Adaptive Mesh Refinement in Chapel: An Acid Test for High Productivity Programming

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Cray Inc. Tech Forum

December 2, 2010

Overview

Goal

- Initially modest: Isolate “motifs” of adaptive mesh refinement, suitable for benchmarking

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- Fully-functional, **dimension-independent** AMR framework in under 4 months, with no prior Chapel experience

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Results

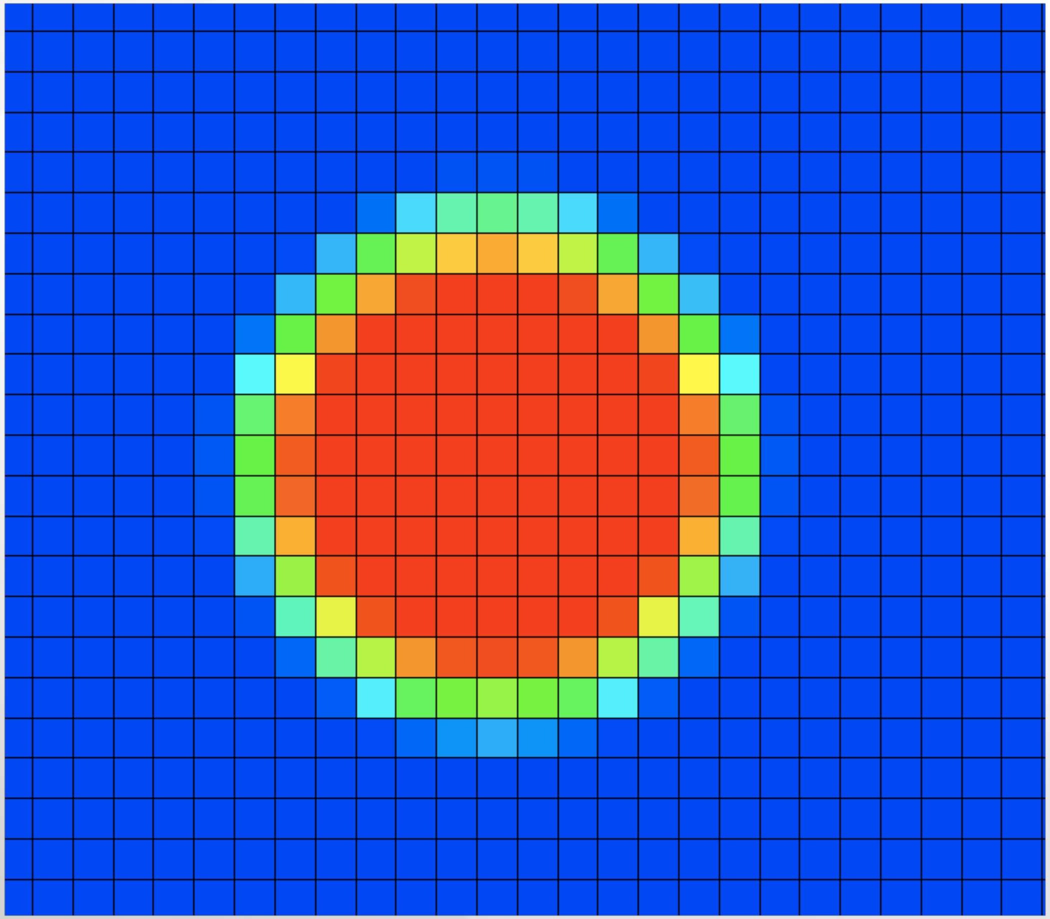
- Fully-functional, **dimension-independent** AMR framework in under 4 months, with no prior Chapel experience
- Code is drastically shorter than existing libraries:

Language	Parallelism	SLOC[1]	Tokens	Relative size (tokens)
Chapel (any D)	Shared mem.	1988	13783	1
Fortran (2D+3D)[2]	Serial	16562	151992	11.03
2D		8297	71639	5.20
3D		8265	80353	5.83
C/C++ (any D)[3]	Dist. mem.	40200	261427	20.22

[1] source ines of code, [2] AMRClaw, [3] Chombo BoxTools+AMRTools

Adaptive Mesh Refinement (AMR)

Provide enhanced resolution in regions where features are poorly resolved



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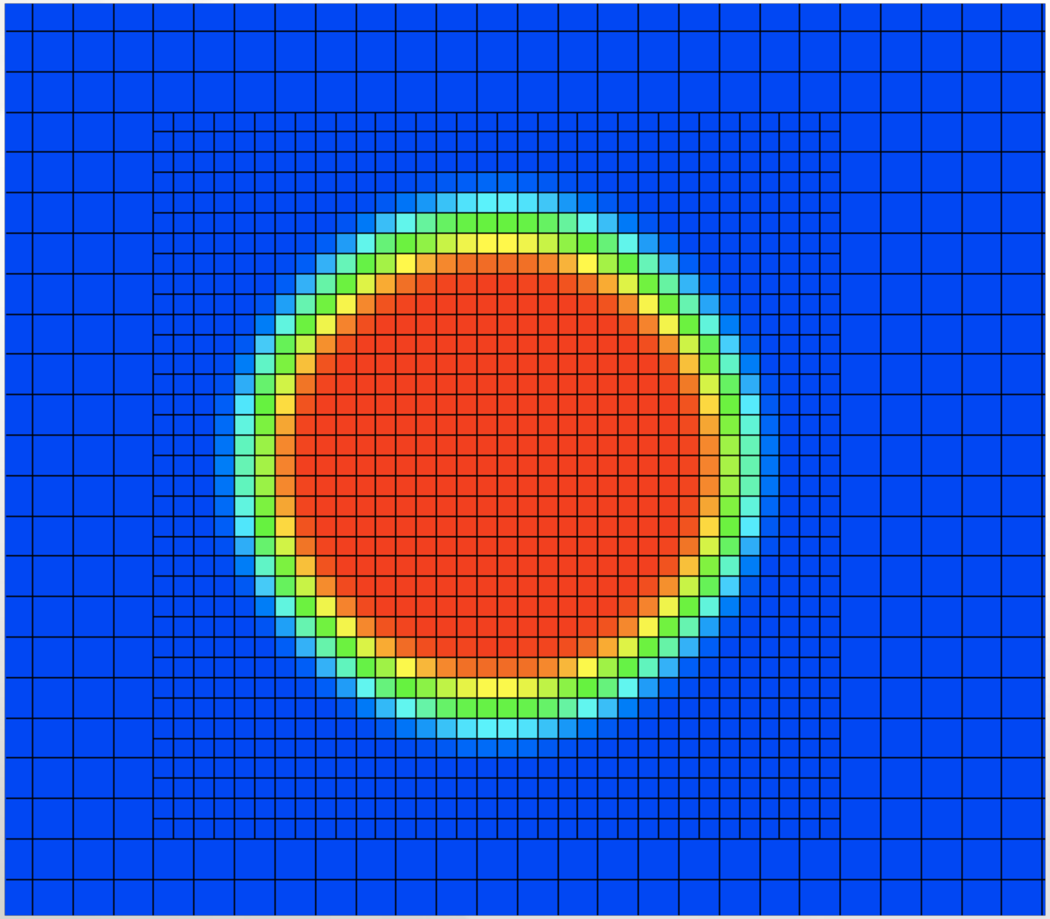

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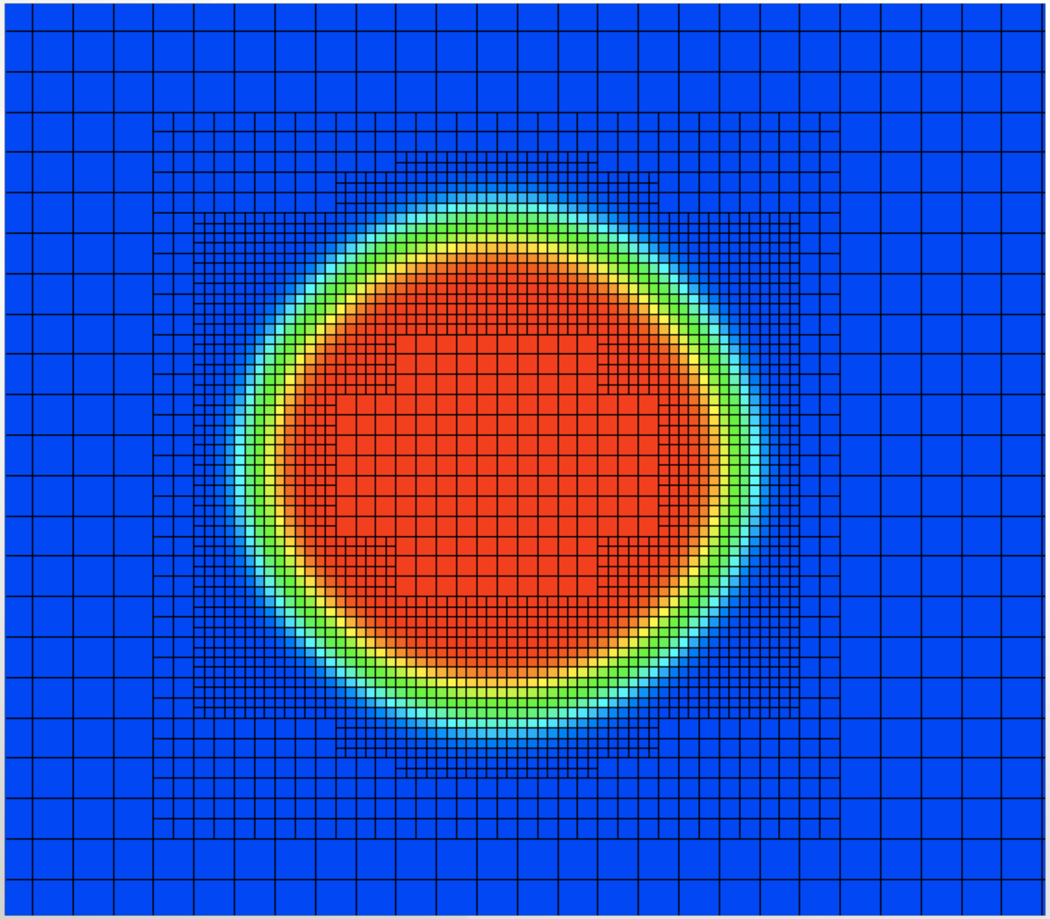
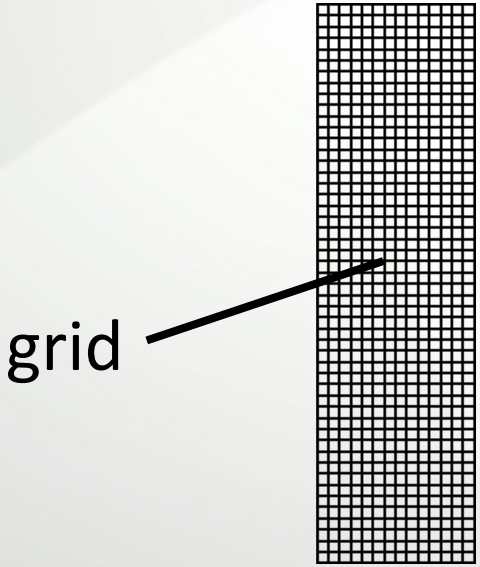


