General Transformations for GPU Execution of Tree Traversals

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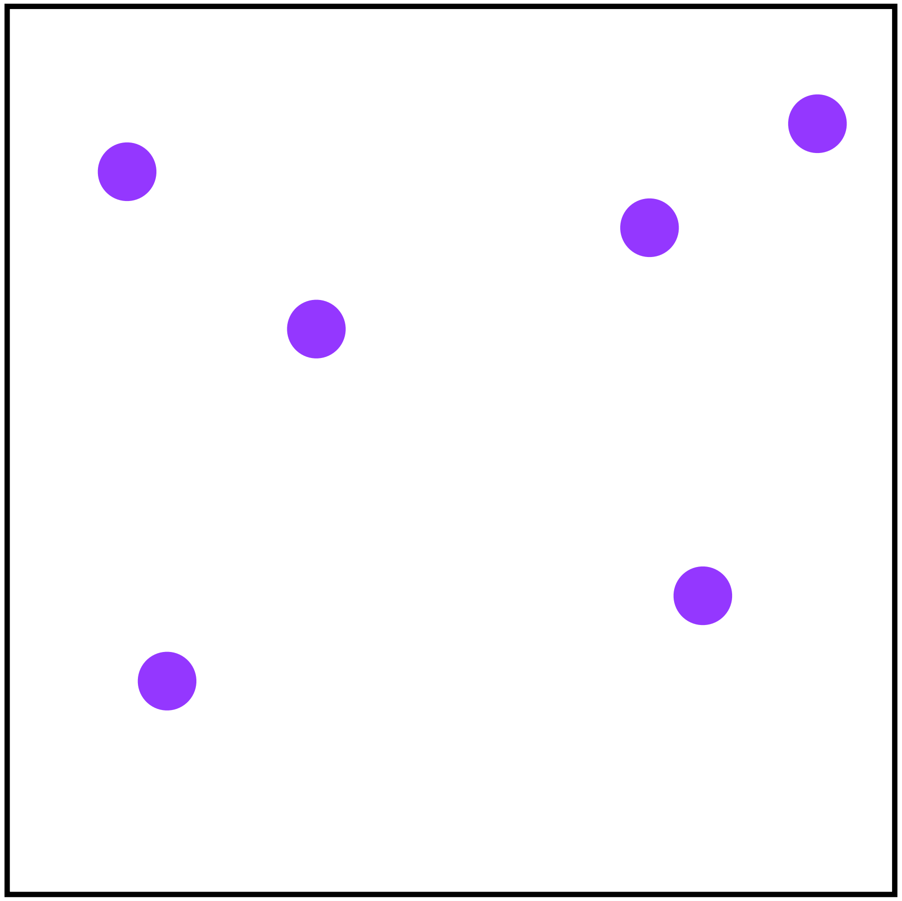
GPU execution of irregular programs

- 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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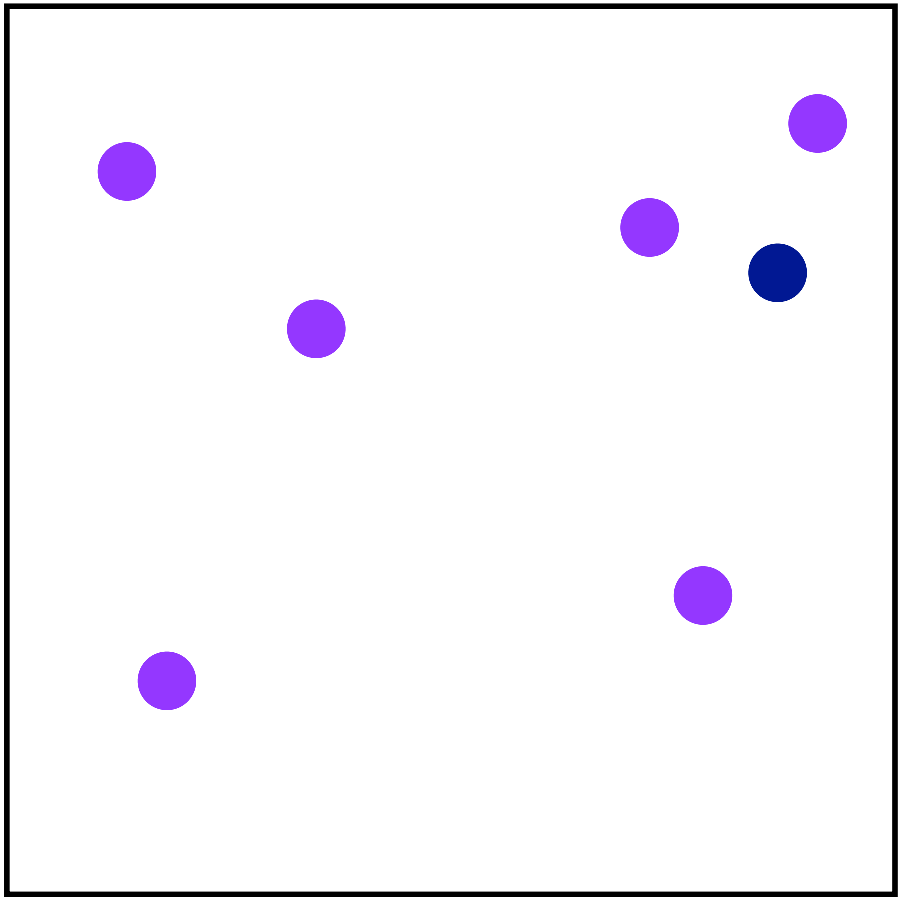

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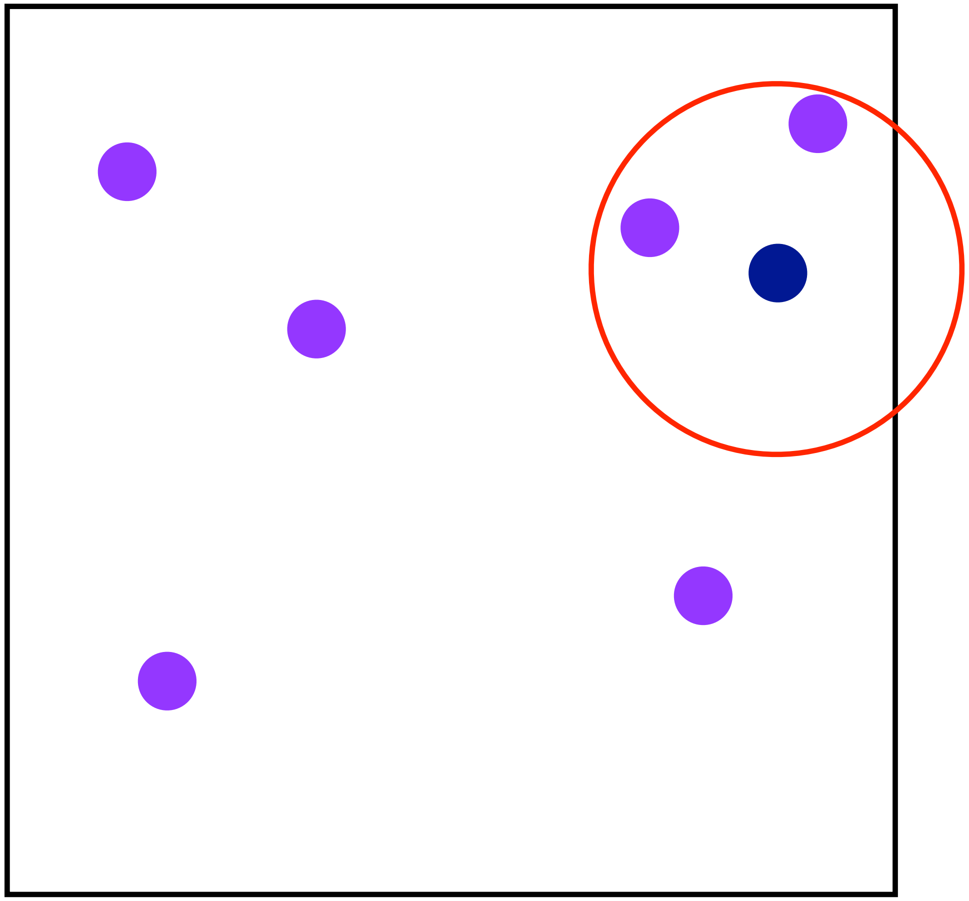

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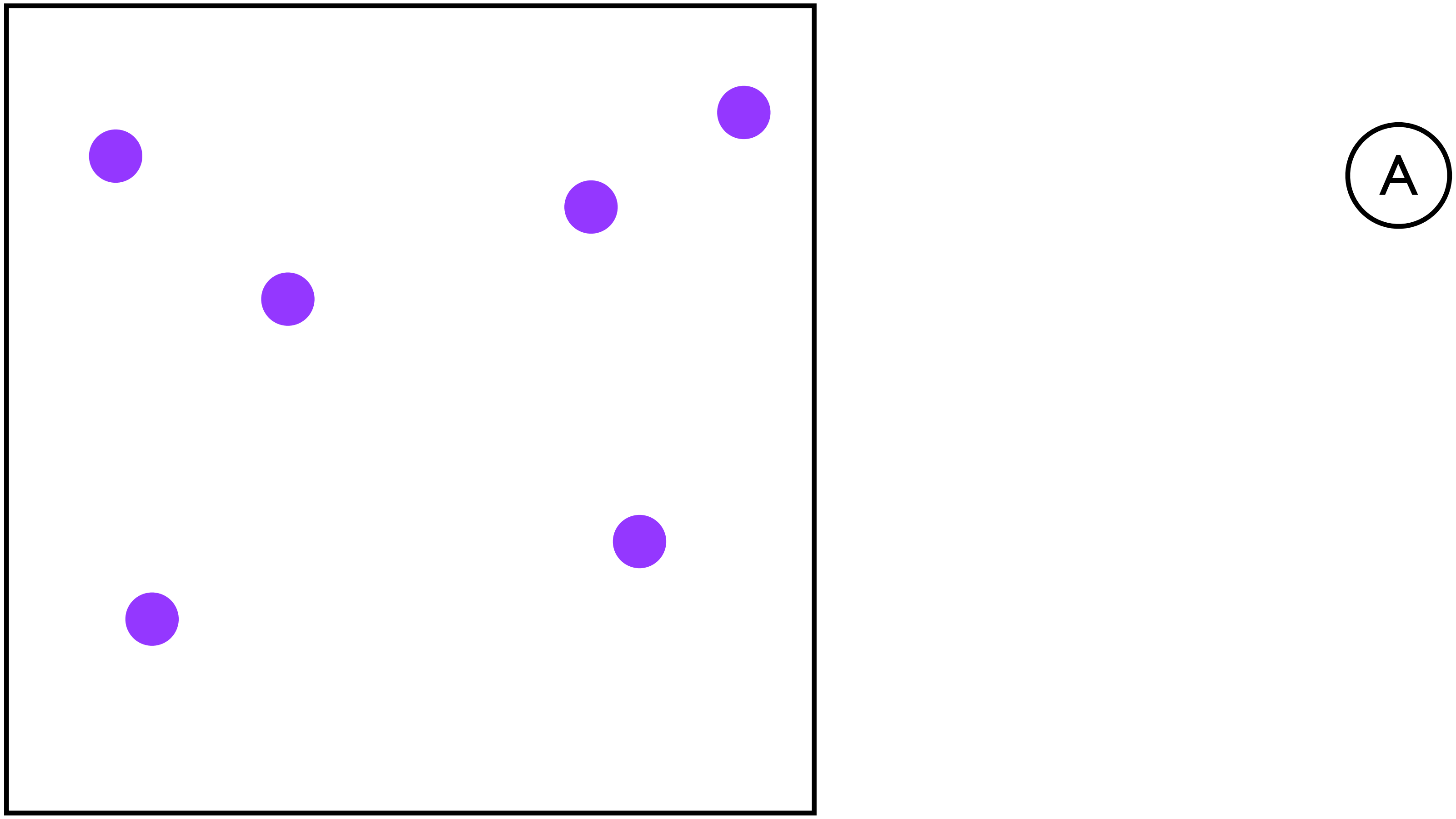

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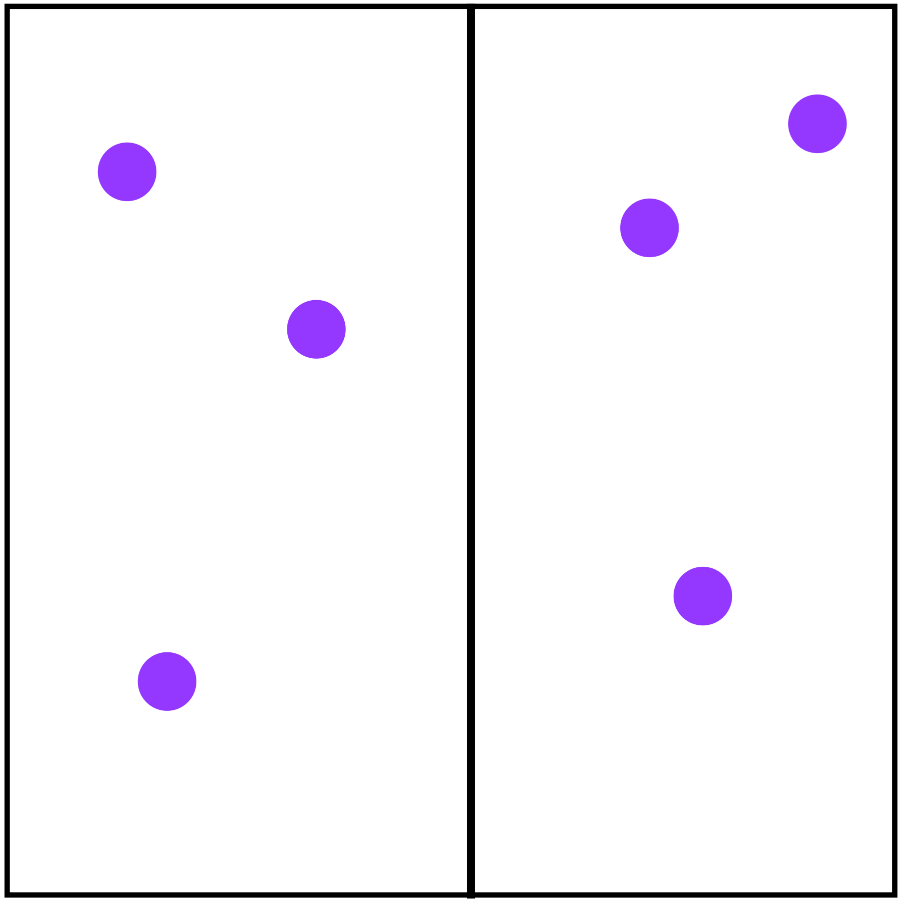

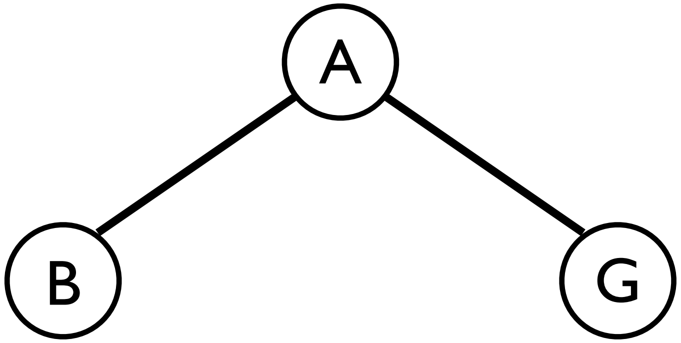

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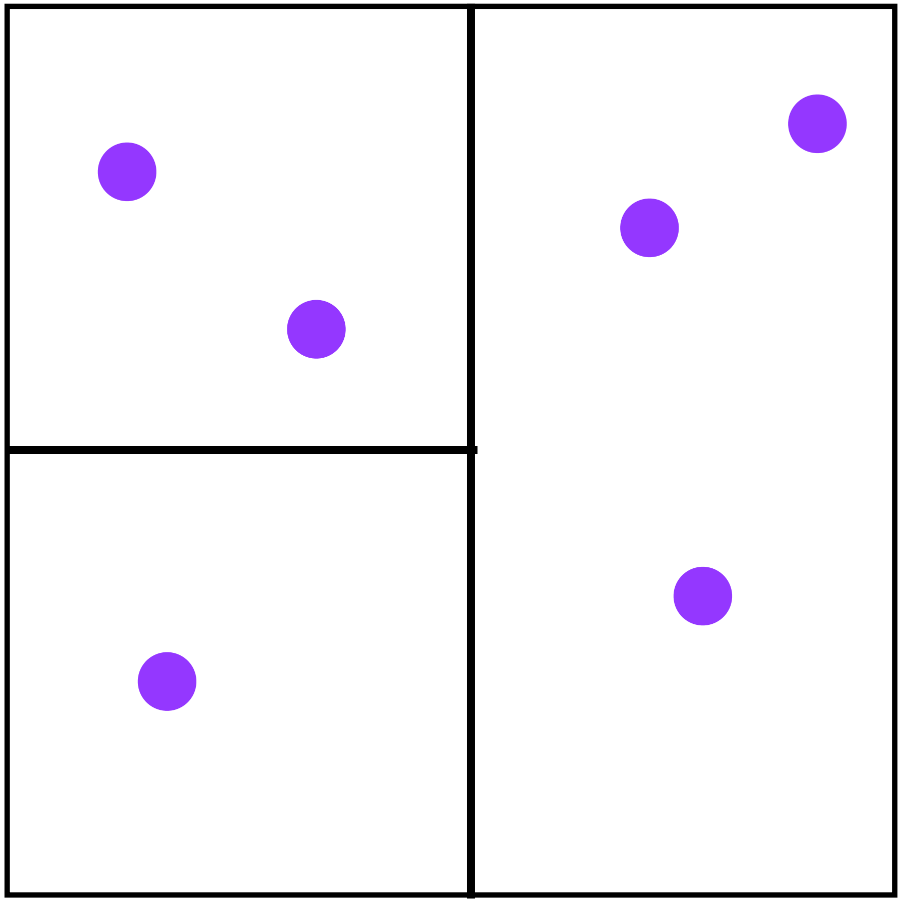

