General Transformations for GPU Execution of Tree Traversals

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GPU execution of irregular programs

- GPUs offer promise of massive, energy-efficient parallelism
- Much success in mapping *regular* applications to GPUs
  - Regular memory accesses, predictable computation
- Much less success in mapping *irregular* applications
  - Pointer-based data structures
  - Unpredictable, input-dependent computation and memory accesses
Tree traversal algorithms

- Many irregular algorithms are built around tree-traversal
  - Barnes-Hut
  - Nearest-neighbor
  - 2-point correlation
- Numerous papers describing how to map tree traversal algorithms to GPUs
Point correlation

- Data mining algorithm
- Goal: given a set of $N$ points in $k$ dimensions and a point $p$, find all points within a radius $r$ of $p$
- Naïve approach: compare all $N$ points with $p$
- Better approach: build $kd$-tree over points, traverse tree for point $p$, prune subtrees that are far from $p$
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Point correlation
**Point correlation**

```java
KDCell root = /* build kdtree */;
Set<Point> ps;
double radius;

foreach Point p in ps {
    recurse(p, root, radius);
}
...
void recurse(Point p, KDCell node, double r) {
    if (tooFar(p, node, r)) return;
    if (node.isLeaf() && (dist(node.point, p) < r))
        p.correlated++;
    else {
        recurse(p, node.left, r);
        recurse(p, node.right, r);
    }
}
```
TreeNode root;
Set<Point> ps;

foreach Point p in ps {
    recurse(p, root, ...);
}

...  
recurse(Point p, KDCell node, ...) {
    if (truncate?(p, node, ...))
        { ... }
    recurse(p, node.child1, ...);
    recurse(p, node.child2, ...);
    ...
}
Basic pattern

TreeNode root;
Set<Point> ps;

foreach Point p in ps {
    recurse(p, root, ...);
}

...  
recurse(Point p, KDCell node, ...) {
    if (truncate?(p, node, ...))
    {
        ...
    }
    recurse(p, node.child1, ...);
    recurse(p, node.child2, ...);
    ...
}

recursive traversal
TreeNode root;
Set<Point> ps;

foreach Point p in ps {
    recurse(p, root, ...);
}

...  
recurse(Point p, KDCell node, ...) {
    if (truncate?(p, node, ...))
    {
        ... }
    recurse(p, node.child1, ...);
    recurse(p, node.child2, ...);
    ...
}
Basic pattern

TreeNode root;
Set<Point> ps;

foreach Point p in ps {
    recurse(p, root, ...);
}

... recurse(Point p, KDCell node, ...) {
    if (truncate?(p, node, ...))
    {
        ...
    }
    recurse(p, node.child1, ...);
    recurse(p, node.child2, ...);
    ...
}

tree structure

repeated traversal

recursive traversal
Basic pattern

TreeNode root;
Set<Point> ps;

foreach Point p in ps {
    recurse(p, root, ...);
}

... recurse(Point p, KDCell node, ...) {
    if (truncate?(p, node, ...)) { ... }
    recurse(p, node.child1, ...);
    recurse(p, node.child2, ...);
    ... 
}

Lots of parallelism!
What’s the problem?

- GPUs add high overhead for recursion
- GPUs work best when memory accesses are regular and strided, but irregular algorithms have unpredictable memory accesses
  - Status quo: *ad hoc* solutions
  - New algorithm? New GPU techniques!
What’s the problem?

- GPUs add high overhead for recursion
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- Status quo: ad hoc solutions
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Contributions

• Two general techniques for mapping tree-traversals to GPUs
  • **Autoropes**: eliminates recursion overhead
  • **Lockstepping**: promotes memory coalescing
• Compiler pass to automatically apply techniques to recursive tree-traversal code
• Significant GPU speedups on 5 tree-traversal algorithms
Naïve GPU implementation

- *Warp*-based *SIMT* (single-instruction, multiple-thread) execution
- 32 points put in a single warp
- Warp traverses tree
- All points in warp must execute same instruction
- If points *diverge*, some points sit idle while other threads execute
Naïve GPU implementation
Naïve GPU implementation
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Naïve GPU implementation

Diagram of a tree structure with nodes labeled A, B, C, D, E, F, G, H, I, J, K.
Naïve GPU implementation
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Lots of accesses to tree

- Many accesses just moving up the tree in order to later move down again
- Lots of function stack manipulation
- Trees are very large, cannot be stored in GPU's fast memory
- Want to minimize accesses to tree
How to avoid extra accesses to tree?

• Typical technique: *ropes*

• Pointers in each tree node that let a traversal jump to the next part of the tree

• Effectively linearizes traversal
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How to avoid extra accesses to tree?

