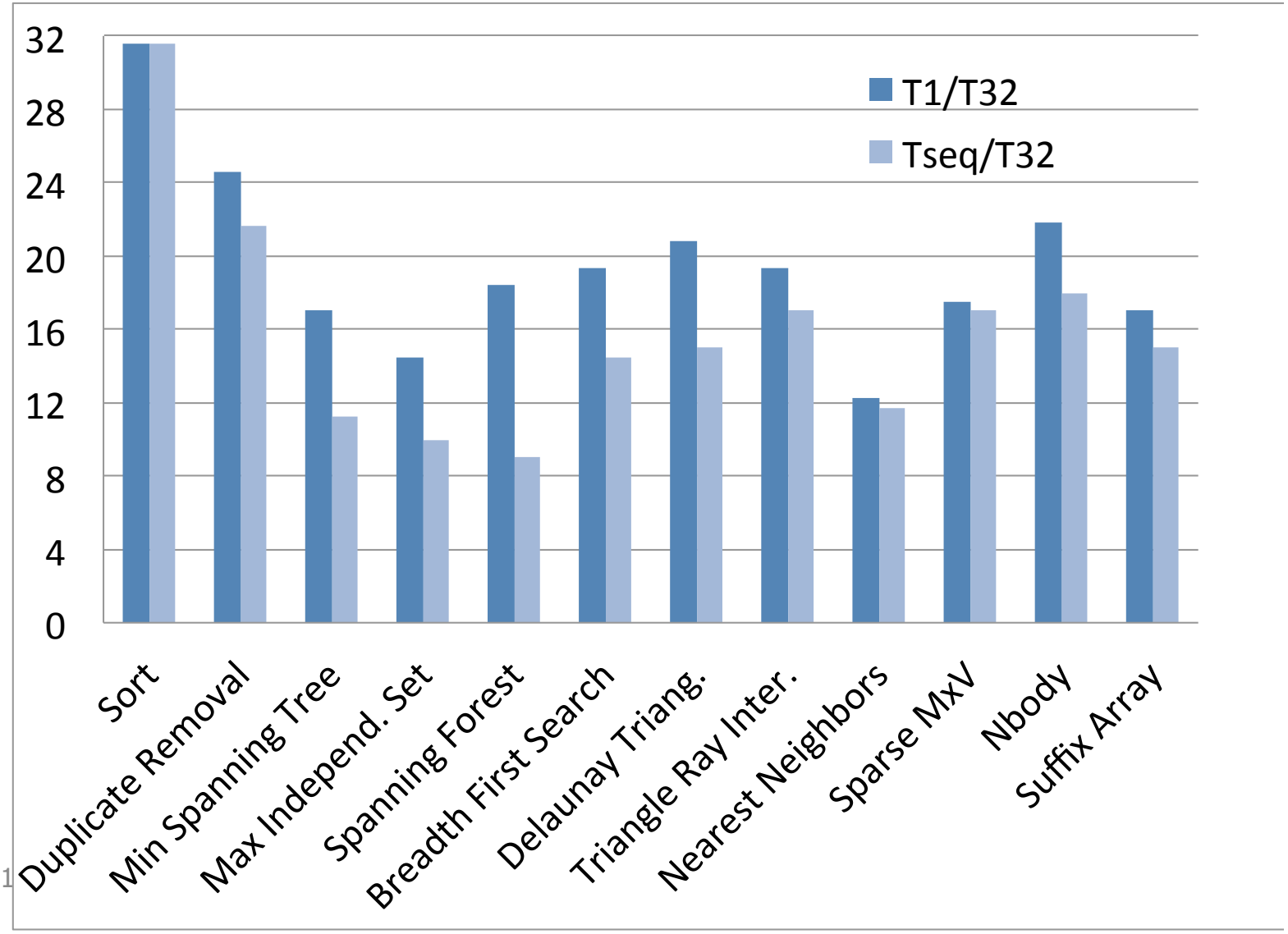
```
cilk void vadd (real *A, real *B, int n){
  if (n<=BASE) {
    int i; for (i=0; i<n; i++) A[i]+=B[i];
  } else {
    spawn vadd(A, B, n/2);
    spawn vadd(A+n/2, B+n/2, n-n/2);
  } sync;
}
```

Parallelization strategy:

1. Convert loops to recursion.
2. Insert Cilk keywords.

Side benefit:
D&C is generally good for caches!

