Exploring Co-Design in Chapel Using LULESH

SIAM CSE13, MS79
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Chapel
What is Chapel?

- **An emerging parallel programming language**
  - Design and development led by Cray Inc.
    - in collaboration with academia, labs, industry
  - Initiated under the DARPA HPCS program

- **Overall goal: Improve programmer productivity**
  - Improve the programmability of parallel computers
  - Match or beat the performance of current programming models
  - Support better portability than current programming models
  - Improve the robustness of parallel codes

- **A work-in-progress**

- **http://chapel.cray.com/**
Chapel's Implementation

- Being developed as open source at SourceForge
- Licensed as BSD software

**Target Architectures:**
- Cray architectures
- multicore desktops and laptops
- commodity clusters
- systems from other vendors
- *in-progress:* CPU+accelerator hybrids, manycore, …
Motivating Chapel Themes

1) General Parallel Programming
2) Global-View Abstractions
3) Multiresolution Design
4) Control over Locality/Affinity
5) Reduce HPC ↔ Mainstream Language Gap
1) General Parallel Programming

With a unified set of concepts...

...express any parallelism desired in a user’s program

- **Styles:** data-parallel, task-parallel, concurrency, nested, …
- **Levels:** model, function, loop, statement, expression

...target all parallelism available in the hardware

- **Types:** machines, nodes, cores, instructions
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3) Multiresolution Design: Motivation

“Why is everything so tedious/difficult?”
“Why don’t my programs port trivially?”

“Why don’t I have more control?”

Target Machine

Low-Level Implementation Concepts
- MPI
- OpenMP
- CUDA

High-Level Abstractions
- HPF
- ZPL

Target Machine
**Multiresolution Design**

*Multiresolution Design*: Support multiple tiers of features

- higher levels for programmability, productivity
- lower levels for greater degrees of control

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*Chapel language concepts*

- Domain Maps
- Data Parallelism
- Task Parallelism
- Base Language
- Locality Control
- Target Machine

- build the higher-level concepts in terms of the lower
- permit the user to intermix layers arbitrarily
LULESH (in Chapel)
What is LULESH?

- **Livermore Unstructured Lagrange Explicit Shock Hydrodynamics** challenge problem
  - Developed as a proxy application at LLNL under DARPA UHPC
  - Includes computations and algorithms used in production codes

- [https://computation.llnl.gov/casc/ShockHydro/](https://computation.llnl.gov/casc/ShockHydro/)

- There are reference implementations in many languages
  - Serial C
  - C + OMP
  - C + OMP + MPI (not publically available yet)
  - CUDA
  - Loci (logic programming)
  - A++ (C++ class library)
  - Chapel
What Does LULESH Do?

- Solve one octant of the spherical Sedov problem (blast wave) using Lagrangian hydrodynamics for a single material

pictures courtesy of Rob Neely, Bert Still, Jeff Keasler, LLNL
Eulerian vs. Lagrangian Meshes

Eulerian mesh (grid stays fixed)

Lagrangian mesh (grid adapts to materials)

Image Source: LULESH specification, LLNL-TR-490254
https://computation.llnl.gov/casc/ShockHydro/
LULESH Compared to a Real Hydrocode

- **LULESH**
  - Structured input provided (3D regular)
  - Single material per cell

- **Real Hydrocodes**
  - Unstructured input (compact, irregular)
  - Could have multiple materials in a cell

- **But:** LULESH uses code idioms similar to those in a real code, so as to stress compilation and execution similarly
Fundamental LULESH Concepts/Terminology

- Mesh
- Nodes
- Element
Abstract Element and Node Domains:

```chapel
const nodesPerEdge = elemsPerEdge + 1;
const ElemSpace = {0..#elemsPerEdge, 0..#elemsPerEdge},
NodeSpace = {0..#nodesPerEdge, 0..#nodesPerEdge};
```
Chapel Representation (Unstructured)

- **Abstract Element and Node Domains:**
  ```
  const ElemSpace = {0..#numElems},
  NodeSpace = {0..#numNodes};
  ```

- **ElemSpace**

- **NodeSpace**
Chapel Representation (Multi-locale)

- **Distributed Element/Node Domains:**
  ```
  const Elems = ElemSpace dmapped Block(ElemSpace),
  Nodes = NodeSpace dmapped Block(NodeSpace);
  ```

![Diagram showing distribution of elements and nodes](image-url)
Some variables (*fields*) are associated with elements, others with nodes.

