15-210: Parallelism in the Real World

- Types of paralellism
- Parallel Thinking
- Nested Parallelism
- Examples (Cilk, OpenMP, Java Fork/Join)
- Concurrency

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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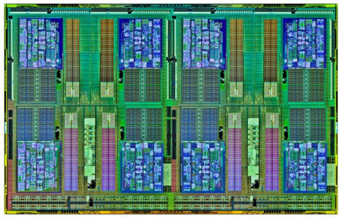
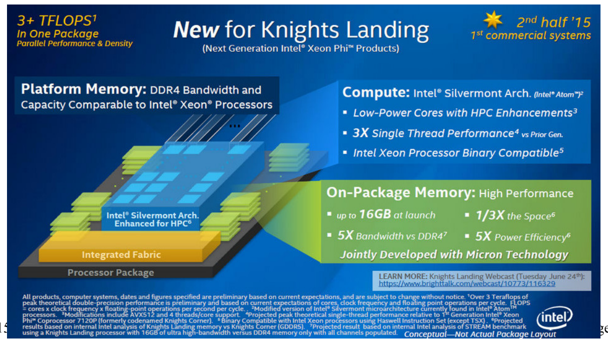


Xeon Phi: Knights Landing

72 Cores, x86, 500Gbytes of memory bandwidth
Summer 2015



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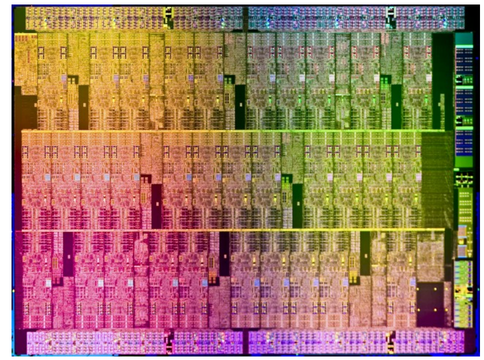
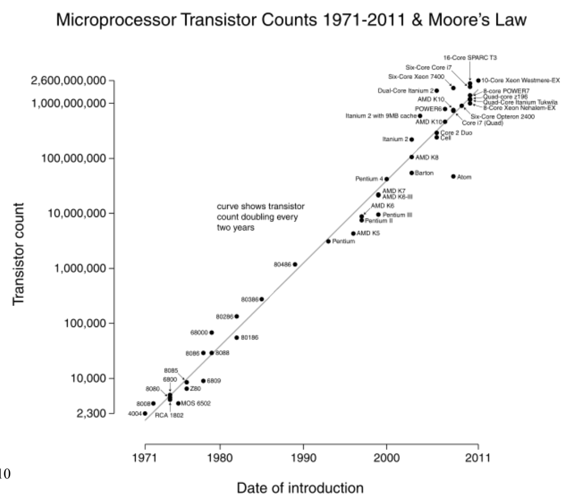
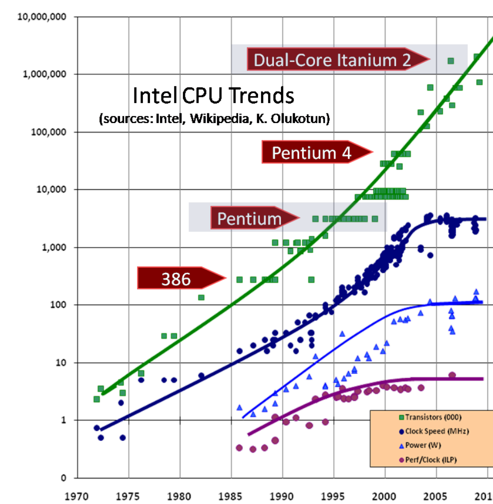
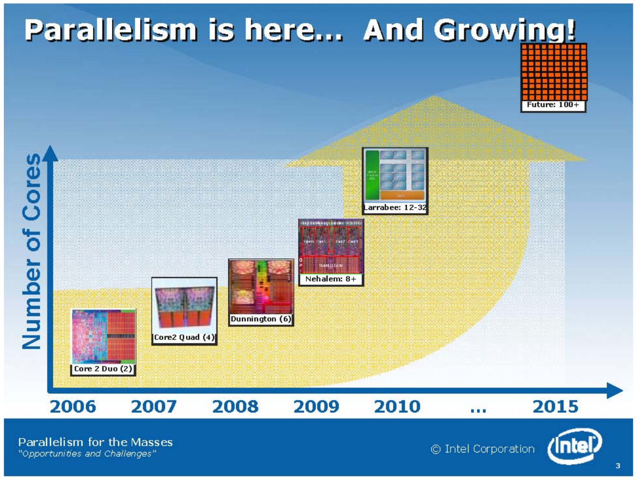


