CMSC 330: Organization of Programming Languages

Multithreading 2

Ruby Threads – Thread Creation

- Create thread using Thread.new
  - New method takes code block argument
```
t = Thread.new { …body of thread… }
t = Thread.new (arg) { | arg | …body of thread… }
```
  - Join method waits for thread to complete
```
t.join
```
- Example
```
myThread = Thread.new {
  sleep 1                  # sleep for 1 second
  puts “New thread awake!"
  $stdout.flush            # flush makes sure output is seen
}
```

Ruby Threads – Locks

- Monitor, Mutex
  - Core synchronization mechanisms
  - Enforces mutual exclusion
    - Mutex is not reentrant, Monitor is
- Create lock using Monitor.new
  - Synchronize method takes code block argument
```
require 'monitor.rb'
myLock = Monitor.new
myLock.synchronize {
        # myLock held during this code block
}
```

Ruby Threads – Condition

- Condition derived from Monitor
  - Create condition from lock using new_cond
  - Sleep while waiting using wait_while, wait_until
  - Wake up waiting threads using broadcast
- Example
```
myLock = Monitor.new                    # new lock
myCondition = myLock.new_cond           # new condition
myLock.synchronize {
  myCondition.wait_while { y > 0 }      # wait as long as y > 0
  myCondition.wait_until { x != 0 }     # wait as long as x == 0
}
myLock.synchronize {
  myCondition.broadcast              # wake up all waiting threads
}
```

Parking Lot Example

```
require "monitor.rb"
class ParkingLot
    def initialize      # initialize synchronization
        @numCars = 0
        @myLock = Monitor.new
        @myCondition = @myLock.new_cond
    end
    def addCar
      …
    end
    def removeCar
      …
    end
end
```

Parking Lot Example

```
def addCar # do work not requiring synchronization
    @myLock.synchronize {
        @myCondition.wait_until { @numCars < MaxCars }
        @numCars = @numCars + 1
        @myCondition.broadcast
    }
end
def removeCar # do work not requiring synchronization
    @myLock.synchronize {
        @myCondition.wait_until { @numCars > 0 }
        @numCars = @numCars - 1
        @myCondition.broadcast
    }
end
```

Parking Lot Example

```
garage = ParkingLot.new
valet1 = Thread.new {        # valet 1 drives cars into parking lot
   while …
     # do work not requiring synchronization
     garage.addCar
   end
}
valet2 = Thread.new {        # valet 2 drives car out of parking lot
   while …
     # do work not requiring synchronization
     garage.removeCar
   end
}
valet1.join            # returns when valet 1 exits
valet2.join            # returns when valet 2 exits
```

Ruby Threads – Comparing to Java

Ruby	**Java** (1.5)
Monitor	ReentrantLock
m = Monitor.new	m = new ReentrantLock()
Condition	Condition
c = m.new_cond	c = m.newCondition()
c.wait_until { *e* }	while (*e*) c.await()
c.broadcast	c.signalAll()

Ruby Threads – Differences from Java

- Ruby thread can access all variables in scope when thread is created, including local variables
  - Java threads can only access object fields, or final local variables
- Exiting
  - All threads exit when main Ruby thread exits
  - Java continues until all non-daemon threads exit
- When thread throws exception
  - Ruby only aborts current thread (by default)
  - Ruby can also abort all threads (better for debugging)
    - Set Thread.abort_on_exception = true

OCaml Threads – Thread Creation

- Create thread using Thread.create
  - method takes closure as its argument

```
let t = Thread.create (fun x -> …body…) arg;;
```

  - Join method waits for thread to complete

```
Thread.join t
```

- Example

```
let myThread = Thread.create (fun _ ->
   Unix.sleep 1;                (* sleep for 1 second *)
   print_string "New thread awake!";
   flush Pervasives.stdout  (* flush ensures output is seen *)
);;
```