AMR Terminology



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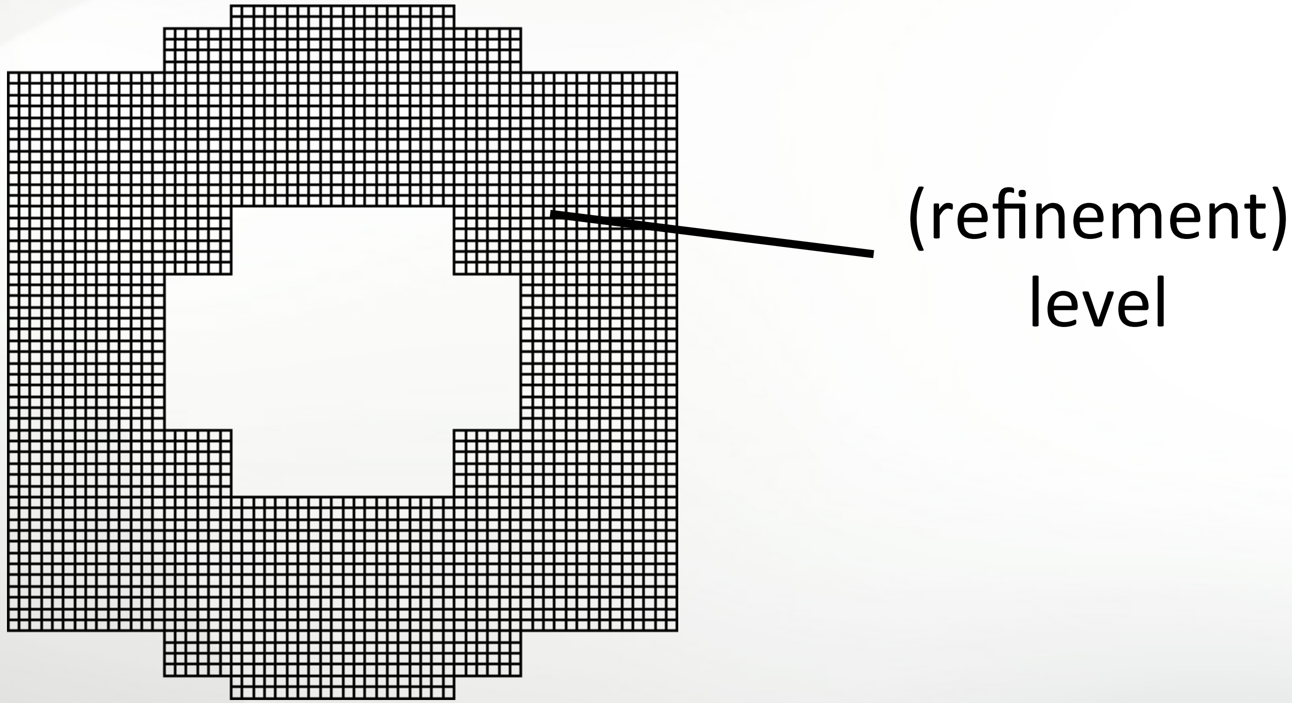

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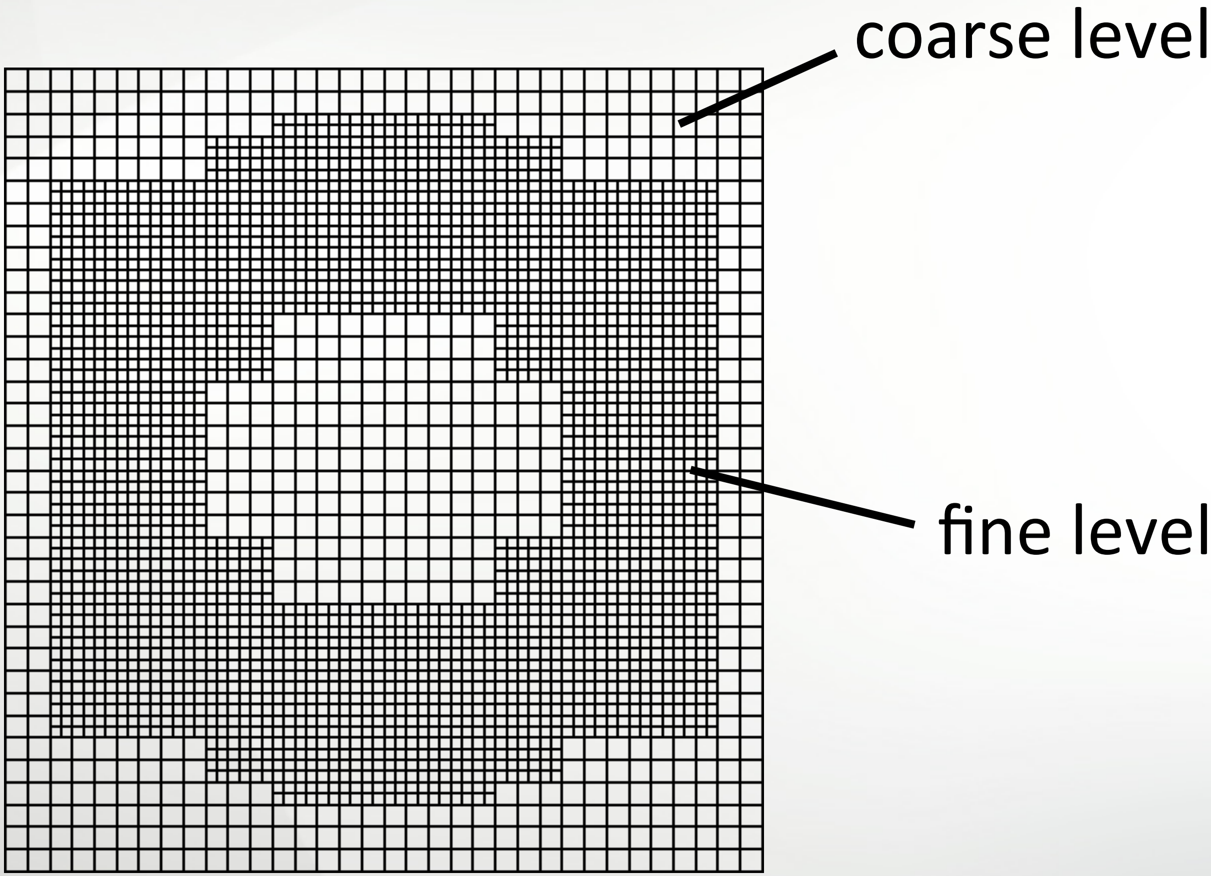

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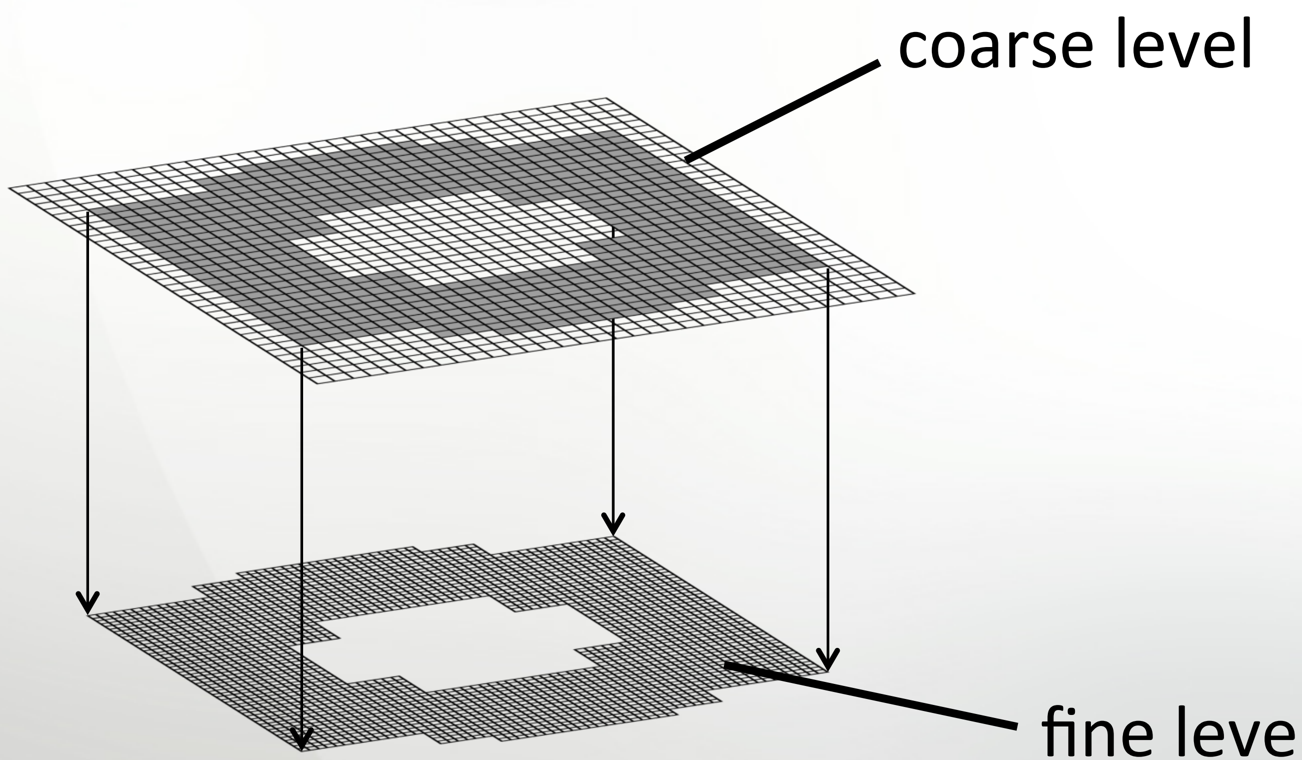