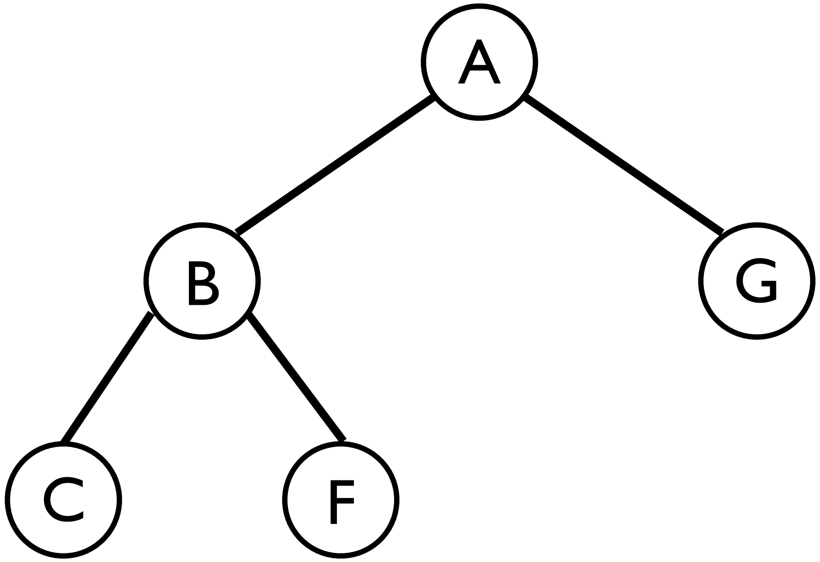

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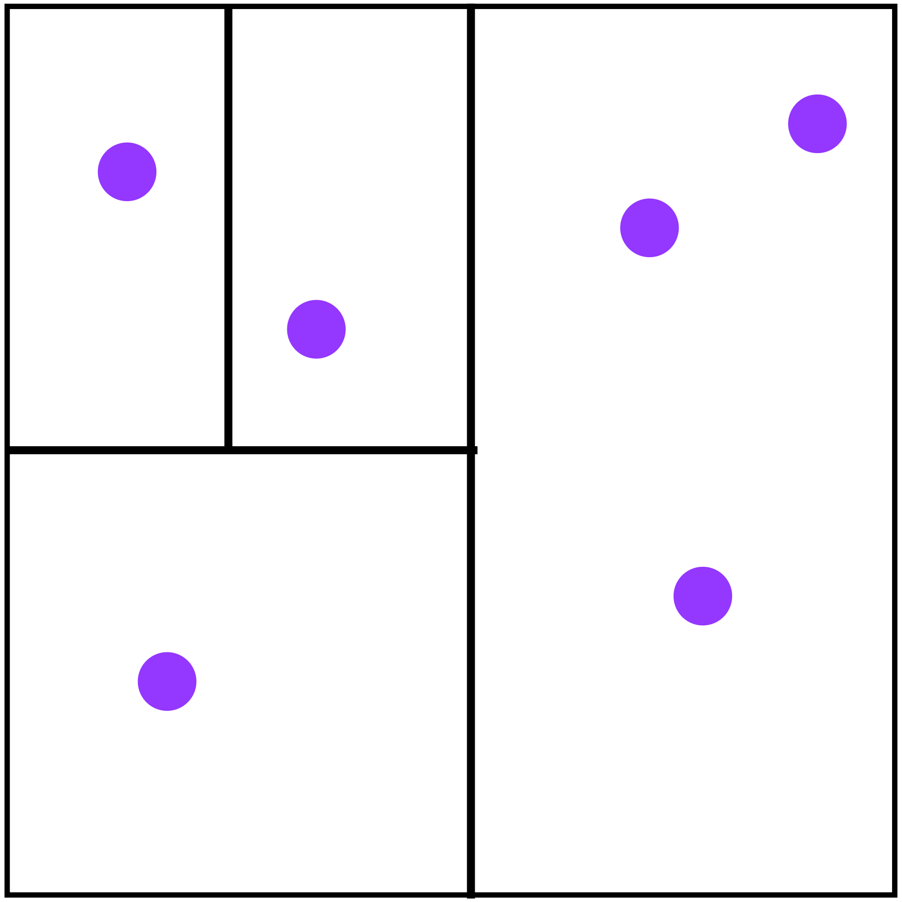

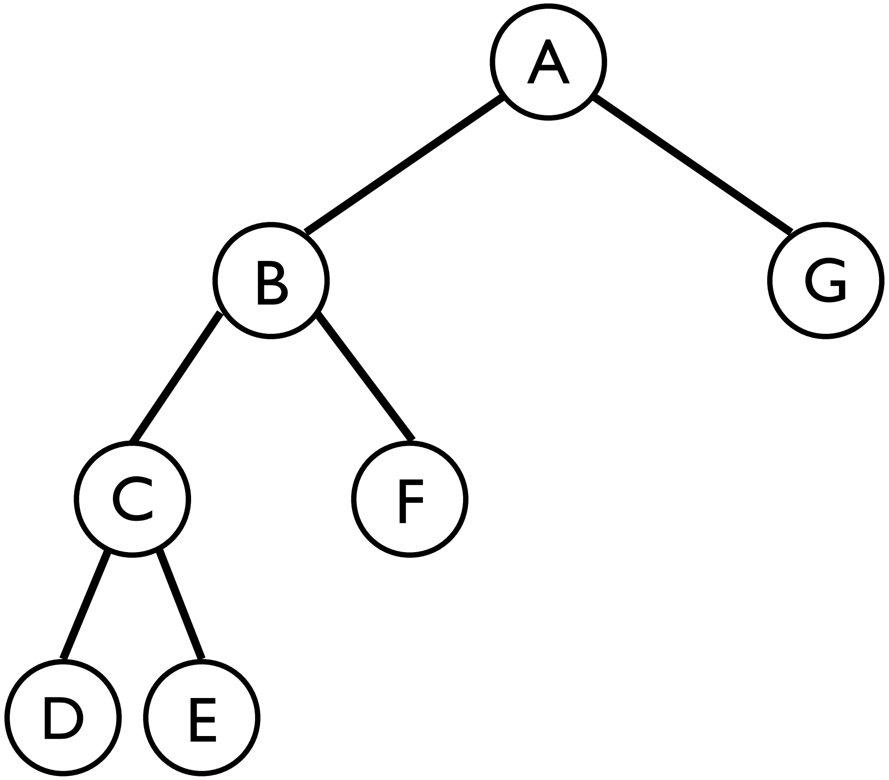

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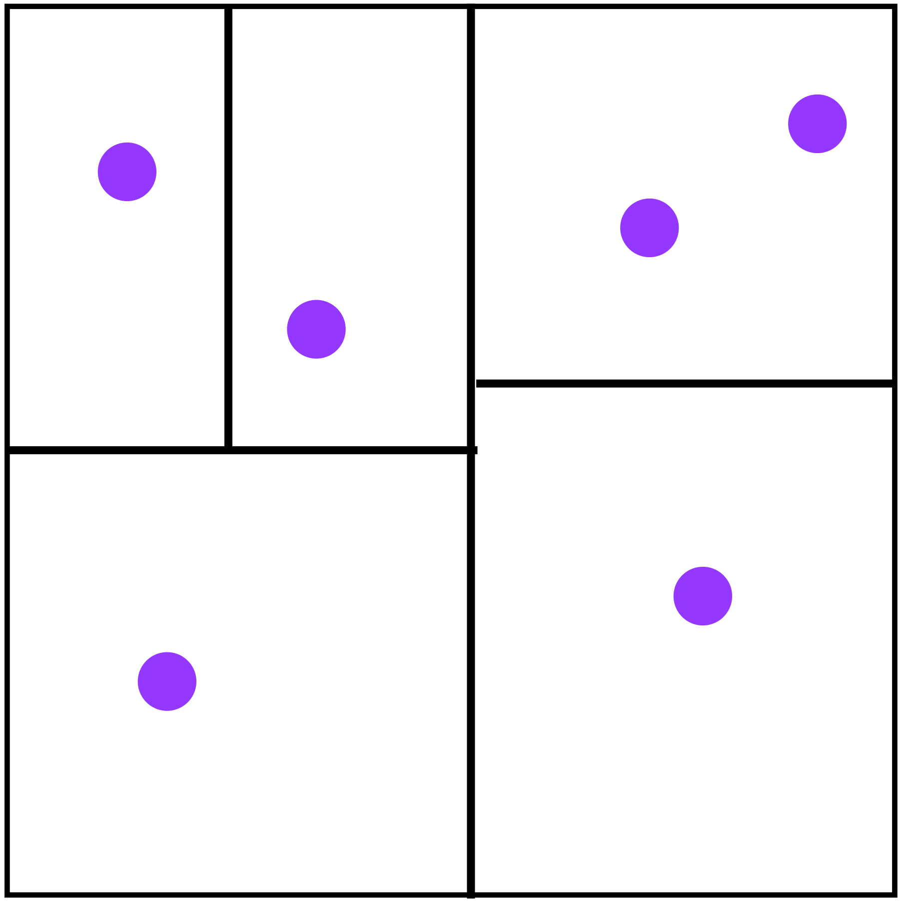

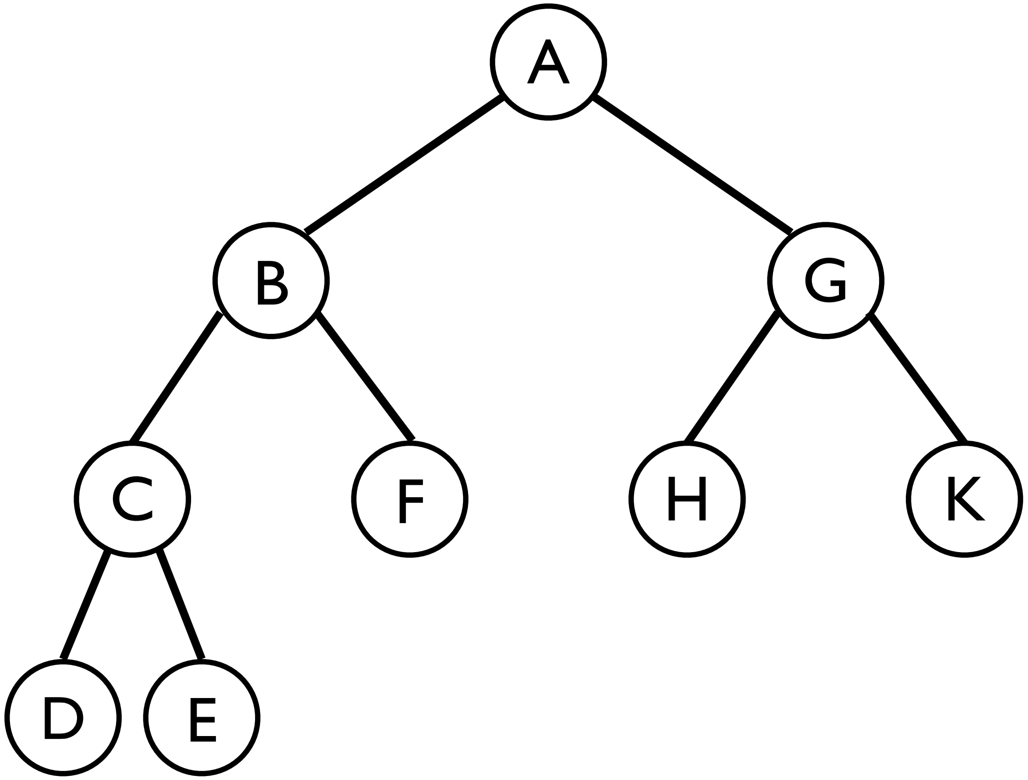

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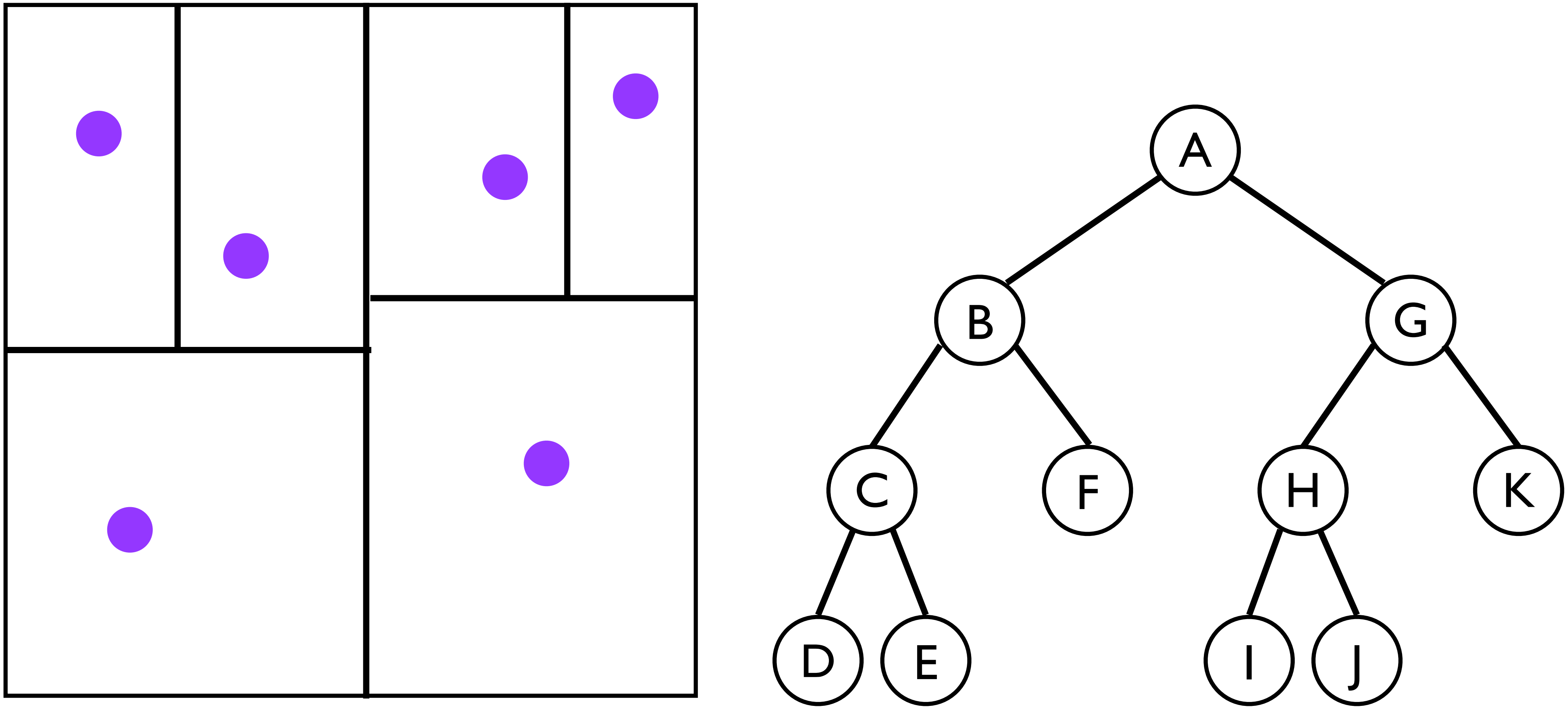

