High-level parallel programming using Chapel

David Bunde, Knox College

Kyle Burke, Wittenberg University

Acknowledgements

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Schedule

- Part I: 1:30-3:00
  - Introduction to Chapel and the Workshop
  - Core Features of Chapel
  - Hands-on Session 1
- Part II: 3:30-5:00
  - Advanced Ranges and Domains
  - Other Chapel Features
  - Hands-on Session 2
  - Using Chapel in the Classroom

Basic Facts about 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; recent work on GPUs (see Sidelnik et al., IPDPS 2012)
- Supports (but doesn't require) global-view programming, in which programmers express whole operation rather than specifying each processor's role

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

  Ex: x = + reduce A   //sets x to sum of elements of A

  Also valid for other operators (min, max, *, ...)

- Scans

  Like a reduction, but computes value for each prefix

  A = [1, 3, 2, 5];

  B = + scan A;   //sets B to [1, 1+3=4, 4+2=6, 6+5=11]

Provides High-level Operations (2)

- 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

Your Presenters are...

- Enthusiastic Chapel users
- Interested in high-level parallel programming
- Educators who use Chapel with students

- **NOT connected to Chapel development team**

Chapel Resources

- Materials for this workshop

  http://faculty.knox.edu/dbunde/teaching/chapel/SC12/
- Our tutorials

  http://faculty.knox.edu/dbunde/teaching/chapel/

  http://www4.wittenberg.edu/academics/mathcomp/kburke/chapelTutorial.html
- Chapel website (tutorials, papers, language specification)

  http://chapel.cray.com
- Mailing lists (on SourceForge)

Accessing Practice Systems (during SC only)

- We have practice accounts set up for use during the workshop
- Get handout from one of the instructors

Installing Chapel Yourself

- Instructions (http://chapel.cray.com/download.html)
  - Download: http://sourceforge.net/projects/chapel
  - Unzip file
  - Enter chapel-1.6 directory and invoke make
  - source util/setchplenv.csh or util/setchplenv.sh to set environment variables
- For multiuser installations (e.g. in /usr/local):

  http://faculty.knox.edu/dbunde/teaching/chapel/install.html

Core Features of Chapel

“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 can contain the following:

  ```
  var/const identifier : type = initial_value;
  ```

- var or const: variable or named constant
- Basic types are int, real, boolean, string
- Also supports imaginary and complex values:

  ```
  var x : imag = 1.0i;
  var y : complex = 1.2 + 3.4i;
  ```

- Type is optional if it can be inferred from initial value

Config Variables

- Optionally set from the command line; they're Chapel's alternative to command-line args
- Declared with config:

```
config var x = 0;        //0 unless overridden on
                         //   command line
```

- Set on command line with two dashes: --

```
./hello --x=23           //runs hello with x set to 23
```

Operators

- Most operators are familiar: +, -, *, <, >, <=, ...
- = for assignment, == for equality testing
- / is integer division if both arguments are int

- Colon for casts:

```
var x = 3.14 : int;    //casts to int (truncates)
var y = 2:real / 3;   //promote 2 to 2.0 before division
```

- ** for exponentiation: 2**3 results in 2^3
- <=> swaps value of two variables

Console I/O

- Output uses write and writeln, which support multiple arguments:

```
writeln("The value of x is ", x);
```

- Input uses stdin.read and stdin.readln, which take type as argument:

```
x = stdin.read(int);
```

- When last of input is read, the built-in variable eof is set to true

Example: Reading until eof

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

Serial Control Structures

- if statements, while loops, and do-while loops are all pretty standard (we'll get to for loops)
- Difference: Statement bodies must either use braces or an extra keyword:

  if(x > 5) **then** y = 3;

  while(x < 5) **do** x++;

- Select is multi-way selection (switch in C/Java)

Procedures/Functions

```
proc name([arg_type] arg1 : type1, ...) : return_type {
	body (with return statement(s))
}
```

- Omit return_type for a function with no return value (or if the type can be inferred)
- arg_type controls how arguments are passed:
  - omitted: variable is constant within function (exceptions on ref sheet)
  - in: pass by value (value copied into function)
  - inout: pass by reference (value copied both in and out)
  - out: final value copied back to calling block
- Omit argument types to write generic functions

Procedures/Functions (2)

- Can include default values for arguments by putting assignment in parameter list

```
proc f(x: int = 5) { ... }
```

- Can have a main function w/o arguments as program starting point

Ranges (Take 1)

- [i..j] denotes the range containing i, i+1, ..., j
- The endpoints can be variables
- Range is empty if 2nd value is less than 1st
- Can declare ranges as variables:

```
var R : range = 1..10;
```

Arrays

- Ranges can be used to declare arrays:

  var A : [1..10] int;   //declares A as array of 10 ints

- Indices determined by the range:

  var B : [-3..3] int;   //has indices -3 thru 3

- Array cells are accessed using indices:

  A[1] = 23;

  A[2] = A[1] + 3;

- Arrays generate runtime out-of-bounds errors if invalid indices are used
- Can also create multi-dimensional arrays:

  var C : [1..10, 1..10] int;

Domains

- Array creation actually requires a domain, which is the set of valid indices
- Anonymous domains created by putting range in brackets, but can also create domain variables:

```
var D : domain(1) = {1..10};  //domain of dimension 1
var A1 : [D] int;
var D2 : domain(2) = {1..10,1..10};  //domain of dim 2
var A2 : [D2] int;
```

Domains vs. Ranges

- Despite how similar they seem so far, domains and ranges are different
  - Domains remain tied to arrays so that resizing the domain resizes the array:

```
var R : range = 1..10;
var A : [R] int;
R = 0..10;        //no effect on array
A[0] = 5;         //runtime error
```

```
var D : domain(1) = {1..10};
var A : [D] int;
D = 0..10;        //resizes array
A[0] = 5;         //ok
```

- Domains are more general; some are not sets of integers

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 a domain, array, or anything supporting iteration

Parallel Loops

- To run loop iterations in parallel change for loop to forall or coforall:

  ```
  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

- Can also create a specific task with begin:

```
begin statement;       //create task for statement
```

- Can also create group of tasks and wait for all of them to finish (fork-join parallelism):

```
cobegin {
  statement1;
  statement2;
  ...
}      //creates task for each statement and
       //waits here for all to finish
```

Sync blocks

- sync blocks also wait for all tasks created within the block
- Example with equivalent cobegin block:

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

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

Sync variables

- sync variables have value and empty/full state
  – writing to an empty variable makes it full
  – reading from full variable makes it empty
  – attempt to write to a full variable blocks
  – reading from empty variable blocks
- Can be used to create a lock:

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

Reductions

- Express reduction operation in single line:

  ```
  var s = + reduce A;   //A is array, s gets sum
  ```

- Supports +, *, ^ (xor), &&, ||, max, min, ...
- Also minloc and maxloc, which return a tuple with min/max value and index where it occurs:

  ```
  var (val, loc) = minloc reduce A;
  ```

- Can define custom reductions; need to define class to store partial work

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));
```

Scans

- Can also compute all partial results of a reduction using scan operation:

```
const R : range = 1..5;
const A : [R] int = [3, -1, 4, -2, 0];
var B : [R] int = + scan A;    //B set to [3, 2, 6, 4, 4]
```

Hands-on Session 1

Advanced Ranges and Domains

Chapel Ranges

- What is a range?
- How are ranges used?
- Range operations

Chapel Ranges

- What is a range?
  - A range of values
  - Ex: var someNaturals : range = 0..50;
- How are they used?
  - Indexes for Arrays
  - Iteration space in loops
- Are there cool operations?