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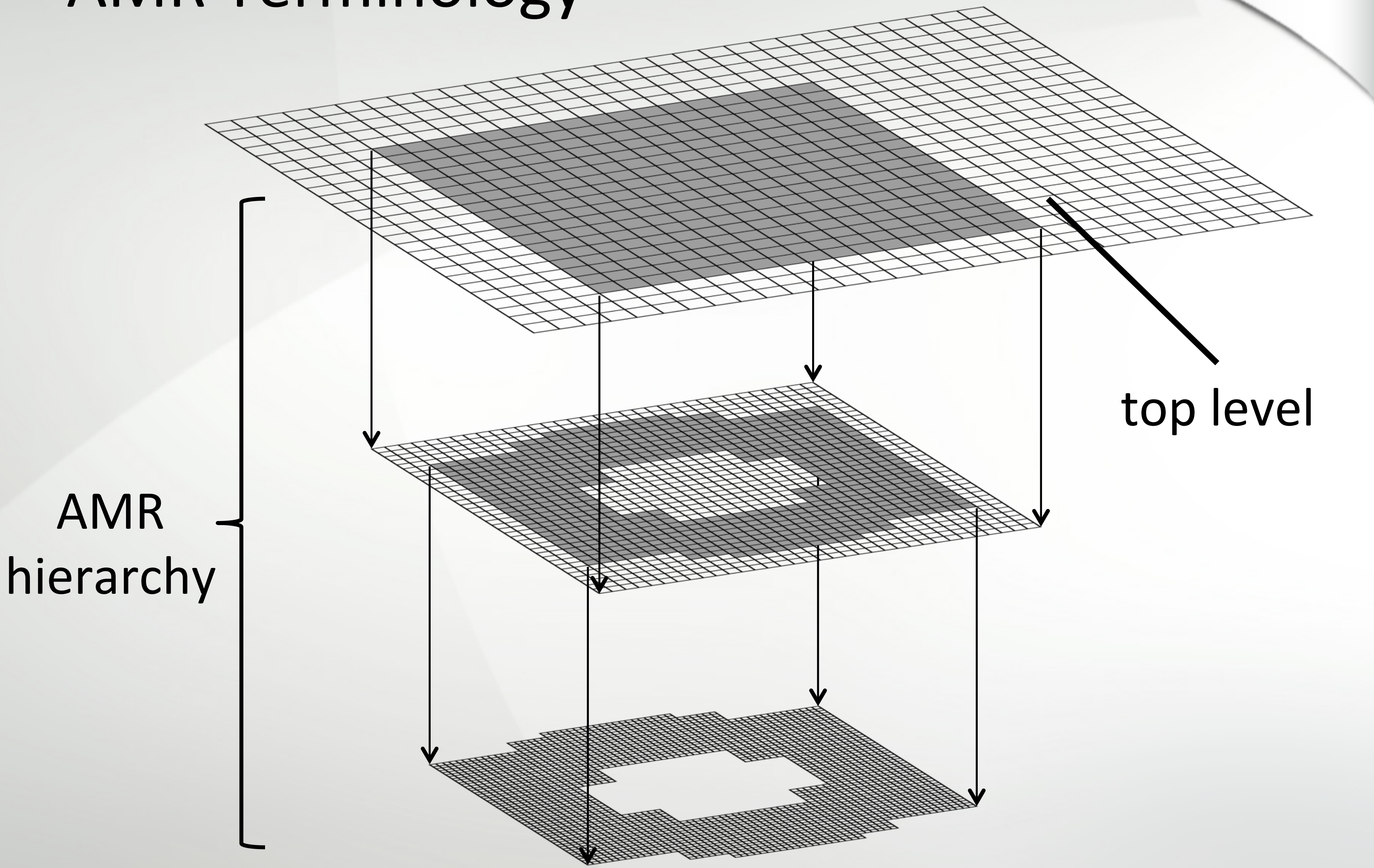

Spatial dimension

```
config param dimension = 2;

const dimensions = 1..dimension;
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May specify value with a command-line flag

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Not modified after assignment; use **var** otherwise

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May specify value with a command-line flag

Value known at compile-time

Default value; type is elided

```
config param dimension = 2;

const dimensions = 1..dimension;
```

Not modified after assignment; use **`var`** otherwise

Range: Arithmetic sequence of integers

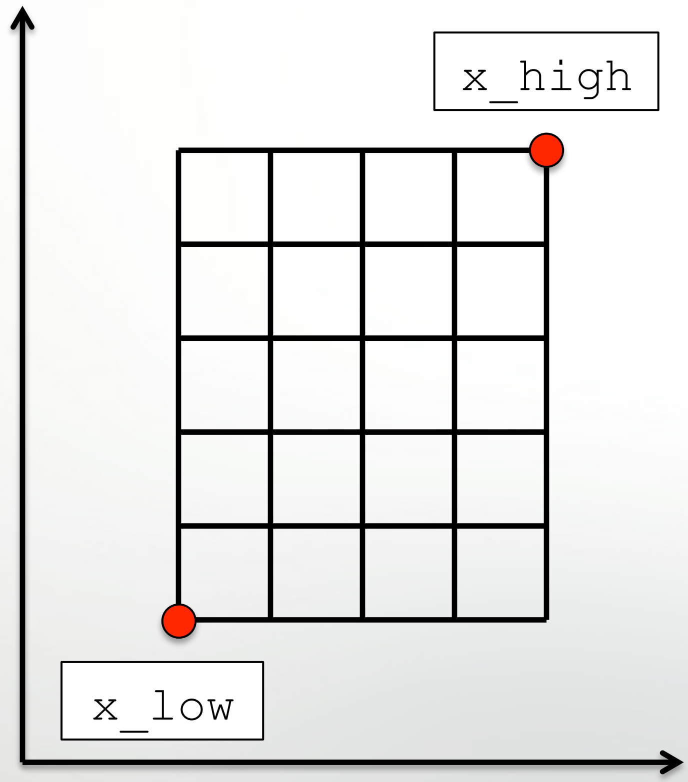
- Supports iteration:

```
for d in dimensions do ...
```

Grids

Basic geometry described by tuples

```
const x_low, x_high: dimension*real;
```

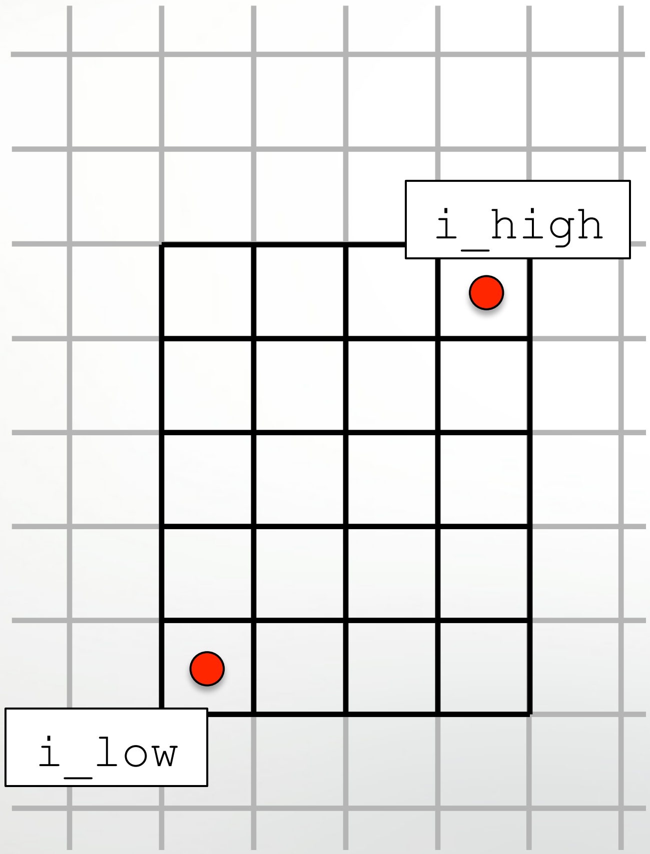


Grids

Basic geometry described by tuples

```
const x_low, x_high: dimension*real;

const i_low, i_high: dimension*int;
```



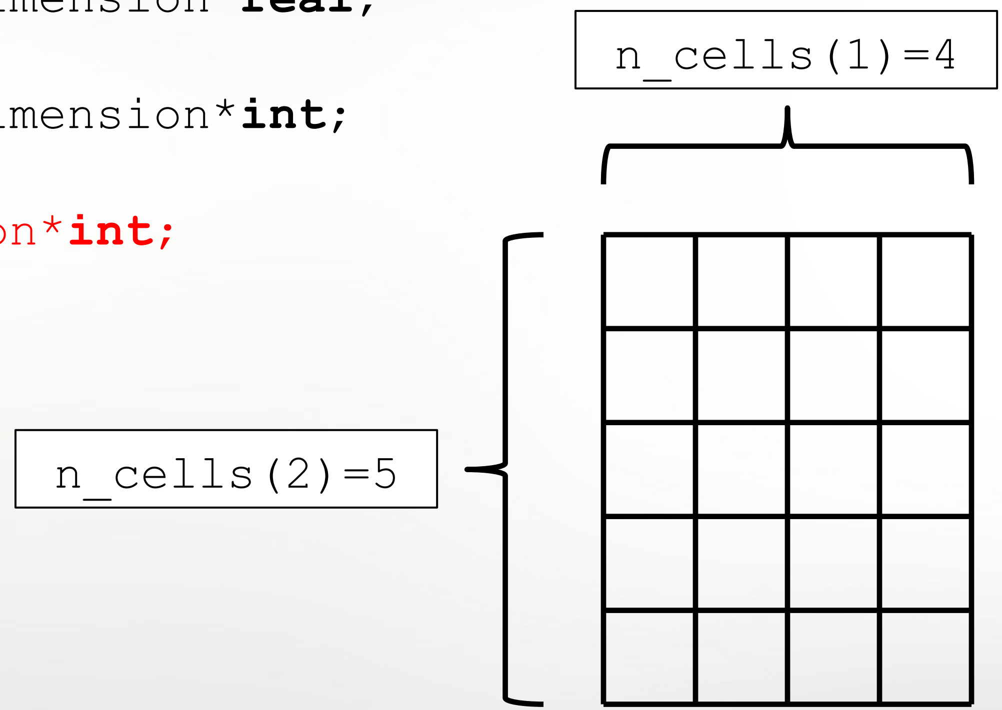
Grids

Basic geometry described by tuples