- **Nodes:** Position, velocity, acceleration, force, mass, …
- **Elements:** Pressure, energy, viscosity, volume, …
Representation of Fields in Chapel

- Sample field declarations:

```chapel
var x, y, z: [Nodes] real;
var e, p: [Elems] real;
```

(Conceptual representation)
Materials Representation

- Not all elements will contain all materials, and some will contain combinations
Materials Representation (Dense)

naïve approach: store all materials everywhere (reasonable for LULESH, but not in practice)

```cpp
const Mat1Elems = Elems,
    Mat2Elems = Elems;
```
improved approach: use sparse subdomains to only store materials where necessary

\texttt{var Mat1Elems: \texttt{sparse subdomain}(Elems) = enumerateMat1Locs(),}\
\texttt{Mat2Elems: \texttt{sparse subdomain}(Elems) = enumerateMat2Locs();}
LULESH in Chapel
LULESH in Chapel

trunk/test/release/examples/benchmarks/lulesh/*.

chpl

in the SourceForge repository, as of r21020 (2/14/13)

There are: 1288 lines of code
266 lines of comments
487 blank lines

(the C+MPI+OpenMP version is nearly 4x bigger)
LULESH in Chapel

this is all of the representation dependent code
The Representation Dependent Code

const ElemSpace = if use3DRepresentation then {0..#elemsPerEdge, 0..#elemsPerEdge, 0..#elemsPerEdge} else {0..#numElems},
NodeSpace = if use3DRepresentation then {0..#nodesPerEdge, 0..#nodesPerEdge, 0..#nodesPerEdge} else {0..#numNodes};

const Elems = if useBlockDist then ElemSpace dmapped Block(ElemSpace) else ElemSpace,
Nodes = if useBlockDist then NodeSpace dmapped Block(NodeSpace) else NodeSpace;

var elemToNode: [Elems] nodesPerElem*index(Nodes);
var XSym, YSym, ZSym: sparse subdomain(Nodes);

const MatElems: MatElemsType = if sparseMaterials then enumerateMatElems() else Elems;

domains for elements and nodes
The Representation Dependent Code

const ElemSpace = if use3DRepresentation
    then {0..#elemsPerEdge, 0..#elemsPerEdge, 0..#elemsPerEdge}
    else {0..#numElems},
NodeSpace = if use3DRepresentation
    then {0..#nodesPerEdge, 0..#nodesPerEdge, 0..#nodesPerEdge}
    else {0..#numNodes};

const Elems = if useBlockDist then ElemSpace dmapped Block(ElemSpace)
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Nodes = if useBlockDist then NodeSpace dmapped Block(NodeSpace)
    else NodeSpace;

var elemToNode: [Elems] nodesPerElem*index(Nodes);

var XSym, YSym, ZSym: sparse subdomain(Nodes);

const MatElems: MatElemsType = if sparseMaterials then enumerateMatElems()
    else Elems;

potentially distributed domains for elements and nodes
The Representation Dependent Code

```
const ElemSpace = if use3DRepresentation
    then {0..#elemsPerEdge, 0..#elemsPerEdge, 0..#elemsPerEdge}
    else {0..#numElems},
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    then {0..#nodesPerEdge, 0..#nodesPerEdge, 0..#nodesPerEdge}
    else {0..#numNodes};

const Elems = if useBlockDist then ElemSpace dmapped Block(ElemSpace)
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var elemToNode: [Elems] nodesPerElem*index(Nodes);

var XSym, YSym, ZSym: sparse subdomain(Nodes);

const MatElems: MatElemsType = if sparseMaterials then enumerateMatElems()
    else Elems;
```

nodes adjacent to each element
The Representation Dependent Code

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symmetry planes
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var XSym, YSym, ZSym: sparse subdomain(Nodes);

const MatElems: MatElemsType = if sparseMaterials then enumerateMatElems()
    else Elems;
```

domain describing elements that contain the material
The Representation Dependent Code