Chapel Ranges

- What is a range?
  - A range of values
  - Ex: var someNaturals : range = 0..50;
- How are they used?
    - Indexes for Arrays
    - Iteration space in loops
- Are there cool operations?

    Yes!

Range Operation Examples

```
var someNaturals: range = 0..50;
var someEvens = someNaturals by 2;
                (someEvens: 0, 2, 4, ..., 48, 50)
var someOdds = someEvens align 1;
                (someOdds: 1, 3, 5, 7, ..., 47, 49)
var fewerOdds = someOdds # 6;
                (fewerOdds: 1, 3, 5, 7, 9, 11)
```

Other Cool Range Things

- Can create “infinite” ranges:

```
var naturals: range = 0..;
```

- Ranges in the “wrong order” are auto-empty:

```
var nothing: range = 2..-2;
```

- Otherwise, negatives are just fine

Chapel Domains

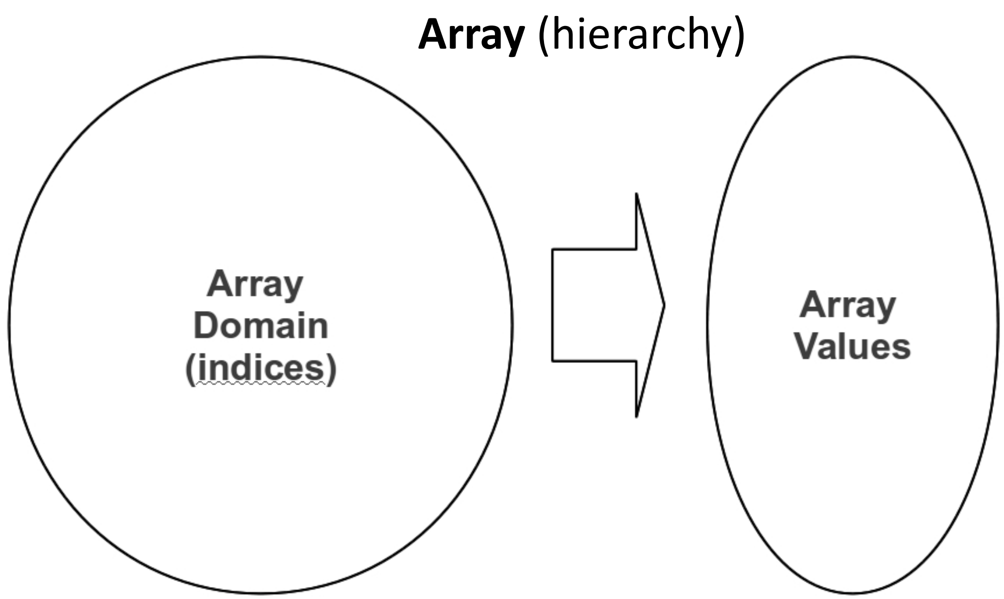
- What is a domain?
- How are domains used?
- Operations on domains
- Running example: Game of Life

Chapel Domains

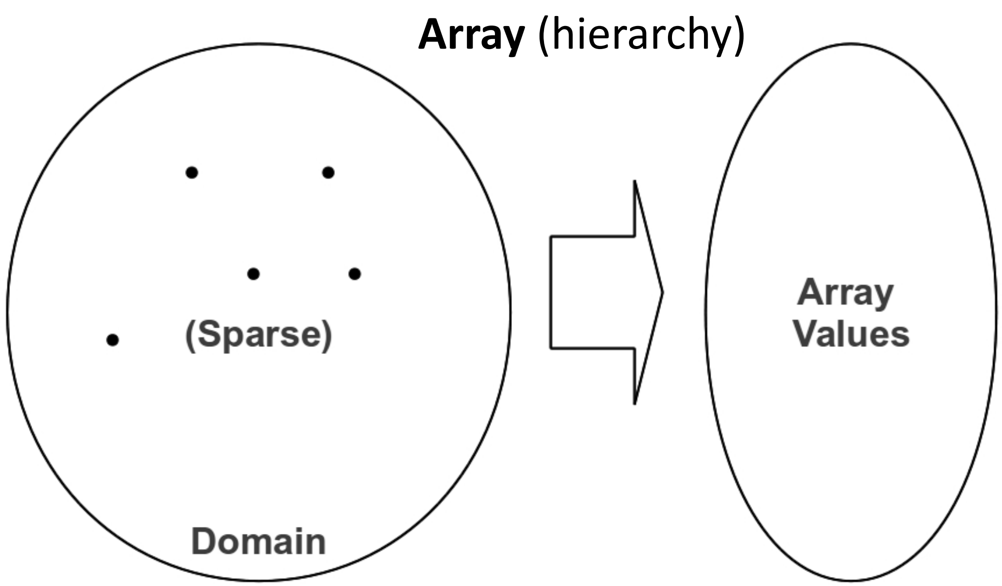
- Domain: index set
  - Used to simplify addressing
  - Every array has a domain to hold its indices
  - Can include ranges or be sparse
- Example:

```
var A: [1..10] int; //indices are 1, 2, ..., 10
...
for i in A.domain {
    //do something with A[i]
}
```