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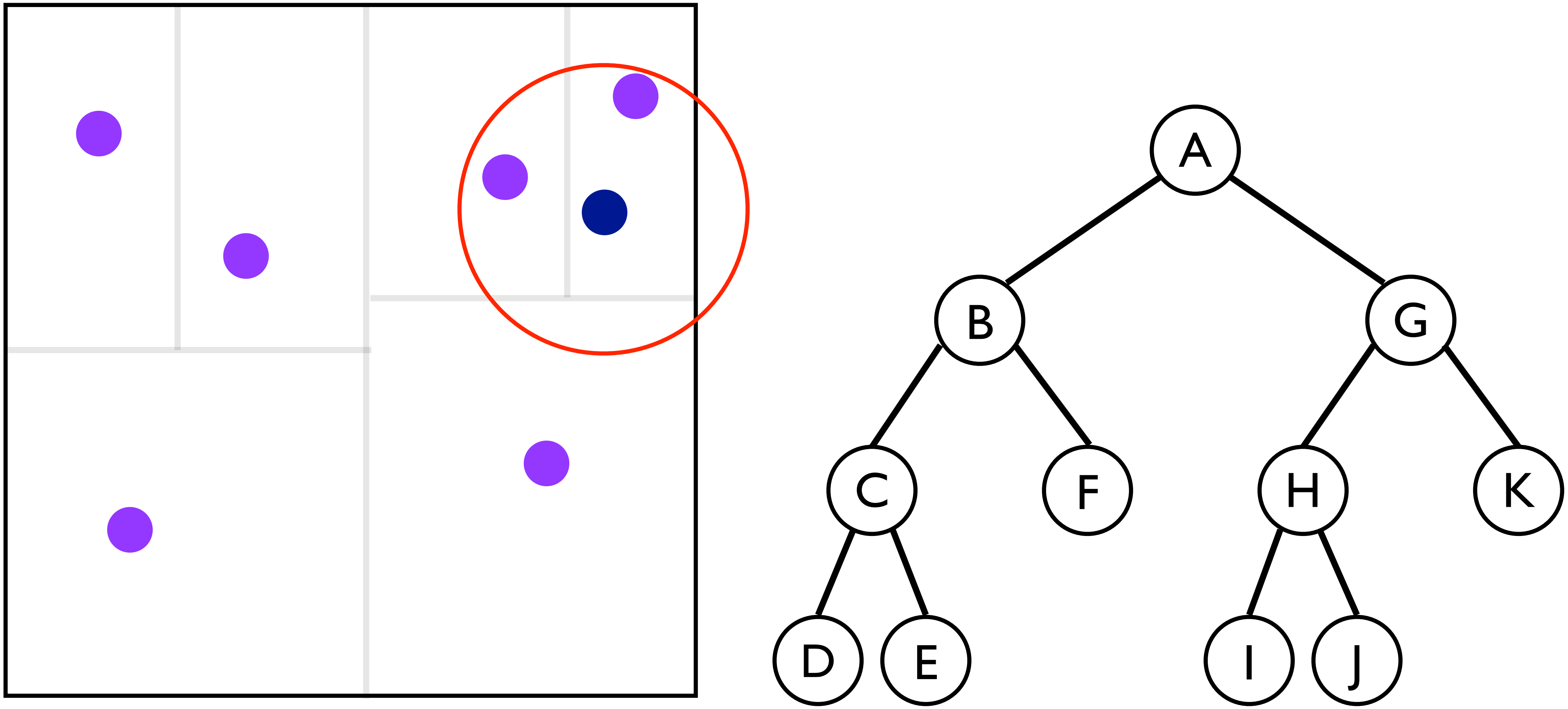

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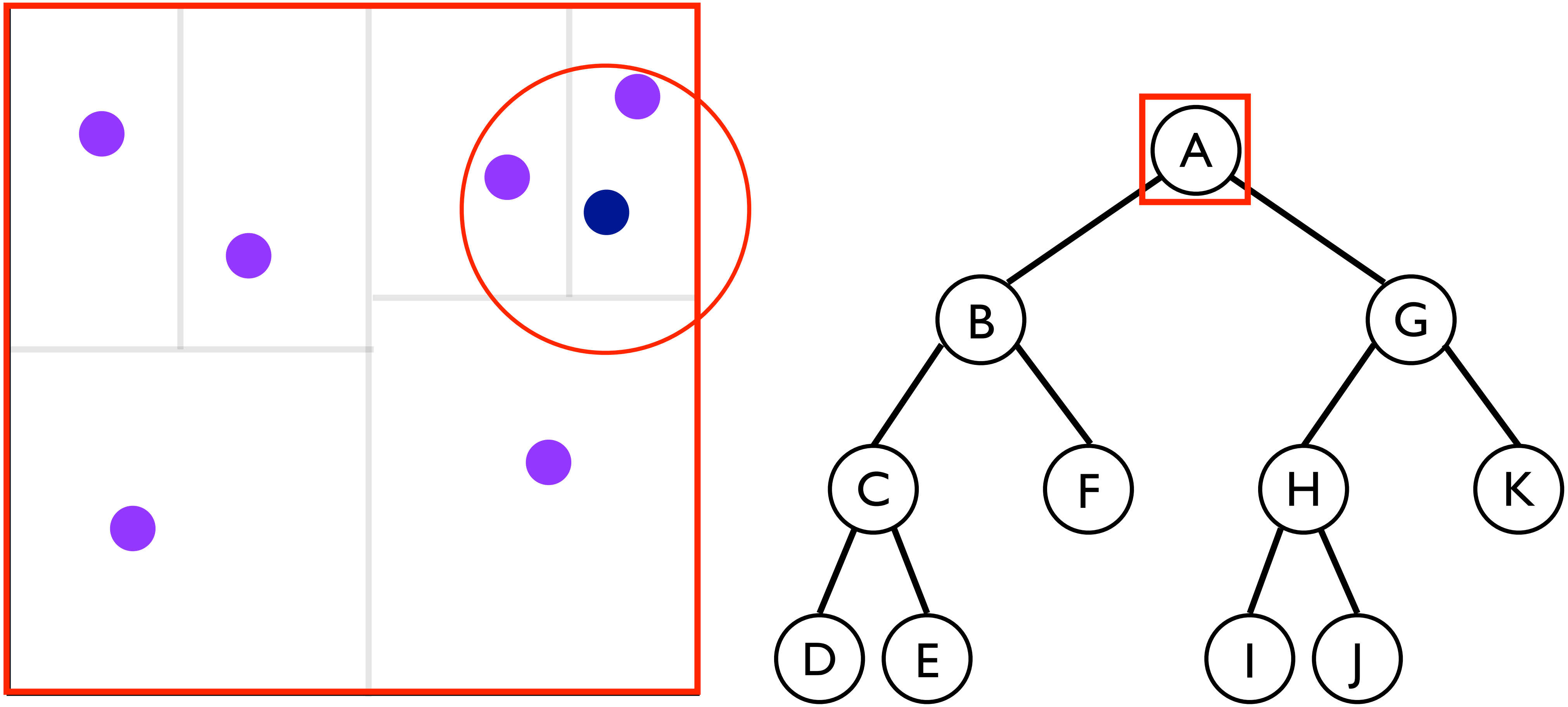

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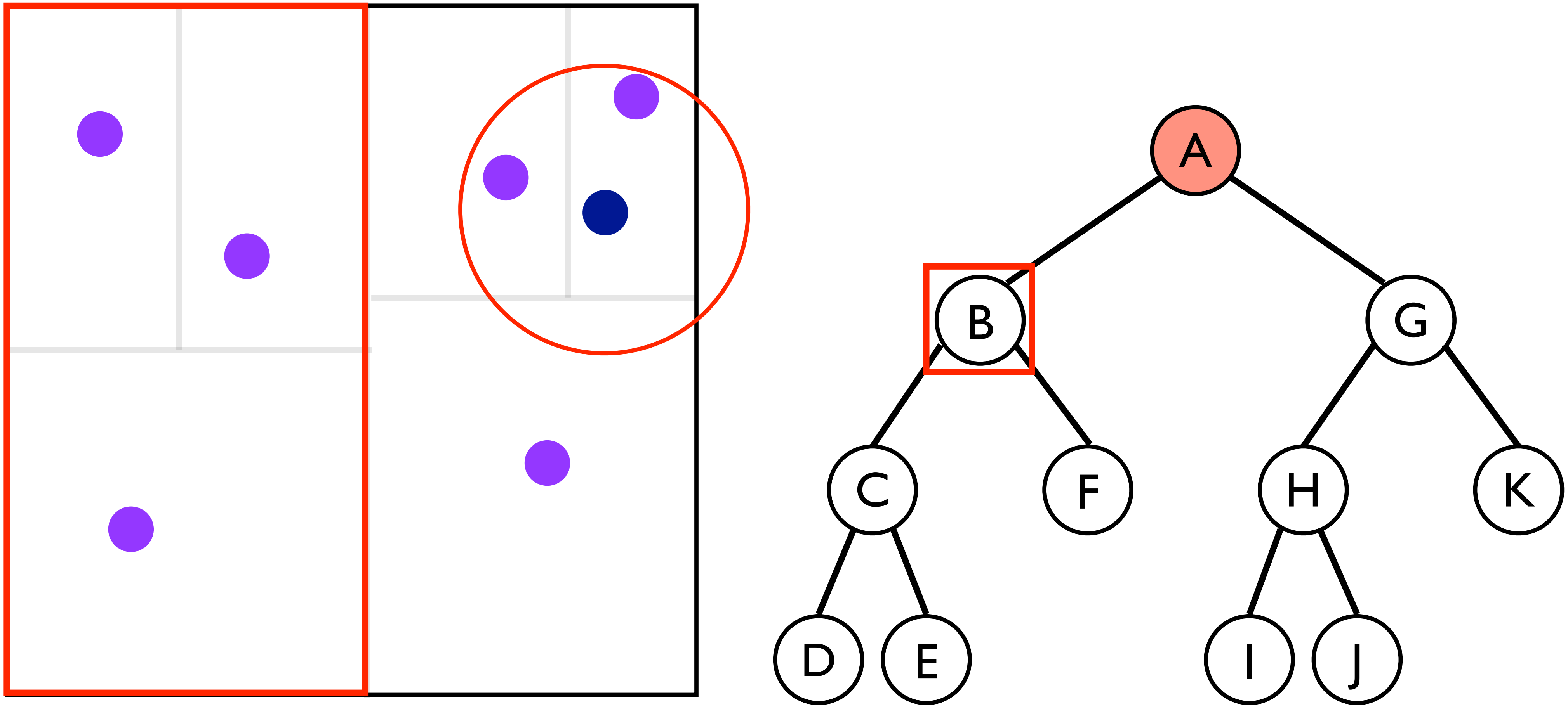

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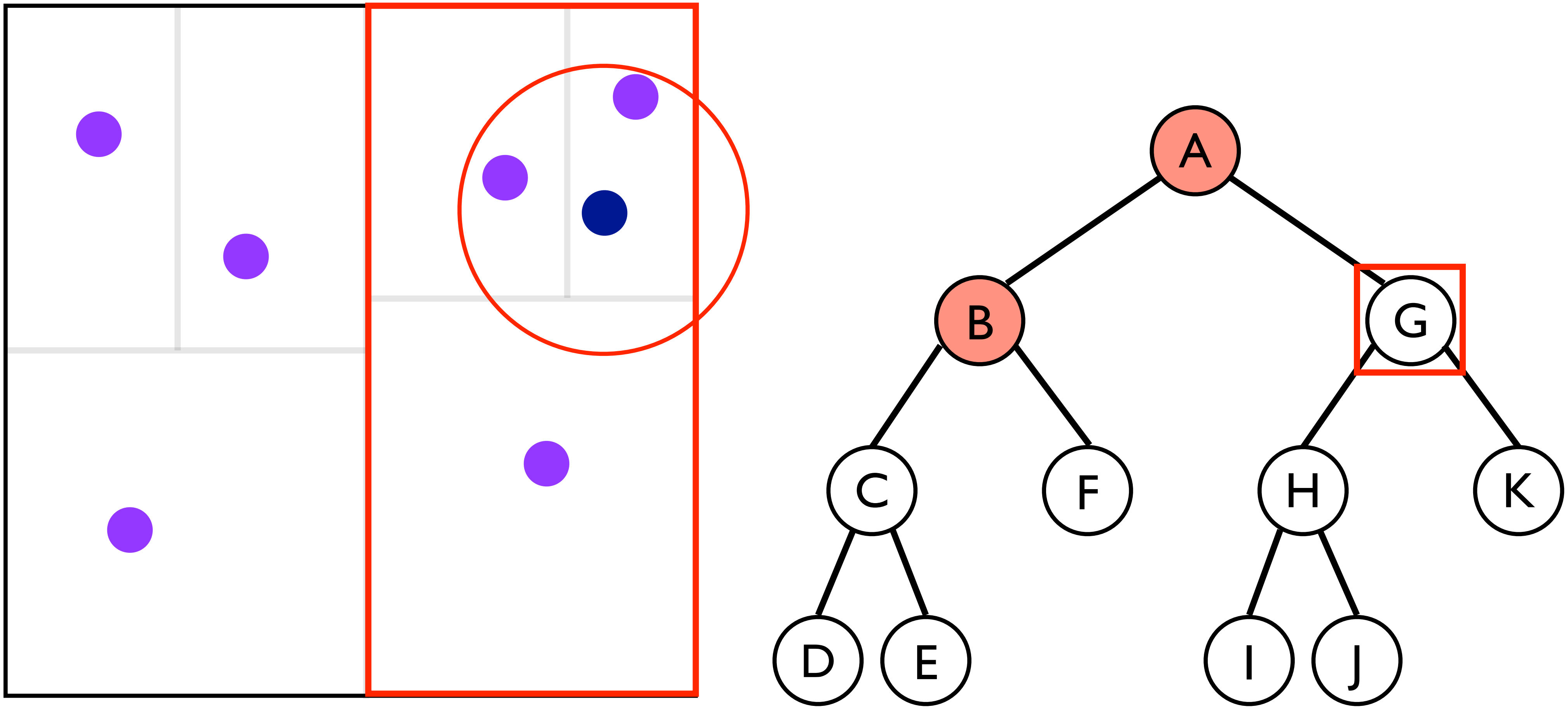

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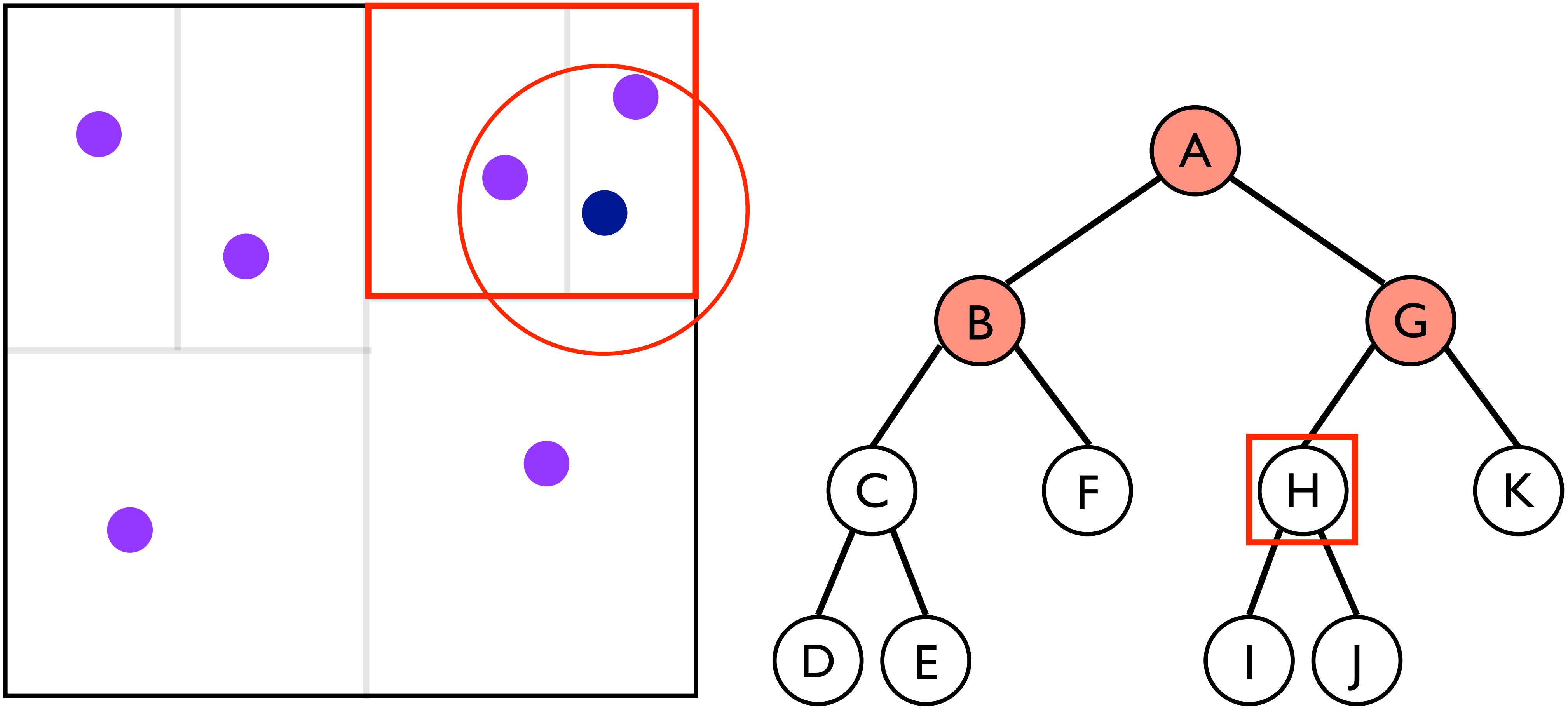

