Short modules for introducing parallel concepts

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Why introduce parallelism?

- It's here
- CC 2013 says you should
- Students want to see it

Module-based approach

- It's hard to revise curriculum or entire course, but relatively easy to carve out a couple of days
- Modules are self-contained 2-3 day units that fit within existing courses
- Include course materials and background support

The modules

- Mandelbrot set with OpenMP
- Short exercises with CUDA
- Chapel in Algorithms

Materials available:
http://faculty.knox.edu/dbunde/teaching/CCSC-MW13

Note on "tutorial"

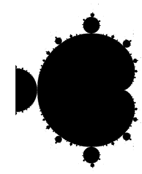
My context

- Dept has 3 FTEs, 27 majors (soph-senior)
- Trimester calendar
  - Students take 3 classes a term, we teach 2
  - Cover ~1 semester of material into 10 weeks
  - 70-minute periods; MWF lecture, Th lab
- Classes with 10-20
- Mac labs, Linux servers

Module 1
Mandelbrot set with OpenMP

Overview

- Built around program that generates Mandelbrot set as .bmp file
- OpenMP
  – threading library built into most C compilers
- Used several ways as part of discussion of threads and concurrency in OS course



Setting all the pixels

```
for (int i = 0; i < numCols; i++) {
   for (int j = 0; j < numRows; j++) {
        x = ((double)i / numCols -0.5) * 2;
        y = ((double)j / numRows -0.5) * 2;
        color = mandelbrot(x,y);

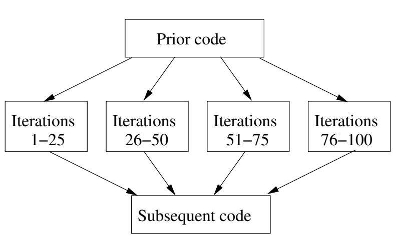
        pixels[i][j].rgbtBlue = pixels[i][j].rgbtGreen =
            pixels[i][j].rgbtRed = color;
   }
}
```

OpenMP

- Old standard (1st in 1997), but still widely used
- Implemented as pragmas in C and Fortran
- Widely supported (gcc, Visual Studio, Intel, ...)
  – requires –fopenmp flag in gcc

Parallel for loop

```
#pragma omp parallel for
for(int i=1; i<=100; i++) ...
```



Applying parallel for

```
#pragma omp parallel for
for (int i = 0; i < numCols; i++) {
   for (int j = 0; j < numRows; j++) {
        x = ((double)i / numCols -0.5) * 2;
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        color = mandelbrot(x,y);

        pixels[i][j].rgbtBlue = pixels[i][j].rgbtGreen =
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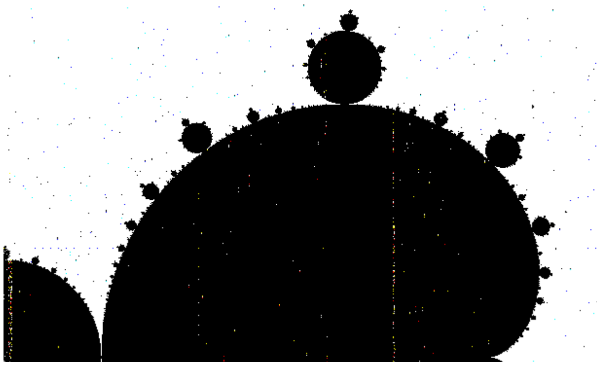
   }
}
```

Resulting output (closeup)



Privatizing local variables

```
#pragma omp parallel for private(x,y,color)
for (int i = 0; i < numCols; i++) {
   for (int j = 0; j < numRows; j++) {
         x = ((double)i / numCols -0.5) * 2;
         y = ((double)j / numRows -0.5) * 2;
         color = mandelbrot(x,y);

         pixels[i][j].rgbtBlue = pixels[i][j].rgbtGreen =
             pixels[i][j].rgbtRed = color;
   }
}
```

How well does it parallelize?