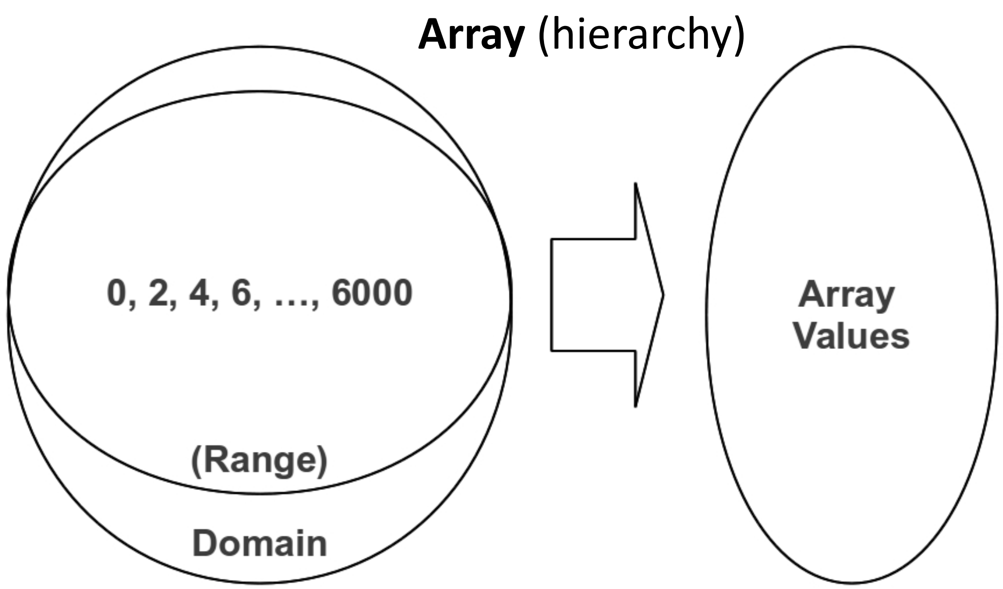
Chapel Domains



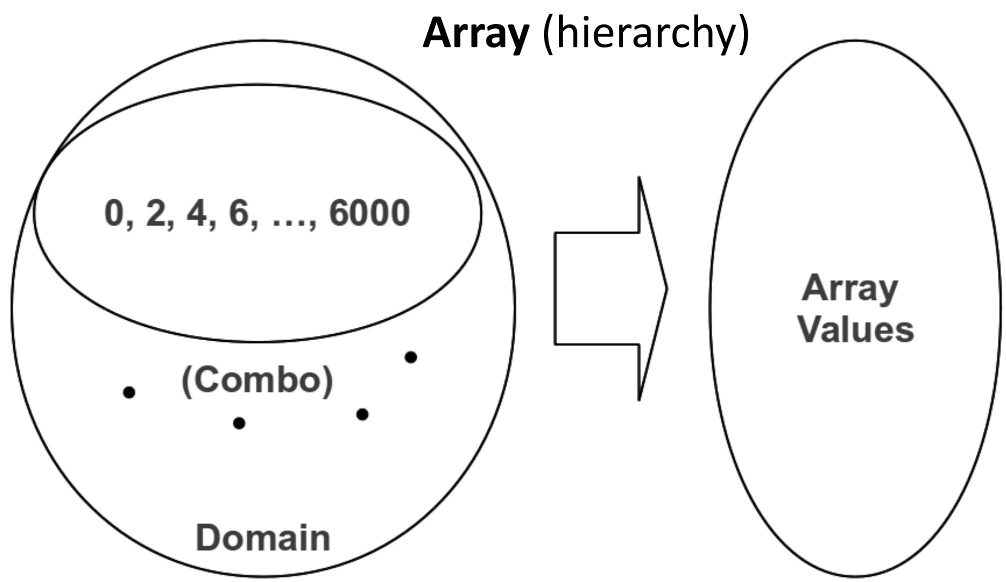
Chapel Domains



Chapel Domains



Chapel Domains



Chapel Domains

- Domain Declaration:
  - var D: domain(2) = {0..m, 0..n};
    - D is 2-D domain with (m+1) x (n+1) entries
  - var A: [D] int;
    - A is an array of integers with D as its domain

Chapel Domains

- Domain Declaration:
  - var D: domain(2) = {0..m, 0..n};
    - D is 2-D domain with (m+1) x (n+1) entries
  - var A: [D] int;
    - A is an array of integers with D as its domain

Why is this useful?

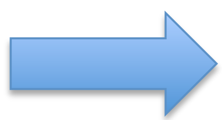
Chapel Domains

- Changing D changes A automatically!
- D = {1..m, 0..n+1}

  decrements height; increments width!

  (adds zeroes)

1	2	3
4	5	6
7	8	9

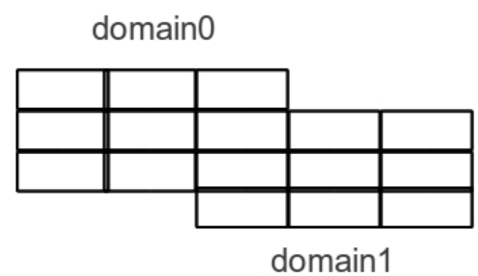


1	2	3	0
4	5	6	0

Domain Slices (Intersection)

domain0: [0..2, 1..3]

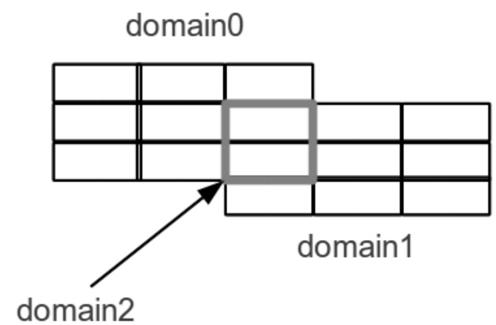
domain1: [1..3, 3..5]



Domain Slices (Intersection)

domain0: [0..2, 1..3]

domain1: [1..3, 3..5]



domain2: [1..2, 3..3]

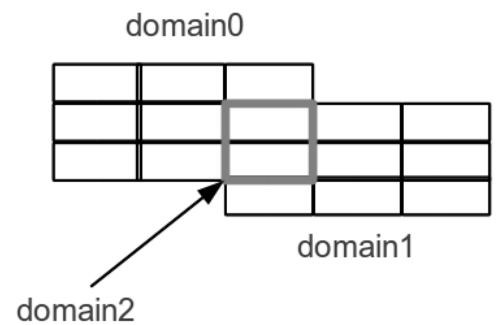
Domain Slices (Intersection)

//domain2 is the intersection of domain1 and domain0

var domain2 = domain1 [domain0];

domain0: [0..2, 1..3]

domain1: [1..3, 3..5]



domain2: [1..2, 3..3]

Domain Slices (Intersection)

```
//domain2 is the intersection of domain1 and domain0
var domain2 = domain1 [domain0];
```

Domains: Unbounded Game of Life

- Example of
  - Domain operations
  - One domain for multiple arrays
  - Changing domain for arrays
- Rules:
  - Each cell is either dead or alive
  - Adjacent to all 8 surrounding cells
  - Dead cell ➔ Living if exactly 3 living neighbors
  - Living cell ➔ Dead if not exactly 2 or 3 living neighbors

Unbounded? How?