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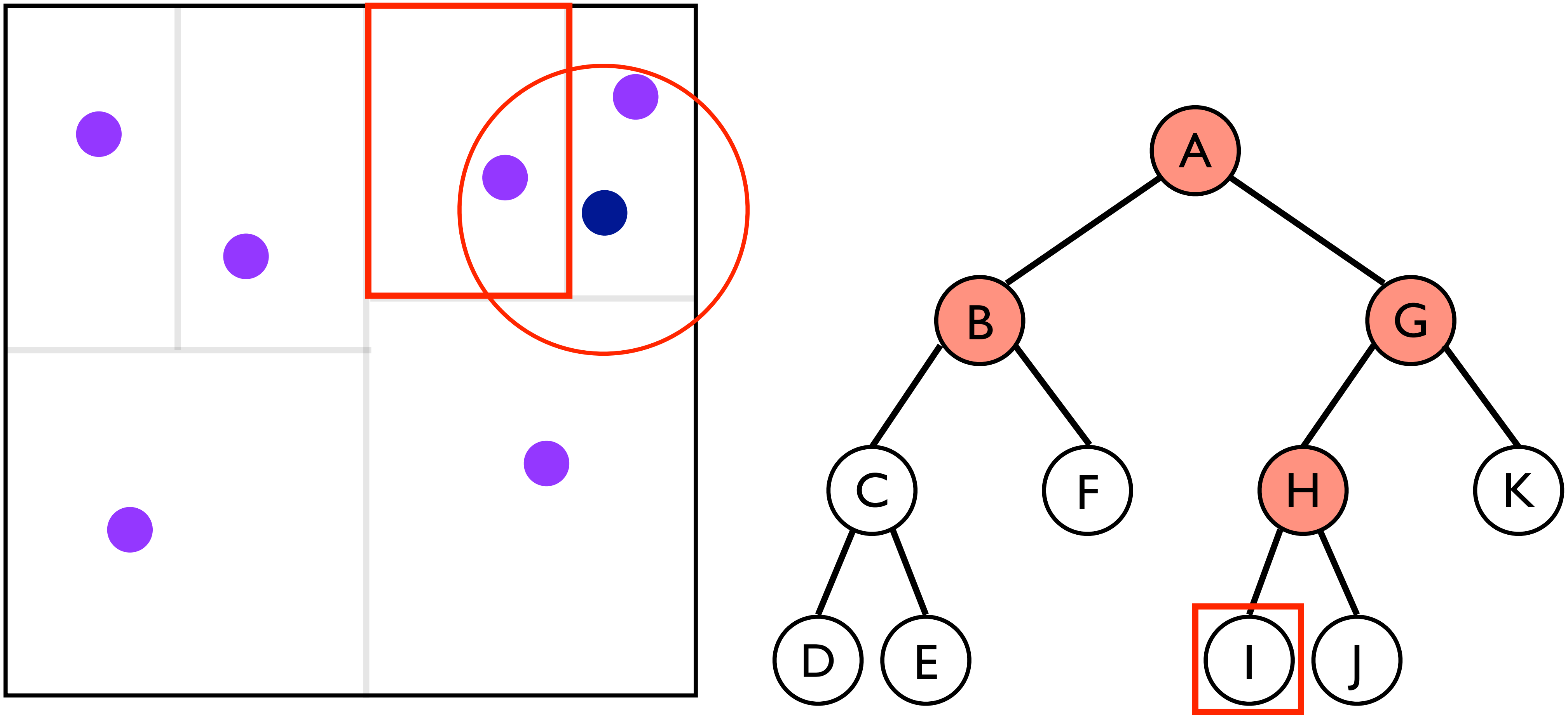

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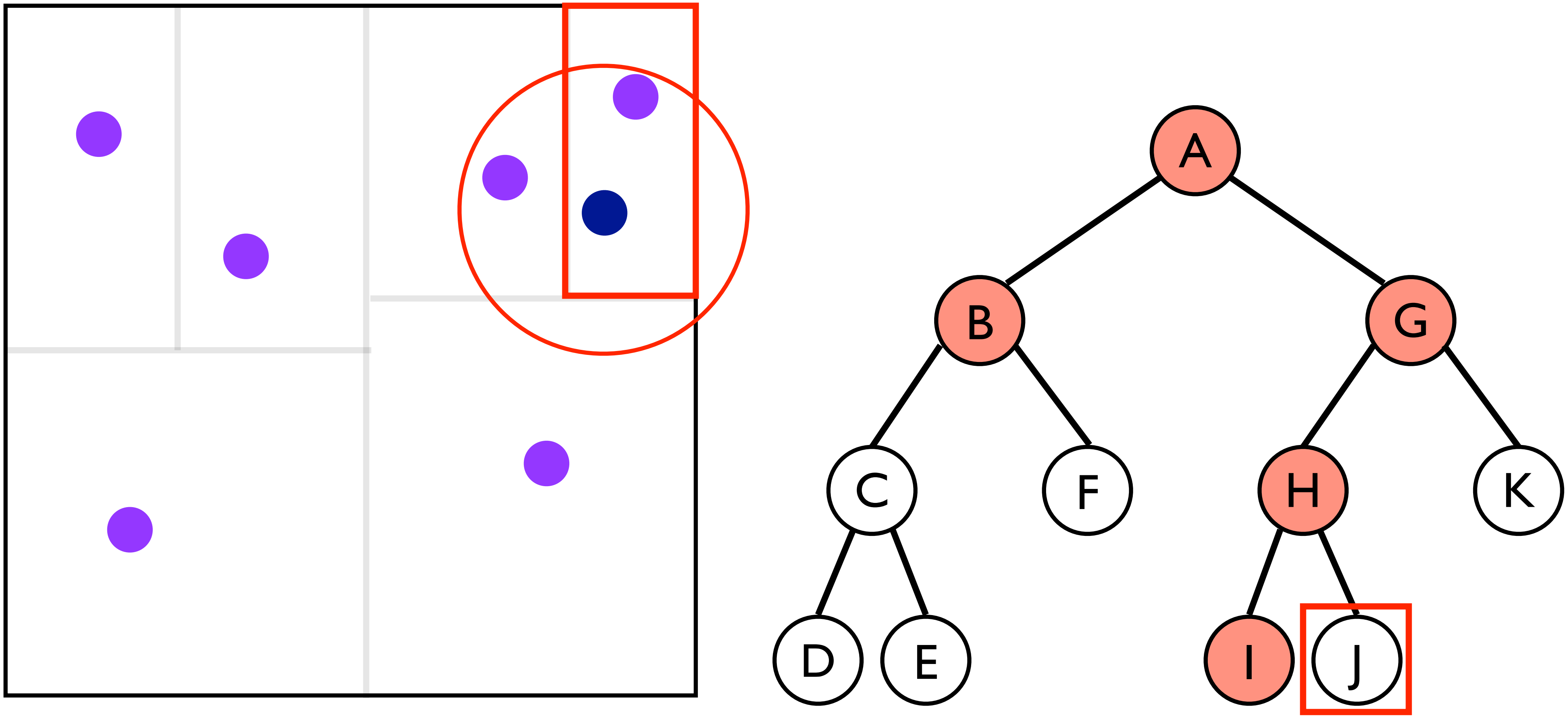

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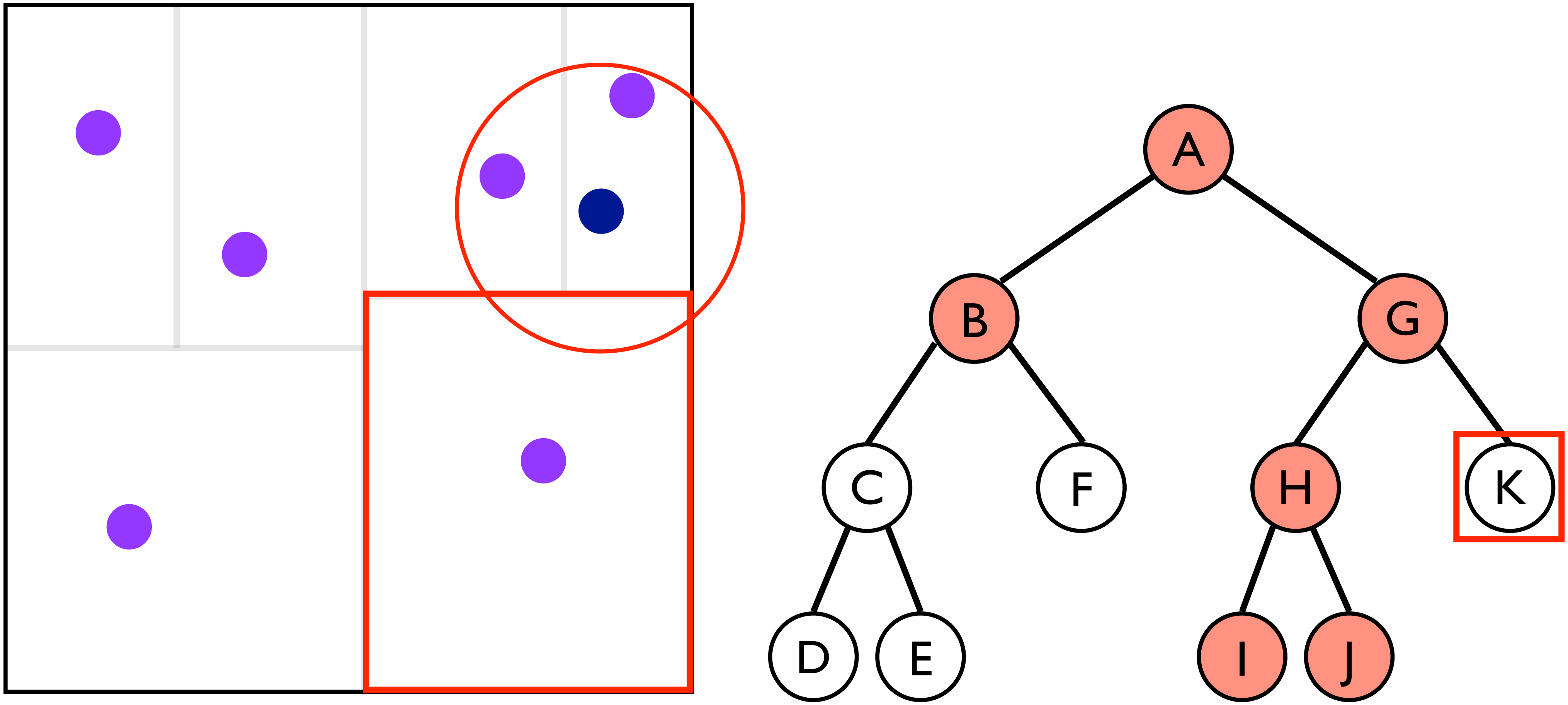

Point correlation

```
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);
   }
}
```

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, ...);
   ...
}
```

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recursive traversal

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tree structure

recursive traversal

Basic pattern

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```

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 (tr
      { ... }
   recurse(p, node.child1, ...);
   recurse(p, node.child2, ...);
   ...
}
```

tree structure

repeated traversal

Lots of parallelism!

recursive traversal

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!

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- *hoc* solutions
  - New algorithm? New GPU techniques!

Want generally applicable techniques for mapping irregular applications to GPUs

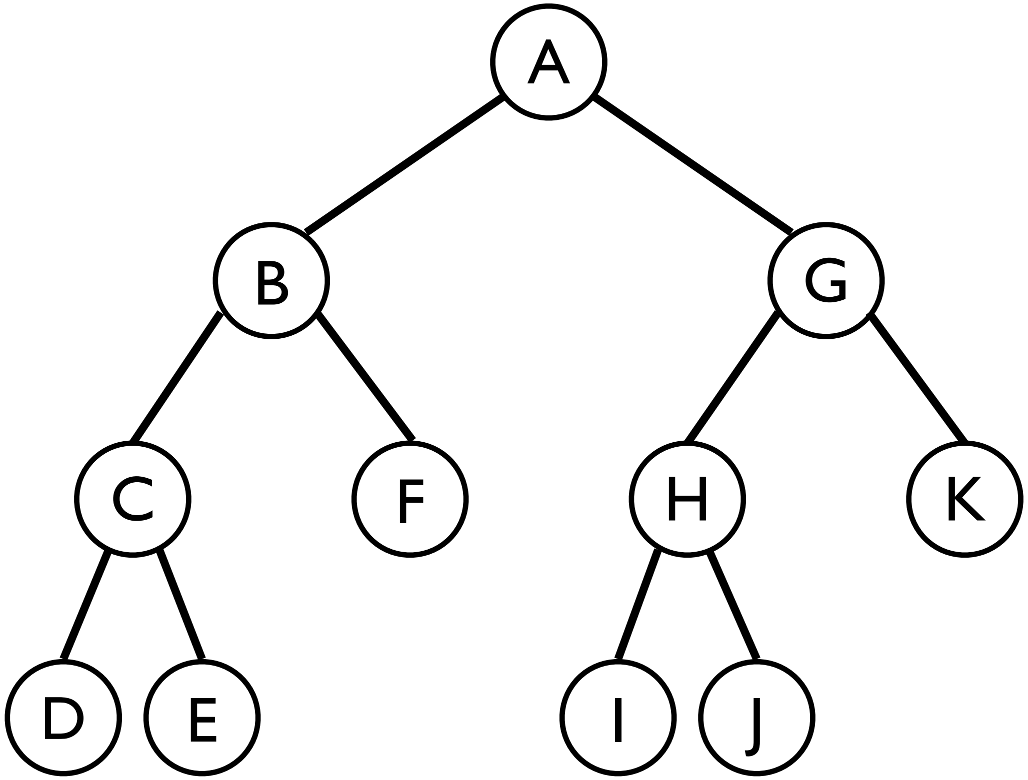
Contributions

- 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



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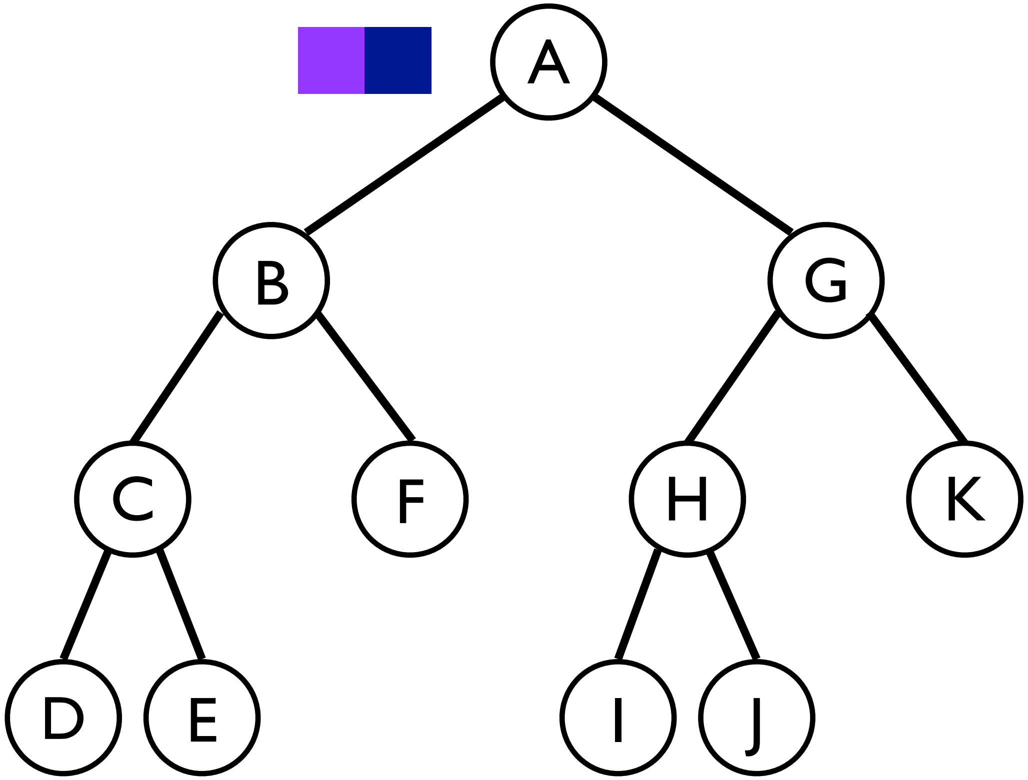