```
const x_low, x_high: dimension*real;

const i_low, i_high: dimension*int;

const n_cells: dimension*int;
```



Grids

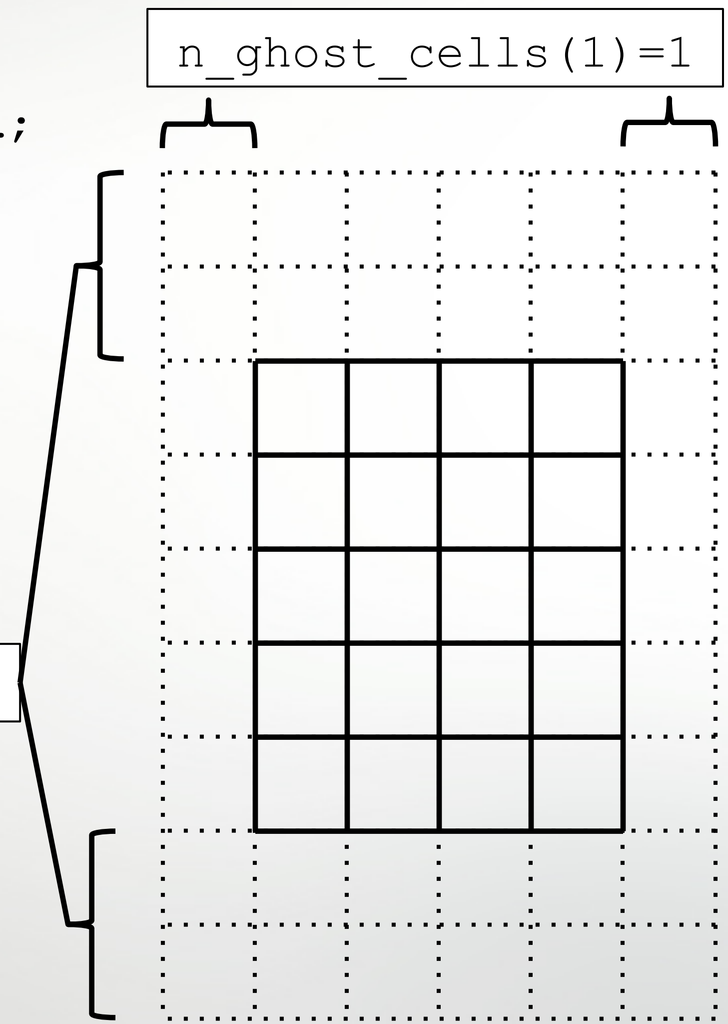
Basic geometry described by tuples

```
const x_low, x_high: dimension*real;

const i_low, i_high: dimension*int;

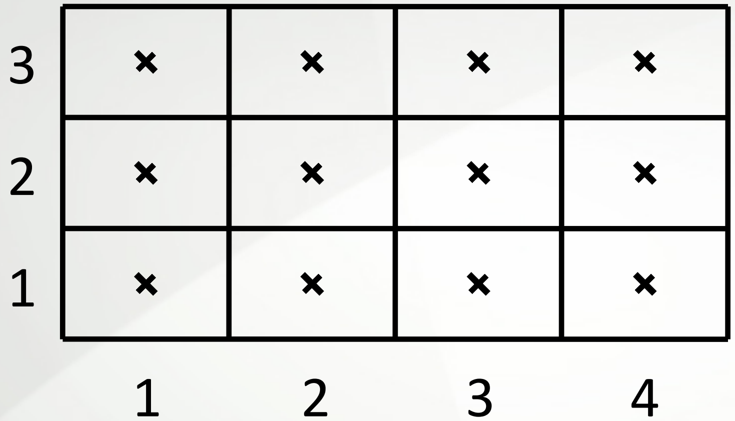
const n_cells: dimension*int;

const n_ghost_cells: dimension*int;
```



Grids: Indexing

Conventional approach – number the cells sequentially



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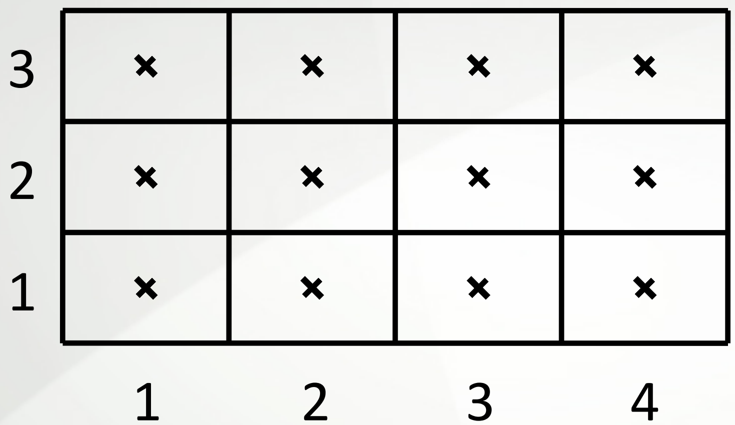


```
const cells = [1..4, 1..3];
```

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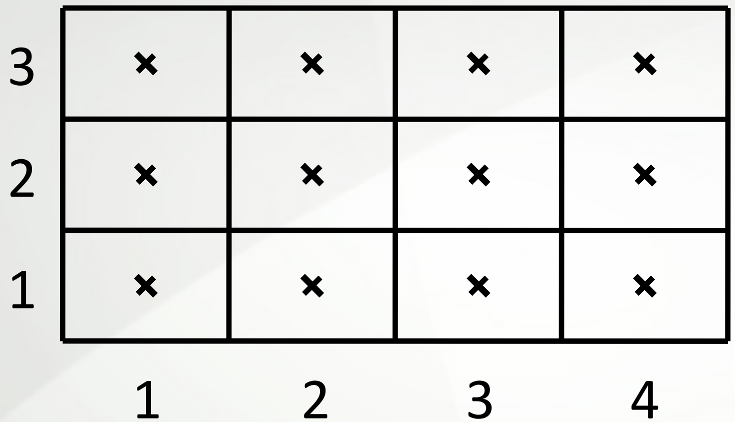


```
const cells = [1..4, 1..3];
```

Arithmetic domain: Multidimensional index space

- Supports storage:

```
var my_array: [cells] real;
```

- Supports (parallel) iteration:

```
for(all) cell in cells do ...
```

- The reason Chapel is so useful for AMR

Grids: Indexing

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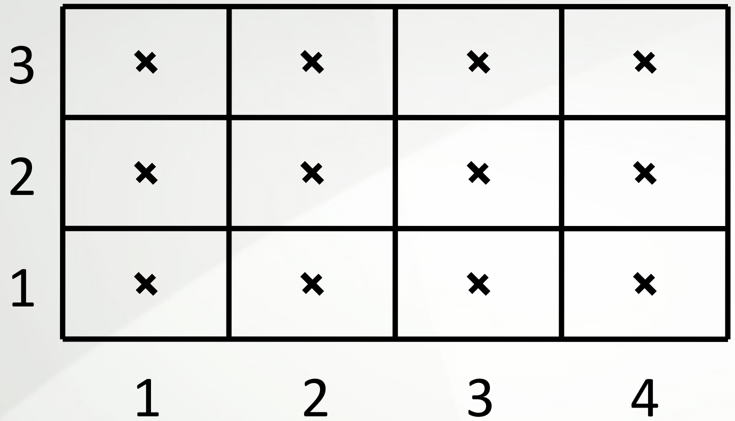


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const cells = [1..4, 1..3];
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Problem with conventional indexing:

- How are interfaces and vertices indexed?

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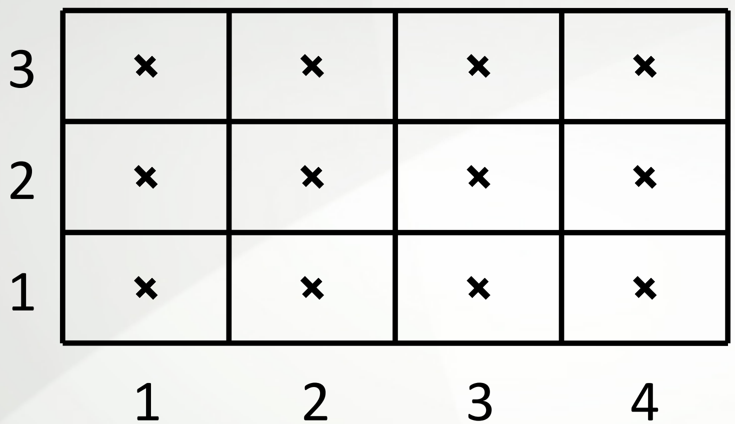


```
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Problem with conventional indexing:

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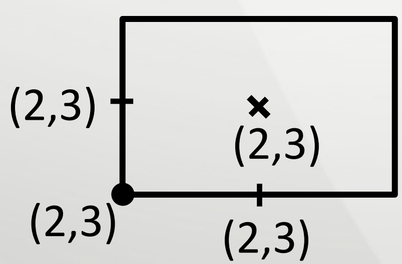
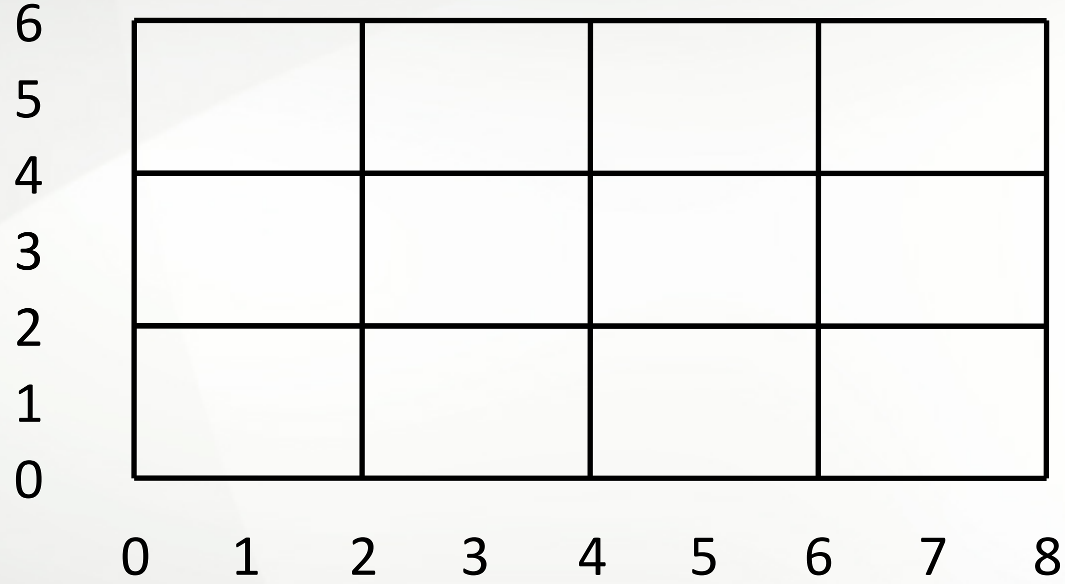


Many objects will have the same indices

Grids: Indexing

Modified approach – denser index space



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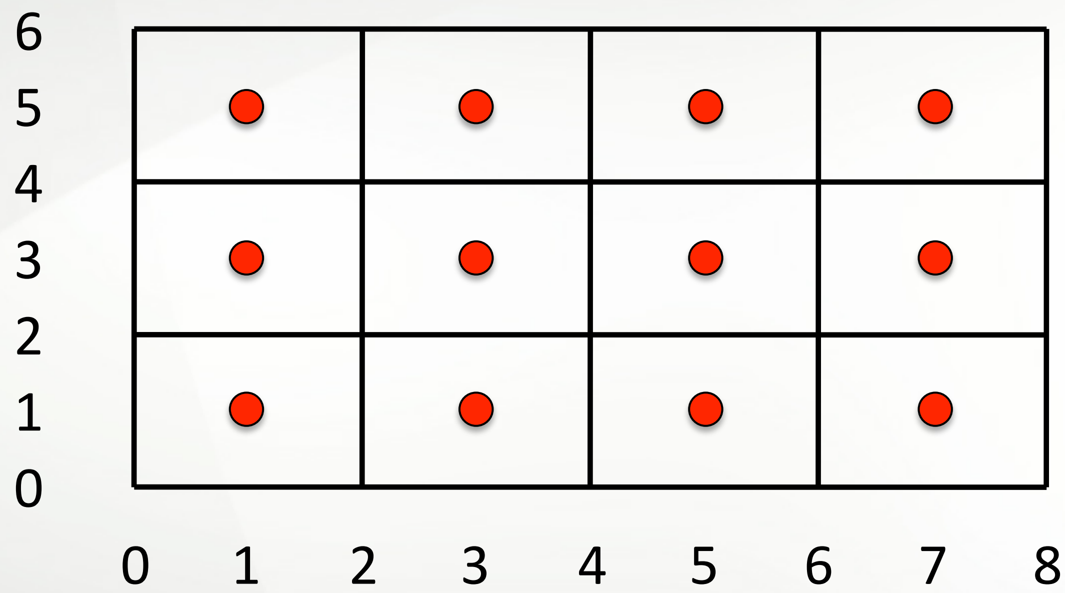
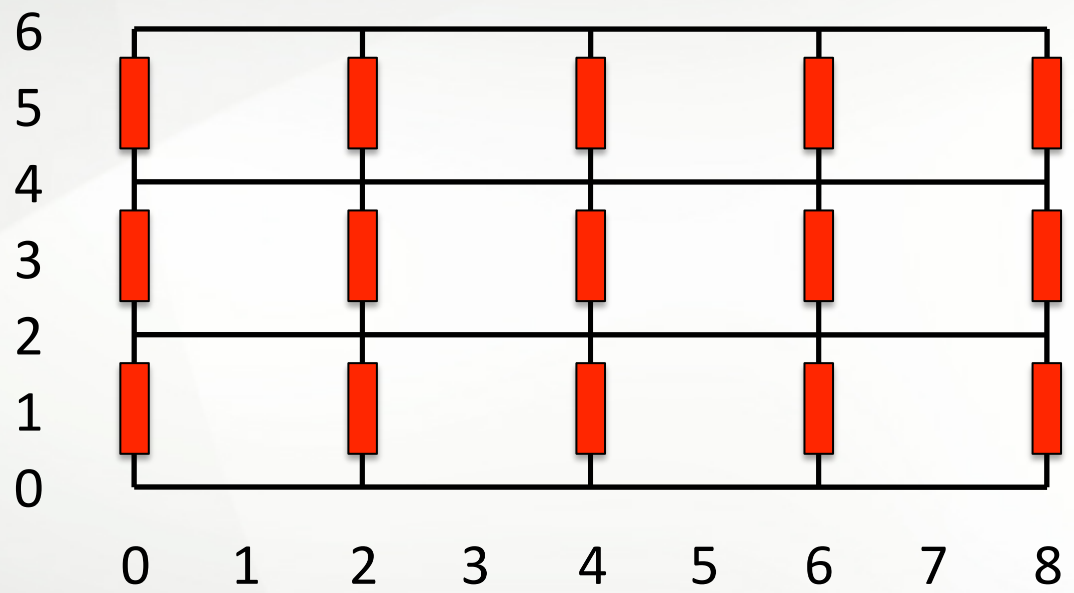



```
const cells            = [1..7 by 2, 1..5 by 2];
```

Grids: Indexing

Modified approach – denser index space




```
const cells        = [1..7 by 2, 1..5 by 2];
const x_interfaces = [0..8 by 2, 1..5 by 2];
```

Grids: Indexing

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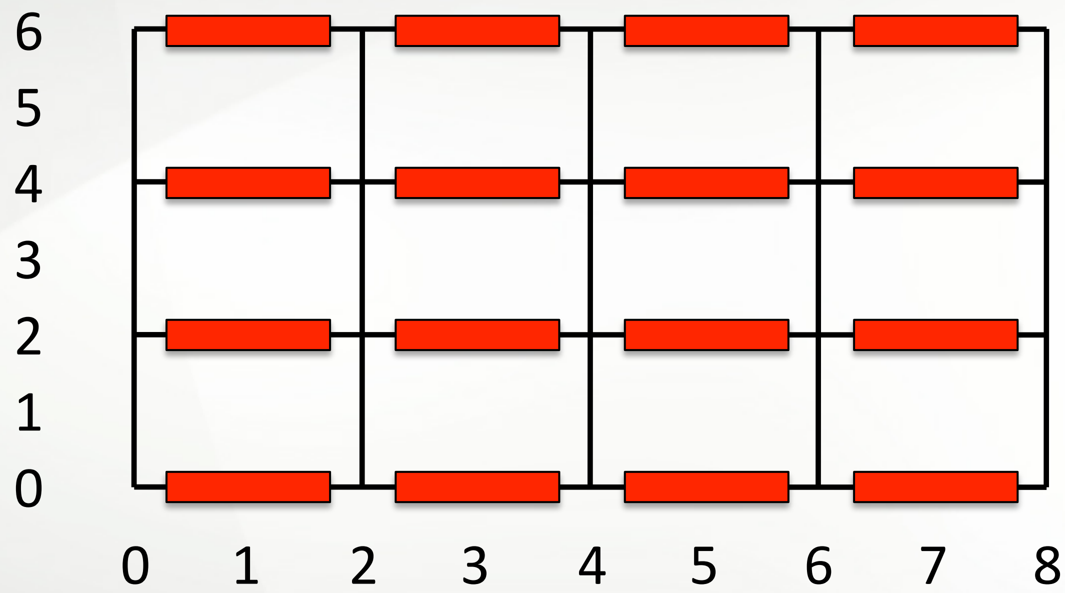


```
const cells        = [1..7 by 2, 1..5 by 2];
const x_interfaces = [0..8 by 2, 1..5 by 2];
const y_interfaces = [1..7 by 2, 0..6 by 2];
```

Grids: Indexing

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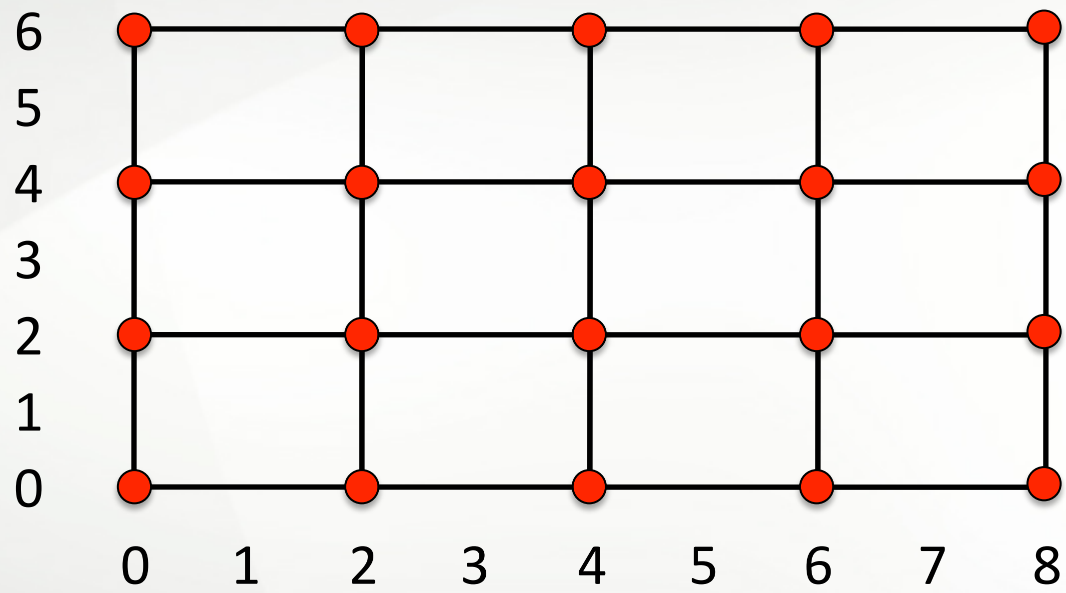


```
const cells       = [1..7 by 2, 1..5 by 2];
const x_interfaces = [0..8 by 2, 1..5 by 2];
const y_interfaces = [1..7 by 2, 0..6 by 2];
const vertices    = [0..8 by 2, 0..6 by 2];
```

