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”

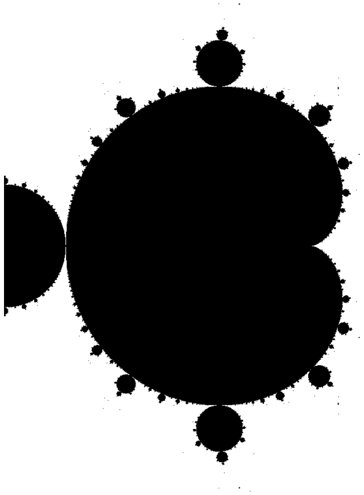
My context

- 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

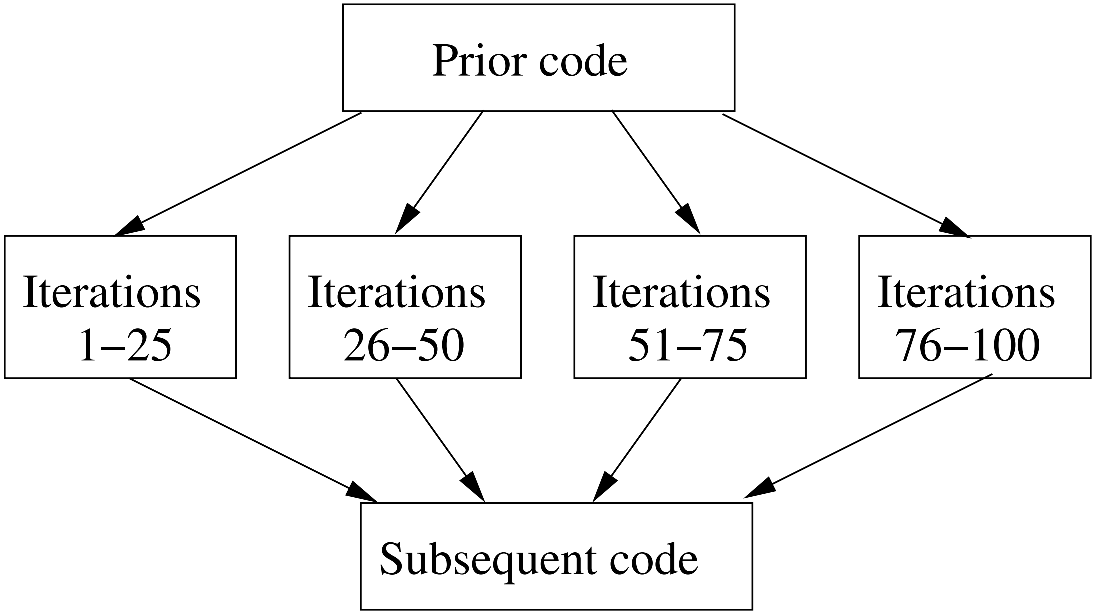
```
for (int i = 0; i < numCols; i++) {
    for (int j = 0; j < numRows; j++) {
          x = ((double)i / numCols -0.5) * 2;
          y = ((double)j / numRows -0.5) * 2;
          color = mandelbrot(x,y);

          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

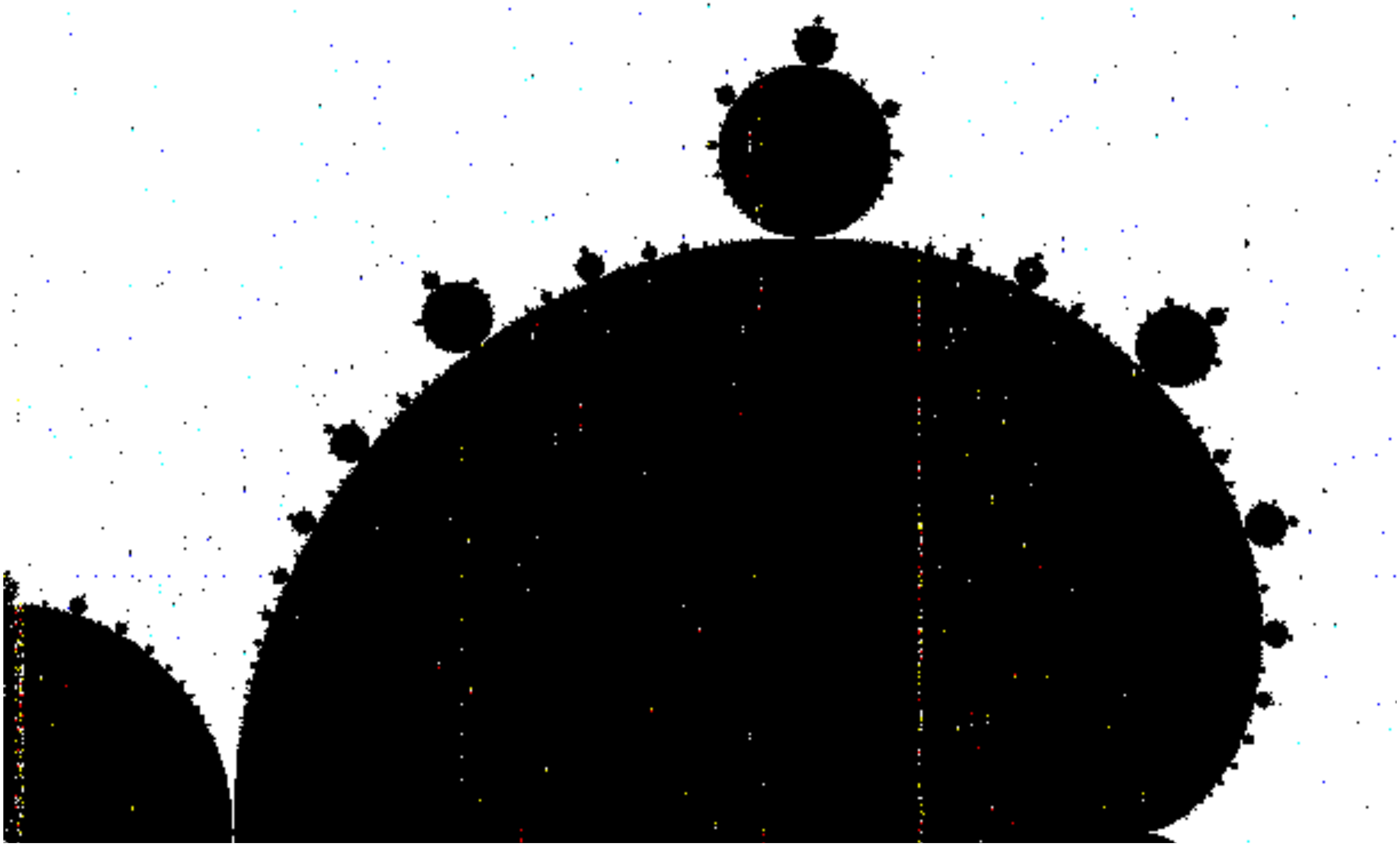
```
#pragma omp parallel for
for(int i=1; i<=100; i++) ...
```



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;
            y = ((double)j / numRows -0.5) * 2;
            color = mandelbrot(x,y);

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

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

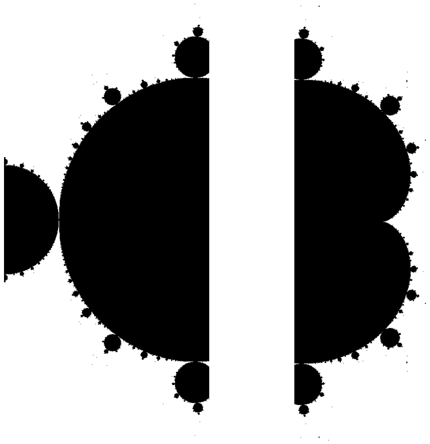
Parallel running time: 1.43 seconds

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

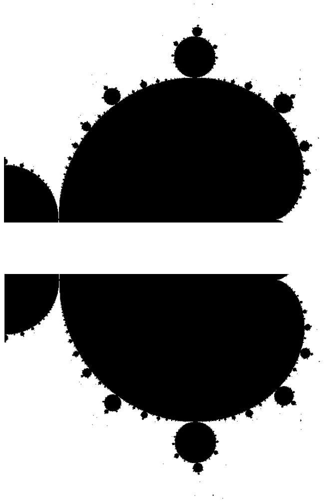
(On my Macbook Pro, with Intel Core i5 processor)

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++) {
                    ...
```