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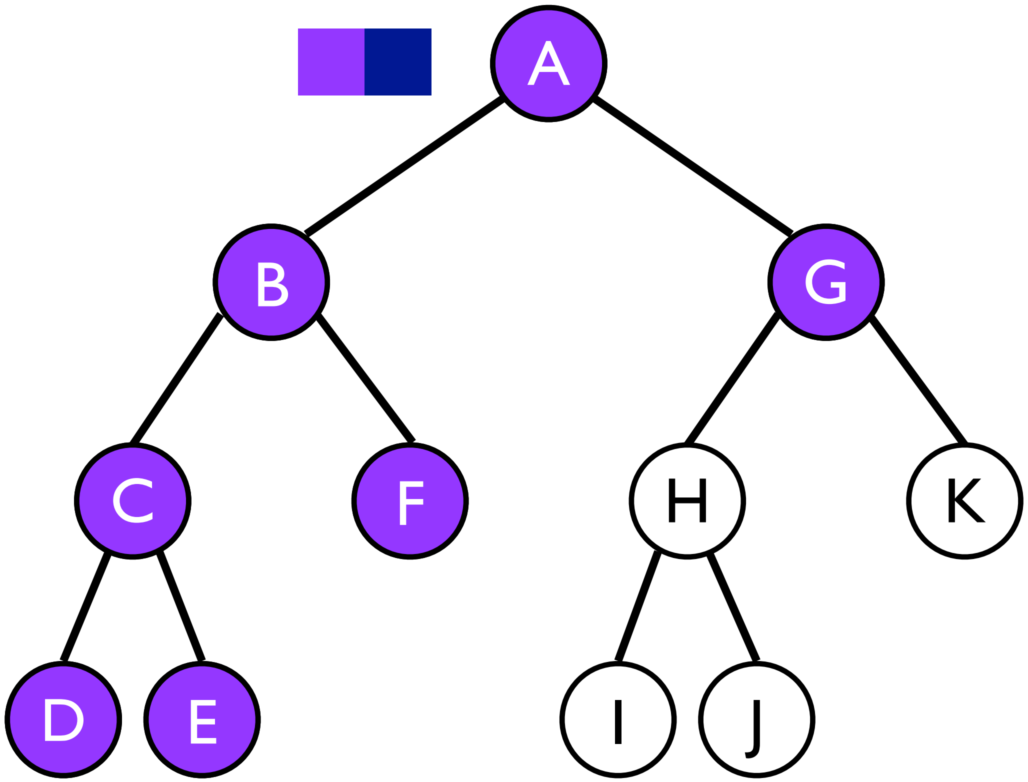

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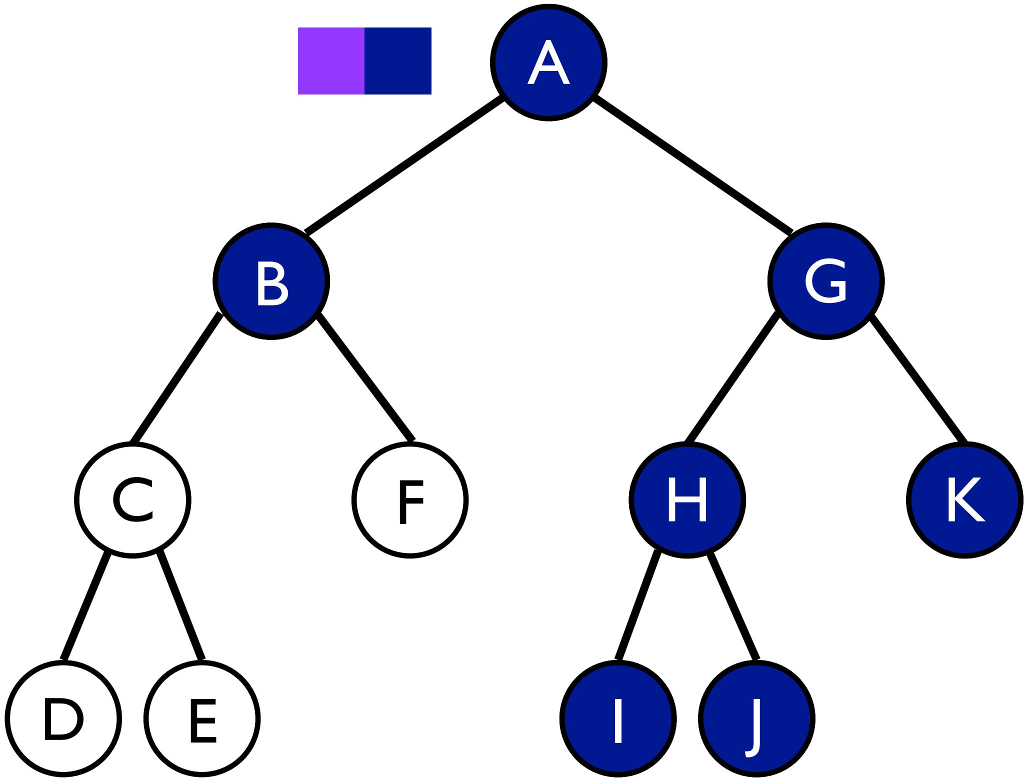

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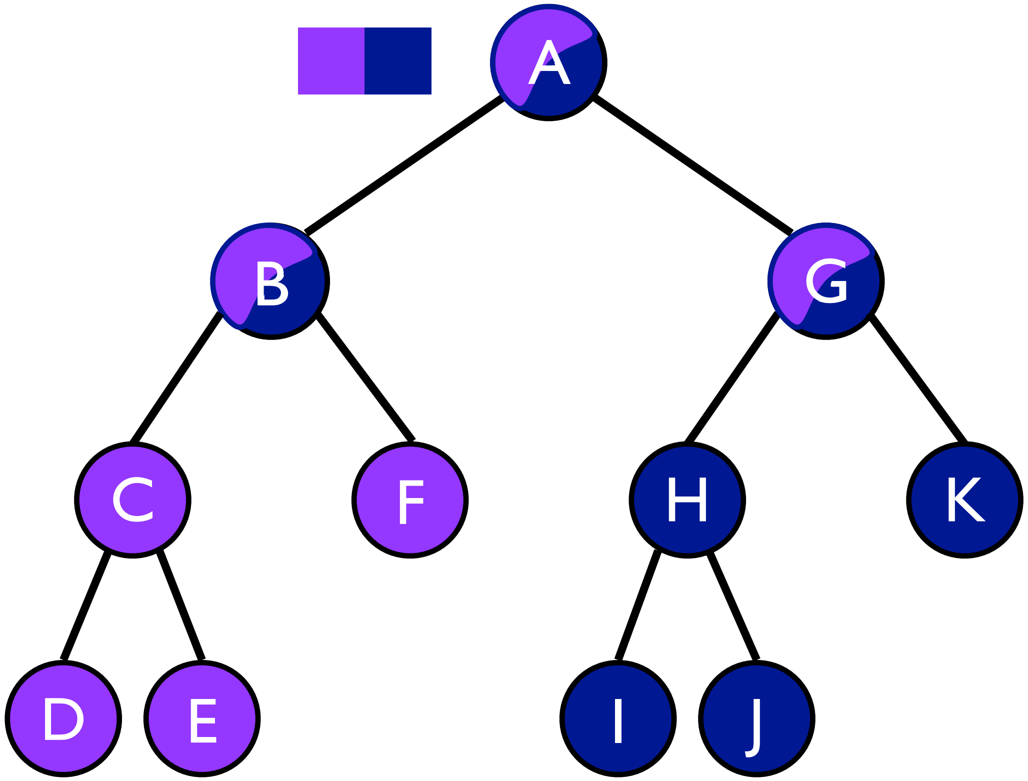

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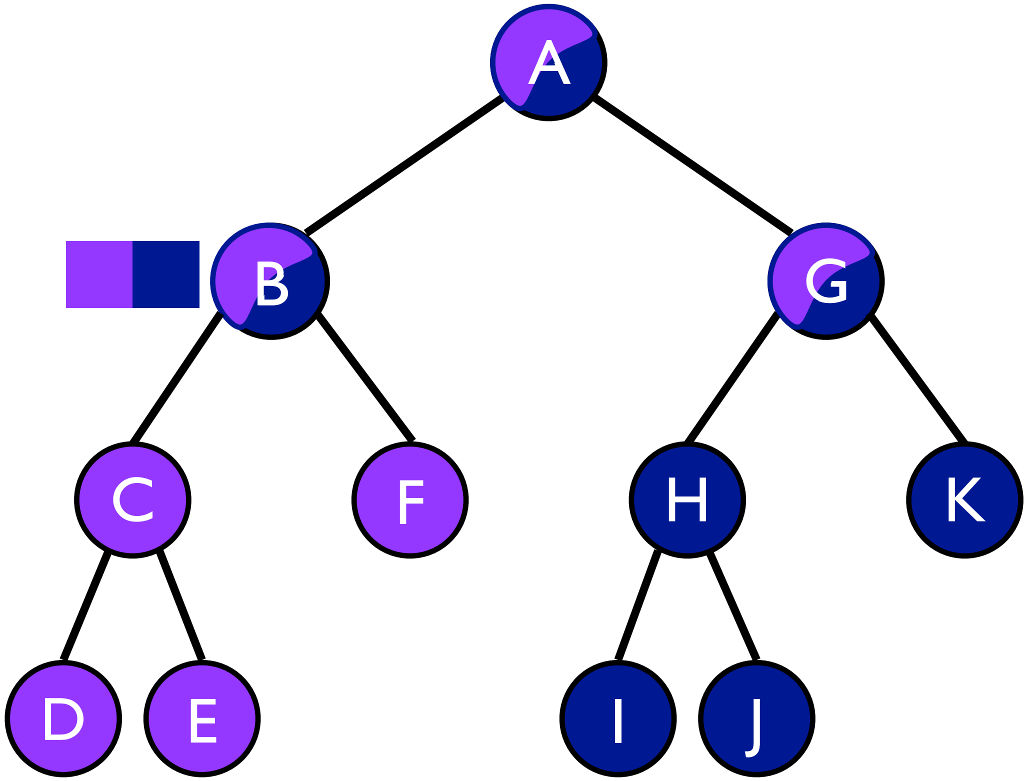

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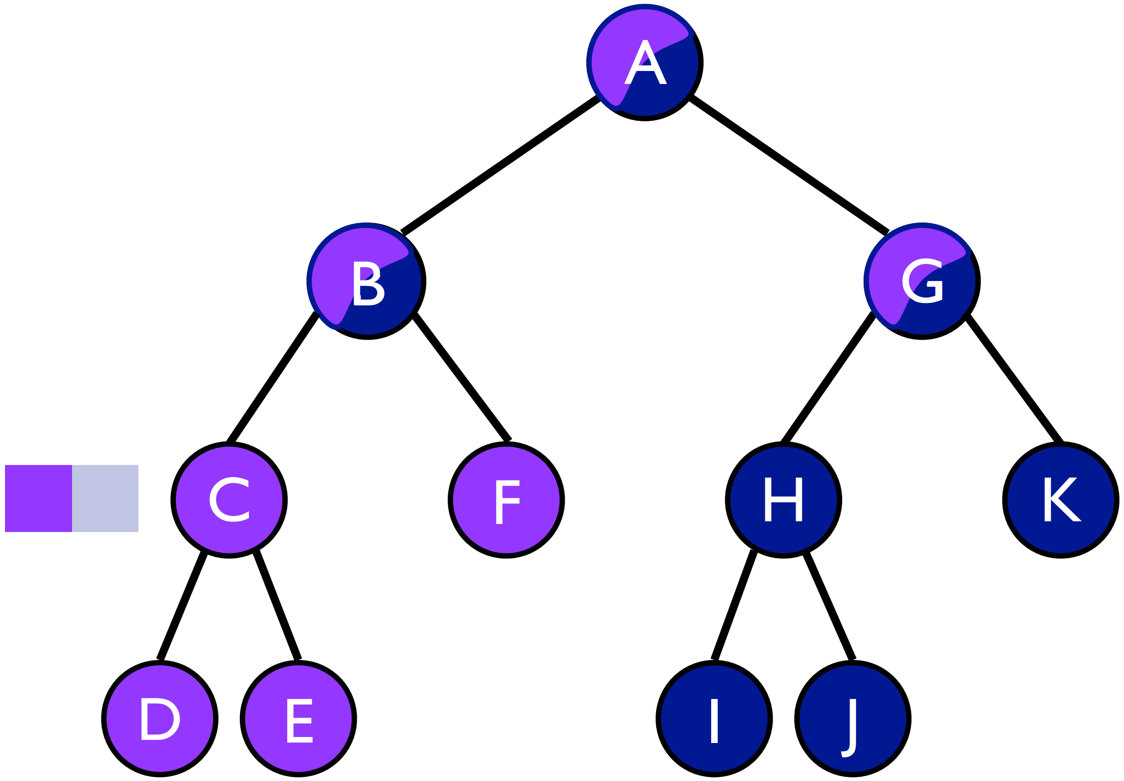

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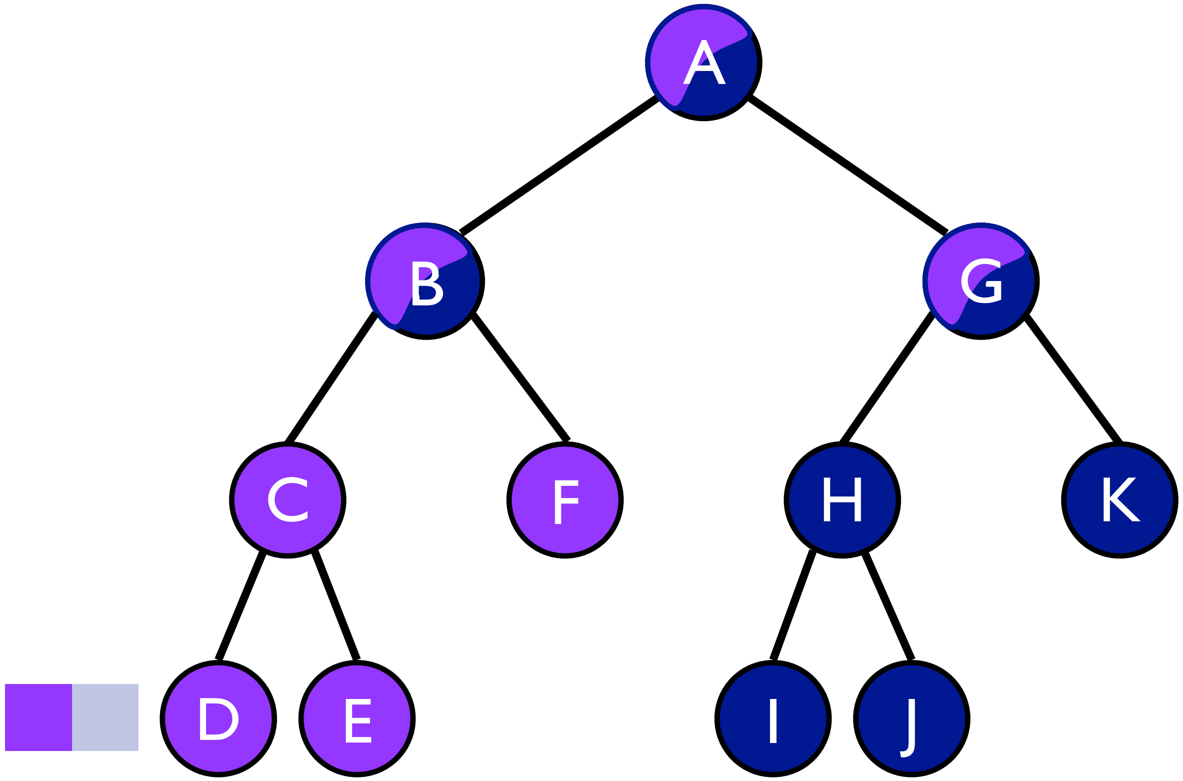