Original (serial) running time: 2.39 seconds

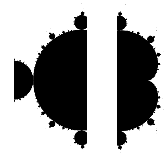
Parallel running time: 1.43 seconds

$$\text{Speedup} = \frac{\text{Serial time}}{\text{Parallel time}} = 1.67$$

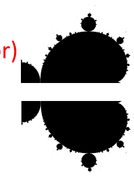
(On my Macbook Pro, with Intel Core i5 processor)

Parallelizing inner loop

```
#pragma omp parallel for private(x,y,color)
for (int i = 0; i < numCols; i++) {
   for (int j = 0; j < numRows; j++) {
                ...
```



```
for (int i = 0; i < numCols; i++) {
   #pragma omp parallel for private(x,y,color)
   for (int j = 0; j < numRows; j++) {
                ...
```



Parallelizing inner loop

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#pragma omp parallel for private(x,y,color)
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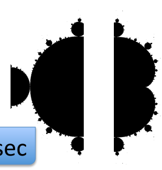
Time: 1.43 sec



```
for (int i = 0; i < numCols; i++) {
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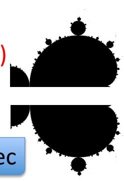
   for (int j = 0; j < numRows; j++) {
                ...
```

Time: 1.35 sec



Inside mandelbrot function

```
double mandelbrot(double x, double y) {
   int maxIteration = 1000;  int iteration = 0;

   double re = 0, im = 0;
   while((re*re + im*im <= 4) && (iteration < maxIteration)) {
         double temp = re*re - im*im + x;
         im = 2*re*im + y;
         re = temp;
         iteration++;
   }

   if(iteration != maxIteration) return 255; else return 0;
}
```

Inside mandelbrot function

```
double mandelbrot(double x, double y) {
    int maxIteration = 1000;  int iteration = 0;

    double re = 0, im = 0;
    while((re*re + im*im <= 4) && (iteration < maxIteration)) {
        double temp = re*re - im*im + x;
        im = 2*re*im + y;
        re = temp;
        iteration++;
    }

    if(iteration != maxIteration) return 255; else return 0;
}
```

Takes longer for points in the set

Swapping loop order

```
#pragma omp parallel for private(x,y,color)
for (int j = 0; j < numRows; j++) {
   for (int i = 0; i < numCols; i++) {
```

Time: 1.35 sec

Dynamic scheduling

```
#pragma omp parallel for ... schedule(dynamic)
for (int i = 0; i < numCols; i++) {
   for (int j = 0; j < numRows; j++) {
        ...
```

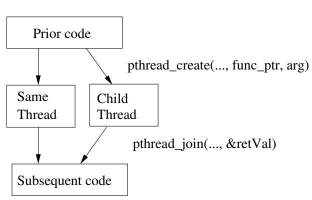
Time: 0.98 sec

Summary of versions

- Serial version 2.39 sec
- Incorrect parallel version (race)
- Parallel outer loop 1.43 sec
- Parallel inner loop 1.35 sec
- Swap loop order 1.26 sec
- Dynamic scheduling 0.98 sec

Alternative: Pthread library

- Can do (most of) lesson using POSIX-standard threads (pthreads)




```
void* func(void* arg) {
  ...
}
```

- Not easy to do dynamic scheduling

Classroom hints

- Can't have too many students sharing same machine
- Go over concepts before and/or after showing code

How I've used it

- Previous lecture introducing threads
- Lab using pthreads (Mandelbrot or other example)
- Lecture on lab and using Mandelbrot (OpenMP) to illustrate concepts
  - Definite improvement over doing same material with Pthreads in lecture

OpenMP or Pthreads first?

- OpenMP first
  - Give high-level concepts before lots of syntax
  - Want to spend most of time on concepts so do it first
- Pthreads first
  - Demonstrate execution model before showing "magic"
  - Could use other examples for simplicity

"TODO" list

- Which order for Pthreads vs. OpenMP?
  - Join my experiment!
- More colorful versions of Mandelbrot
- Interactive image generation
- Other examples

Please share!