Moore's Law



Moore's Law and Performance





 Andrew Chien, 2008

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

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(1 customer review)

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x 4 =

[1024 "cuda" cores]

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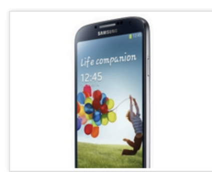
Samsung Galaxy S IV is now Official: Octa-Core CPU, 5" Full HD Display & 13MP Camera

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
- GPUs, on chip vector units
- Instruction-level parallelism

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.

Take 15-418 (Parallel Computer Architecture and Prog.)

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

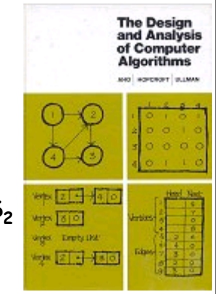
Recognizing true dependences: unteach sequential programming.

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

Cost model based on work and span

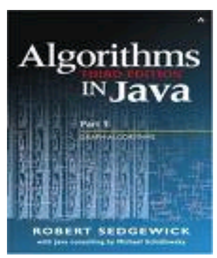
Quicksort from Aho-Hopcroft-Ullman (1974)

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); }
```



Styles of Parallel Programming

Data parallelism/Bulk Synchronous/SPMD
Nested parallelism : what we covered
Message passing
Futures (other pipelined parallelism)
General Concurrency

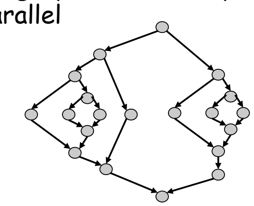
Nested Parallelism

Nested Parallelism =
arbitrary nesting of parallel loops + fork-join
- Assumes no synchronization among parallel tasks except at joint points.
- Deterministic if no race conditions

Advantages:
- Good schedulers are known
- Easy to understand, debug, and analyze costs
- Purely functional, or imperative…either works

Serial Parallel DAGs

Dependence graphs of nested parallel computations are series parallel



Two tasks are parallel if not reachable from each other.

A data race occurs if two parallel tasks are involved in a race if they access the same location and at least one is a write.

Nested Parallelism: parallel loops

```
cilk_for (i=0; i < n; i++)
   B[i] = A[i]+1;
```

Cilk

```
Parallel.ForEach(A, x => x+1);
```

Microsoft TPL (C#,F#)

```
B = {x + 1 : x in A}
```

Nesl, Parallel Haskell

```
#pragma omp for
for (i=0; i < n; i++)
  B[i] = A[i] + 1;
```

OpenMP

Nested Parallelism: fork-join

```
cobegin {
  S1;
  S2;}
```

Dates back to the 60s. Used in dialects of Algol, Pascal

```
coinvoke(f1,f2)
Parallel.invoke(f1,f2)
```

Java fork-join framework
Microsoft TPL (C#,F#)

```
#pragma omp sections
{
  #pragma omp section
  S1;
  #pragma omp section
  S2;
}
```

OpenMP (C++, C, Fortran, …)

Nested Parallelism: fork-join

`spawn S1;`
`S2;`
`sync;`
	cilk, cilk+

`(exp1 || exp2)`	Various functional languages

`plet`
`  x = exp1`
`  y = exp2`
`in`
`  exp3`
	Various dialects of ML and Lisp

Cilk vs. what we've covered

Fork Join

ML: val (a,b) = par(fn () => f(x), fn () => g(y))

Psuedocode: val (a,b) = (f(x) || g(y))

Cilk:
```
cilk_spawn a = f(x);
b = g(y);
cilk_sync;
```

Map

ML: S = map f A

Psuedocode: S = <f x : x in A>

Cilk:
```
cilk_for (int i = 0; i < n; i++)
  S[i] = f(A[i])
```


Cilk vs. what we've covered

Tabulate

ML: S = tabulate f n

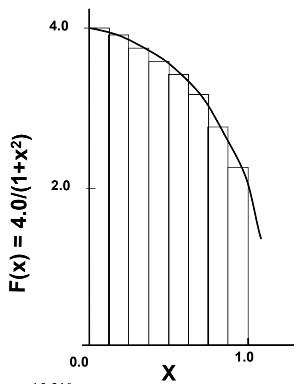
Psuedocode: S = <f i : i in <0,..n-1>>

Cilk:
```
cilk_for (int i = 0; i < n; i++)
  S[i] = f(i)
```


Example Cilk

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

Example OpenMP: 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 C 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 C/openMP code for Approx. 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

Example : Java Fork/Join