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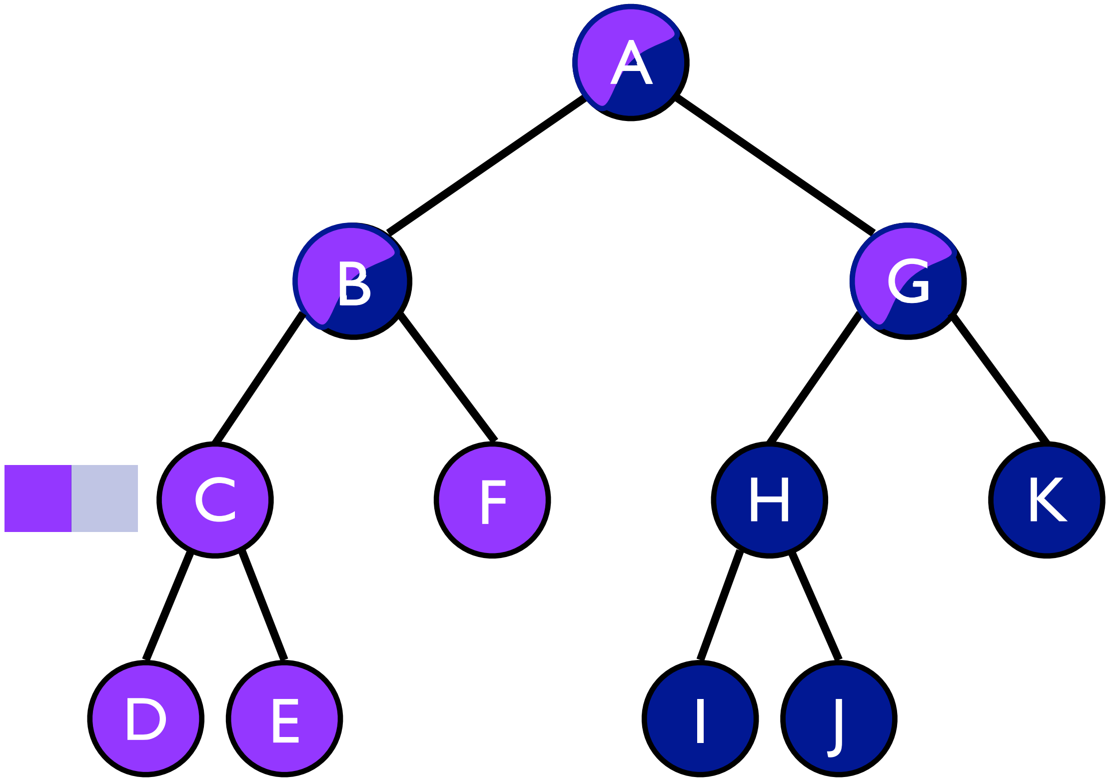

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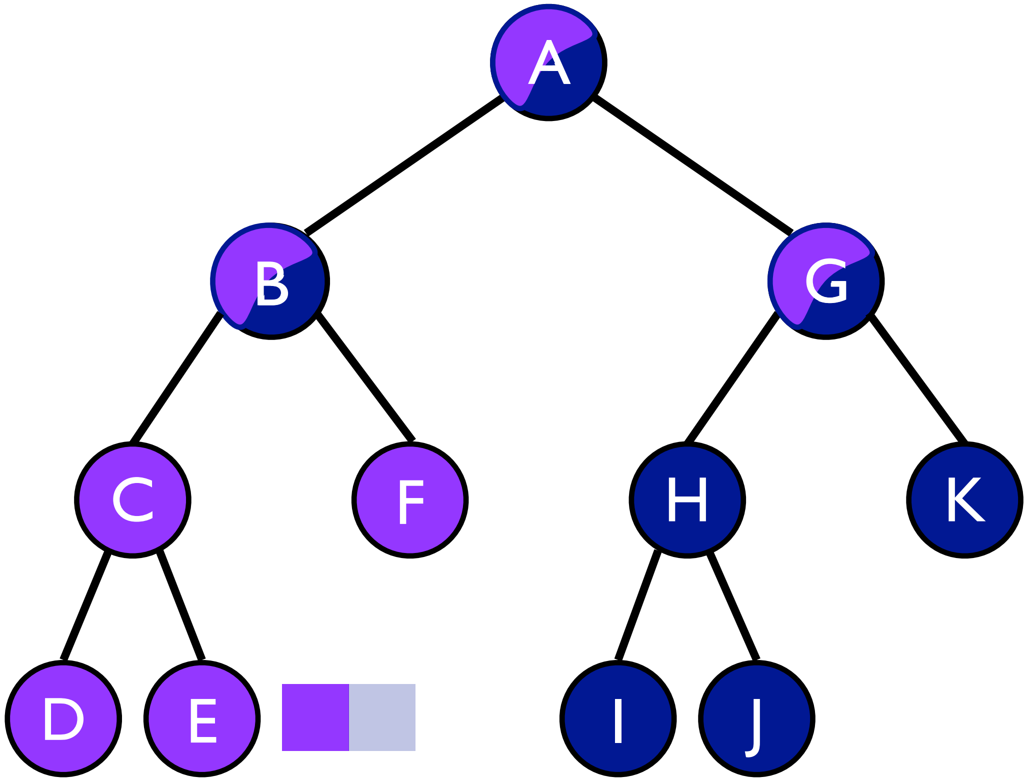

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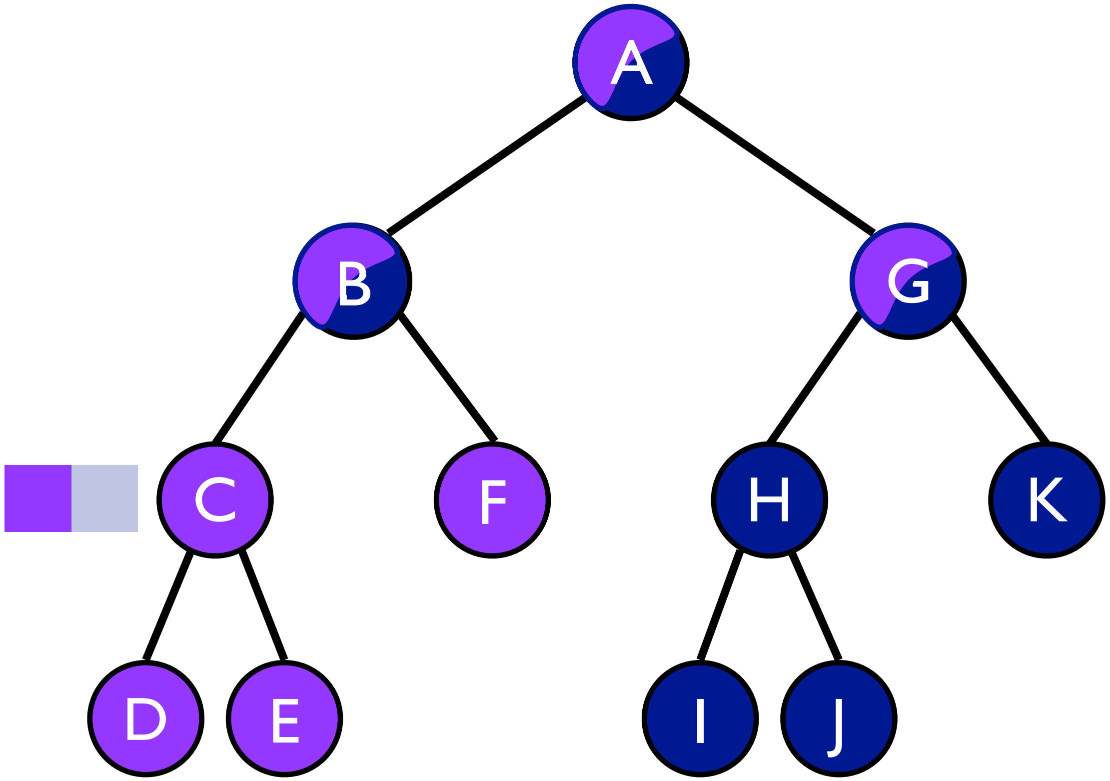

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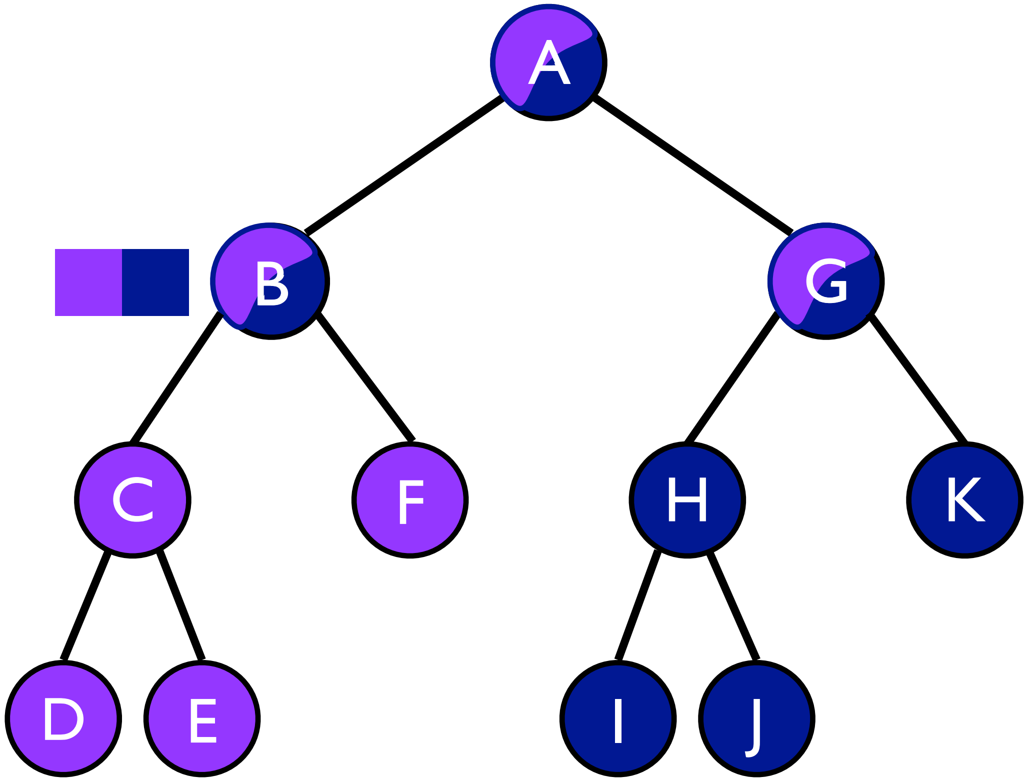

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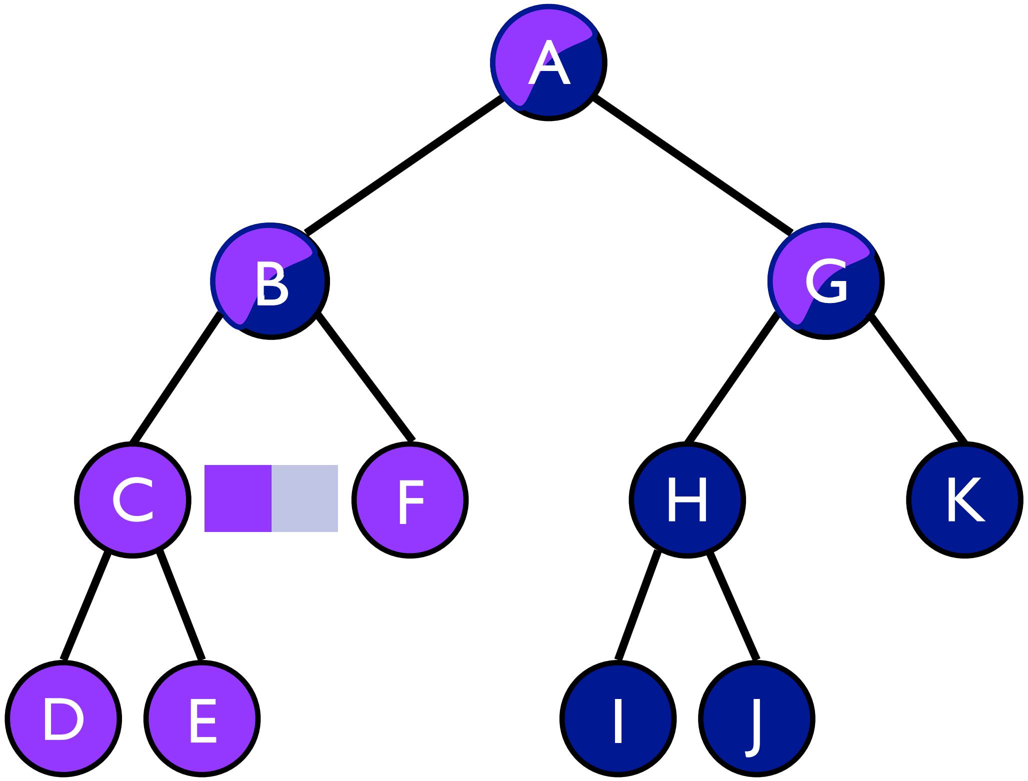

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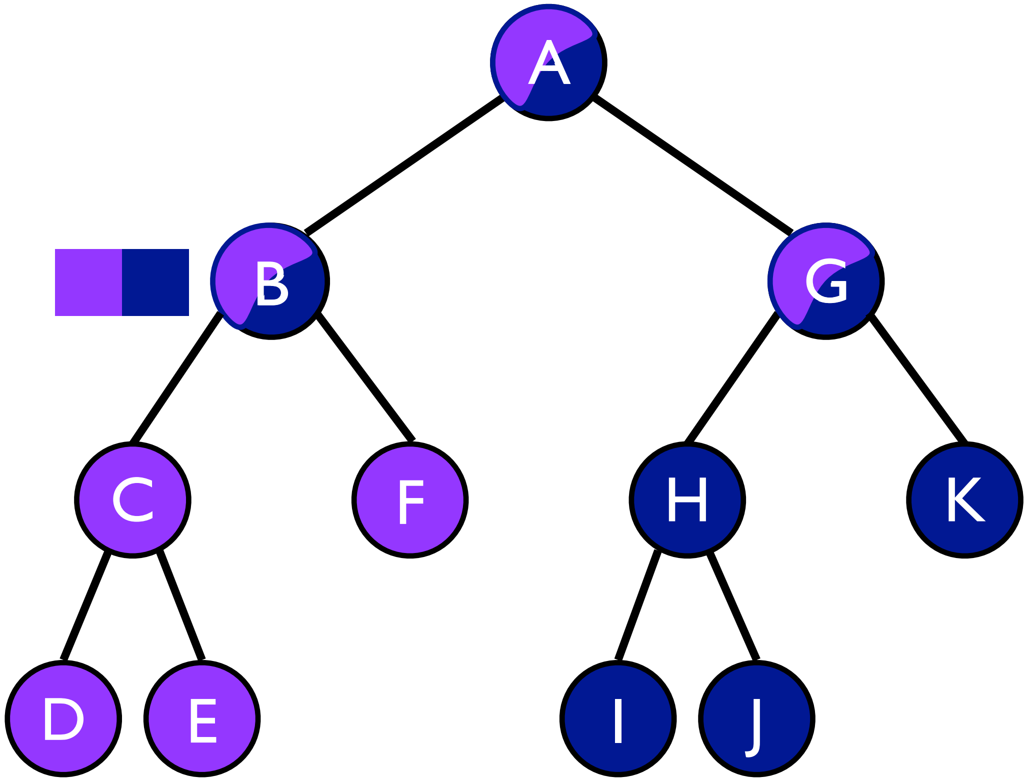