- Plan: board starts with small living area, but can grow!
  - Start with 4x4 board

0	1	1	1
1	0	0	1
0	0	0	1
0	0	1	1

Unbounded? How?

- Plan: board starts with small living area, but can grow!
  - Start with 4x4 board
  - Pad all sides with zeros

0	1	1	1
1	0	0	1
0	0	0	1
0	0	1	1

0	0	0	0	0	0
0	0	1	1	1	0
0	1	0	0	1	0
0	0	0	0	1	0
0	0	0	1	1	0
0	0	0	0	0	0

Unbounded? How?

- Plan: board starts with small living area, but can grow!
  - Start with 4x4 board
  - Pad all sides with zeros
  - Iterate forward one round

0	1	1	1
1	0	0	1
0	0	0	1
0	0	1	1

0	0	0	0	0	0
0	0	1	1	1	0
0	1	0	0	1	0
0	0	0	0	1	0
0	0	0	1	1	0
0	0	0	0	0	0

0	0	0	1	0	0
0	0	1	1	1	0
0	0	1	0	1	1
0	0	0	0	1	1
0	0	0	1	1	0
0	0	0	0	0	0

Unbounded? How?

- Plan: board starts with small living area, but can grow!
  - Start with 4x4 board
  - Pad all sides with zeros
  - Iterate forward one round
  - Recalculate subboard with living cells

0	1	1	1
1	0	0	1
0	0	0	1
0	0	1	1

0	0	0	0	0	0
0	0	1	1	1	0
0	1	0	0	1	0
0	0	0	0	1	0
0	0	0	1	1	0
0	0	0	0	0	0

0	0	0	1	0	0
0	0	1	1	1	0
0	0	1	0	1	1
0	0	0	0	1	1
0	0	0	1	1	0
0	0	0	0	0	0

0	0	0	1	0	0
0	0	1	1	1	0
0	0	1	0	1	1
0	0	0	0	1	1
0	0	0	1	1	0
0	0	0	0	0	0

Unbounded? How?

- Plan: board starts with small living area, but can grow!
  - Start with 4x4 board
  - Pad all sides with zeros
  - Iterate forward one round
  - Recalculate subboard with living cells
  - (Un)Pad as necessary

0	1	1	1
1	0	0	1
0	0	0	1
0	0	1	1

0	0	0	0	0	0
0	0	1	1	1	0
0	1	0	0	1	0
0	0	0	0	1	0
0	0	0	1	1	0
0	0	0	0	0	0

0	0	0	1	0	0
0	0	1	1	1	0
0	0	1	0	1	1
0	0	0	0	1	1
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0	0	0	0	0	0

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Unbounded? How?

- Plan: board starts with small living area, but can grow!
  - Start with 4x4 board
  - Pad all sides with zeros
  - Iterate forward one round
  - Recalculate subboard with living cells
  - (Un)Pad as necessary
  - Repeat

0	1	1	1
1	0	0	1
0	0	0	1
0	0	1	1

0	0	0	0	0	0
0	0	1	1	1	0
0	1	0	0	1	0
0	0	0	0	1	0
0	0	0	1	1	0
0	0	0	0	0	0

0	0	0	1	0	0
0	0	1	1	1	0
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0	0	0	1	1	0
0	0	0	0	0	0

0	0	0	1	0	0
0	0	1	1	1	0
0	0	1	0	1	1
0	0	0	0	1	1
0	0	0	1	1	0
0	0	0	0	0	0

0	0	0	0	0	0
0	0	1	0	0	0
0	1	1	1	0	1
0	1	0	1	1	0
0	0	0	1	1	0
0	0	1	1	0	0
0	0	0	0	0	0

Game of Life: Setting the Domain

```
//set the bounds
var minLivingRow = 3;
var maxLivingRow = 6;
var minLivingColumn = 1;
var maxLivingColumn = 4;
```

Game of Life: Setting the Domain

```
//set the bounds
var minLivingRow = 3;
var maxLivingRow = 6;
var minLivingColumn = 1;
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//ranges for the board size
var boardRows = (minLivingRow-1)..(maxLivingRow+1);
var boardColumns = (minLivingColumn-1)..(maxLivingColumn+1);
```

Game of Life: Setting the Domain

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//set the bounds
var minLivingRow = 3;
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//ranges for the board size
var boardRows = (minLivingRow-1)..(maxLivingRow+1);
var boardColumns = (minLivingColumn-1)..(maxLivingColumn+1);

//domain of the game board
//this will change every iteration of the simulation!
var gameDomain: domain(2) = [boardRows, boardColumns];
```

Game of Life: Setting the Domain

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//set the bounds
var minLivingRow = 3;
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var minLivingColumn = 1;
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//ranges for the board size
var boardRows = (minLivingRow-1)..(maxLivingRow+1);
var boardColumns = (minLivingColumn-1)..(maxLivingColumn+1);

//domain of the game board
//this will change every iteration of the simulation!
var gameDomain: domain(2) = [boardRows, boardColumns];

//alive: 1; dead: 0
var lifeArray: [gameDomain] int;          //defaults to zeroes
```

Game of Life: Implementing Rules

```
//returns whether there will be life at (x, y) next round
//(0 means no life, 1 means life)
proc lifeValueNextRound(x, y, currentBoard) {

}
```

Game of Life: Implementing Rules

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//returns whether there will be life at (x, y) next round
//(0 means no life, 1 means life)
proc lifeValueNextRound(x, y, currentBoard) {
```

How can we just focus on the neighboring cells?

```
}
```

Game of Life: Implementing Rules

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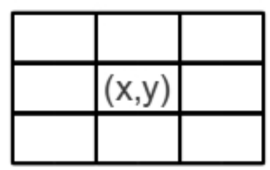
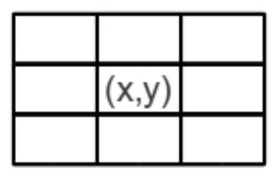
How can we just focus on the neighboring cells?




```
}
```

Game of Life: Implementing Rules

```
//returns whether there will be life at (x, y) next round
//(0 means no life, 1 means life)
proc lifeValueNextRound(x, y, currentBoard) {
    //the 9 cells adjacent to (x, y)
    var adjacentDomain : domain(2) = [x-1..x+1, y-1..y+1];
```




```
}
```

Game of Life: Implementing Rules

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proc lifeValueNextRound(x, y, currentBoard) {
    //the 9 cells adjacent to (x, y)
    var adjacentDomain : domain(2) = [x-1..x+1, y-1..y+1];
```
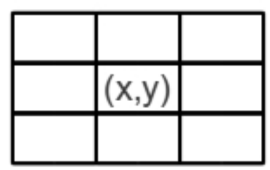

How can we (easily) handle border cases?