Module 2
Short exercises with CUDA

Part of Bunde, Karavanic, Mache, Mitchell, "Adding GPU computing to Computer Organization courses", EduPar 2013

What is CUDA?

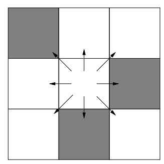
- "Compute Unified Device Architecture"
- NVIDIA's architecture and language for general-purpose programming on graphics cards
- Really a library and extension of C (and other languages)

Why CUDA?

- Easy to get the hardware
  - My laptop came with a 48-core card
  - Department has 448-core card (< $600)
  - NVIDIA willing to donate equipment
- Exciting for students
  - They have cards and want to use them
  - Easy to see performance benefits

Game of Life (GoL)

- Simulation with cells updating in lock step
- Each turn, count living neighbors
- Cell alive next turn if
  – alive this time and have 2 living neighbors, or
  – have 3 living neighbors



Module constraints

- Brief time: Course has lots of other goals
  – One 70-minute lab and parts of 2 lectures
- Relatively inexperienced students
  – Some just out of CS 2
  – Many didn't know C or Unix programming

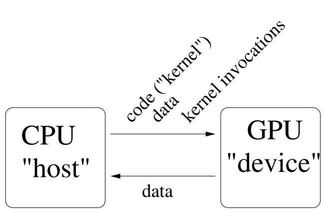
Unit goals

- Idea of parallelism
- Benefits and costs of system heterogeneity
- Data movement and NUMA
- Generally, the effect of architecture on program performance

Approach taken

- Introductory lecture
  – GPUs: massively parallel, outside CPU, kernels, SIMD
- Lab illustrating features of CUDA architecture
  – Data transfer time
  – Thread divergence
  – Memory types (next time)
- "Lessons learned" lecture
  – Reiterate architecture
  – Demonstrate speedup with Game of Life
  – Talk about use in Top 500 systems

CUDA programming model



- Device has many cores, organized into groups
- 32-thread warps execute the same instruction

Data transfer

```
//allocate memory on the device:
cudaMalloc((void**) &a_dev, N*sizeof(int));
...

//transfer array a to GPU
cudaMemcpy(a_dev, a, N*sizeof(int), cudaMemcpyHostToDevice);
 ...

//transfer array res back from GPU:
cudaMemcpy(res, res_dev, N*sizeof(int), cudaMemcpyDeviceToHost);
```

direction indicator

Invoking the kernel

```
int threads = 512;                        //# threads per block
int blocks = (N+threads−1)/threads;       //# blocks (N/threads rounded up)
kernel<<<blocks,threads>>>(res_dev, a_dev, b_dev);
```

- Blocks are an organizational unit for threads
- Performance is very dependent on #blocks and #threads
- One rule: #threads should be multiple of 32

Kernel itself

```
__global__ void kernel(int* res, int* a, int* b) {
  //function that runs on GPU to do the addition
  //sets res[i] = a[i] + b[i]; each thread is responsible for one value of i

  int thread_id = threadIdx.x + blockIdx.x*blockDim.x;
  if(thread_id < N) {
    res[thread_id] = a[thread_id] + b[thread_id];
  }
}
```

since #threads potentially > array size

Lab activity 1: Data transfer time

- Students compare running time of
  - working CUDA program to add pair of vectors
  - program with data transfer, but no arithmetic
  - program that does arithmetic and only 1 direction of data transfer

Lab activity 1: Data transfer time

- Students compare running time of
  - working CUDA program to add pair of vectors
  - program with data transfer, but no arithmetic
  - program that does arithmetic and only 1 direction of data transfer

- Observe that data transfer is bulk of the time

Lab activity 2: Thread divergence

- Compare two apparently equivalent kernels:

```
__global__ void kernel_1(int *a) {
  int tid = threadIdx.x;
  int cell = tid % 32;
  a[cell]++;
}
```

```
__global__ void kernel_2(int *a) {
  int cell = threadIdx.x % 32;
  switch(cell) {
  case 0: a[0]++; break;
  case 1: a[1]++; break;
  ...  //continues to case 7
  default: a[cell]++;
  }
}
```