OCaml Threads – Locks

- Mutex module
  - Not reentrant
  - Has lock, unlock functions

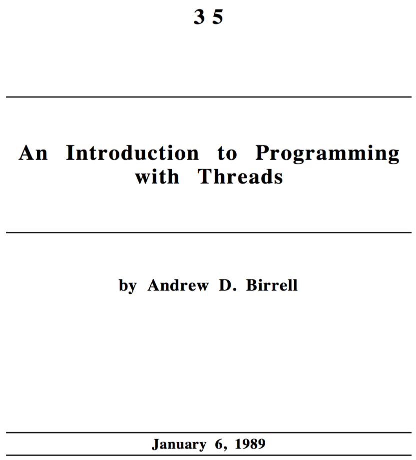
```
let my_lock = Mutex.create ();;
Mutex.lock my_lock;
          (* my_lock held here *)
Mutex.unlock my_lock
```

OCaml Threads – Conditions

- Condition module
  - Create condition directly
    - let my_cond = Condition.create ()
  - Sleep while waiting using wait (takes mutex arg)
    - while (e) do
    -   Condition.wait my_cond my_lock
    - done; (* condition now satisfied *)
  - Wake up waiting threads using broadcast
    - Condition.broadcast my_cond

OCaml Threads – Comparing to Java

OCaml	**Java** (1.5)
Monitor	(Non)ReentrantLock
let m = Mutex.create ()	m = new *Non*ReentrantLock()
Condition	Condition
let c = Condition.create ()	c = m.newCondition()
while (not *e*) do Condition.wait c m done	while (*e*) c.await()
Condition.broadcast c	c.signalAll()



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An Introduction to Programming with Threads

by Andrew D. Birrell

January 6, 1989

These ideas have been around a long time …

`http://www.cs.princeton.edu/courses/archive/fall09/cos318/reading/birrell_threads.pdf`

Looking beyond shared-memory multithreading

Shared-memory Multithreading

- \+ Portable, high degree of control
- \- Low-level and unstructured
  - Thread management, synchronization via locks and signals essentially manual
    - Blocking synchronization is not compositional, which inhibits nested parallelism
  - Easy to get wrong, hard to debug
    - Data races, deadlocks all too common

Parallel Language Extensions

- MPI – expressive, portable, but
  - Hard to partition data and get good performance
    - Temptation is to hardcode data locations, number of processors
  - Hard to write the program correctly
    - Little relation to the sequential algorithm
- OpenMP, HPF – parallelizes certain code patterns (e.g., loops), but
  - Limited to built-in types (e.g., arrays)
  - Code patterns, scheduling policies brittle

MPI C Example

But see: `http://www.dursi.ca/hpc-is-dying-and-mpi-is-killing-it/`

```
int count_primes (int n) {
  …
  MPI_Init ( &argc, &argv );
  MPI_Comm_size ( MPI_COMM_WORLD, &p );  // p = total # proc
  MPI_Comm_rank ( MPI_COMM_WORLD, &id ); // id = my proc #
  if ( id == 0 ) { printf ( "  # of processes is %d\n", p ); }
  MPI_Bcast ( &n, 1, MPI_INT, 0, MPI_COMM_WORLD ); // broadcast n
  primes_part = prime_number ( n, id, p );  // do my portion of work
  MPI_Reduce ( &primes_part, &primes, 1, MPI_INT,
        MPI_SUM, 0, MPI_COMM_WORLD ); // global sum for # primes
  if ( id == 0 ) { printf ( "  %d %d \n", n, primes); // proc 0 prints answer
  MPI_Finalize ( );
  …
}
```

SPMD model (single program multiple data)
all processors execute same program

OpenMP C Example

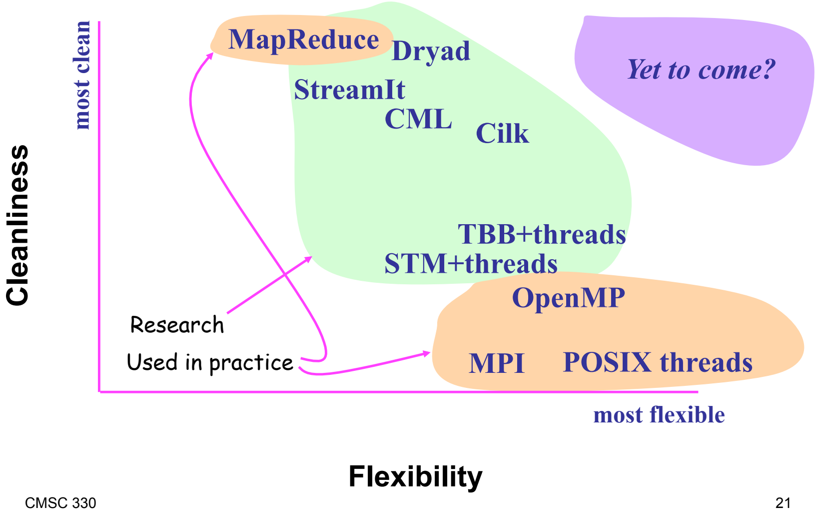
```
int count_primes (int n) {
  int i, j, prime, total = 0;
  # pragma omp parallel shared ( n ) private ( i, j, prime )
  # pragma omp for reduction ( + : total )
  for ( i = 2; i <= n; i++ ) {
    prime = 1;
    for ( j = 2; j < i; j++ ) {
      if ( i % j == 0 ) {
        prime = 0;
        break;
    } } total = total + prime;
  } return total;
}
```