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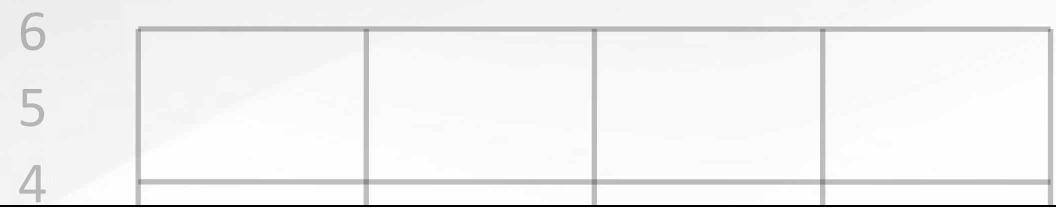


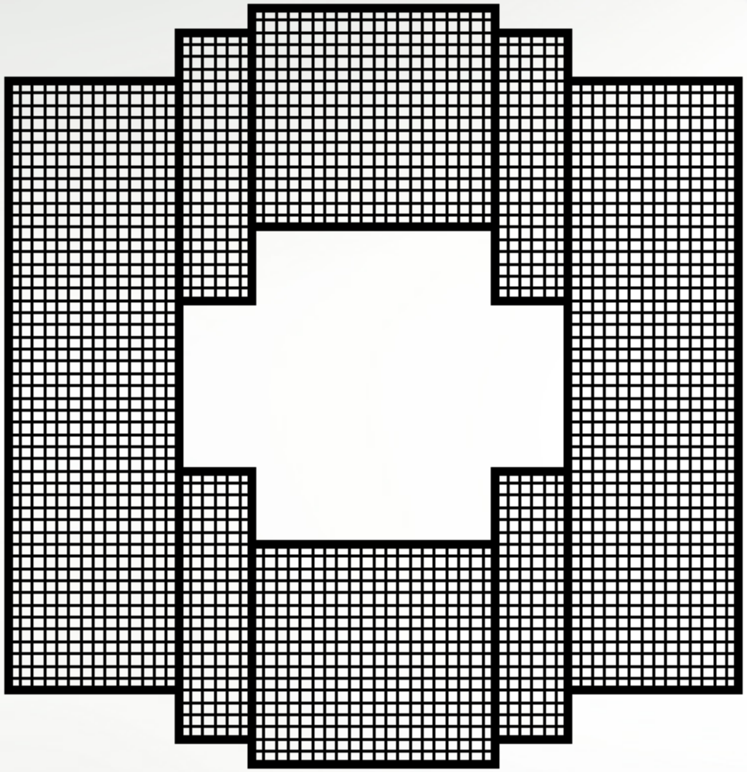
***Strided* domains**

- Array and iteration syntax are **unchanged**
- Chapel helps us describe the physical problem *much* more effectively

```
const cells =          [1..7 by 2, 1..5 by 2];
const x_interfaces = [0..8 by 2, 1..5 by 2];
const y_interfaces = [1..7 by 2, 0..6 by 2];
const vertices =      [0..8 by 2, 0..6 by 2];
```

Levels

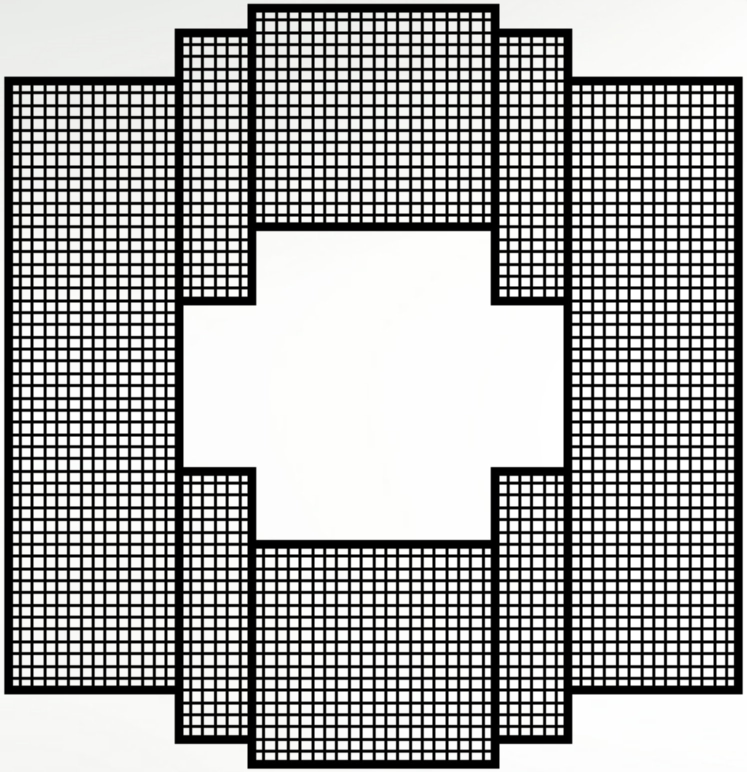
Essentially a union of grids



Levels

Essentially a union of grids

```
var grids: domain(Grid);
```



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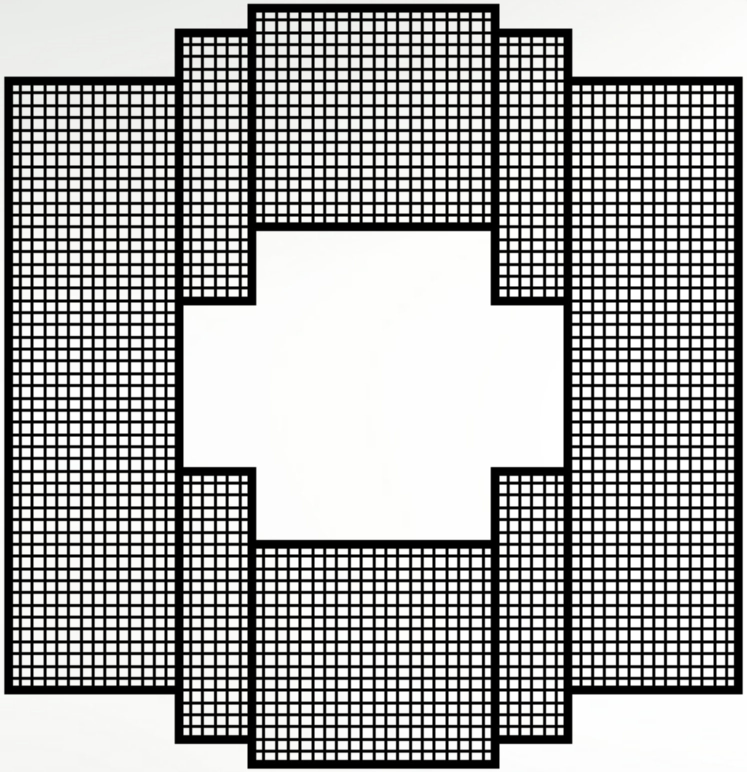


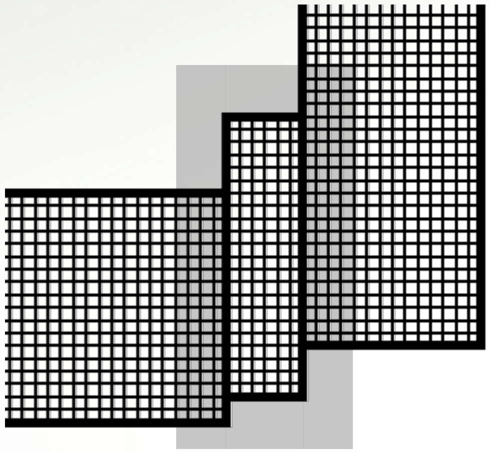
```
var grids: domain(Grid);
```

Associative domain

- A list of indices of *any* type
- Array and iteration syntax remains **unchanged**

Levels: Overlaps

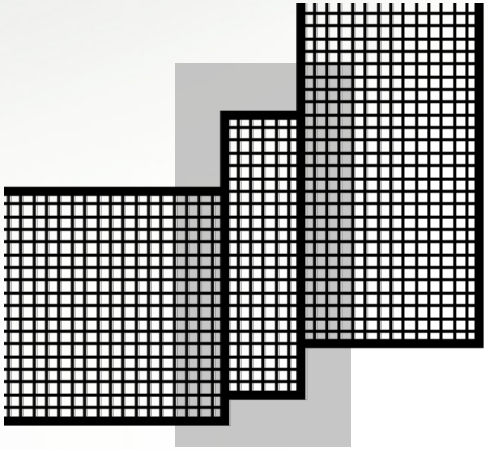
Each grid has a layer of **ghost cells** to facilitate data transfer



Levels: Overlaps

Each grid has a layer of **ghost cells** to facilitate data transfer

```
const extended_cells =
      cells.expand(n_ghost_cells);
```



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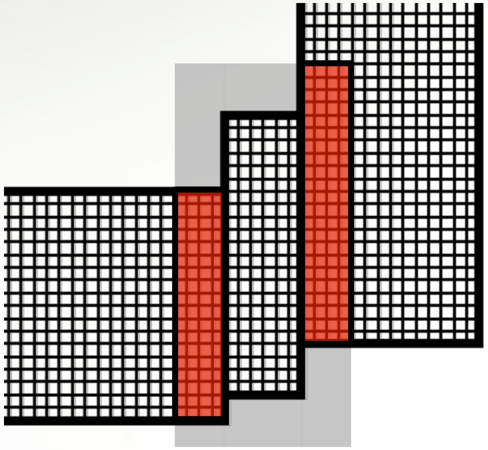

Calculating the overlaps

Levels: Overlaps

Each grid has a layer of **ghost cells**
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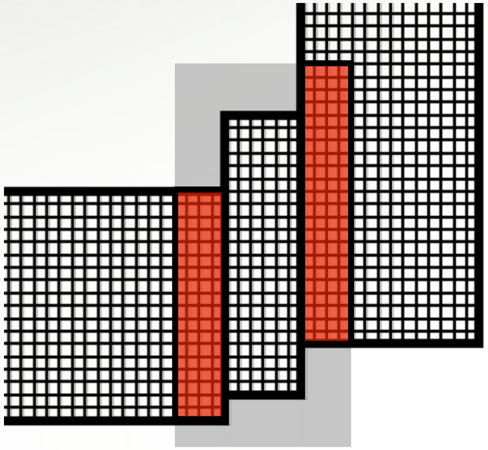

Calculating the overlaps

```
var neighbors: domain(Grid);
var overlap                        ension,stridable=true);

for sibling in parent_level.grids {
  var overlap = extended_cells( sibling.cells );

  if overlap.numIndices > 0 && sibling != this {
    neighbors.add(sibling);
    overlaps(sibling) = overlap;
  }
}
```

Declare associative domain to store neighbors; initializes to empty.