Lab activity 2: Thread divergence

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  case 1: a[1]++; break;
  ...  //continues to case 7
  default: a[cell]++;
  }
}
```


- Observe vastly different running times
  - Threads in a warp devote time to 1 instruction per clock cycle *even if not all run it* (others nop)

Lab activity 3: Memory types

Based on Chap 6 of [Sanders and Kandrot, “CUDA by example”, 2011]

- “Ray tracing” that tests intersections with array of objects in the same order
- Speeds up with switch to constant memory
  - values are transmitted to entire half warp
  - allows caching

Lab activity 3: Memory types

Based on Chap 6 of [Sanders and Kandrot, “CUDA by example”, 2011]

- “Ray tracing” that tests intersections with array of objects in the same order
- Speeds up with switch to constant memory
  - values are transmitted to entire half warp
  - allows caching
- Performance is worse if threads access objects in different orders

Survey results: Good news

- Asked to describe CPU/GPU interaction:
  - 9 of 11 mention both data movement and invoking kernel
  - Another just mentions invoking the kernel

Survey results: Good news

- Asked to describe CPU/GPU interaction:
  - 9 of 11 mention both data movement and invoking kernel
  - Another just mentions invoking the kernel
- Asked to explain experiment illustrating data movement cost:
  - 9 of 12 say comparing computation and communication cost
  - 2 more talk about comparing different operations

Survey results: Not so good news

- Asked to explain experiment illustrating thread divergence:
  - 2 of 9 were correct
  - 2 more seemed to understand, but misused terminology
  - 3 more remembered performance effect, but said nothing about the cause

Conclusions

- Unit was mostly successful, but thread divergence is a harder concept
- Students interested in CUDA and about half the class requested more of it
- Bottom line: A brief introduction is possible even to students with limited background

Classroom hints

- Need graphics card on local machine (at least for GoL)
- For my unit, show GoL before doing the lab

Alternate models

- Lewis and Clark, Portland State
  - Lecture introducing CUDA
  - Lab/HW using it to speed up Game of Life
- Daniel Ernst
  - Longer unit with both OpenMP and CUDA
  - General emphasis on tuning data layout and access pattern

"TODO" list

- New example for types of memory
- Explain thread divergence better
- Middle ground: adding programming to mine or conceptual material to L&C version
- Porting code to other base languages (Java)
- Other programming example (?)

Please share!

Module 3a
Chapel in Algorithms

(Based on experiences of Kyle Burke and our joint tutorial at SC Ed Program, 2012)

What is Chapel?

- Parallel programming language developed with programmer productivity in mind
- Originally Cray's project under DARPA's High Productivity Computing Systems program
- Suitable for shared- or distributed memory systems
- Installs easily on Linux and Mac OS; use Cygwin to install on Windows

Why Chapel?

- Flexible syntax; only need to teach features that you need
- Provides high-level operations
- Designed with parallelism in mind

Flexible syntax

- Supports scripting-like programs:
  writeln("Hello World!");
- Also provides objects and modules

Provides high-level operations

- Reductions and scans (more later)
- Function promotion:
  B = f(A); //applies f elementwise for any function f
- Includes built-in operators:
  C = A + 1;
  D = A + B;
  E = A * B;
  ...

Designed with parallelism in mind

- Operations on previous slides parallelized automatically
- Create asynchronous task w/ single keyword
- Built-in synchronization for tasks and variables

"Hello World" in Chapel

- Create file hello.chpl containing
  writeln("Hello World!");
- Compile with
  chpl –o hello hello.chpl
- Run with
  ./hello

Variables and Constants

- Variable declaration format:
  [config] var/const identifier : type;

var x : int;
const pi : real = 3.14;
config const numSides : int = 4;

Serial Control Structures

- if statements, while loops, and do-while loops are all pretty standard
- Difference: Statement bodies must either use braces or an extra keyword:
  if(x == 5) **then** y = 3; else y = 1;
  while(x < 5) **do** x++;

Example: Reading until eof