Fork-join model (main thread assigns iterations of parallel loop to workers)

Two Directions To A Solution

- Start with clean, but limited, languages/ abstractions and generalize
  - MapReduce (Google, 2004)
  - StreamIt (MIT, 2002)
  - Cilk (MIT, 1994)
- Start with full-featured languages and add cleanliness
  - Software transactional memory
  - Static analyzers (Locksmith, Chord, …)
  - Threaded Building Blocks (Intel)

Space of Solutions



most clean

Cleanliness

MapReduce

Dryad

StreamIt

CML

Cilk

Yet to come?

TBB+threads

STM+threads

OpenMP

Research

Used in practice

MPI

POSIX threads

most flexible

Flexibility

Kinds of Parallelism

- Data parallelism
  - Can divide parts of the data between different tasks and perform the same action on each part in parallel
- Task parallelism
  - Different tasks running on the same data
- Hybrid data/task parallelism
  - A parallel pipeline of tasks, each of which might be data parallel
- Unstructured
  - Ad hoc combination of threads with no obvious top-level structure

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MapReduce: Programming the Pipeline

- Pattern inspired by Lisp, ML, etc.
  - Many problems can be phrased this way
- Results in clean code
  - Easy to program / debug / maintain
    - Simple programming model
    - Nice retry / failure semantics
  - Efficient and portable
    - Easy to distribute across nodes

Thanks to Google, Inc. for some of the slides that follow

`fold_right` in OCaml

Map & ~~Reduce~~

Unary operator

Binary operator

- map ***f list***
- map square [1; 2; 3; 4]
  - [1; 4; 9; 16]
- fold_right (+) [1; 4; 9; 16] 0
  - (1 + (4 + (9 + (16 + 0))))
  - 30
- fold_right (+) (map square [1; 2; 3; 4]) 0

MapReduce a la Google

- map(key, val) is run on each item in set
  - emits new-key / new-val pairs
- reduce(key, vals) is run for each unique key emitted by map()
  - emits final output

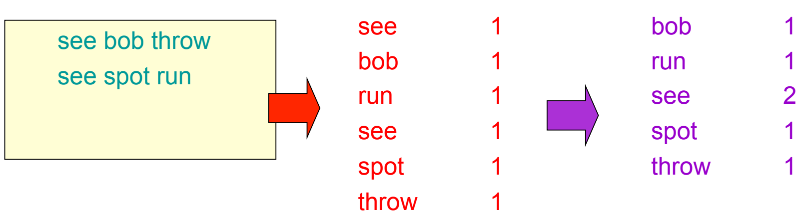
Count Words In Documents

- Input consists of (url, contents) pairs
- map(key=url, val=contents):
  - For each word *w* in contents, emit (w, “1”)
- reduce(key=word, values=uniq_counts):
  - Sum all “1”s in values list
  - Emit result “(word, sum)”

Count, Illustrated

map(key=url, val=contents):
For each word *w* in contents, emit (w, “1”)

reduce(key=word, values=uniq_counts):
Sum all “1”s in values list
Emit result “(word, sum)”