Levels: Overlaps

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to facilitate data transfer

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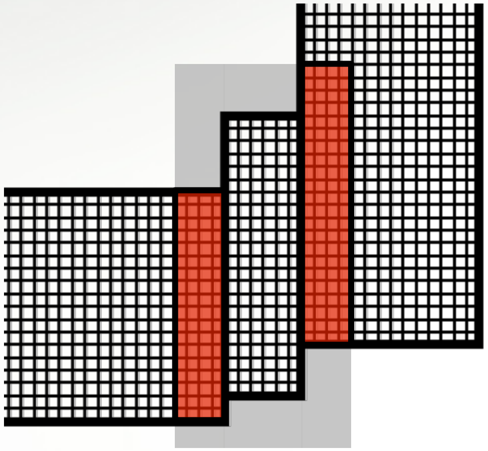


Calculating the overlaps

```
var neighbors: domain(Grid);
var overlaps:  [neighbors] domain(dimension,stridable=true);

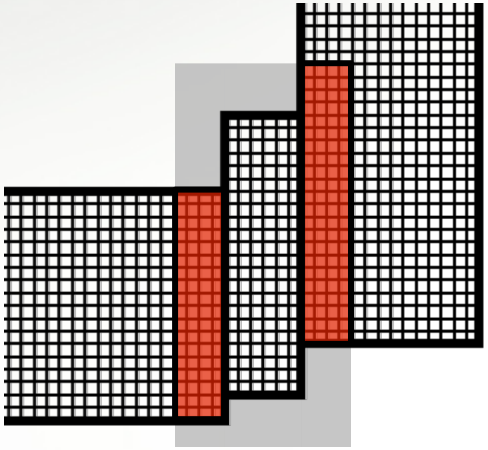
for sibling in p
  var overlap =                          ls );

  if overlap.num                          this {
    neighbors.add(sibling);
    overlaps(sibling) = overlap;
  }
}
```

An array of domains; stores one domain for each neighbor.
New space allocated as `neighbors` grows.

Levels: Overlaps

Each grid has a layer of **ghost cells** to facilitate data transfer



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  if over                    bling != this {
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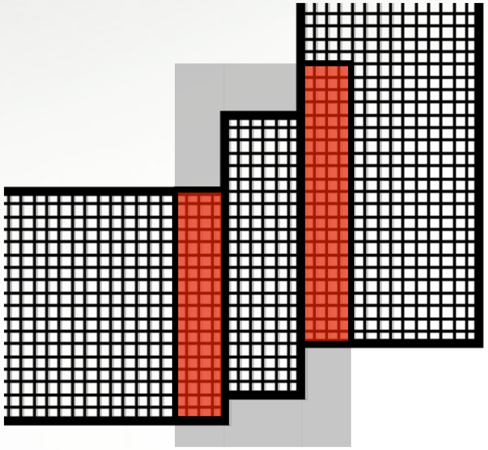
  }
}
```

Loop over all grids on the same level, checking for neighbors.

Levels: Overlaps

Each grid has a layer of **ghost cells** to facilitate data transfer



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Calculating the overlaps

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var overlaps:  [neighbors] domain(dimension,stridable=true);

for sibling in parent_level.grids {
  var overlap = extended_cells( sibling.cells );

  if overl                                his {
    neighb
    overlaps(sibling) = overlap;
  }
}
```

Computes intersection of the domains `extended_cells` and `sibling.cells`.

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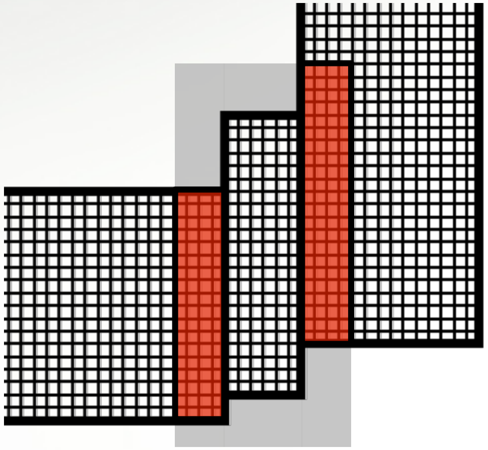

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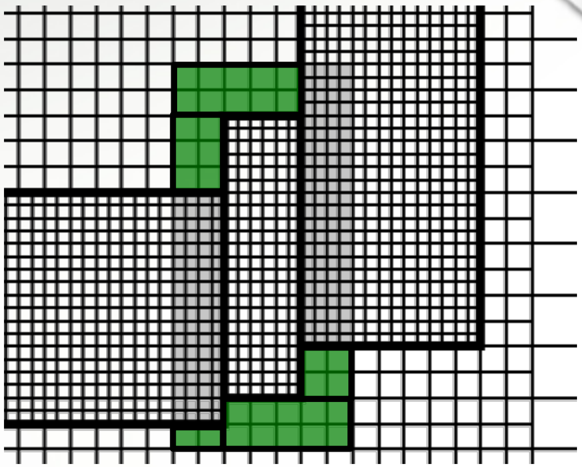
for sibling in parent_level.grids {
  var overlap = extended_cells( sibling.cells );

  if overlap.numIndices > 0 && sibling != this {
    neighbors.add(sibling);
    overlaps(sibling) = overlap;
  }
}
```

If `overlap` is nonempty, and `sibling` is distinct from this grid, then update stored data.

Levels: Interpolation

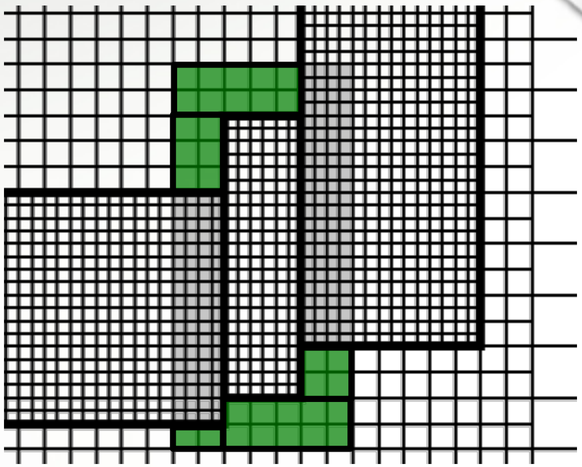
Remaining ghost cells will receive data interpolated from the coarser level



Levels: Interpolation

Remaining ghost cells will receive data interpolated from the coarser level

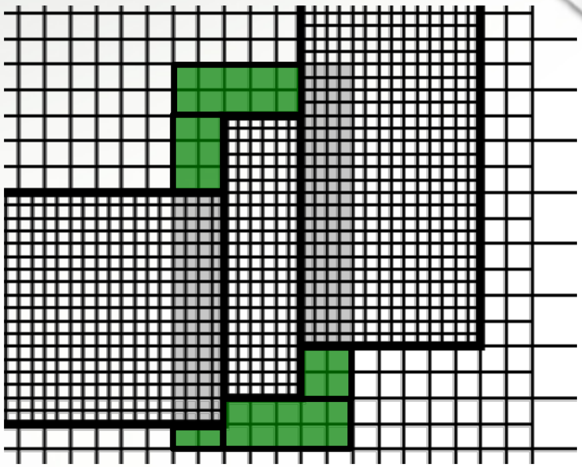
- Region is naturally described by a union of domains



Levels: Interpolation

Remaining ghost cells will receive data interpolated from the coarser level

- Region is naturally described by a union of domains
- Region is naturally calculated by *subtraction* of domains



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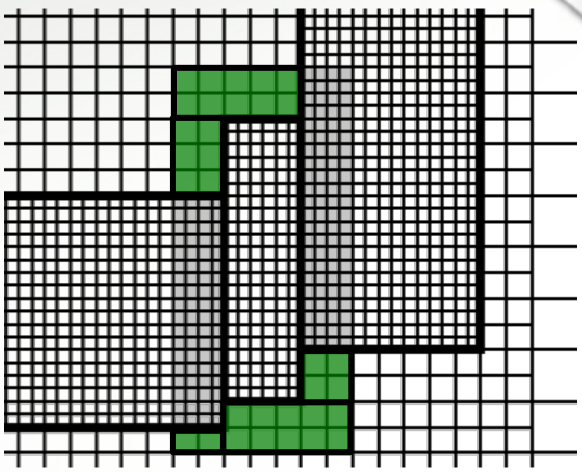

New object: **MultiDomain**

- Stores a collection of domains
- Supports subtraction of domains with a set-minus interpretation

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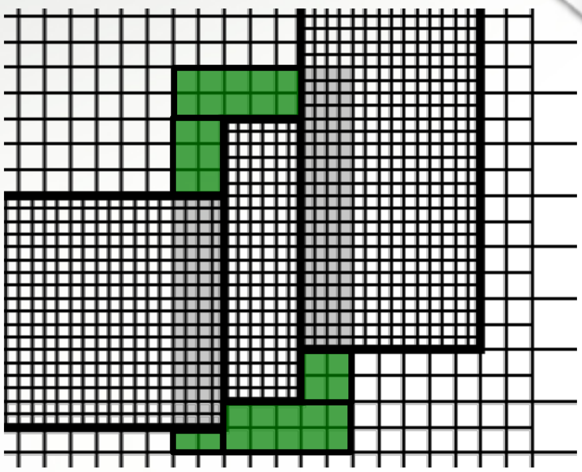

Computing the interpolation region

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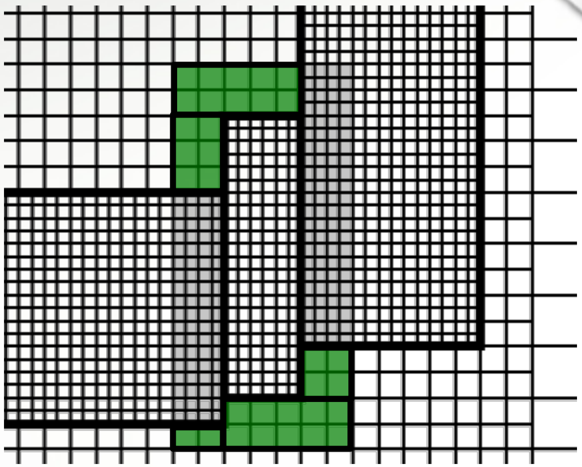

Computing the interpolation region