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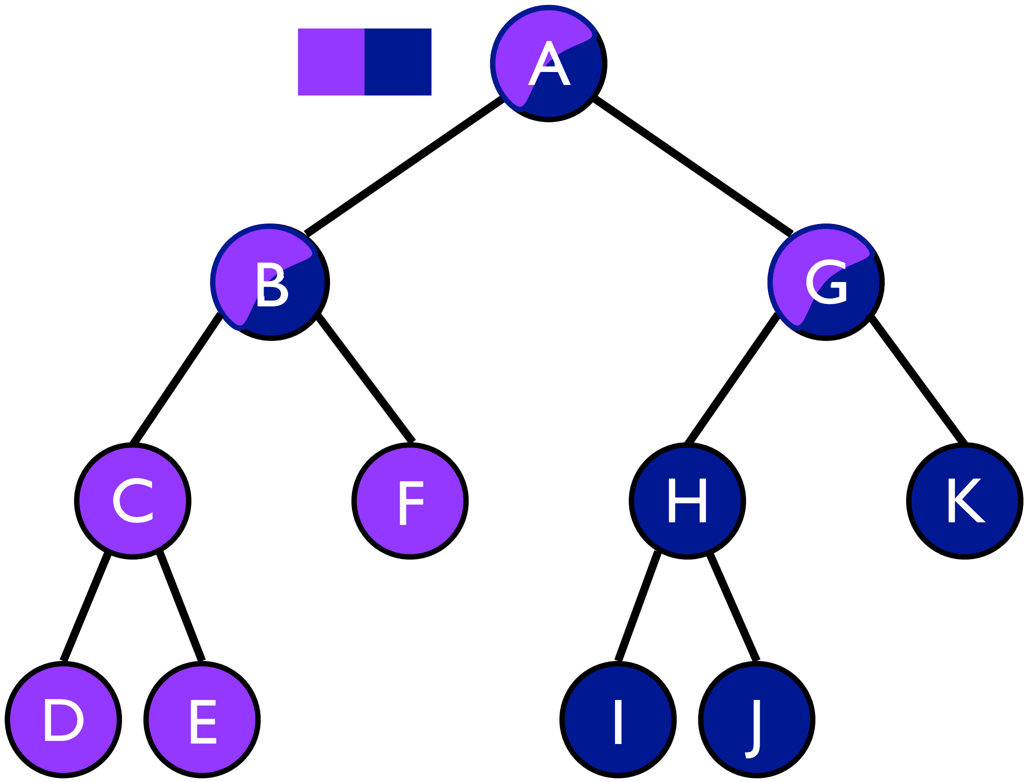

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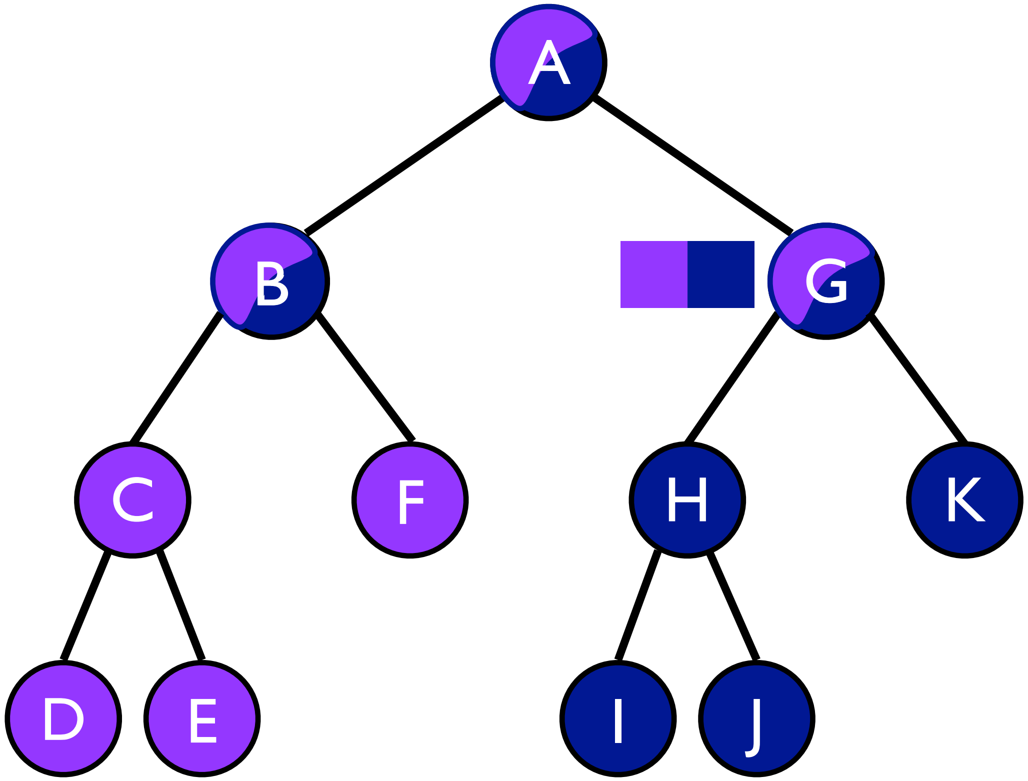

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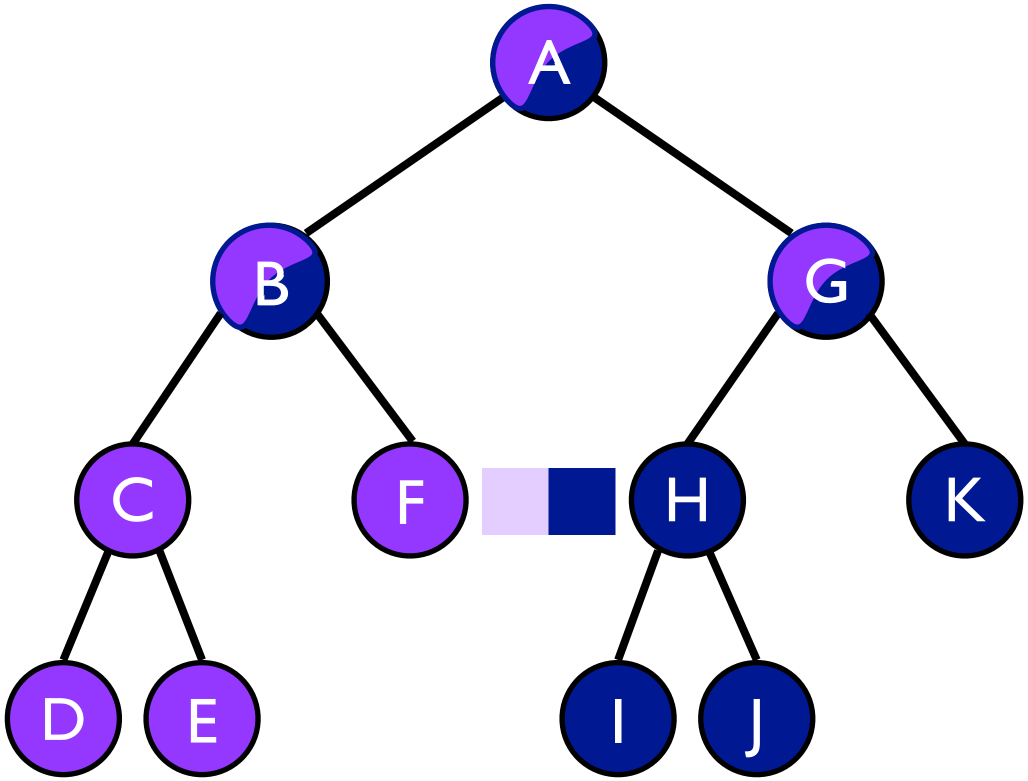

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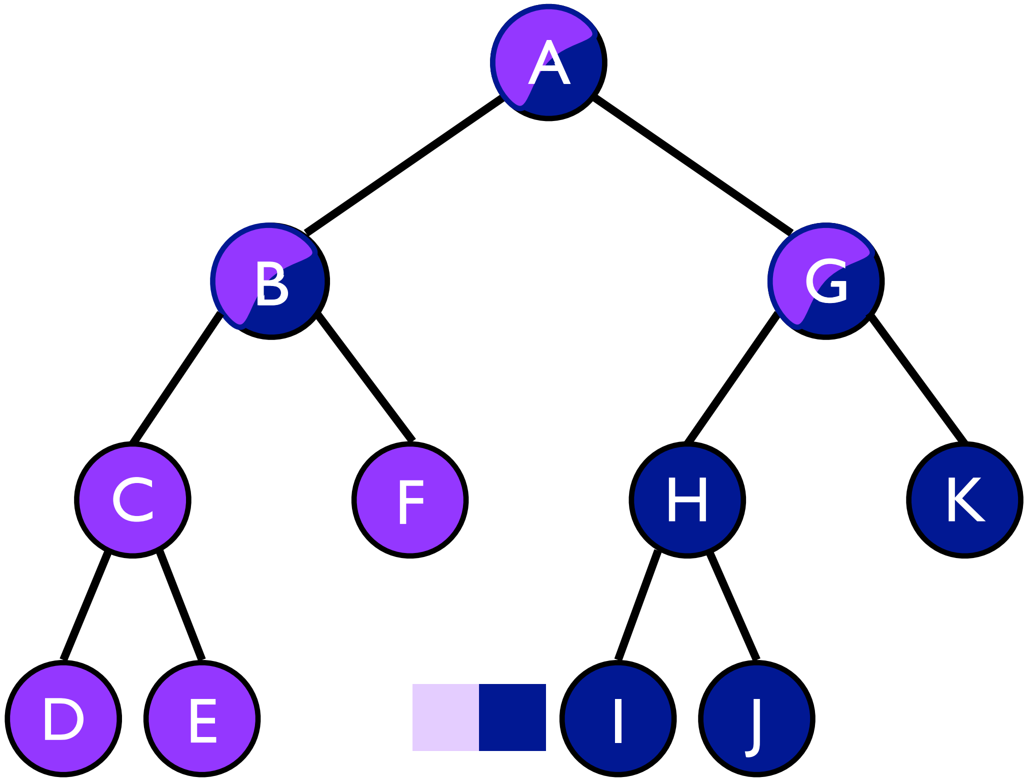
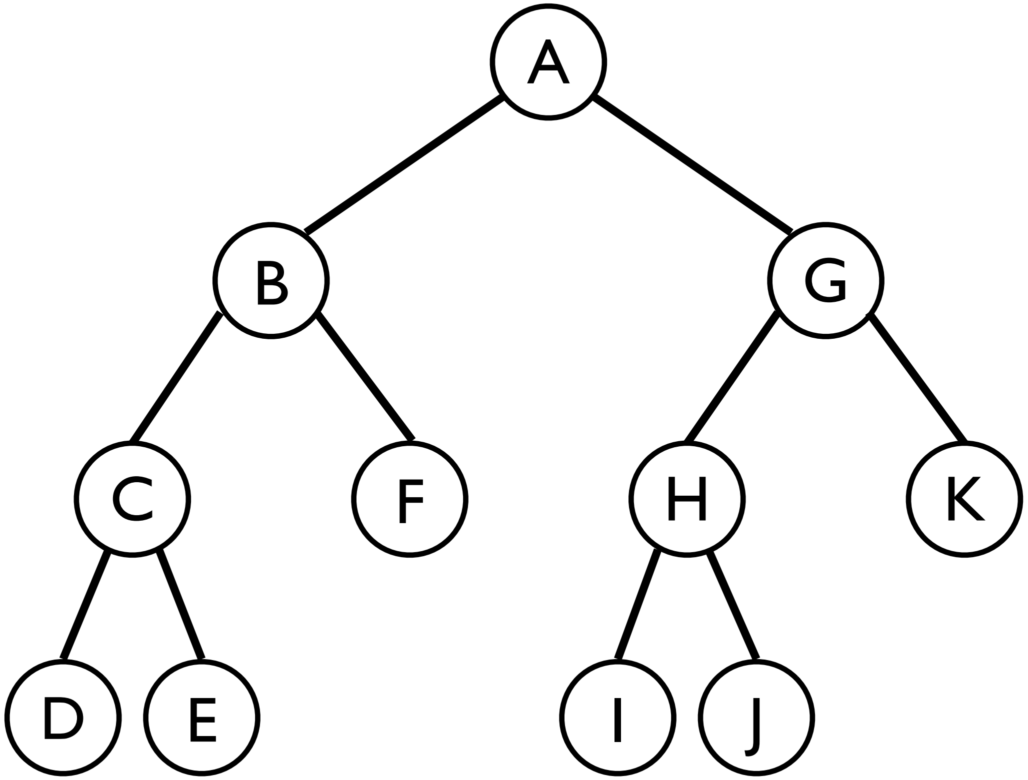


Lots of accesses to tree

- 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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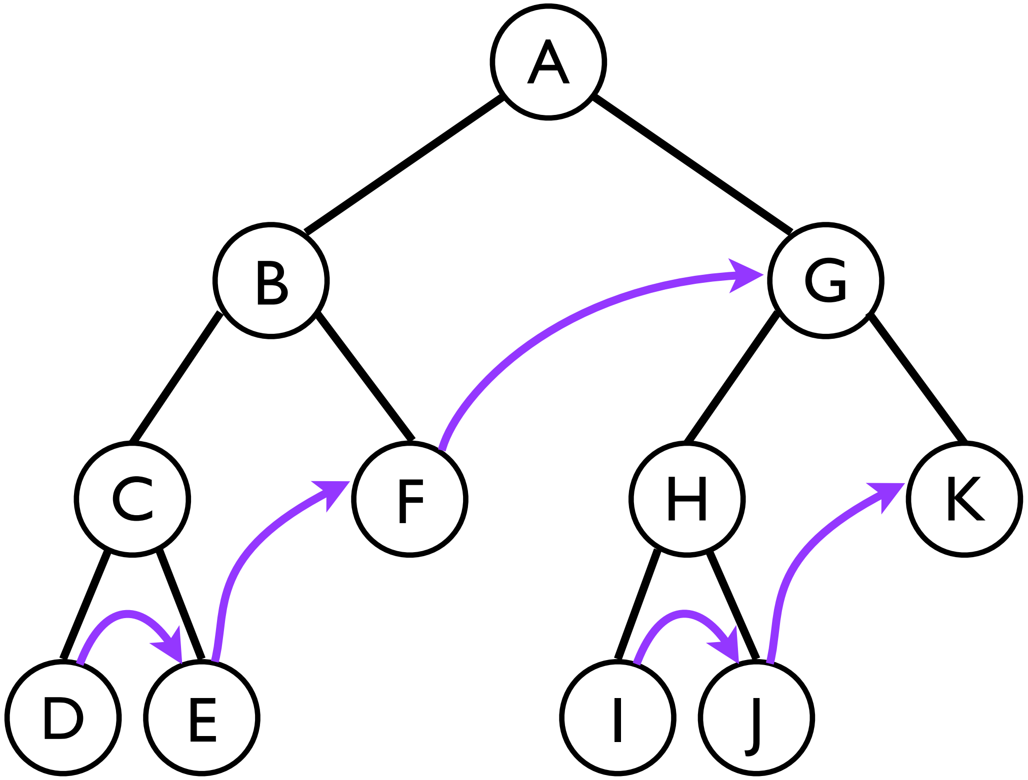

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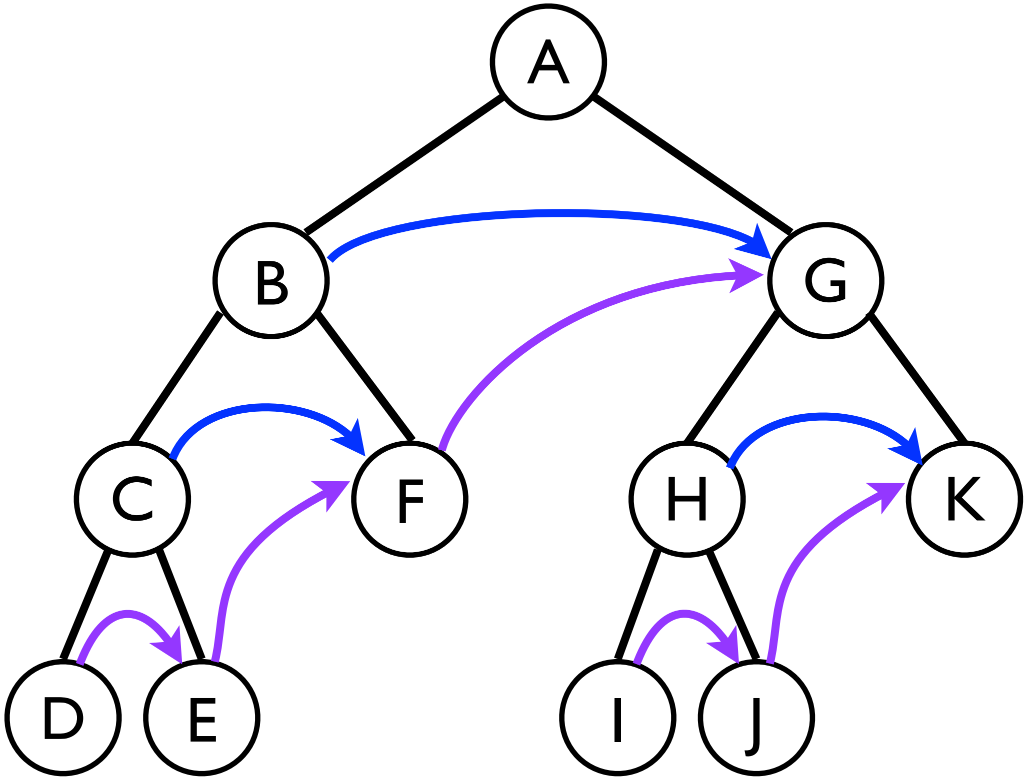