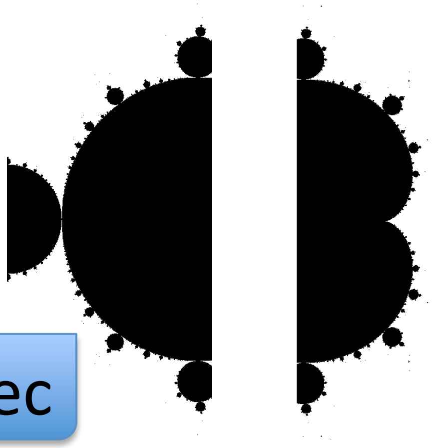


```
for (int i = 0; i < numCols; i++) {
   #pragma omp parallel for private(x,y,color)
    for (int j = 0; j < numRows; j++) {
                    ...
```



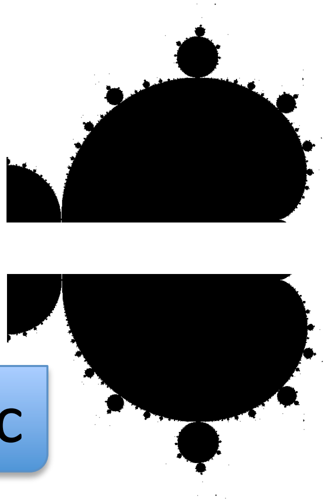
Parallelizing inner loop

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



Time: 1.43 sec

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

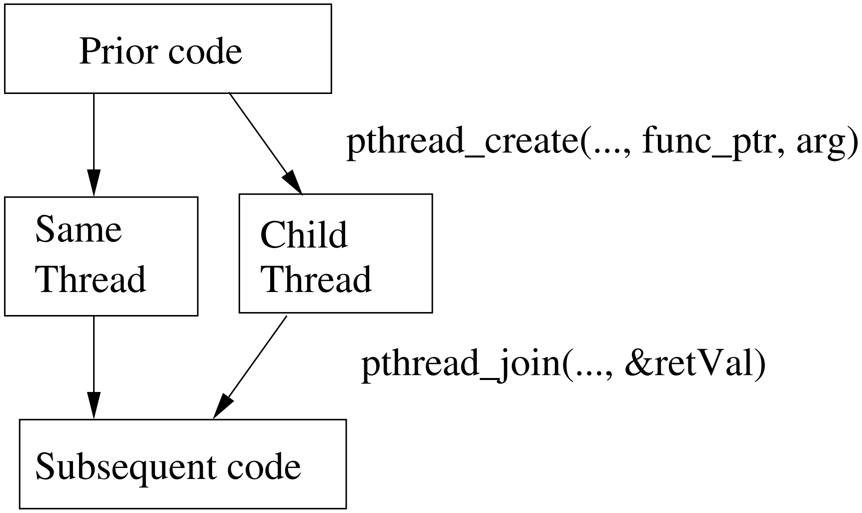
Time: 0.98 sec

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)



Prior code

pthread_create(..., func_ptr, arg)

Same Thread

Child Thread

pthread_join(..., &retVal)

Subsequent code

```
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)

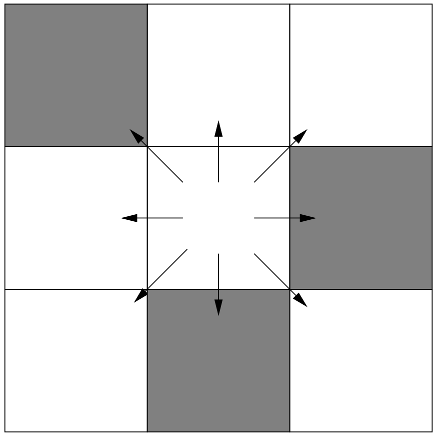
Why CUDA?

- 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

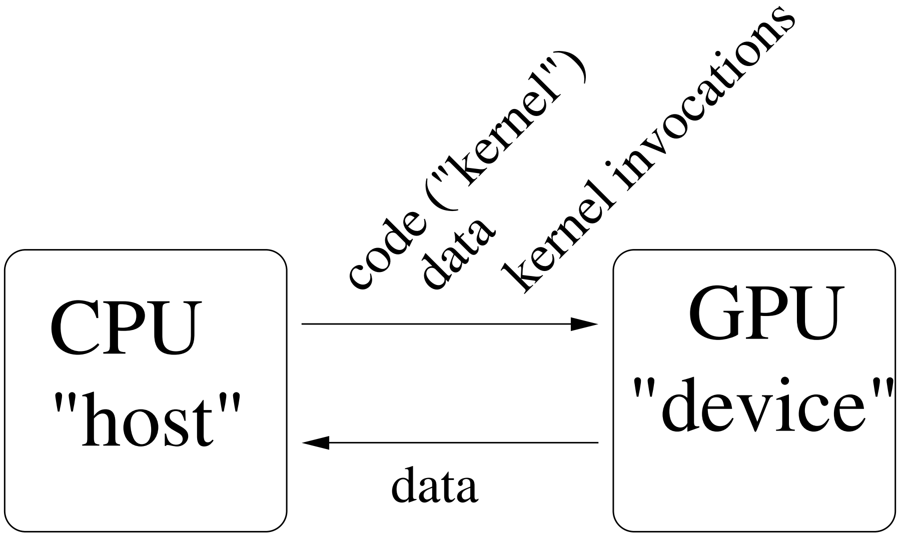
Unit goals

- 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

- 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]++;
  }
}
```