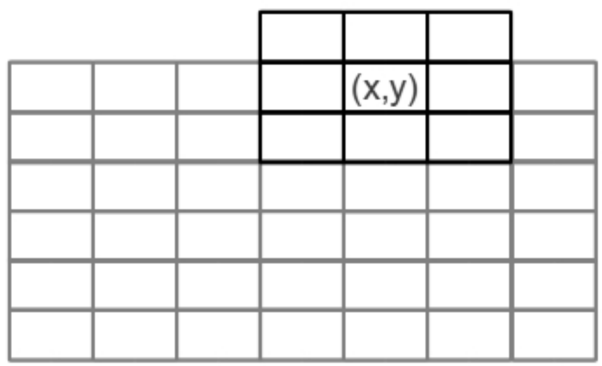



```
}
```

Game of Life: Implementing Rules

```
//returns whether there will be life at (x, y) next round
//(0 means no life, 1 means life)
proc lifeValueNextRound(x, y, currentBoard) {
    //the 9 cells adjacent to (x, y)
    var adjacentDomain : domain(2) = [x-1..x+1, y-1..y+1];
```

How can we (easily) handle border cases?




```
}
```

Game of Life: Implementing Rules

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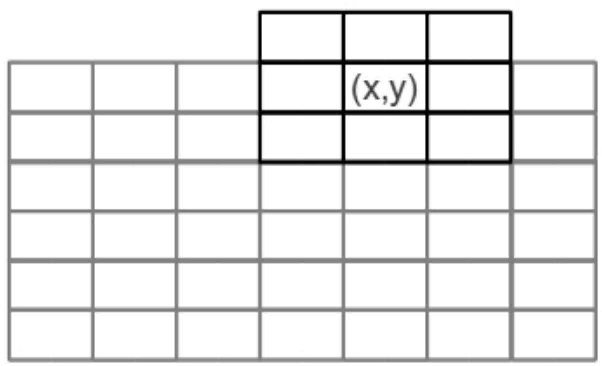
//(0 means no life, 1 means life)
proc lifeValueNextRound(x, y, currentBoard) {
    //the 9 cells adjacent to (x, y)
    var adjacentDomain : domain(2) = [x-1..x+1, y-1..y+1];

    //domain slicing!
    var neighborDomain = adjacentDomain [currentBoard.domain];
```

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Game of Life: Implementing Rules

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proc lifeValueNextRound(x, y, currentBoard) {
    //the 9 cells adjacent to (x, y)
    var adjacentDomain : domain(2) = [x-1..x+1, y-1..y+1];

    //domain slicing!
    var neighborDomain = adjacentDomain [currentBoard.domain];
    var neighborSum = + reduce currentBoard[neighborDomain];
    neighborSum = neighborSum - currentBoard[x, y];





}
```

Game of Life: Implementing Rules

```
//returns whether there will be life at (x, y) next round
//(0 means no life, 1 means life)
proc lifeValueNextRound(x, y, currentBoard) {
	//the 9 cells adjacent to (x, y)
	var adjacentDomain : domain(2) = [x-1..x+1, y-1..y+1];

	//domain slicing!
	var neighborDomain = adjacentDomain [currentBoard.domain];
	var neighborSum = + reduce currentBoard[neighborDomain];
	neighborSum = neighborSum - currentBoard[x, y];

	//the survival/reproduction rules for the Game of Life
	if 2 <= neighborSum && neighborSum <= 3 && currentBoard[x, y] == 1 {
		return 1;
	} else if currentBoard[x, y]== 0 && neighborSum == 3 {
		return 1;
	} else { return 0; }
}
```

Game of Life: Supporting Boards

```
//next turn's board
var nextLifeArray: [gameDomain] int;
```