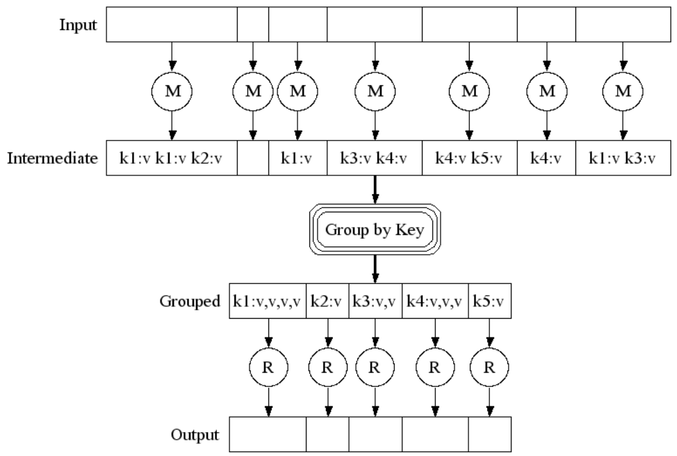


see bob throw
see spot run

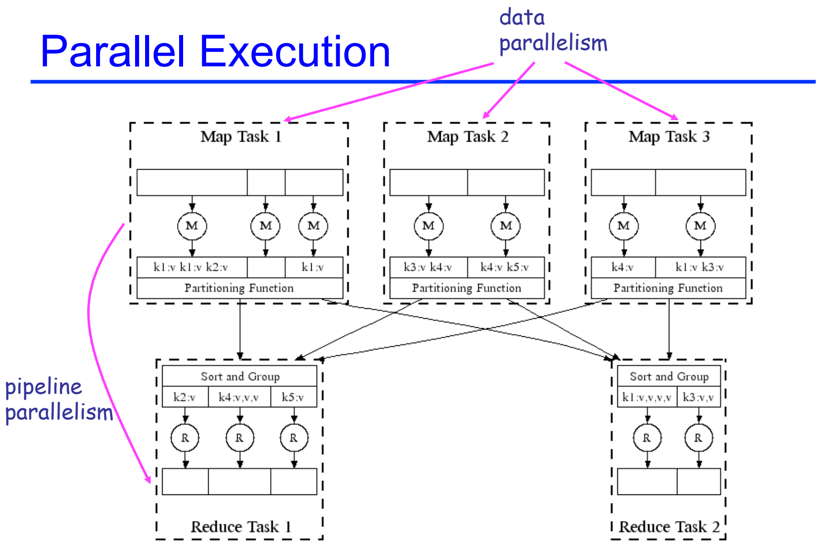
see	1
bob	1
run	1
see	1
spot	1
throw	1

bob	1
run	1
see	2
spot	1
throw	1

Execution



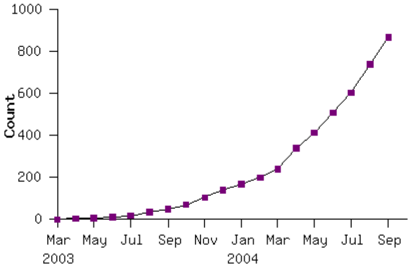
Parallel Execution



Key: no implicit dependencies between map or reduce tasks

Model Is Widely Applicable

MapReduce Programs In Google Source Tree 2004



Example uses:

distributed grep
term-vector / host
document clustering
clustering for Google News

distributed sort
web access log stats
machine learning
popularity for Google Trends

web link-graph reversal
inverted index construction
statistical machine translation for Google Translate
...

The Programming Model Is Key

- Simple control makes dependencies evident
  - Can automate scheduling of tasks and optimization
    - Map, reduce for different keys, embarassingly parallel
    - Pipeline between mappers, reducers evident
- map and reduce are pure functions
  - Can rerun them to get the same answer
    - In the case of failure, or
    - To use idle resources toward faster completion
  - No worry about data races, deadlocks, etc. since there is no shared state

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Compare to Dedicated Supercomputers

- According to Wikipedia, in 2009 Google uses
  - 450,000 servers (2006), mostly commodity Intel boxes
  - 2TB drive per server, at least
  - 16GB memory per machine
  - More recent details are kept secret by Google
- More computing power than even the most powerful supercomputer

Apache Hadoop

- Open source framework for large scale
  - Storage – based on Google File System
  - Computation – based on MapReduce
- Mostly written in Java
- Widely used commercially
  - Used by over half of Fortune 50 (largest) companies
  - Applications include marketing analytics, machine learning, web crawling, image processing
  - Yahoo (2008) used 10K core system for web indexing
  - Facebook (2012) uses system to manage 100+ PB db