```
var x : int;
while stdin.read(x) {
    writeln("Read value ", x);
}
```

Procedures/Functions

arg_type → "in"; argument → "val"; omit for generic function → ": int" (of val2); return type (omit if none or if can be inferred) → ": int" (after the parameter list)

```
proc addOne(in val : int, inout val2 : int) : int {
    val2 = val + 1;
    return val + 1;
}
```

Arrays

- Indices determined by a range:
  ```
  var A : [1..5] int;          //declares A as array of 5 ints
  var B : [-3..3] int;         //has indices -3 thru 3
  var C : [1..10, 1..10] int;  //multi-dimensional array
  ```
- Accessing individual cells:
  ```
  A[1] = A[2] + 23;
  ```
- Arrays have runtime bounds checking

For Loops

- Ranges also used in for loops:
  ```
  for i in 1..10 do statement;
  for i in 1..10 {
    loop body
  }
  ```
- Can also use array or anything iterable

Parallel Loops

- Two kinds of parallel loops:
  ```
  forall i in 1..10 do statement;  //omit do w/ braces
  coforall i in 1..10 do statement;
  ```
- forall creates 1 task per processing unit
- coforall creates 1 per loop iteration
  - Used when each iteration requires lots of work and/or they must be done in parallel

Asynchronous Tasks

- Easy asynchronous task creation:
  ```
  begin statement;
  ```
- Easy fork-join parallelism:
  ```
  cobegin {
    statement1;
    statement2;
    ...
  }      //creates task per statement and waits here
  ```

Sync blocks

- sync blocks wait for tasks created inside it
- These are equivalent:

```
sync {                      cobegin {
  begin statement1;             statement1;
  begin statement2;             statement2;
  ...                           ...
}                           }
```

Sync variables

- sync variables have value and empty/full state
  – store ≤ 1 value and block operations can't proceed
- Can be used as lock:

```
var lock : sync int;
lock = 1;              //acquires lock
...
var temp = lock;       //releases the lock
```

Analysis of Algorithms

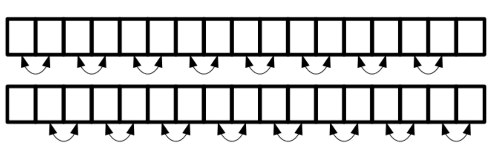
- Chapel material
  – Assign basic tutorial
  – Teach forall & cobegin (also algorithmic notation)
- Projects
  – Partition integers
  – BubbleSort
  – MergeSort
  – Nearest Neighbors

Algorithms Project: List Partition

- Partition a list to two equal-summing halves.
- Brute-force algorithm (don't know P vs NP yet)
- Questions:
  – What are longest lists you can test?
  – What about in parallel?
- Trick: enumerate possibilities and use forall

Algorithms Project: BubbleSort

- Instead of left-to-right, test all pairs in two steps!



- Two nested forall loops (in sequence) inside a for loop

Algorithms Project: MergeSort

- Parallel divide-and-conquer: use cobegin
- Elegant division: split the Domain
- Speedup not as noticeable
- Example of expensive parallel overhead

Algorithms Project: Nearest Neighbors

- Find closest pair of (2-D) points.
- Two algorithms:
  - Brute Force
    - (use a forall like bubbleSort)
  - Divide-and-Conquer
    - (use cobegin)
    - A bit tricky
- Value of parallelism: much easier to program the brute-force method

Algorithms Takeaway

- Learning curve of Chapel is so low, students can start using parallelism very quickly

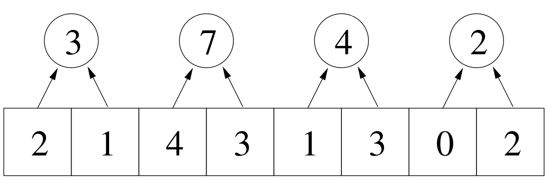
Module 3b
Reductions

(Reduction framework from Lin and Snyder, *Principles of parallel programming*, 2009.)

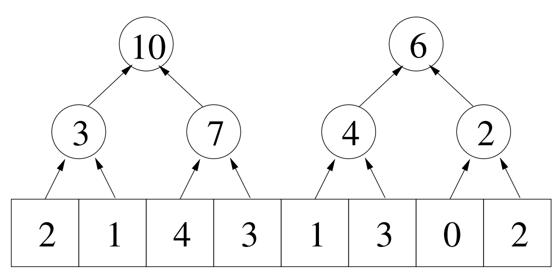
Summing values in an array

2	1	4	3	1	3	0	2

Summing values in an array



Summing values in an array



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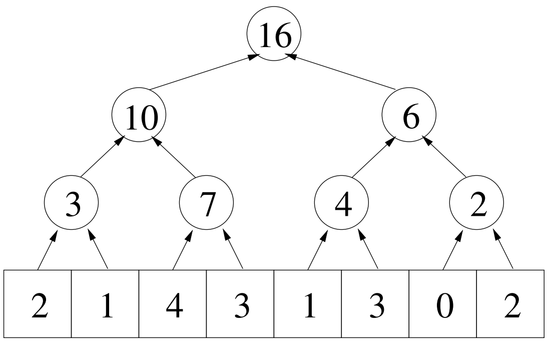
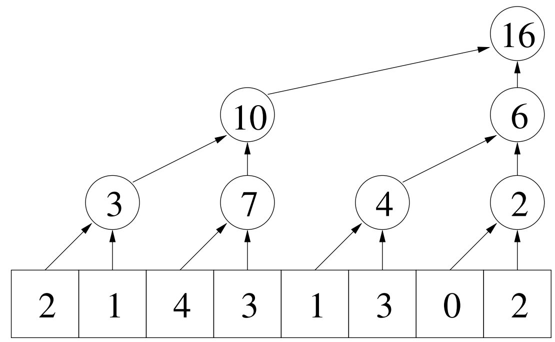
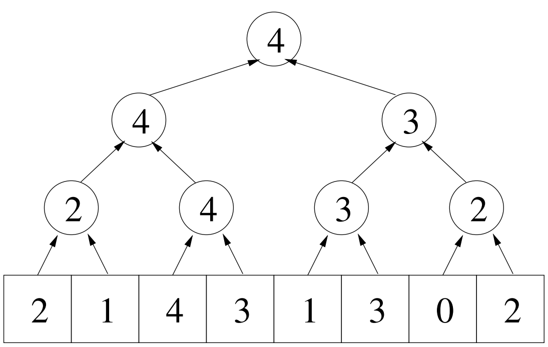


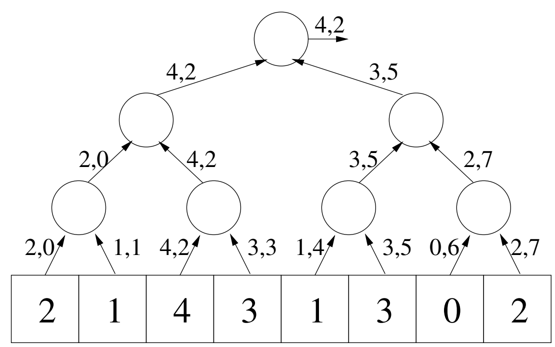
Summing values in an array



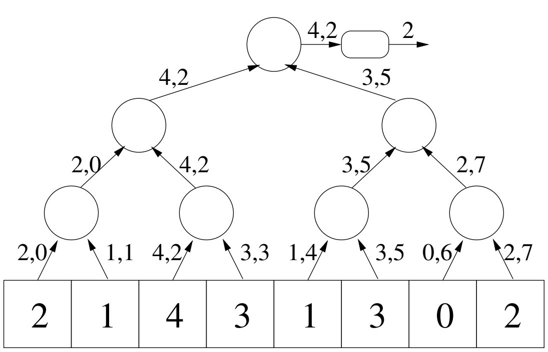
Finding max of an array



Finding the maximum index



Finding the maximum index



Parts of a reduction

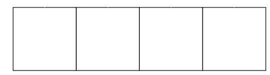
- Tally: Intermediate state of computation
- Combine: Combine 2 tallies
- Reduce-gen: Generate result from tally

Parts of a reduction

- Tally: Intermediate state of computation