Game of Life: Supporting Boards

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var nextLifeArray: [gameDomain] int;
```

Also, want to easily determine bounds on where life is! How?

Game of Life: Supporting Boards

//next turn's board
var nextLifeArray: [gameDomain] int;

Also, want to easily determine bounds on where life is! How?

	6			9
1	0	0	0	0
	0	0	0	0
	0	1	1	0
	1	1	0	0
5	0	1	0	0

Game of Life: Supporting Boards

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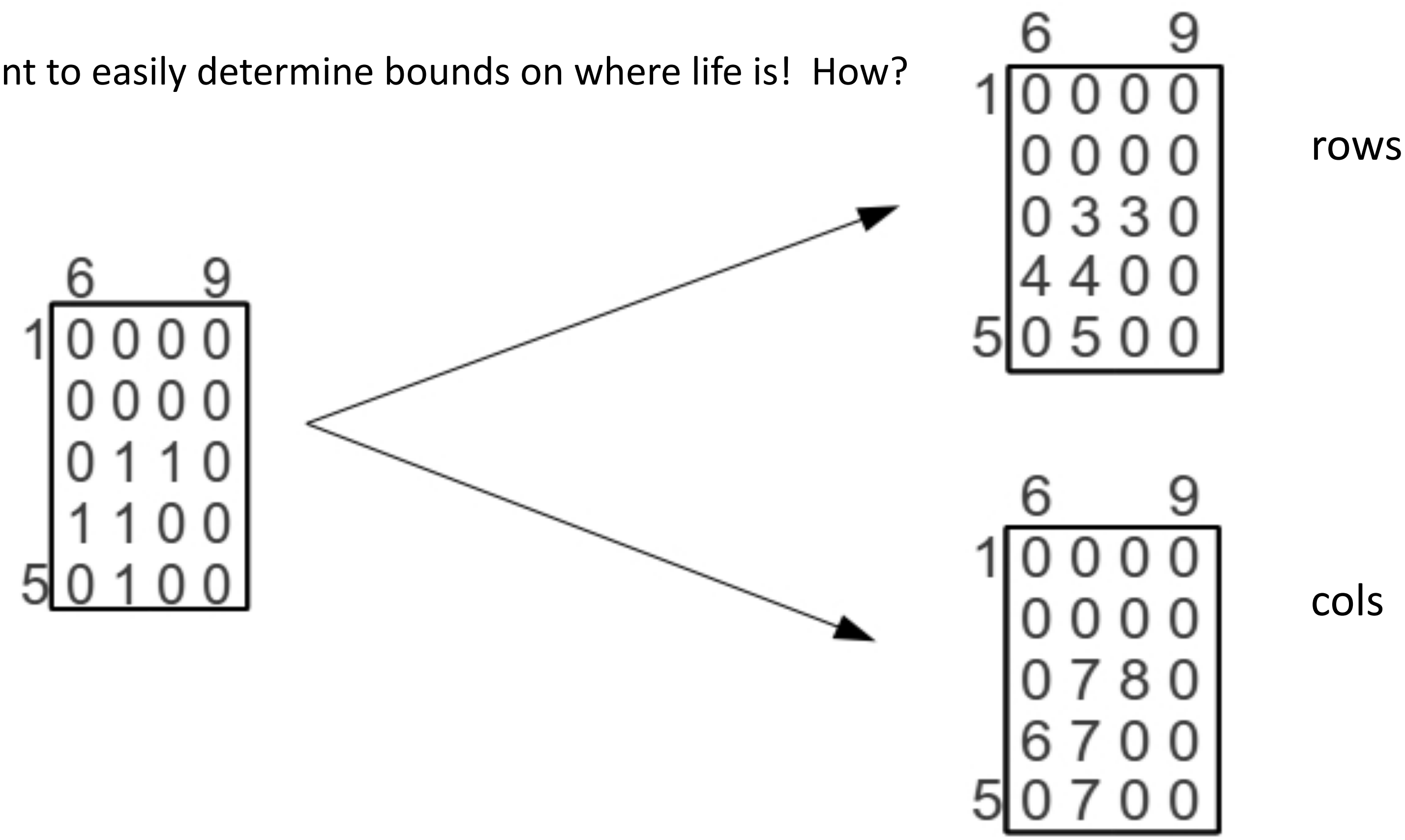
Also, want to easily determine bounds on where life is! How?



Game of Life: Supporting Boards

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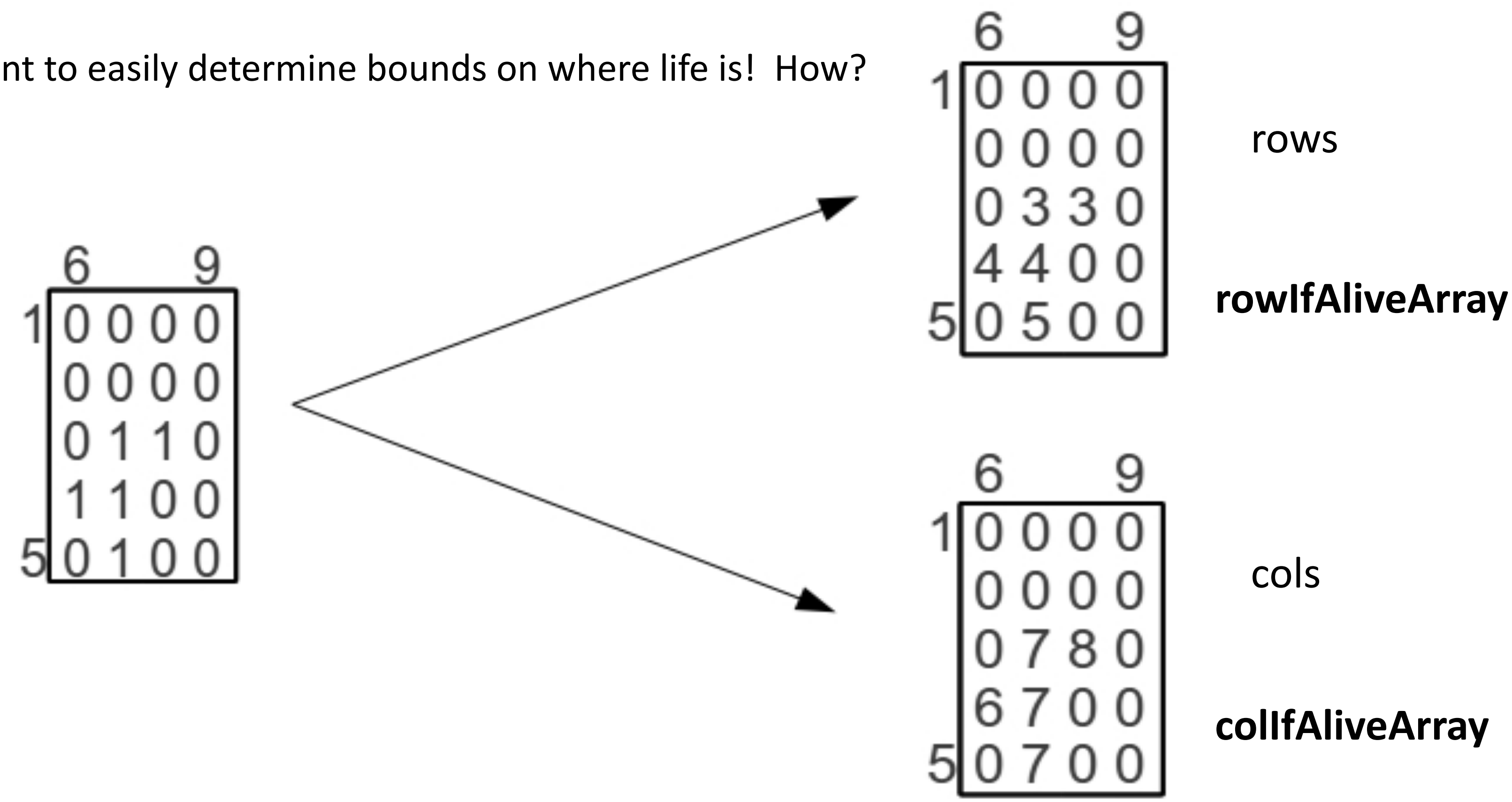

Game of Life: Supporting Boards

//next turn's board

var nextLifeArray: [gameDomain] int;

Also, want to easily determine bounds on where life is! How?

maxLivingRow =

max reduce rowIfAliveArray;

minLivingRow =

min reduce rowIfAliveArray;

maxLivingColumn =

max reduce columnIfAliveArray;

minLivingColumn =

min reduce columnIfAliveArray;

rows

	6			9
1	0	0	0	0
	0	0	0	0
	0	3	3	0
	4	4	0	0
5	0	5	0	0

rowIfAliveArray

cols

	6			9
1	0	0	0	0
	0	0	0	0
	0	7	8	0
	6	7	0	0
5	0	7	0	0

colIfAliveArray

Game of Life: Supporting Boards

//next turn's board
var nextLifeArray: [gameDomain] int;

Doesn't work! Zeros!

maxLivingRow =
max reduce rowIfAliveArray;
minLivingRow =
min reduce rowIfAliveArray;
maxLivingColumn =
max reduce columnIfAliveArray;
minLivingColumn =
min reduce columnIfAliveArray;

rows

	6			9
1	0	0	0	0
	0	0	0	0
	0	3	3	0
	4	4	0	0
5	0	5	0	0

rowIfAliveArray

cols

	6			9
1	0	0	0	0
	0	0	0	0
	0	7	8	0
	6	7	0	0
5	0	7	0	0

colIfAliveArray

Game of Life: Supporting Boards

//next turn's board
var nextLifeArray: [gameDomain] int;

Doesn't work! Zeros!

Solution: replace with middle index

maxLivingRow =
max reduce rowIfAliveArray;
minLivingRow =
min reduce rowIfAliveArray;
maxLivingColumn =
max reduce columnIfAliveArray;
minLivingColumn =
min reduce columnIfAliveArray;

rows

	6			9
1	0	0	0	0
	0	0	0	0
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rowIfAliveArray

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1	0	0	0	0
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colIfAliveArray

Game of Life: Supporting Boards

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Doesn't work! Zeros!

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maxLivingRow =
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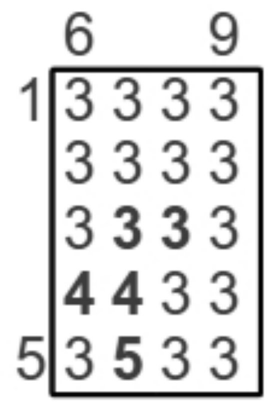
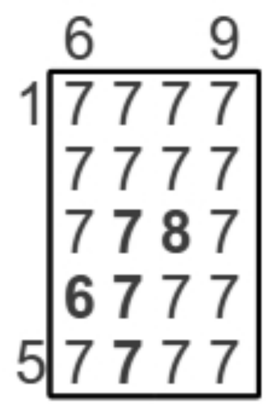


rows

rowIfAliveArray



cols

colIfAliveArray

Game of Life: Supporting Boards