```
var interp_region =
      new MultiDomain(dimension,stridable=true);
int
int

for neighbor in neighbors do
  interp_region.subtract( overlaps(neighbor) );
```

Declare a new MultiDomain; initializes to empty.

Levels: Interpolation

Remaining ghost cells will receive data interpolated from the coarser level

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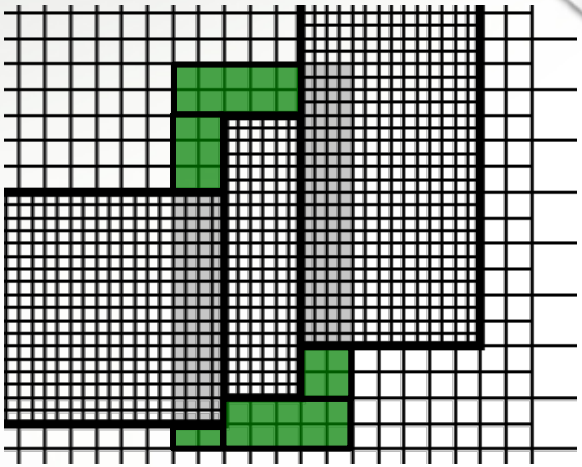

Computing the interpolation region

```
var interp_region =
      new MultiDomain(dimension,stridable=true);
interp_region.add( extended_cells );
interp_region.subtract( cells );

for neighbor in neighbors do
  interp_region.subtract( overlaps(neighbor) );
```

Fill with **only** the ghost cells.

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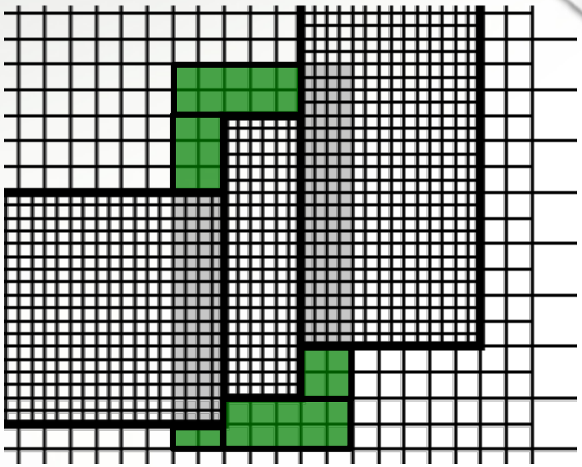

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```

Remove any regions of overlap with a neighboring grid.

Levels: Interpolation

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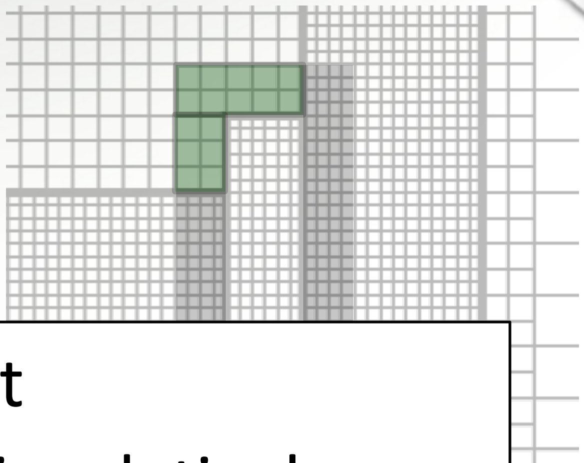


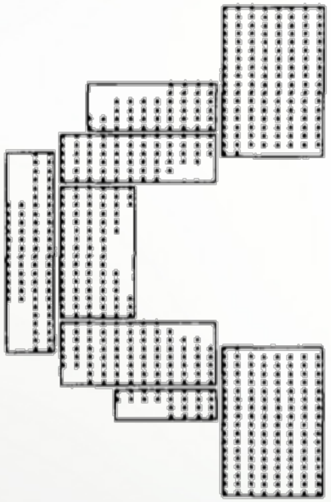
- This code is dimension-independent
- Underlying code for MultiDomains is relatively simple because domains do most of the hard work

```
var interp_region =
      new MultiDomain(dimension,stridable=true);
interp_region.add( extended_cells );
interp_region.subtract( cells );

for neighbor in neighbors do
  interp_region.subtract( overlaps(neighbor) );
```

Regridding (very briefly)

- Primarily the work of a **partitioning algorithm**: Given a set of flags, find rectangles that cover them (Berger & Rigoutsos, 1991)



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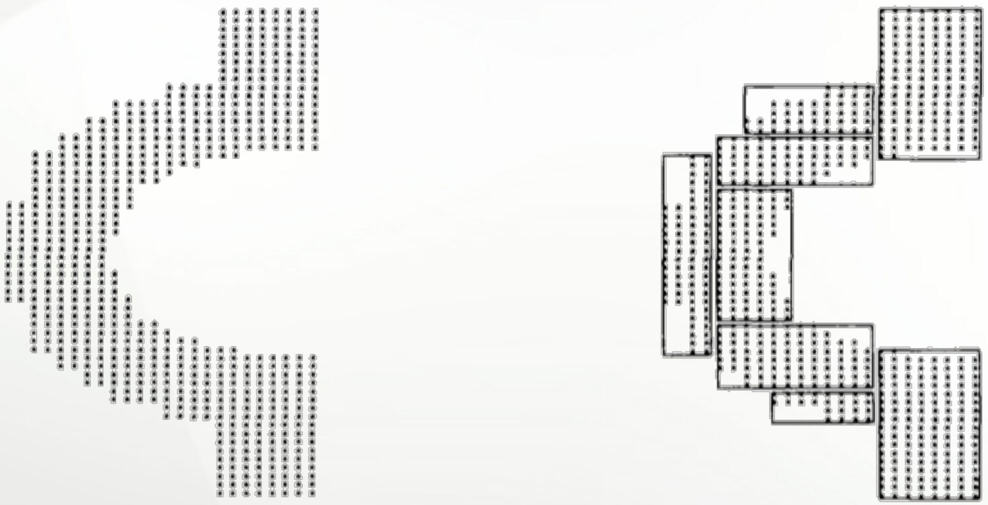

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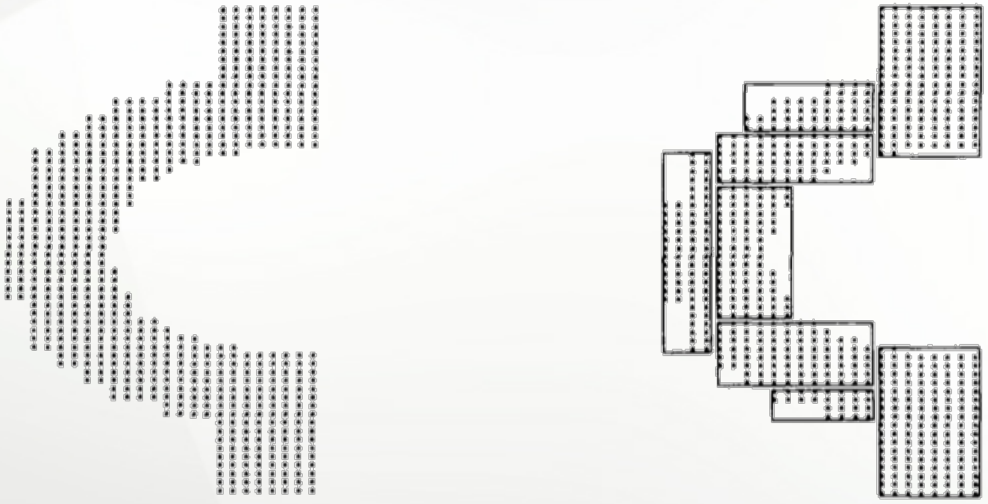

- More rectangles and unions of rectangles – naturally described by domains and MultiDomains
- Dimension-independent code is ≈200 lines

Parallelism

Shared-memory parallelism

- Genuinely trivial:

```
forall cell in grid.cells do ...
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Distributed-memory parallelism

- Not implemented yet, but not difficult once grids have been mapped to processors

```
forall grid in level.grids {
  forall cell in grid.cells do ...
}
```

Performance

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- Will at least test:
  - What fraction of time is spent number crunching?
  - How good is scaling on a multicore machine?

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- Dimension-independence and parallelism are so simple that you can almost forget about them.

- Massive reductions in code size:

Language	Parallelism	SLOC[1]	Tokens	Relative size (tokens)
Chapel (any D)	Shared mem.	1988	13783	1
Fortran (2D+3D) [2] 2D 3D	Serial	16562 8297 8265	151992 71639 80353	11.03 5.20 5.83
C/C++ (any D) [3]	Dist. mem.	40200	261427	20.22

[1] source ines of code, [2] AMRClaw, [3] Chombo BoxTools+AMRTools