```chapel
proc MatElemsType type {
    if sparseMaterials {
        if (printWarnings && useBlockDist && numLocales > 1) then
            writeln("WARNING: The LULESH Material Elements (MatElems) are not yet\n", "
            distributed, so result in excessive memory use on,\n", "
            and communication with, locale 0\n");
        return sparse subdomain(Elems);
    } else
        return Elems.type;
}

iter elemToNodes(elem) {
    for param i in 1..nodesPerElem do
        yield elemToNode[elem][i];
}

iter elemToNodesTuple(e) {
    for i in 1..nodesPerElem do
        yield (elemToNode[e][i], i);
}
```

the type of the domain describing elements that contain the material
The Representation Dependent Code

proc MatElemsType type {
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iter elemToNodes(elem) {
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}

iter elemToNodesTuple(e) {
    for i in 1..nodesPerElem do
        yield (elemToNode[e][i], i);
}

iterators mapping elements to their adjacent nodes
here is example representation-independent code:

```plaintext
IntegrateStressForElems()
```

**LULESH spec**, section 1.5.1.1 (2.)
proc IntegrateStressForElems(sigxx, sigyy, sigzz, determ) {
  forall k in Elems {
    var b_x, b_y, b_z: 8*real;
    var x_local, y_local, z_local: 8*real;
    localizeNeighborNodes(k, x, x_local, y, y_local, z, z_local);
    var fx_local, fy_local, fz_local: 8*real;
    local {
      /* Volume calculation involves extra work for numerical consistency. */
      CalcElemShapeFunctionDerivatives(x_local, y_local, z_local, b_x, b_y, b_z, determ[k]);

      CalcElemNodeNormals(b_x, b_y, b_z, x_local, y_local, z_local);

      SumElemStressesToNodeForces(b_x, b_y, b_z, sigxx[k], sigyy[k], sigzz[k],
        fx_local, fy_local, fz_local);
    }
    for (noi, t) in elemToNodesTuple(k) {
      fx[noi].add(fx_local[t]);
      fy[noi].add(fy_local[t]);
      fz[noi].add(fz_local[t]);
    }
  }
}
Codesign
LULESH in Chapel, Codesign Timeline

**Apr 2011:** LLNL expresses interest in Chapel at Salishan Conference

- Introduced us to the LULESH benchmark
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  ● impact on code minimal (mostly in declarations)
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Sep-Nov 2012: performance tuning

Nov 2012: SC12
  ● Chapel HPC Challenge entry
  ● LLNL talk at the Chapel Lightning Talks BoF
  ● Cray talk at Proxy Apps BoF

Dec 2012: Multi-institution LULESH paper accepted to IPDPS ‘13
Next Steps

- **Performance Optimizations and Tuning**
  - Reductions
  - Communication optimizations
    - Aggregation
    - Overlap
    - Atomics

- Explore array-of-structs vs. struct-of-arrays ideas

- Identify funding to dedicate focus on DOE proxy apps
Codesign Takeaways for Chapel Team

- Improved comprehension of the science behind the code and data structures
- Deeper understanding of array-of-struct vs. struct-of-arrays tensions
- Awareness of performance issues based on past LLNL experience

“The opportunity to work on LULESH with computational scientists at LLNL has been incredibly valuable. In part, this is due to the level of expertise that we've had access to. In part it’s due to LULESH’s design: it is compact enough to be manageable for our team to understand while being realistic enough to carry weight with actual users.”

Brad Chamberlain, Chapel Technical Lead, Cray Inc.
Codesign Takeaways for LULESH Team

- Impact of representation-independent features made evident firsthand
- Saw value of using global-view sparse domains to avoid local↔global index translation
- View Chapel as an opportunity for code that ports across next-gen architectures

“Chapel is a maintainable future-proof language. With additional back-end performance enhancements, we would be using it to develop science codes, with an eye towards multiphysics production codes.”

Jeff Keasler, ASC code developer, LLNL
Summary of the LULESH Effort in Chapel

● **Evidence that Chapel’s language design is solid**
  ● Not just an HPCS technology demonstrator

● **Evidence that people are getting serious about Chapel**
  ● LLNL sees Chapel as a serious contender for hydrocodes

● **Co-design success story**
  ● Access to experts for a code that people actually care about
  ● Feedback on the language and implementation
  ● New challenges for the language and implementation
Questions?