```
//next turn's board
var nextLifeArray: [gameDomain] int;

//if life is here, it will contain its column index,
//otherwise, the board's middle column index
var columnIfAliveArray: [gameDomain] int;

//if life is here, it will contain its row index,
//otherwise, the board's middle row index
var rowIfAliveArray: [gameDomain] int;
```

Game of Life: Supporting Boards

```
//next turn's board
var nextLifeArray: [gameDomain] int;

//if life is here, it will contain its column index,
//otherwise, the board's middle column index
var columnIfAliveArray: [gameDomain] int;

//if life is here, it will contain its row index,
//otherwise, the board's middle row index
var rowIfAliveArray: [gameDomain] int;

...

//later on, use simple reductions:
maxLivingRow = max reduce rowIfAliveArray;
minLivingRow = min reduce rowIfAliveArray;
maxLivingColumn = max reduce columnIfAliveArray;
minLivingColumn = min reduce columnIfAliveArray;
```

Game of Life: Initial Life

```
//default values are 0 (no life) and 1 (life)
//following locations start alive:
lifeArray[minLivingRow, minLivingColumn + 1] = 1;
lifeArray[minLivingRow, minLivingColumn + 2] = 1;
lifeArray[minLivingRow, minLivingColumn + 3] = 1;
lifeArray[minLivingRow + 1, minLivingColumn] = 1;
lifeArray[minLivingRow + 1, minLivingColumn + 3] = 1;
lifeArray[minLivingRow + 2, minLivingColumn + 3] = 1;
lifeArray[minLivingRow + 3, minLivingColumn + 2] = 1;
lifeArray[minLivingRow + 3, minLivingColumn + 3] = 1;
```

Game of Life: "If Alive" Functions

```
/* If life exists in array at location (x, y), then this returns the index of the row (x). Otherwise, this returns the index of
       the middle row of array. */
proc rowIfAlive(x, y, array) {




}
```

Game of Life: “If Alive” Functions

- Easy: returning the row/column number

```
/* If life exists in array at location (x, y), then this returns the index of the row (x). Otherwise, this returns the index of
       the middle row of array. */
proc rowIfAlive(x, y, array) {
       if array[x, y] == 1 {
              return x;
       }




}
```

Game of Life: "If Alive" Functions

- Easy: returning the row/column number
- Less easy: getting the index of the middle row

```
/* If life exists in array at location (x, y), then this returns the index of the row (x). Otherwise, this returns the index of
       the middle row of array. */
proc rowIfAlive(x, y, array) {
       if array[x, y] == 1 {
              return x;
       }




}
```

Game of Life: "If Alive" Functions

- Easy: returning the row/column number
- Less easy: getting the index of the middle row
  - Use dim domain method to get 1-D subrange

```
/* If life exists in array at location (x, y), then this returns the index of the row (x). Otherwise, this returns the index of
       the middle row of array. */
proc rowIfAlive(x, y, array) {
       if array[x, y] == 1 {
              return x;
       }
       //determine and return the middle row index
       var rowRange = array.domain.dim(1);



}
```

Game of Life: “If Alive” Functions

- Easy: returning the row/column number
- Less easy: getting the index of the middle row
  - Use dim domain method to get 1-D subrange
  - Use high and low range properties

```
/* If life exists in array at location (x, y), then this returns the index of the row (x). Otherwise, this returns the index of
    the middle row of array. */
proc rowIfAlive(x, y, array) {
    if array[x, y] == 1 {
        return x;
    }
    //determine and return the middle row index
    var rowRange = array.domain.dim(1);
    var rowHigh = rowRange.high;
    var rowLow = rowRange.low;

}
```

Game of Life: “If Alive” Functions

- Easy: returning the row/column number
- Less easy: getting the index of the middle row
  - Use dim domain method to get 1-D subrange
  - Use high and low range properties
  - Calculate and return middle index

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/* If life exists in array at location (x, y), then this returns the index of the row (x). Otherwise, this returns the index of
    the middle row of array. */
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    if array[x, y] == 1 {
        return x;
    }
    //determine and return the middle row index
    var rowRange = array.domain.dim(1);
    var rowHigh = rowRange.high;
    var rowLow = rowRange.low;
    return (rowLow + rowHigh)/2;
}
```

Game of Life: “If Alive” Functions

- Easy: returning the row/column number
- Less easy: getting the index of the middle row
  - Use dim domain method to get 1-D subrange
  - Use high and low range properties
  - Calculate and return middle index
  - (Doesn't work if the range is strided.)

```
/* If life exists in array at location (x, y), then this returns the index of the row (x). Otherwise, this returns the index of
   the middle row of array. */
proc rowIfAlive(x, y, array) {
    if array[x, y] == 1 {
        return x;
    }
    //determine and return the middle row index
    var rowRange = array.domain.dim(1);
    var rowHigh = rowRange.high;
    var rowLow = rowRange.low;
    return (rowLow + rowHigh)/2;
}
```

Game of Life: Main Loop

```
for round in 1..numRounds {
    forall (i , j) in gameDomain {
        //set the elements of the next life array
        nextLifeArray[i,j] = lifeValueNextRound(i,j, lifeArray);

        //set the "location if alive" arrays
        rowIfAliveArray[i,j] = rowIfAlive(i,j, nextLifeArray);
        columnIfAliveArray[i,j] = columnIfAlive(i,j, nextLifeArray);
    }

    //reset the bounds with reductions
    maxLivingRow = max reduce rowIfAliveArray;
    minLivingRow = min reduce rowIfAliveArray;
    maxLivingColumn = max reduce columnIfAliveArray;
    minLivingColumn = min reduce columnIfAliveArray;

    //reset the game domain, including buffer of no life
    gameDomain = [(minLivingRow-1)..(maxLivingRow+1),
                  (minLivingColumn-1)..(maxLivingColumn+1)];
    lifeArray = nextLifeArray;
}
```

Game of Life: Add writeln and Go!