- 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

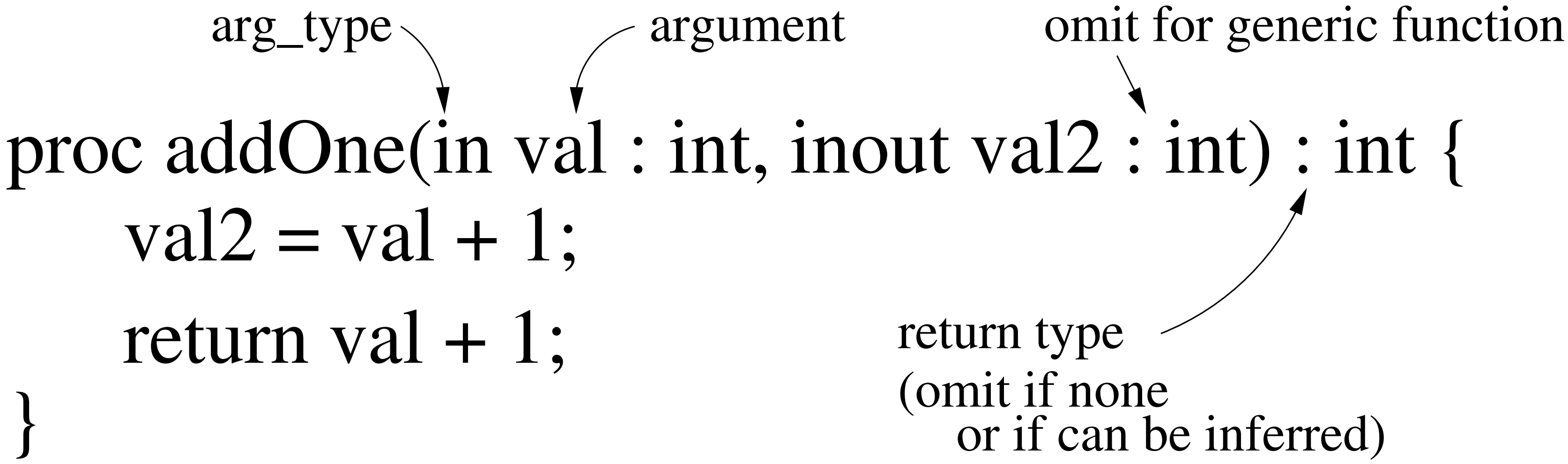
- if statements, while loops, and do-while loops are all pretty standard
- Difference: Statement bodies must either use braces or an extra keyword:

```
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

argument

omit for generic function

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

return type
(omit if none
or if can be inferred)

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 {
   begin statement1;
   begin statement2;