```
class Fib extends FJTask {
   volatile int result; // serves as arg and result
   int n;
   Fib(int _n) { n = _n; }

   public void run() {
      if (n <= 1) result = n;
      else if (n <= sequentialThreshold) number = seqFib(n);
      else {
         Fib f1 = new Fib(n - 1);
         Fib f2 = new Fib(n - 2);
         coInvoke(f1, f2);
         result = f1.result + f2.result;
      }
   }
}
```

Cost Model (General)

Compositional:

Work : total number of operations

- costs are added across parallel calls

Span : depth/critical path of the computation

- Maximum span is taken across forked calls

Parallelism = Work/Span

- Approximately # of processors that can be effectively used.

Combining costs (Nested Parallelism)

Combining for parallel for:

```
pfor (i=0; i<n; i++)
  f(i);
```

$$W_{pexp}(\text{pfor} \ldots) = \sum_{i=0}^{n-1} W_{exp}(\text{f(i)})$$ work

$$D_{pexp}(\text{pfor} \ldots) = \max_{i=0}^{n-1} D_{exp}(\text{f(i)})$$ span

Why Work and Span

Simple measures that give us a good sense of efficiency (work) and scalability (span).

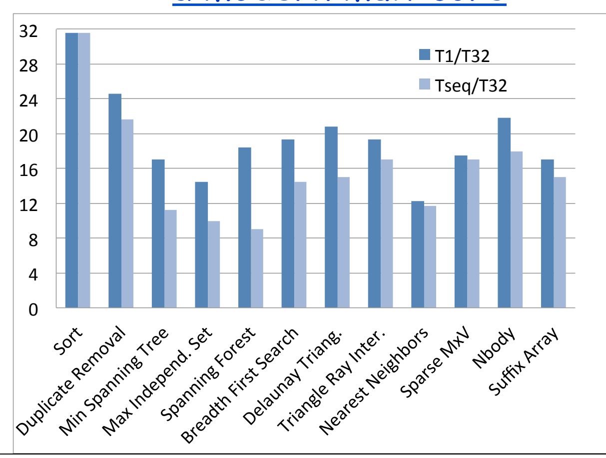
Can schedule in O(W/P + D) time on P processors.

This is within a constant factor of optimal.

Goals in designing an algorithm

1. Work should be about the same as the sequential running time. When it matches asymptotically we say it is **work efficient.**
2. Parallelism (W/D) should be polynomial. $O(n^{1/2})$ is probably good enough

How do the problems do on a modern multicore



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Parallelism vs. Concurrency

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

		Concurrency	
		sequential	concurrent
Parallelism	serial	Traditional programming	Traditional OS
	parallel	Deterministic parallelism	General parallelism

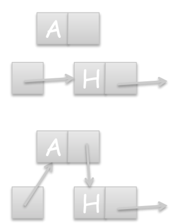
Concurrency : Stack Example 1

```
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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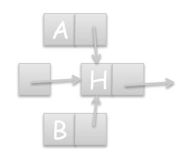
      headPtr = headPtr->next;
    return h;}
}
```



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

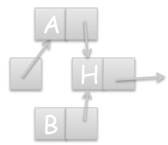

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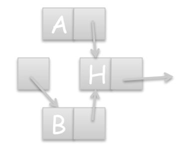
    headPtr = a;    }

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



CAS