  (value, index)
- Combine: Combine 2 tallies
  take whichever pair has larger value
- Reduce-gen: Generate result from tally
  return the index

Two issues

- Need to convert initial values into tallies
- May want separate operation for values local to a single processor



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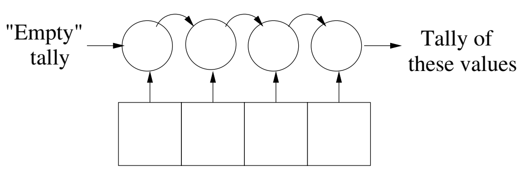
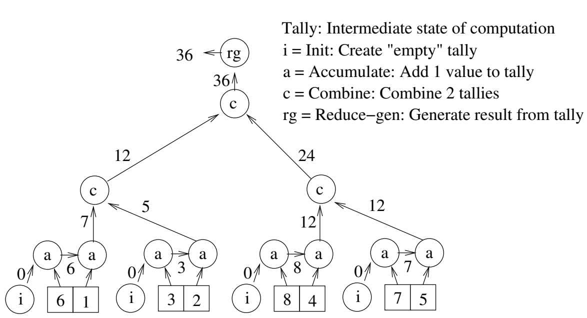


Parts of a reduction

- Tally: Intermediate state of computation
- Combine: Combine 2 tallies
- Reduce-gen: Generate result from tally
- Init: Create “empty” tally
- Accumulate: Add 1 value to tally

Parallel reduction framework



Defining reductions

- Tally: Intermediate state of computation
- Combine: Combine 2 tallies
- Reduce-gen: Generate result from tally
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Sample problems: +

Defining reductions

- Tally: Intermediate state of computation
- Combine: Combine 2 tallies
- Reduce-gen: Generate result from tally
- Init: Create "empty" tally
- Accumulate: Add 1 value to tally

Sample problems: +, histogram

Defining reductions

- Tally: Intermediate state of computation
- Combine: Combine 2 tallies
- Reduce-gen: Generate result from tally
- Init: Create "empty" tally
- Accumulate: Add 1 value to tally

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Sample problems: +, histogram, max, 2^{nd} largest, length of longest run

Can go beyond these...

- indexOf (find index of first occurrence)
- sequence alignment [Srinivas Aluru]
- n-body problem [Srinivas Aluru]

Relationship to dynamic programming

- Challenges in dynamic programming:
  - What are the table entries?
  - How to compute a table entry from previous entries?
- Challenges in reduction framework:
  - What is the tally?
  - How to compute a new tallies from previous ones?

Reductions in Chapel

- Express reduction operation in single line:
  ```
  var s = + reduce A;   //A is array, s gets sum
  ```
- Supports +, *, ^ (xor), &&, ||, max, min, ...
- minloc and maxloc return a tuple with value and its index:
  ```
  var (val, loc) = minloc reduce A;
  ```

Reduction example

- Can also use reduce on function plus a range
- Ex: Approximate π/2 using $\int_{-1}^{1} \sqrt{1-x^2}\,dx$:

```
config const numRect = 10000000;
const width = 2.0 / numRect;          //rectangle width
const baseX = -1 - width/2;
const halfPI = + reduce [i in 1..numRect]
      (width * sqrt(1.0 – (baseX + i*width)**2));
```

Defining a custom reduction

- Create object to represent intermediate state
- Must support
  - accumulate: adds a single element to the state
  - combine: adds another intermediate state
  - generate: converts state object into final output

Classes in Chapel

```
class Circle {
     var radius : real;
     proc area() : real {
          return 3.14 * radius * radius;
     }
}

var c1, c2 : Circle;          //creates 2 Circle references
c1 = new Circle(10);     /* uses system-supplied constructor
                              to create a Circle object
                              and makes c1 refer to it */
c2 = c1;                 //makes c2 refer to the same object
delete c1;               //memory must be manually freed
```

Inheritance

```
class Circle : Shape {     //Circle inherits from Shape
   ...
}

var s : Shape;
s = new Circle(10.0);   //automatic cast to base class
var area = s.area();    /* call recipient determined
                             by object's dynamic type */
```

Example “custom” reduction

```
class MyMin : ReduceScanOp { //finds min element (equiv. to built-in “min”)
   type eltType;                          //type of elements
   var soFar : eltType = max(eltType);    //minimum so far

   proc accumulate(val : eltType) {
        if(val < soFar) { soFar = val; }
   }

   proc combine(other : MyMin) {
        if(other.soFar < soFar) { soFar = other.soFar; }
   }

   proc generate() { return soFar; }
}
```

And that's not all... (scans)

- Instead of just getting overall value, also compute value for every prefix

A	2	1	4	3	1	3	0	2
sum	2	3	7	10	11	14	14	16

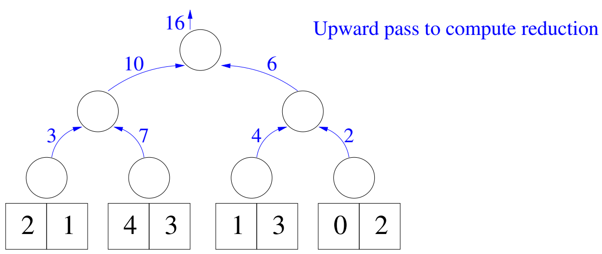
And that's not all... (scans)

- Instead of just getting overall value, also compute value for every prefix

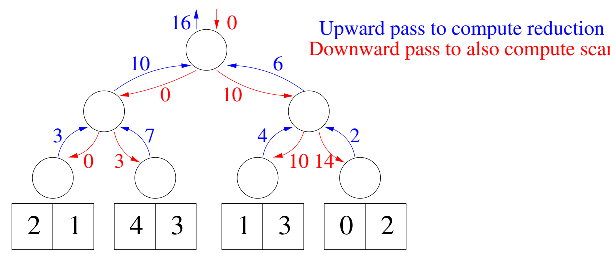
A	2	1	4	3	1	3	0	2
sum	2	3	7	10	11	14	14	16

- Useful answering queries like
  "What is the sum of elements 2 thru 7?"
  = sum[7] – sum[1]

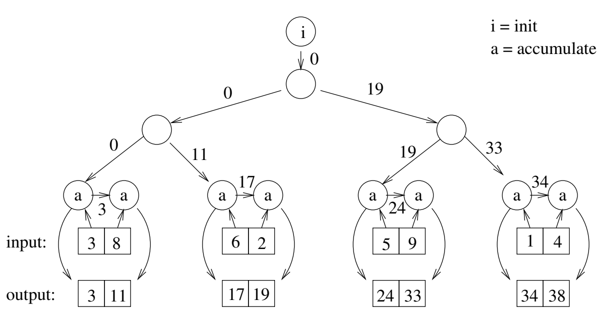
Computing the scan in parallel



Computing the scan in parallel



Downward pass with function labels



Many options for module 3

- Using Chapel for ease of parallelization
- Reductions on paper (defining and/or using)
- Also implementing reductions in Chapel

Side question: Where to put it?

Caveats

- Still in development
  - Reductions serialized on multicore (as of 1.6)
  - Error messages thin
  - New versions every 6 months – some big changes
  - Not many libraries
- No development environment
  - Command-line compilation in Linux

"TODO" list

- Notes, slides, assignments, etc
- Evidence on tie to dynamic programming
- Sample adoption strategies
- More applications of reductions and scans

Please share!

Other resources

- CS in Parallel
  http://csinparallel.org
- Dan Grossman's CS 2 notes
  http://homes.cs.washington.edu/~djg/teachingMaterials/spac/
- NSF/IEEE-TCPP Curriculum Initiative
  http://www.cs.gsu.edu/~tcpp/curriculum/

Thanks for your time

dbunde@knox.edu
http://faculty.knox.edu/dbunde/teaching/CCSC-MW13