   …
}
```

```
cobegin {
     statement1;
     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)

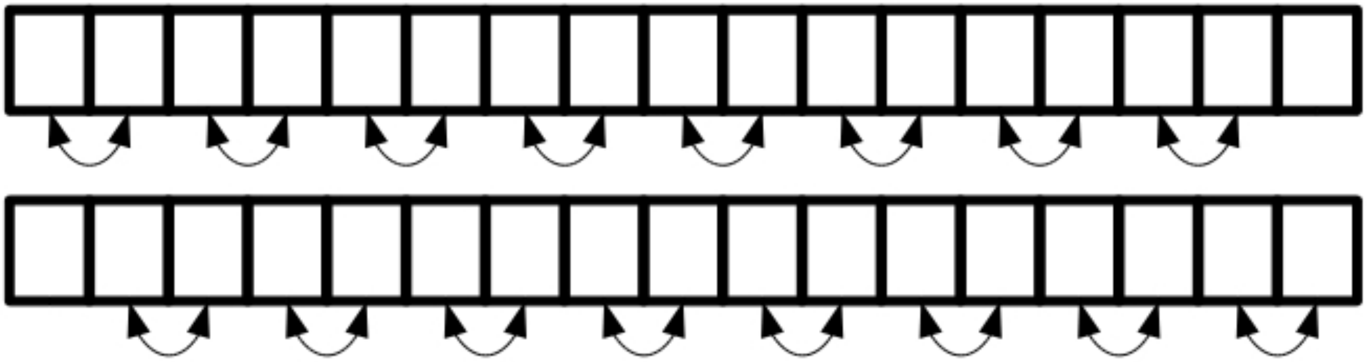
- Projects
  - Partition integers
  - BubbleSort
  - MergeSort
  - Nearest Neighbors

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

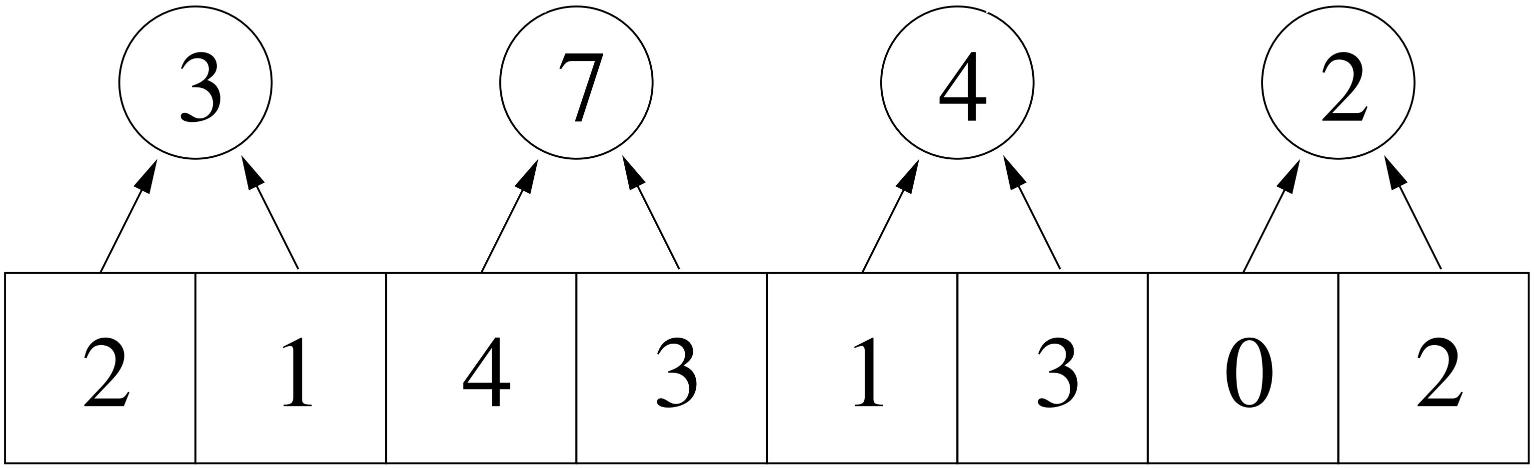
Module 3b
Reductions

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

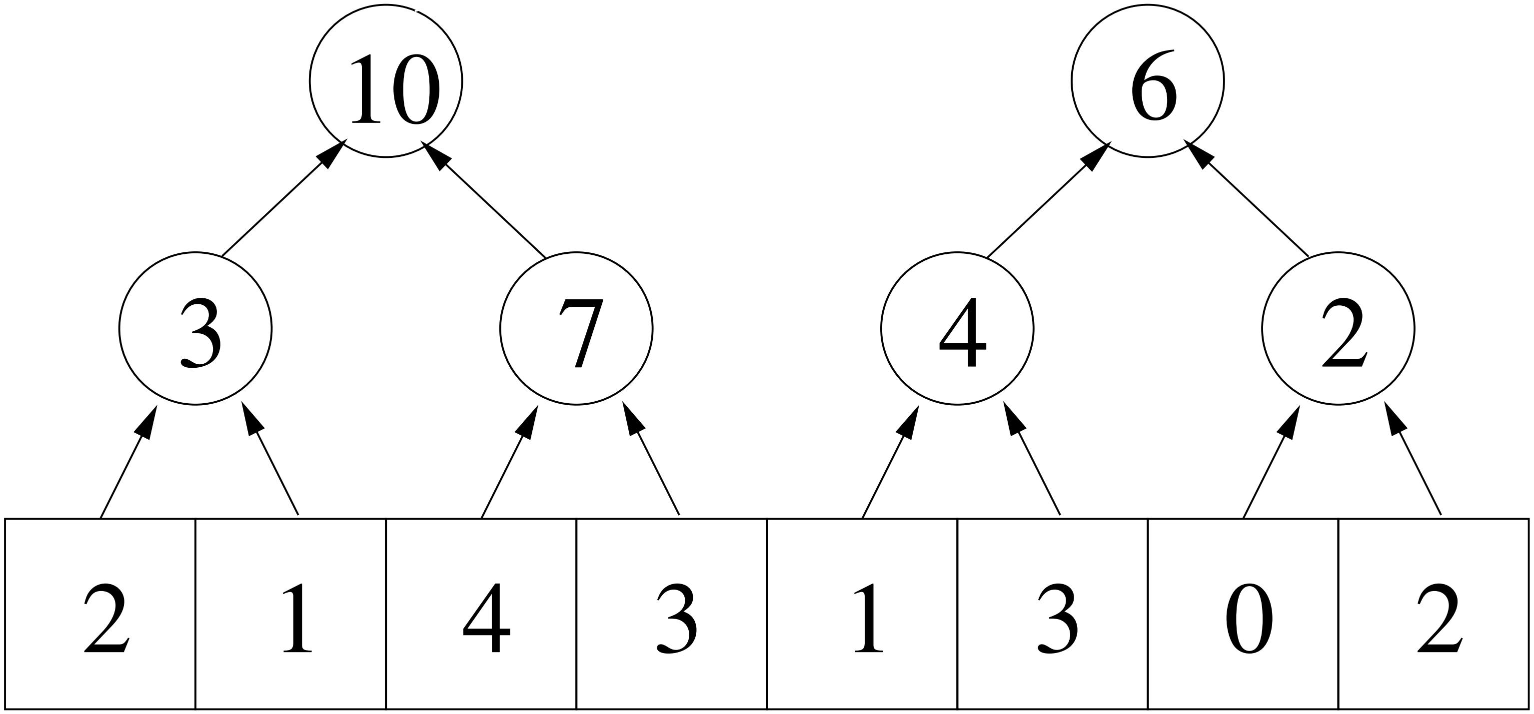
Summing values in an array

2	1	4	3	1	3	0	2

Summing values in an array