```
bool CAS(ptr* addr, ptr a, ptr b) {
  atomic {
    if (*addr == a) {
      *addr = b;
      return 1;
    } else
      return 0;
  }
}
```

A built in instruction on most processors:

CMPXCHG8B – 8 byte version for x86

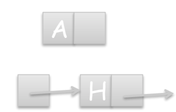
CMPXCHG16B – 16 byte version

Concurrency : Stack Example 2

```
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;}
}
```

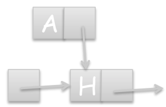


Concurrency : Stack Example 2

```
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;}
}
```

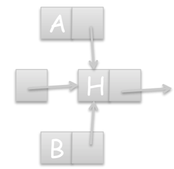


Concurrency : Stack Example 2

```
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 2

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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;}
}
```
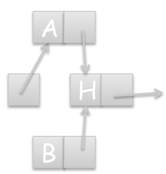
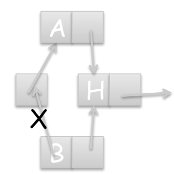



Concurrency : Stack Example 2

```
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 2'

```
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…

Concurrency : Stack Example 3

```
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;}}
}
```


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.

Styles of Parallel Programming

Data parallelism/Bulk Synchronous/SPMD
Nested parallelism : what we covered
Message passing
➡ Futures (other pipelined parallelism)
General Concurrency

Futures: Example

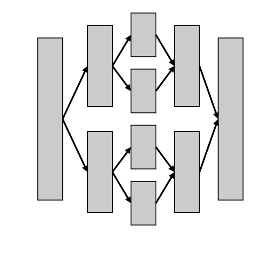
```
fun quickSort S = let
  fun qs([], rest) = rest
    | qs(h::T, rest) =
       let
         val L1 = filter (fn b => b < a) T
         val L2 = filter (fn b => b >= a) T
       in
         qs(L1,(a::(qs(L2, rest)))
       end

  fun filter(f,[]) = []
    | filter(f,h::T) =
        if f(h) then(h::filter(f,T))
        else filter(f,T)
in
  qs(S,[])
end
```


Futures: Example

```
fun quickSort S = let
  fun qs([], rest) = rest
    | qs(h::T, rest) =
       let
         val L1 = filter (fn b => b < a) T
         val L2 = filter (fn b => b >= a) T
       in
         qs(L1, future(a::(qs(L2, rest)))
       end