- Installing ropes into a tree requires complex, application-specific preprocessing.
- Using ropes correctly during execution requires complex, application-specific logic.
Autoropes

- General technique for “linearizing” tree traversal for *arbitrary traversal algorithms*
- Achieve generality, simplicity and space-efficiency at the cost of overhead
- Key insight: *recursive tree algorithms are just depth-first traversals of a tree; can transform into iterative algorithm*
Autoropes

Rope stack
Autoropes

Rope stack
Autoropes

Rope stack

G
F
C
Autoropes

Rope stack

| G | F | E | D |

A

B

C

D

E

F

H

I

J

K
Autoropes

Rope stack
Autoropes

Rope stack
Autoropes

Rope stack
Autoropes

- Ropes stored on *rope stack* instead of in tree
- No application-specific code to use ropes
- Ropes instantiated *dynamically*
- No preprocessing required
- Same access patterns as with manual ropes
- Extra pushes and pops on rope stack add some overhead
void recurse(Point p, KDCell node, double r) {
    if (tooFar(p, node, r)) return;
    if (node.isLeaf() && (dist(node.point, p) < r))
        p.correlated++;
    else {
        recurse(p, node.left, r);
        recurse(p, node.right, r);
    }
}
ropeStack.push(root);
while (!ropeStack.isEmpty()) {
    node = ropeStack.pop();
    if (tooFar(p, node, r)) continue;
    if (node.isLeaf() && (dist(node.point, p) < r))
        p.correlated++;
    else {
        ropeStack.push(node.right);
        ropeStack.push(node.left);
    }
}

See paper for details of how to transform more complex code
Unintended consequence

- Recursive calls naturally lead to thread divergence
- If some threads make recursive calls, other threads wait until calls return
- Does not happen for iterative code
- All threads reconverge at beginning of loop

```java
ropeStack.push(root);
while (!ropeStack.isEmpty()) {
    node = ropeStack.pop();
    if (tooFar(p, node, r))
        continue;
    if (...) p.correlated++;
    else {
        ropeStack.push(node.right);
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```
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```
Autoropese on GPU
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Authoropes on GPU

Threads no longer diverge in execution
But do diverge in tree!
Thread divergence vs. memory coalescing

- Memory accesses on GPU only well behaved if accesses by all threads in warp can be coalesced
- Same memory or strided access
- Bad memory behavior of autoropes outweighs lack of thread divergence
- Goal: benefits of autoropes while maintaining memory coalescing
Lockstepping

• Essentially, force GPU to let threads diverge
  • If any thread in a warp wants to visit a node’s children, all threads in a warp visit the child
  • Threads that are “dragged along” are programmatically masked out
  • Warp execution takes longer (proportional to union of threads’ traversals, rather than longest traversal), but improved memory performance makes up for it
  • Automatically implemented during autoropes compiler pass
Dynamic lockstepping

- Some algorithms allow different traversal orders
- Some points visit left child before right, and others visit right before left
- Optimization reduces traversal size
- Inherently bad memory access patterns
Dynamic lockstepping

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Dynamic lockstepping
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Dynamic lockstepping

• Dynamic lockstepping allows all points in a warp to “vote” on which traversal order to use
• Maintains memory coalescing
• Some points do more work than in original algorithm
• Tradeoff can still be worth it!
Engineering details

• Transform point data from array of structures format to structure of arrays

• Use analysis from [PACT 2013] to prove safety and transform automatically

• Copy tree data to GPU in linearized fashion

• Lay out fields of tree and point according to use (more commonly-accessed fields placed in shared memory)

• Interleave rope stacks for points in warp to allow strided access
Results

• Two platforms
  • GPU platform: NVIDIA Tesla C2070 (6GB global memory, 14 SMs)
  • CPU platform: 32-core, 2.3 GHz Opteron

• Five benchmarks
  • Barnes-Hut, Point correlation, Nearest neighbor, k-Nearest neighbor, Vantage point trees
  • Multiple inputs per benchmark
  • Used sorted and unsorted points
High-level takeaways

• Autoropes+lockstep always faster than simple recursive GPU implementation (up to 14x faster)

• For most benchmarks/inputs, best GPU implementation faster than CPU implementation up to 16 threads

• Speedups comparable to hand-written implementations
Barnes-Hut

CPU Performance vs. GPU vs. Number of Threads

Random Plummer

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Point correlation
Nearest-neighbor
Conclusions

• Mapping irregular applications to GPUs is very difficult

• Developed two general techniques, autoropes and lockstepping, that can achieve significant speedup on GPU

• vs. baseline GPU code and CPU implementations

• Automatic approaches competitive with previous hand-written implementations
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