Summing values in an array



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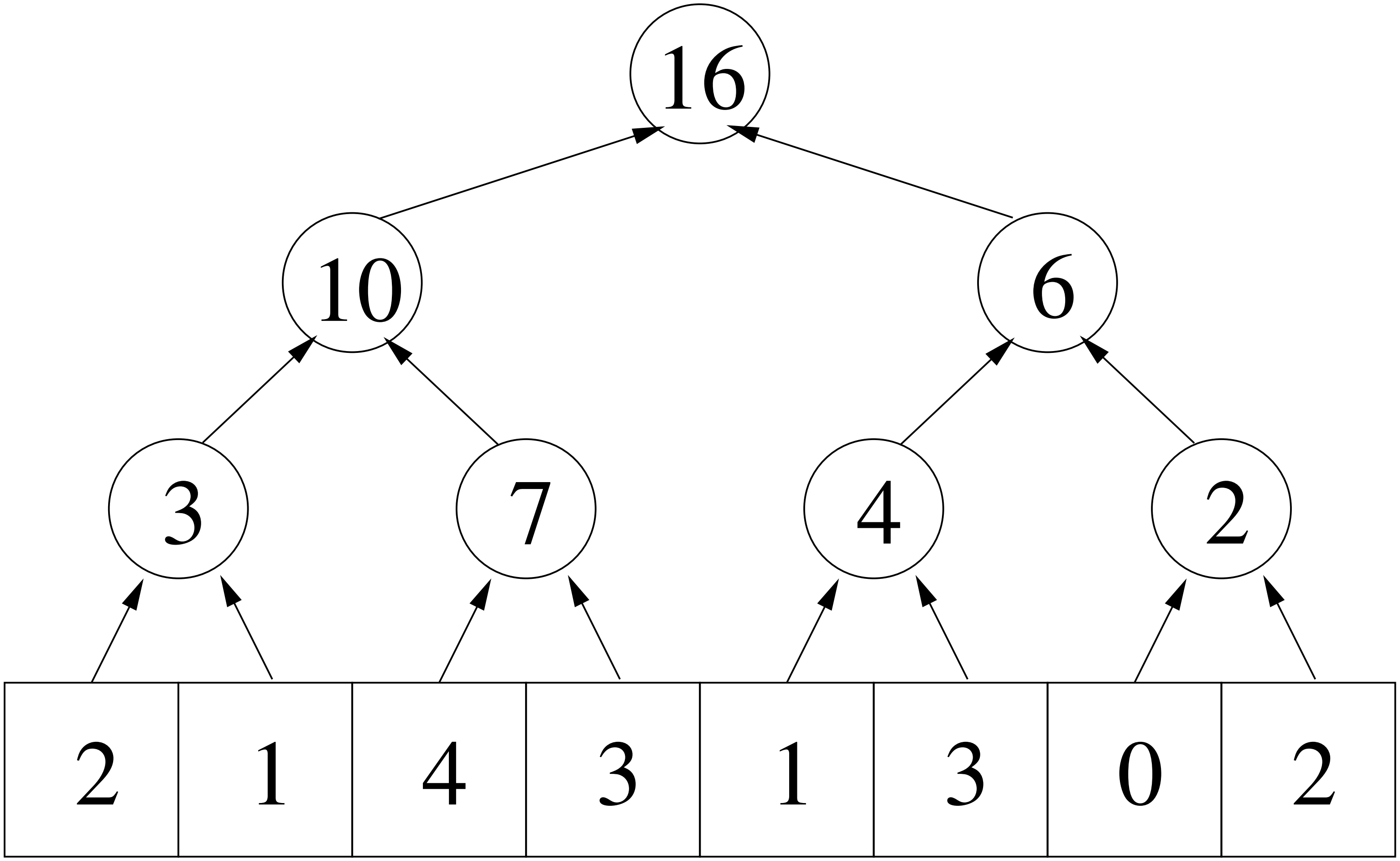
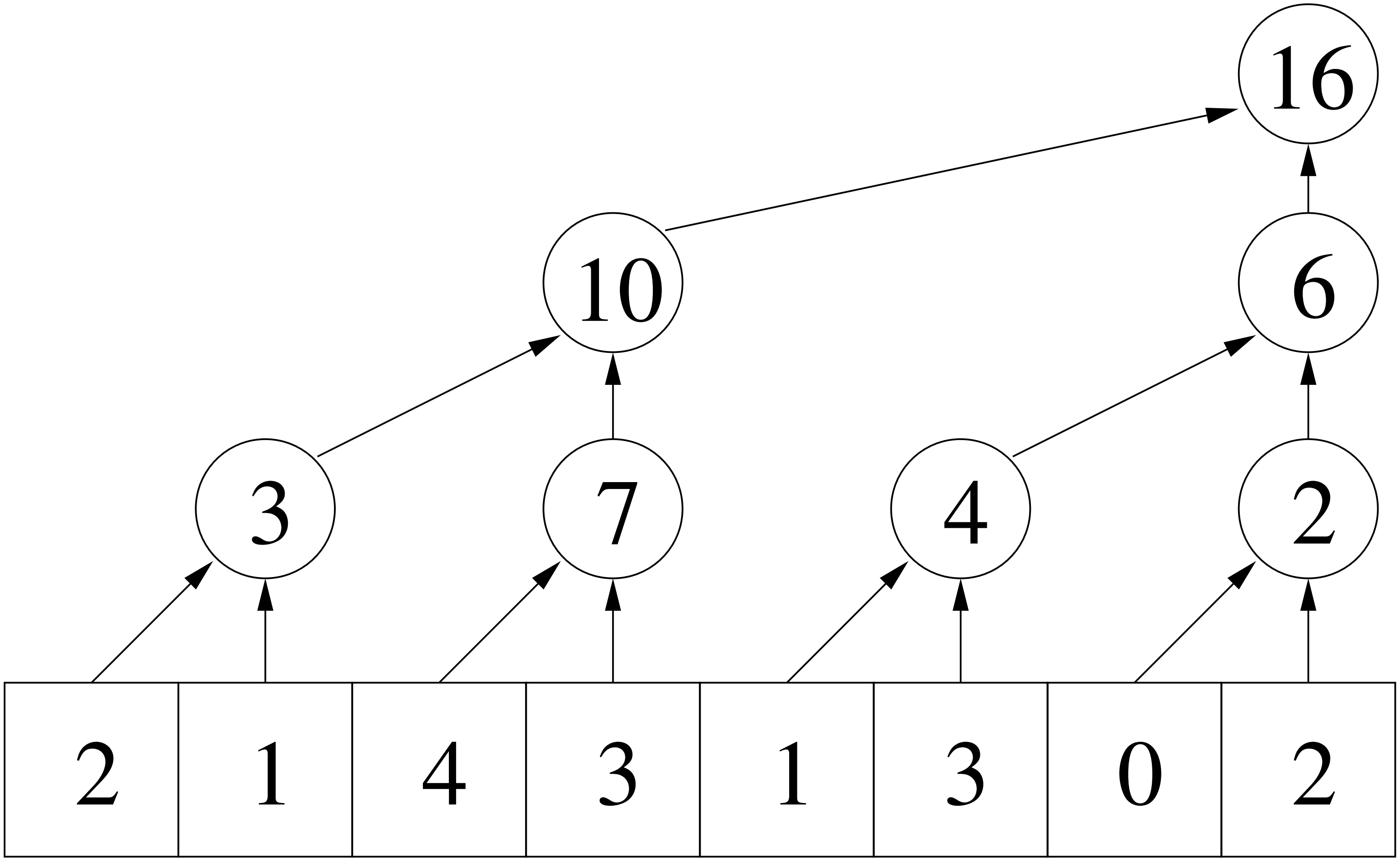
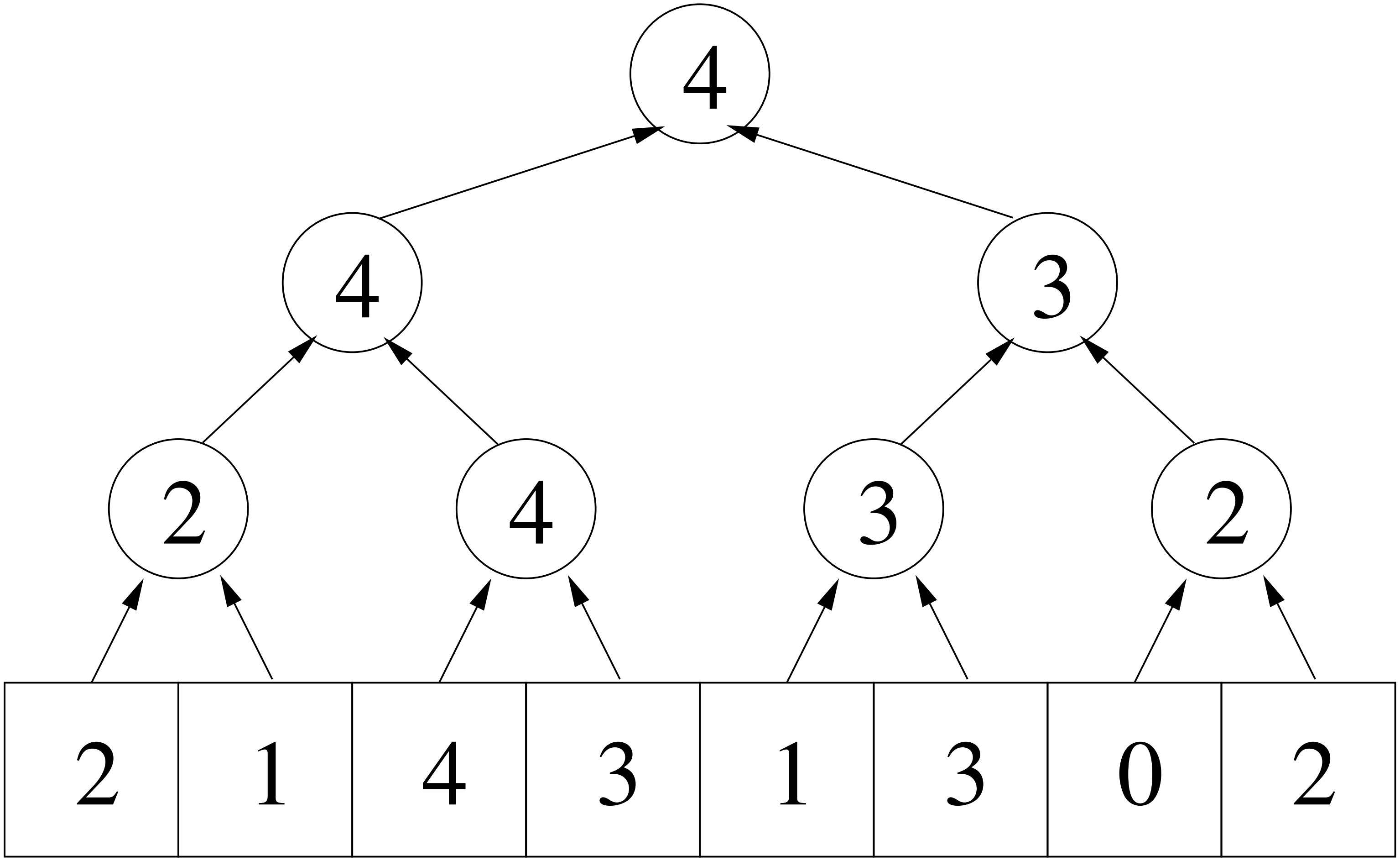


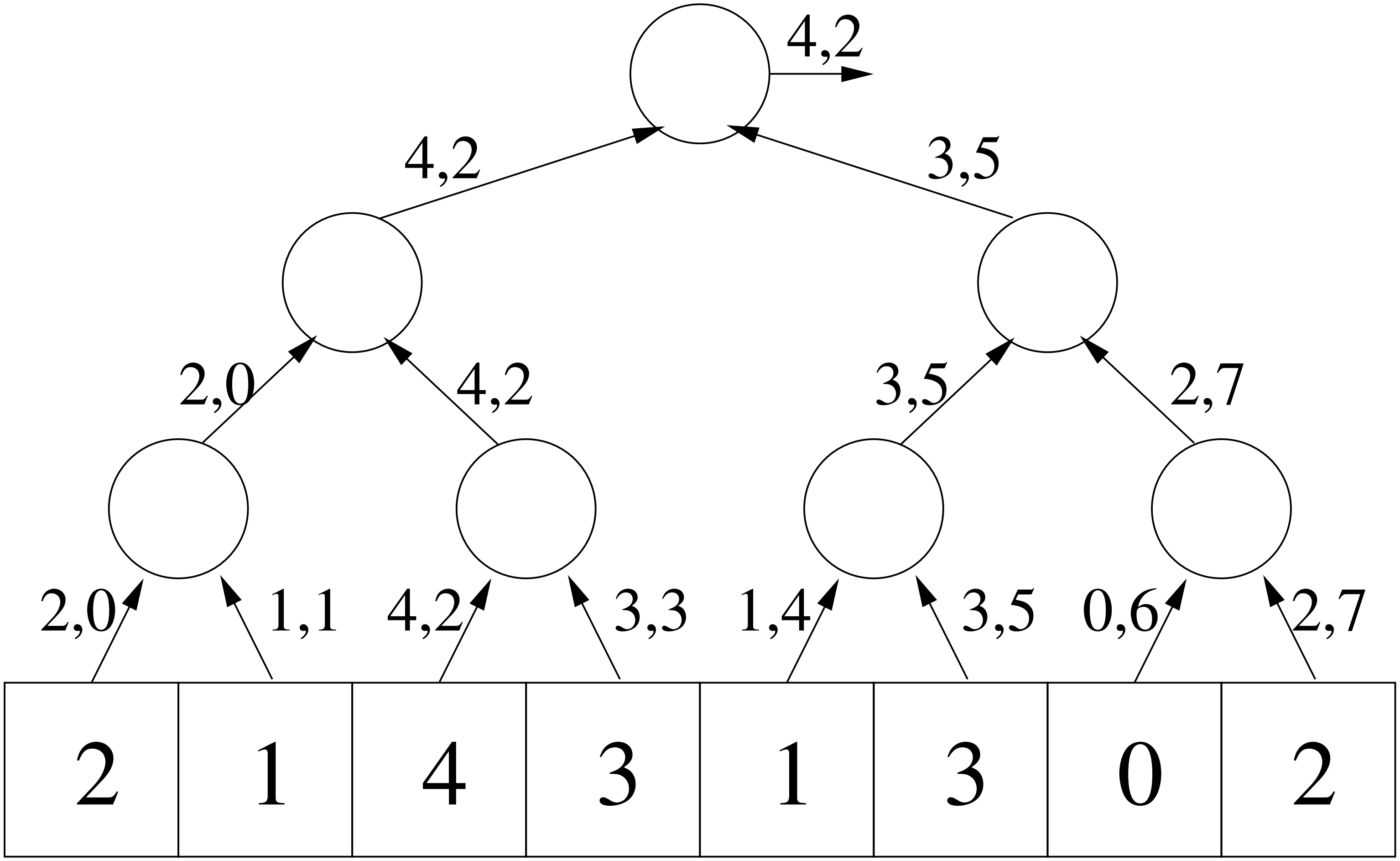
Summing values in an array



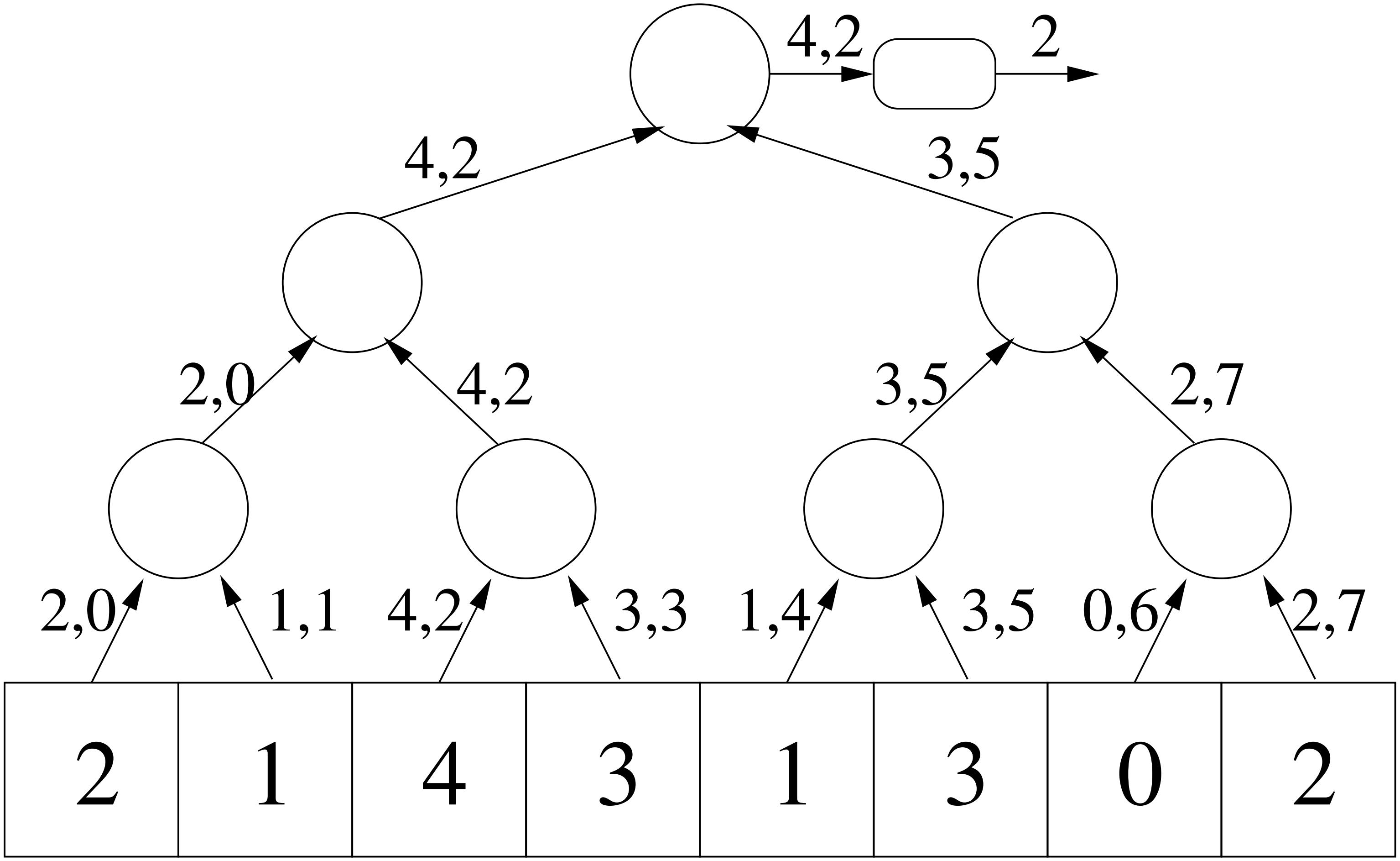
Finding max of an array



Finding the maximum index



Finding the maximum index



Parts of a reduction

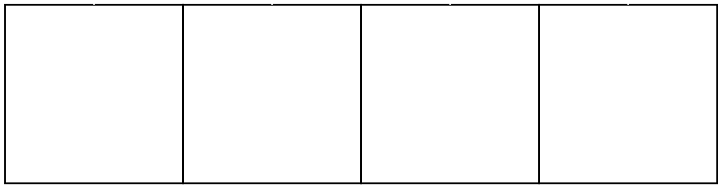
- Tally: Intermediate state of computation
- Combine: Combine 2 tallies