  fun filter(f,[]) = []
    | filter(f,h::T) =
        if f(h) then future(h::filter(f,T))
        else filter(f,T)
in
  qs(S,[])
end
```


Quicksort: Nested Parallel

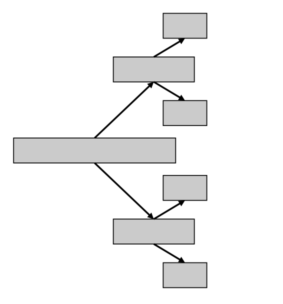
Parallel Partition and Append



Work = O(n log n)

Span = $O(\lg^2 n)$

Quicksort: Futures



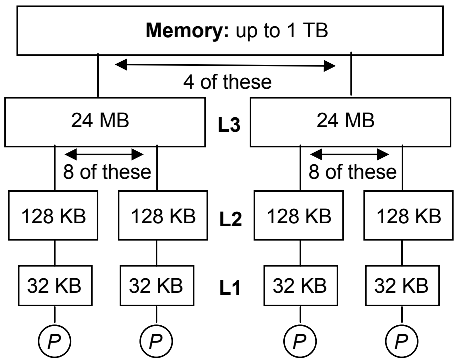
Work = O(n log n)

Span = O(n)

Styles of Parallel Programming

Data parallelism/Bulk Synchronous/SPMD
* Nested parallelism : what we covered
Message passing
* Futures (other pipelined parallelism)
* General Concurrency

Xeon 7500



Question

How do we get nested parallel programs to work well on a fixed set of processors? Programs say nothing about processors.

Answer: good schedulers

Greedy Schedules

"Speedup versus Efficiency in Parallel Systems", Eager, Zahorjan and Lazowska, 1989

For any greedy schedule:

Efficiency = $\frac{W}{T_P} \geq \frac{PW}{W + D(P-1)}$

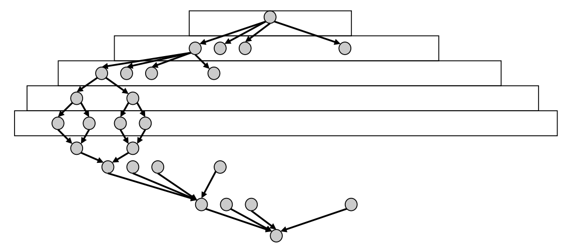
Parallel Time = $T_P \leq \frac{W}{P} + D$

Types of Schedulers

Bread-First Schedulers
Work-stealing Schedulers
Depth-first Schedulers

Breadth First Schedules

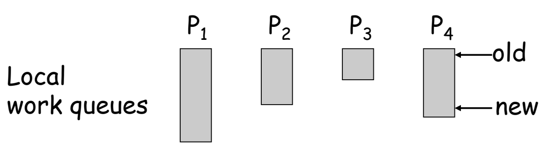
Most naïve schedule. Used by most implementations of P-threads.



$O(n^3)$ tasks

Bad space usage, bad locality

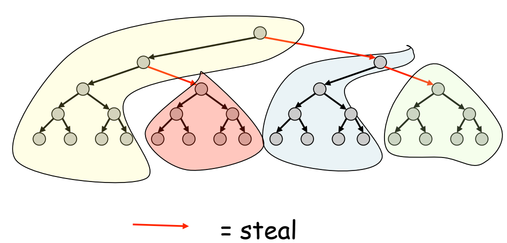
Work Stealing



push new jobs on "new" end
pop jobs from "new" end
If processor runs out of work, then "**steal**" from another "old" end
Each processor tends to execute a sequential part of the computation.

Work Stealing

Tends to schedule "sequential blocks" of tasks



Work Stealing Theory

For strict computations

Blumofe and Leiserson, 1999

\# of steals = $O(PD)$

Space = $O(PS_1)$ S_1 is the sequential space

Acar, Blelloch and Blumofe, 2003

\# of cache misses on distributed caches

$M_1 + O(CPD)$

M_1 = sequential misses, C = cache size

Work Stealing Practice

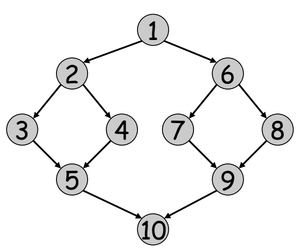
Used in Cilk Scheduler

- Small overheads because common case of pushing/popping from local queue can be made fast (with good data structures and compiler help).
- No contention on a global queue
- Has good distributed cache behavior
- Can indeed require $O(S_1P)$ memory

Used in X10 scheduler, and others

Parallel Depth First Schedules (P-DFS)

List scheduling based on Depth-First ordering



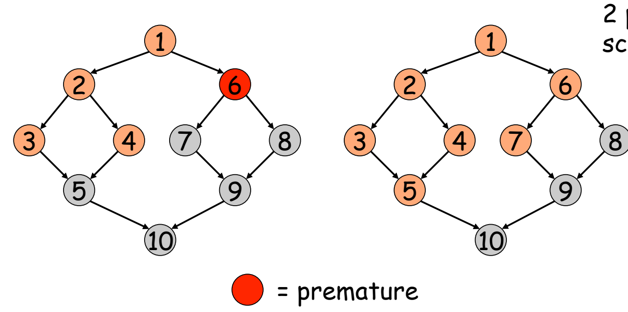
2 processor schedule

1
2, 6
3, 4
5, 7
8
9
10

For strict computations a shared stack implements a P-DFS

"Premature task" in P-DFS

A running task is premature if there is an earlier sequential task that is not complete



2 processor schedule

1
2, 6
3, 4
5, 7
8
9
10

P-DFS Theory

Blelloch, Gibbons, Matias, 1999

For any computation:

Premature nodes at any time = O(PD)

Space = S_1 + O(PD)

Blelloch and Gibbons, 2004

With a shared cache of size C_1 + O(PD) we have M_p = M_1

P-DFS Practice

Experimentally uses less memory than work stealing and performs better on a shared cache.

Requires some “coarsening” to reduce overheads

Conclusions

- lots of parallel languages
- lots of parallel programming styles
- high-level ideas cross between languages and styles
- scheduling is important