How do the problems do on a modern multicore

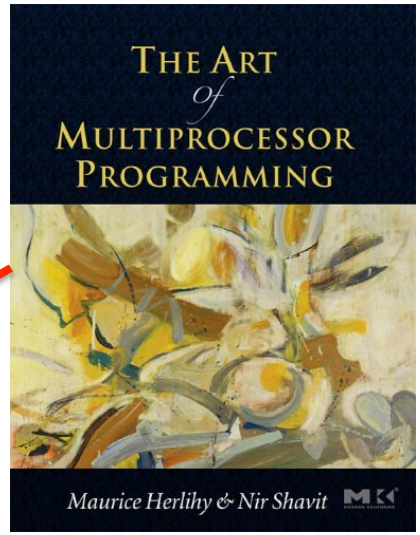


Demo Time

Concurrency versus Parallelism

- **Concurrency:** non-determinacy due to interleaving multiple processes. Property of the application.
- **Parallelism:** using multiple processors/cores running at the same time. Property of the machine.

		Concurrency	
		Deterministic	Concurrent
Parallelism	Serial	Traditional programming	Traditional OS
	Parallel	Deterministic parallelism	Concurrent parallelism



Concurrency is Hard

Stack Example

- Serial
- Using locks
- Using compare and swap
- Using transactions

This is just a simple stack.

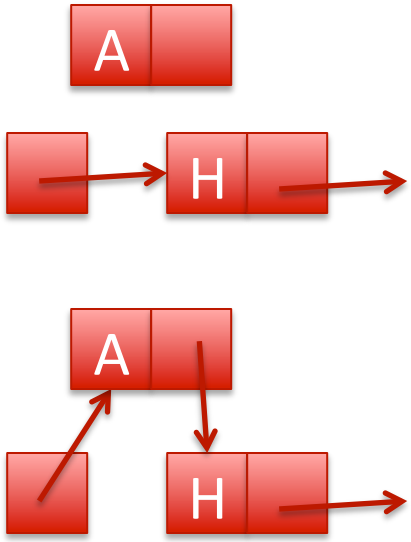
Concurrency : Stack Example 1

```
struct link {int v; link* next;}

struct stack {
  link* headPtr;

  void push(link* a) {
    a->next = headPtr;
    headPtr = a;   }

  link* pop() {
    link* h = headPtr;
    if (headPtr != NULL)
      headPtr = headPtr->next;
    return h;}
}
```



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    if (headPtr != NULL)
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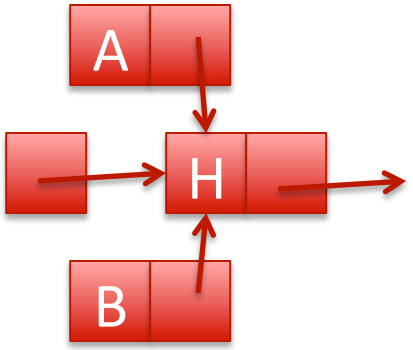
    return h;}
}
```



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  void push(link* a) {
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}
```

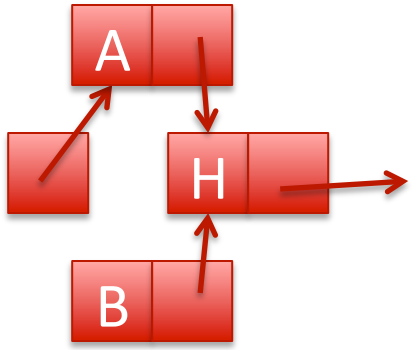

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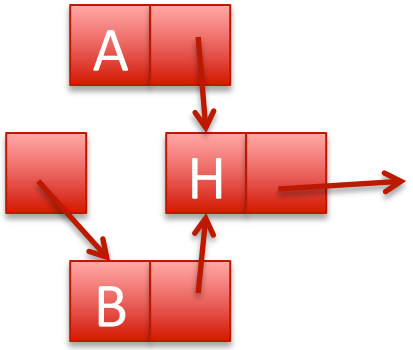
    link* h = headPtr;
    if (headPtr != NULL)
      headPtr = headPtr->next;
    return h;}
}
```



Stack Example

- Serial
- Using locks
- Using compare and swap
- Using transactions

This is just a simple stack.

Concurrency : Stack Example 2

```
struct link {int v; link* next;}

struct stack {
  link* headPtr;

  void push(link* a) {
    withlock {
      a->next = headPtr;
      headPtr = a;   }}

  link* pop() {
    withlock {
      link* h = headPtr;
      if (headPtr != NULL)
        headPtr = headPtr->next;
      return h;}}
}
```

Concurrency : Stack Example 2

Locks are bad for many reasons

- Easy to create deadlocks
- If a process stalls in a lock it holds everyone else up

Stack Example

- Serial
- Using locks
- Using compare and swap
- Using transactions

This is just a simple stack.

Concurrency : CAS

The **Compare and Swap** instruction is a built in instruction on many machines that atomically Compares a value in a register to one in memory and swaps in a new value if equal