- Reduce-gen: Generate result from tally

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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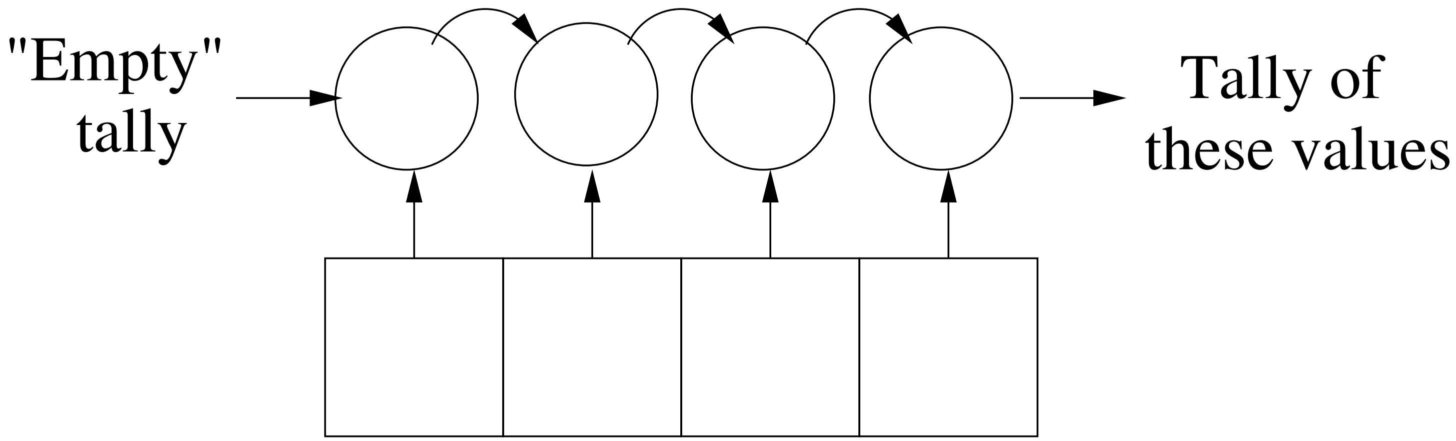
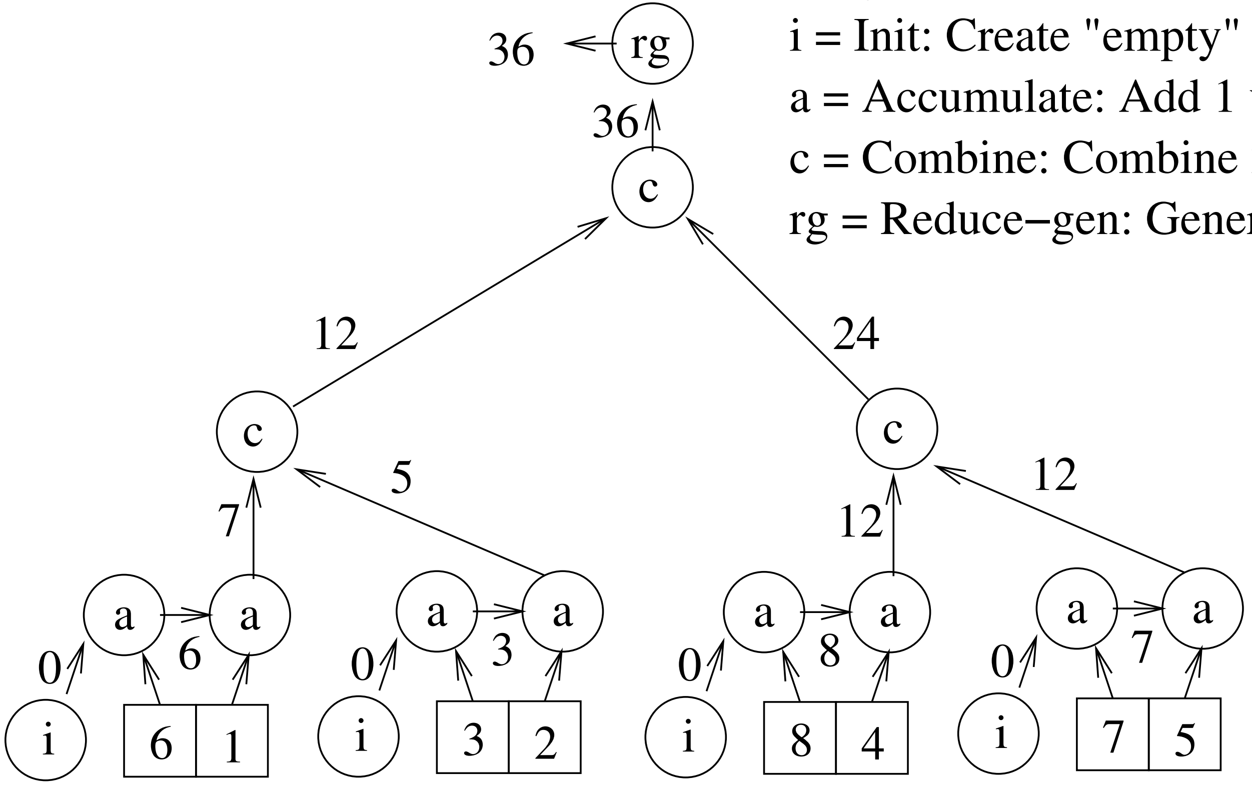


Parts of a reduction

- 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



Tally: Intermediate state of computation
i = Init: Create "empty" tally
a = Accumulate: Add 1 value to tally
c = Combine: Combine 2 tallies
rg = Reduce−gen: Generate result from tally

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: +