- Add print statements for each iteration of the loop and watch it go
- I added a printLifeArray function
- Final version available at:

  https://dl.dropbox.com/u/43416022/SC12/GameOfLife.chpl

Other Chapel Features

OO programming in Chapel

- Structures: Records and Classes
  - Several named variables combined into one object
  - Can have accompanying methods
  - Difference: Assignment copies contents of a record, but only a reference for a class

Circle as a Record

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

var c1, c2 : Circle;        //creates 2 Circle records
c1 = new Circle(10);        /* uses system-supplied constructor
                                to initialize attribute in another
                                and copy values into c1 */
c2 = c1;                    //copies fields from c1 to c2
```

Circle as a Class

```
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 */
```

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

Example "Custom" Reduction

```
class MyMin {       //finds minimum element (equiv. to built-in reduction 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; }
}
```

Hands-on Session 2

Using Chapel in the Classroom

Chapel in the Classroom

- Use in courses
  - Analysis of Algorithms
  - Programming Languages
  - Other courses?
- Hurdles
  - Still in development
- Discussion: How do you want to use Chapel?

Analysis of Algorithms

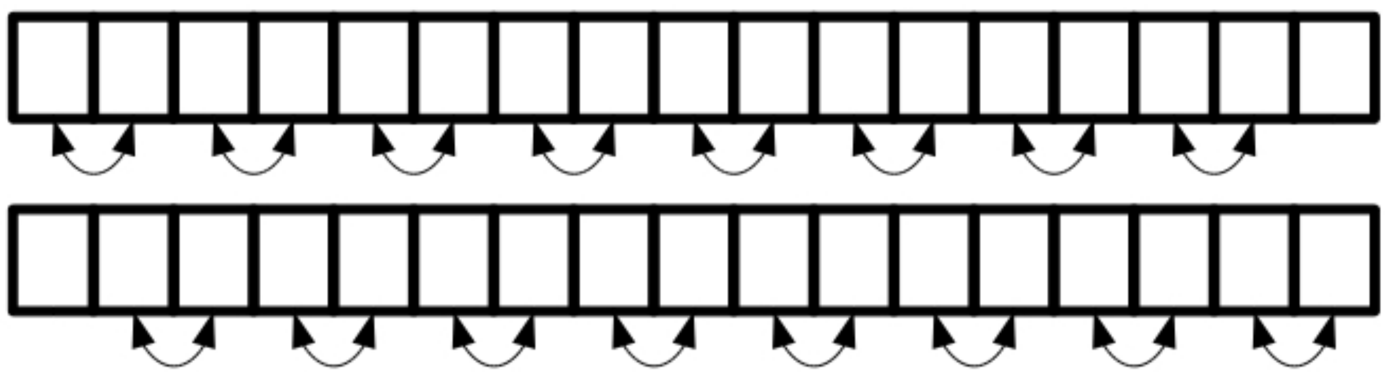
- Chapel material
  - Assign basic tutorial
  - Teach forall & cobegin (also algorithmic notation)
- Projects
  - Partition integers
  - BubbleSort
  - MergeSort
  - Nearest Neighbors

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

Programming Languages

- High-Performance Computing as Paradigm
- Lots of design choices in Chapel to discuss:
  - Task Creation (instead of Threads) with 'begin'.
  - Task Synchronicity with 'sync' and cobegin
  - Parallel loops: forall and coforall
  - Thread safety using variable 'sync'
  - reduce overcomes bottleneck
- Project:
  - Matrix Multiplication (two different ways)

PL: Thread Generation

- Ex. Java: have to create an object
- Chapel: instead create tasks
  - Chapel decides when to generate threads
  - Basic keyword: begin

```
begin {
    producer.run();
}
```

PL: Array Sum

- Divide between two tasks:

```
begin {
    // save value in lowerHalfSum
}
//loop to find upperHalfSum
total = lowerHalfSum + upperHalfSum
```

- Problem: new task might not finish in time
  - Solution: Chapel includes keyword 'sync'

PL: Synchronized Tasks

- Use sync:

```
sync {
    begin {
        //loop to find lowerHalfSum
    }
    begin {
        //loop to find upperHalfSum
    }
}
sum = lowerHalfSum + upperHalfSum
```

- Pattern used often; Chapel uses 'cobegin' to simplify.

PL: cobegin

- Use cobegin:

```
cobegin {
    //loop to find lowerHalfSum
    //loop to find upperHalfSum
}
```

- Much simpler!

PL: forall

- "forall": common command in parallel algorithm design
  - Give example
  - forall vs. coforall (data vs. task parallelism)
- Thread safety
  - Write arraySum with forall
  - Run it; get different results!
  - Define thread safe
  - Use 'sync' (for variables) to fix

PL: sync bottleneck and reduce

- sync causes a bottleneck:
  - Threads may block; Running time still linear!
- Reductions:
  - Divide-and-conquer solution
  - Simplify with 'reduce' keyword!

PL: Projects

- Matrix Multiplication
  - Did matrix-vector multiplication in class
  - Different algorithms:
    - Column-by-column
    - One entry at a time
- Collatz conjecture testing
  - Generate lots of tasks (coforall)
  - How to synchronize?

PL: Takeaways

- Lots of language features to discuss!
- Motivation is obvious
- Students love it!

How else might you use Chapel?

- Parallel Computing
  - Quick prototyping, easily-changed data distribution, ...
- Operating Systems
  - Easy thread generation for scheduling projects
- Software Design
  - Some parallel design patterns have lightweight Chapel implementations
- Artificial Intelligence
  (or other courses w/ computationally-intense projects)
- Independent Projects

Disclaimer!

- Still in development
  - Error Messages thin
  - Recursive functions can't return arrays
  - Basic libraries missing
  - (Students thought this was awesome!)
- No Development Environment
  - Command-line compilation/running
  - Linux learning curve?

Conclusions

- Chapel is easy to pick up
- Chapel can be used in many courses
- Loads of features, but...
- Flexible depth of material
- Students will dig in!

Your Feedback

- What are your impressions of Chapel?
- How likely are you to adopt Chapel?
  - What course(s) will you use it in?
- What resources would help you adopt it?