```
bool CAS(int *ptr, int oldv, in newv) {
   if (*ptr = oldv) {
     *ptr = newv;
     return true;}
   } else return false;
}
```

On x86 instruction set implemented with

```
lock cmpxchg ptr,newv
```

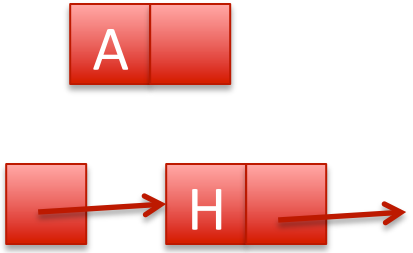
`oldv` in EAX, puts flag in ZF

Concurrency : Stack Example 3

```
struct stack {
  link* headPtr;

  void push(link* a) {
    do {
      link* h = headPtr;
      a->next = h;
    while (!CAS(&headPtr, h, a)); }

  link* pop() {
    do {
      link* h = headPtr;
      if (h == NULL) return NULL;
      link* nxt = h->next;
    while (!CAS(&headPtr, h, nxt))}
    return h;}
}
```

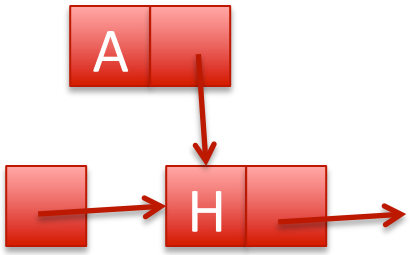


Concurrency : Stack Example 3

```
struct stack {
  link* headPtr;

  void push(link* a) {
    do {
      link* h = headPtr;
      a->next = h;
    while (!CAS(&headPtr, h, a)); }

  link* pop() {
    do {
      link* h = headPtr;
      if (h == NULL) return NULL;
      link* nxt = h->next;
    while (!CAS(&headPtr, h, nxt))}
    return h;}
}
```



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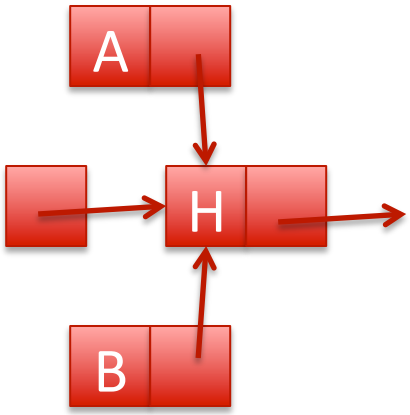

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    while (!CAS(&headPtr, h, nxt))}
    return h;}
}
```

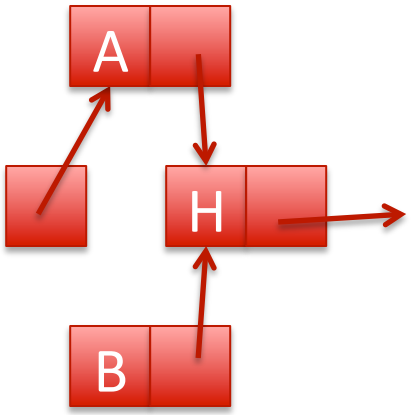

Concurrency : Stack Example 3'

```
P1 : x = s.pop();  y = s.pop();  s.push(x);
P2 : z = s.pop();
```

Before:

After:


```
P2: h = headPtr;
P2: nxt = h->next;
P1: everything
P2: CAS(&headPtr,h,nxt)
```

The ABA problem

Can be fixed with counter and 2CAS, but…

Stack Example

- Serial
- Using locks
- Using compare and swap
- Using transactions

This is just a simple stack.

Concurrency : Stack Example 4

```
struct link {int v; link* next;}

struct stack {
  link* headPtr;

  void push(link* a) {
    atomic {
      a->next = headPtr;
      headPtr = a;   }}

  link* pop() {
    atomic {
      link* h = headPtr;
      if (headPtr != NULL)
        headPtr = headPtr->next;
      return h;}}
}
```

"using transactional memory"

Concurrency : Stack Example 3’

```
void swapTop(stack s) {
  link* x = s.pop();
  link* y = s.pop();
  push(x);
  push(y);
}
```

Queues are trickier than stacks.

Complications due to **non-determinacy** in interleaving of instructions/operations on shared data

Summary

- Hardware parallelism
  - Plenty and ubiquitous: datacenters, mainframes, GPUs, multicore chips on desktops and mobiles
- Parallel software is a major challenge
  - Good solutions in specific domains.
  - Inadequate programming systems.
- 15210
  - Parallel thinking at a high abstraction level
  - Parallelism, not concurrency. Avoid concurrency if not needed (e.g., for deterministic computations)