Defining reductions

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- Combine: Combine 2 tallies
- Reduce-gen: Generate result from tally
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Sample problems: +, histogram

Defining reductions

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Sample problems: +, histogram, max

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, max, 2nd largest

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, max, 2nd 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

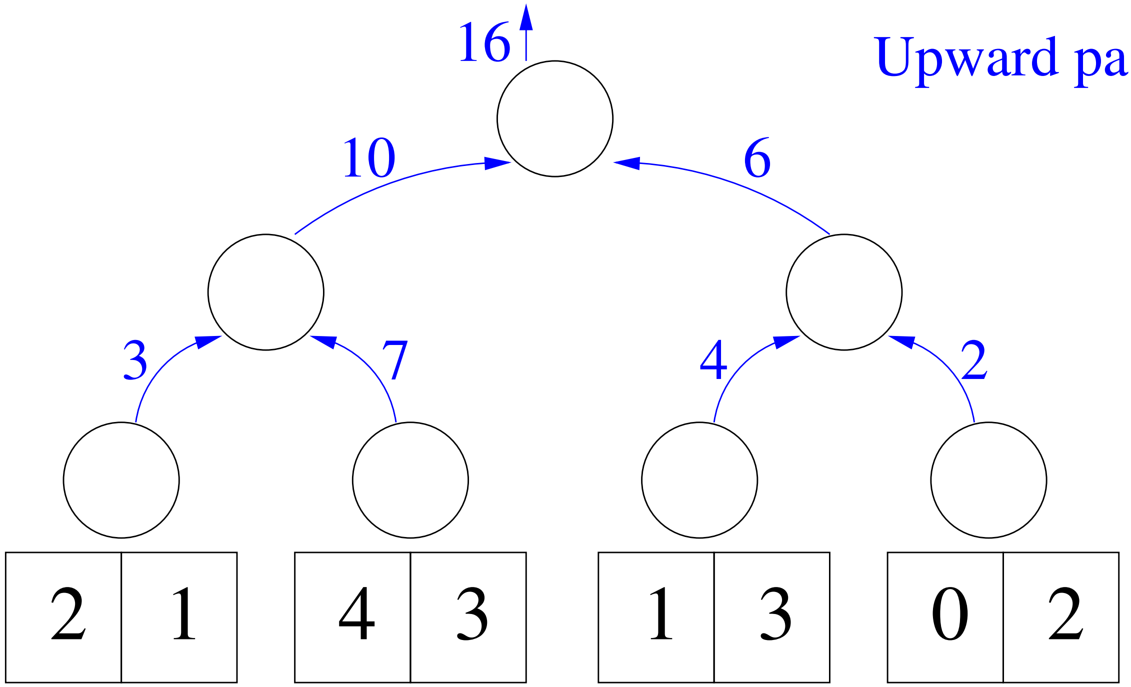
A	2	1	4	3	1	3	0	2
sum	2	3	7	10	11	14	14	16

- Useful answering queries like

“What is the sum of elements 2 thru 7?”

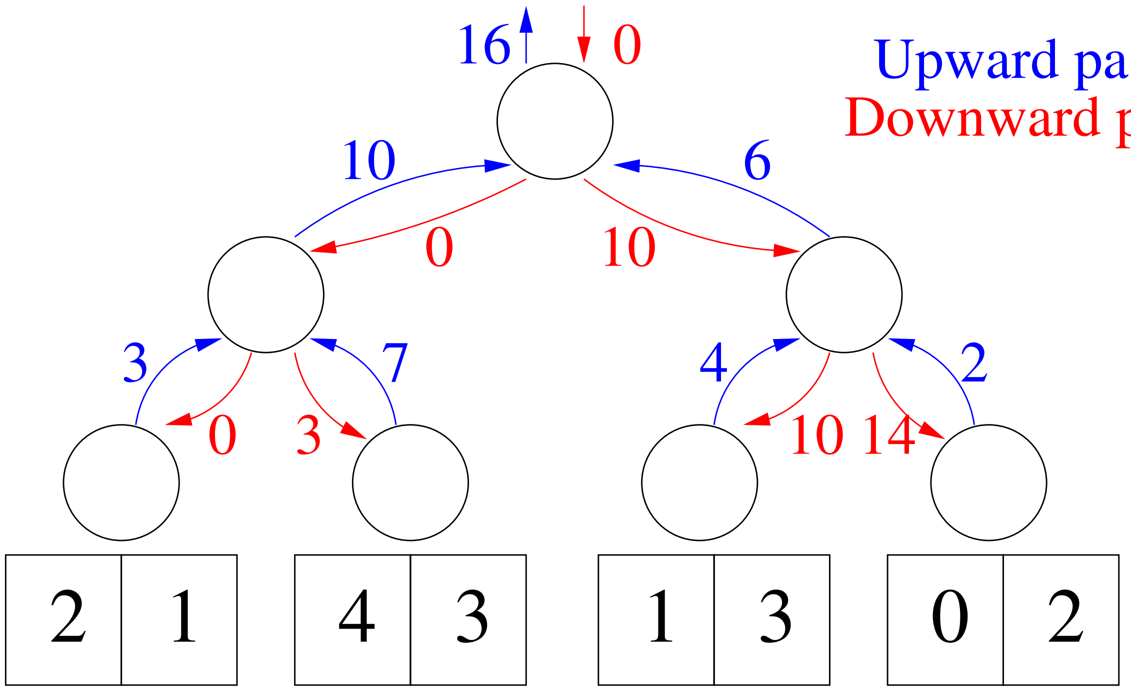
= sum[7] – sum[1]

Computing the scan in parallel



Upward pass to compute reduction

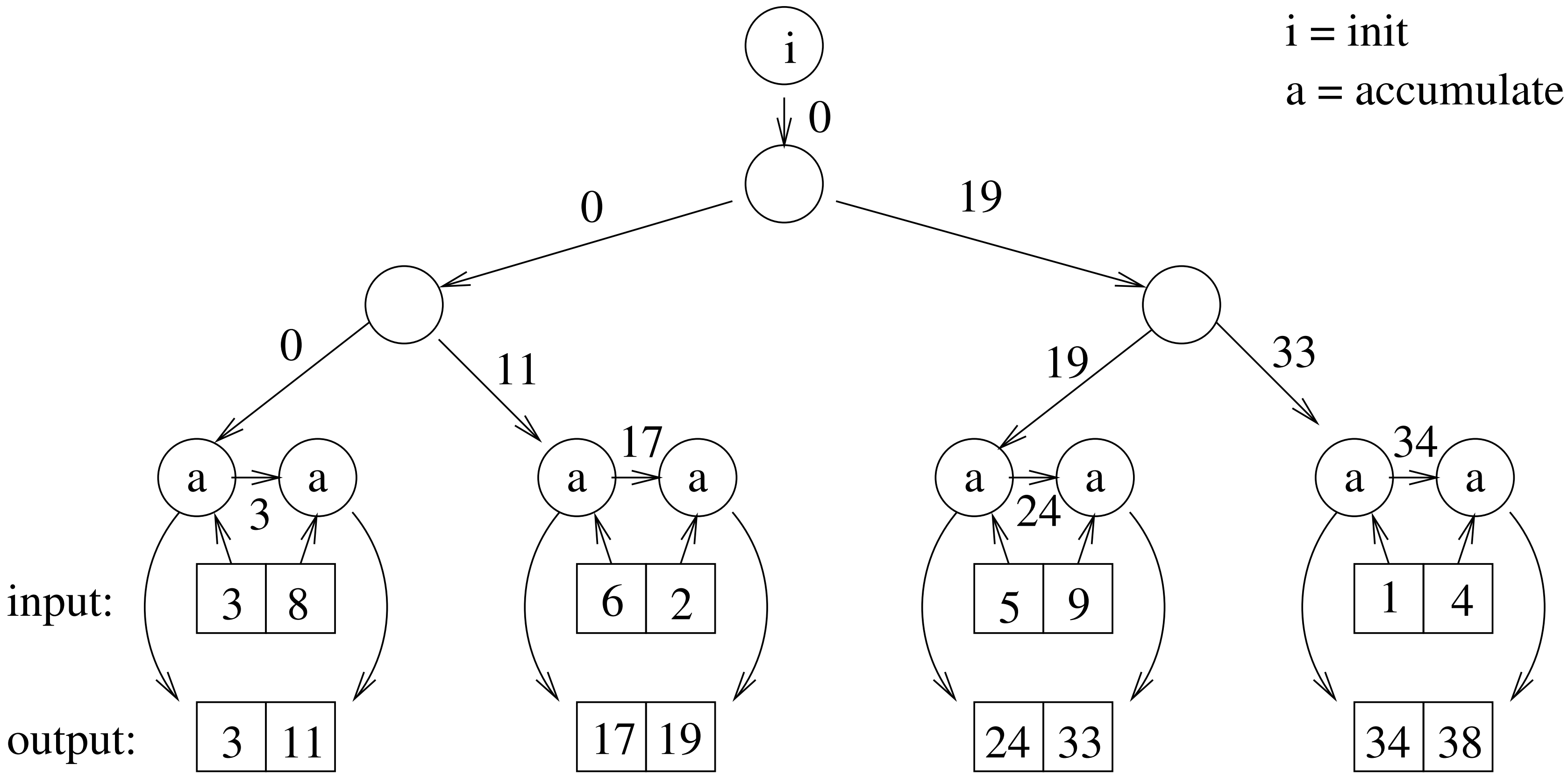
Computing the scan in parallel



Upward pass to compute reduction

Downward pass to also compute scan

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

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