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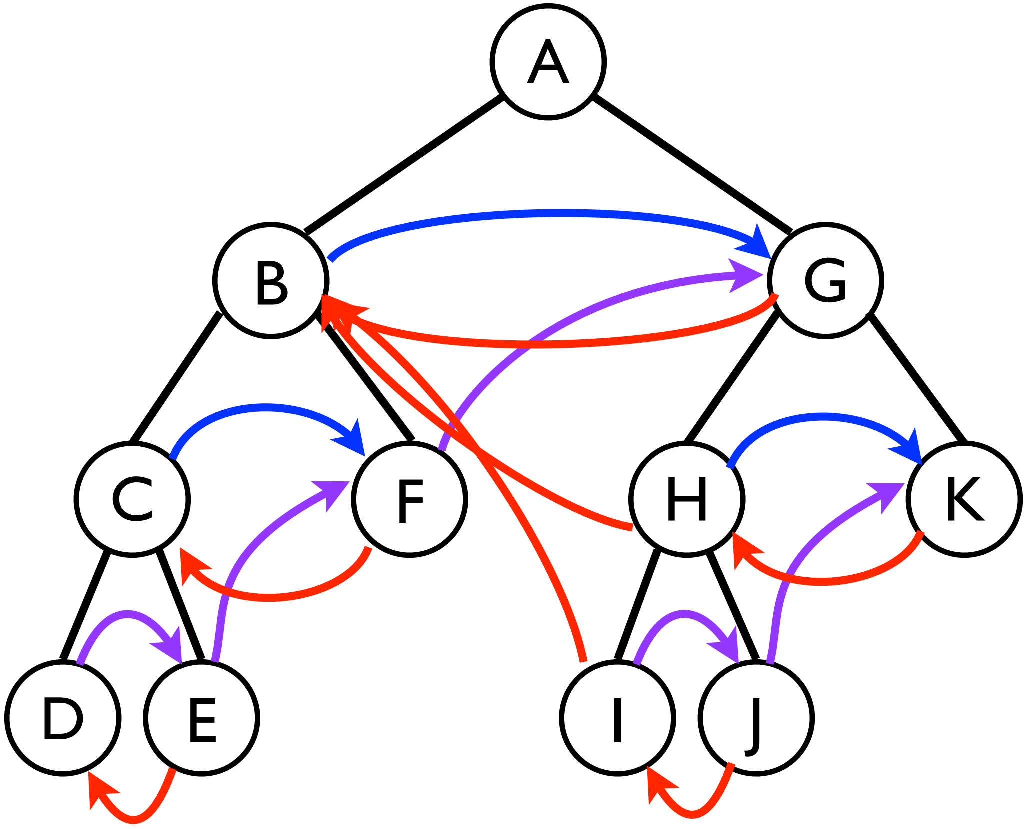
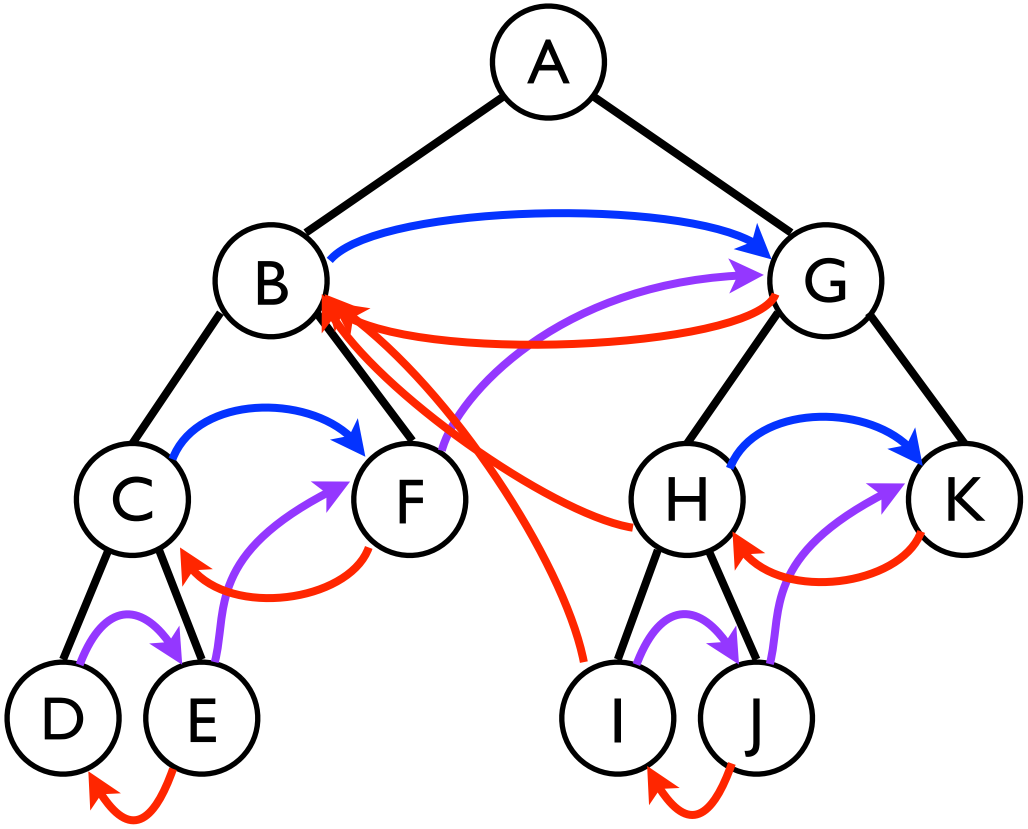


How to avoid extra accesses to tree?

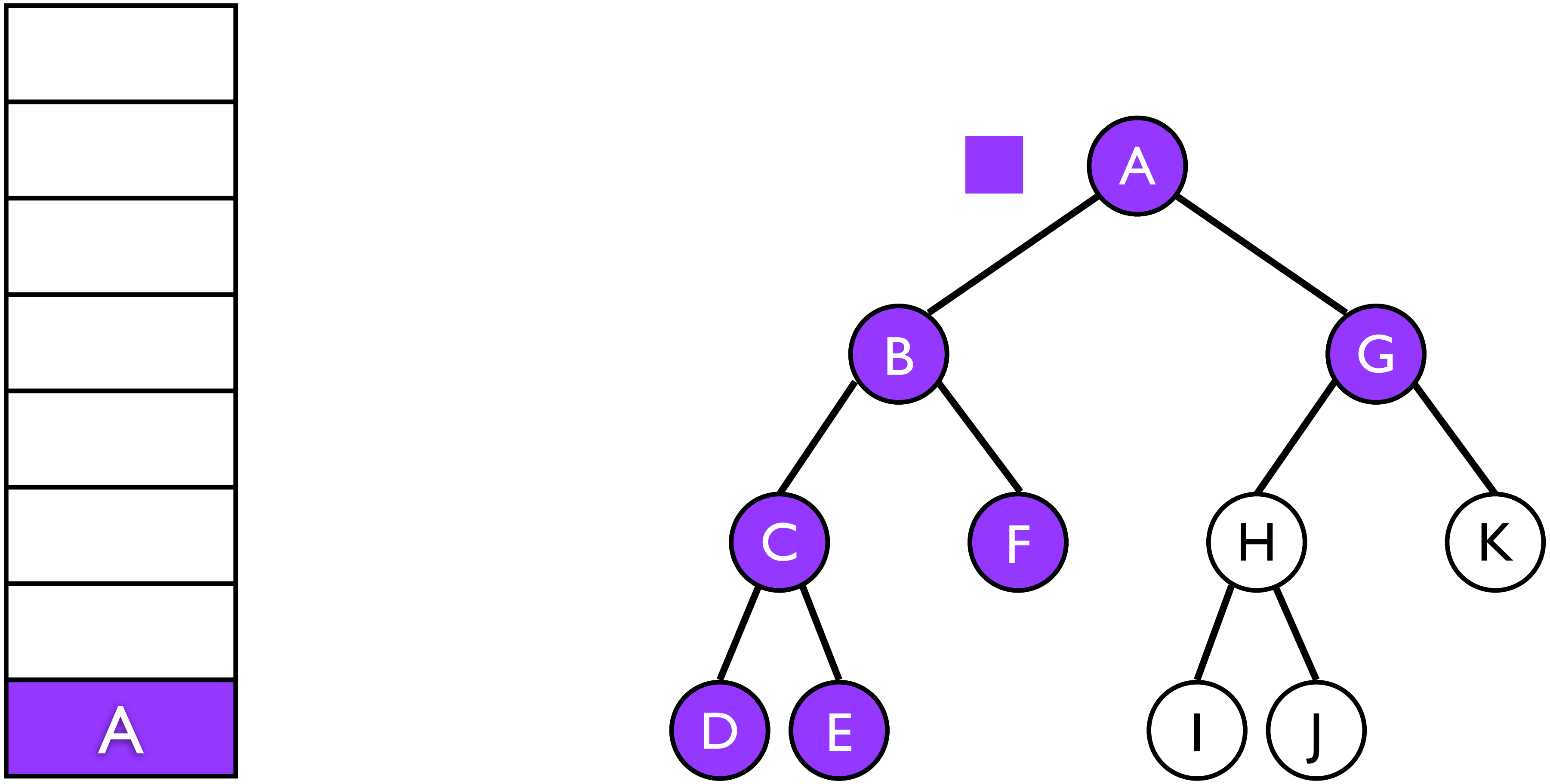
- Installing ropes into a tree requires complex, application-specific preprocessing
- Using ropes correctly during execution requires complex, application-specific logic



Autoropes

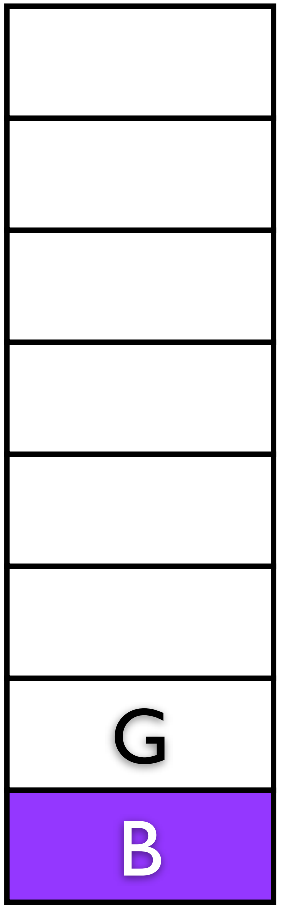
- General technique for “linearizing” tree traversal for *arbitrary traversal algorithms*
- Achieve generality, simplicity and space-efficiency at the cost of overhead
- Key insight: recursive tree algorithms are just depth-first traversals of a tree; can transform into iterative algorithm

Autoropes



Rope stack

Autoropes



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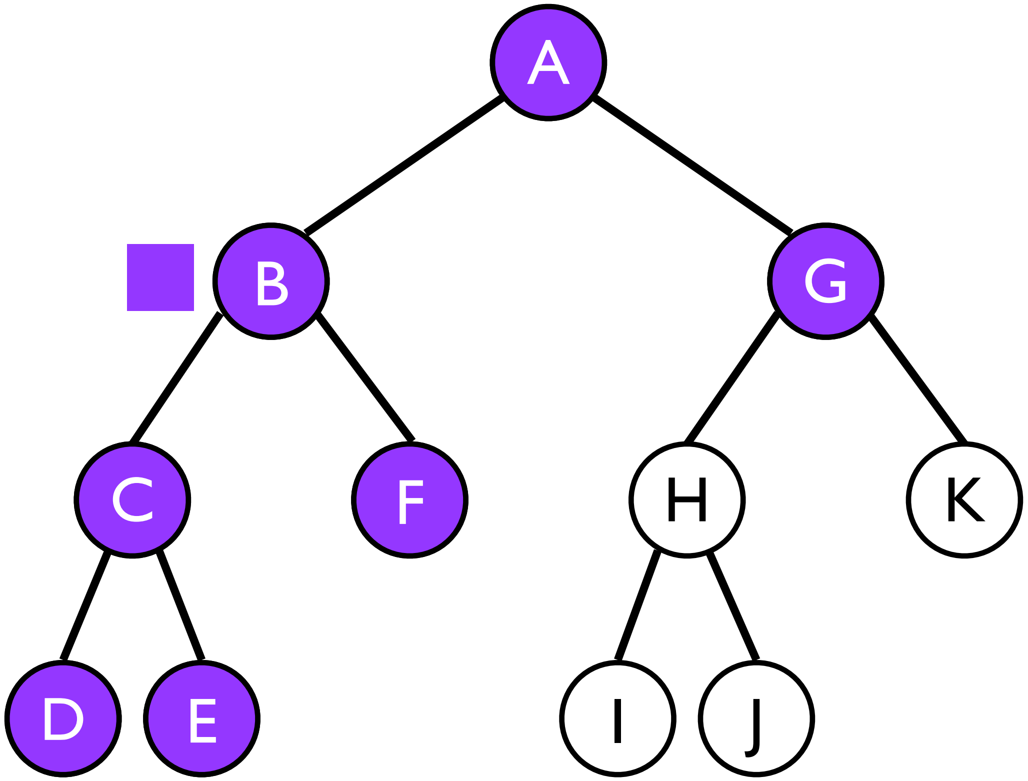

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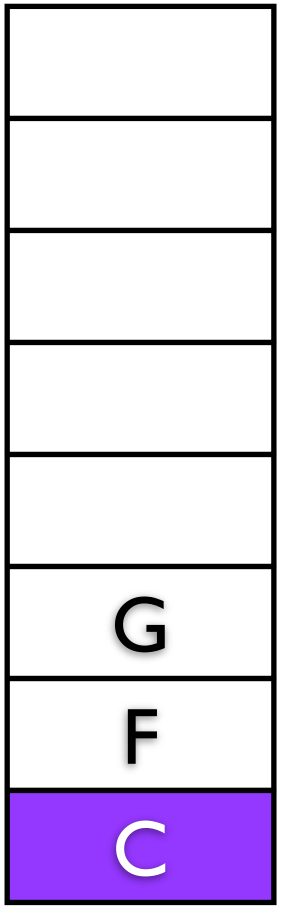

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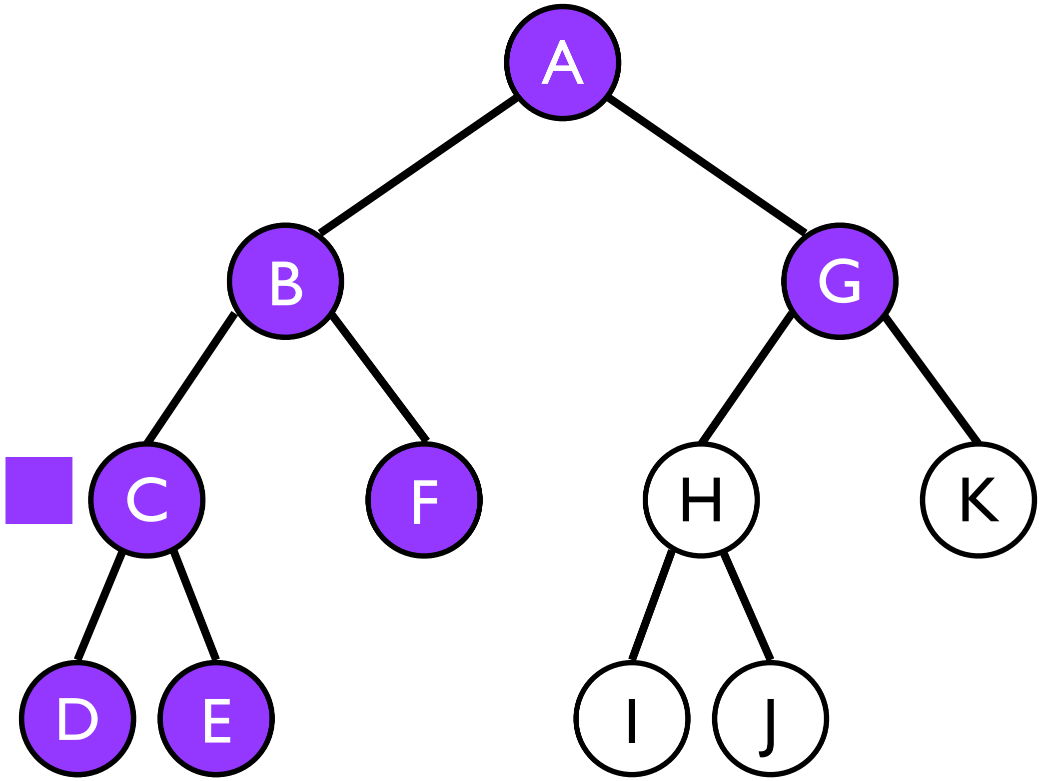

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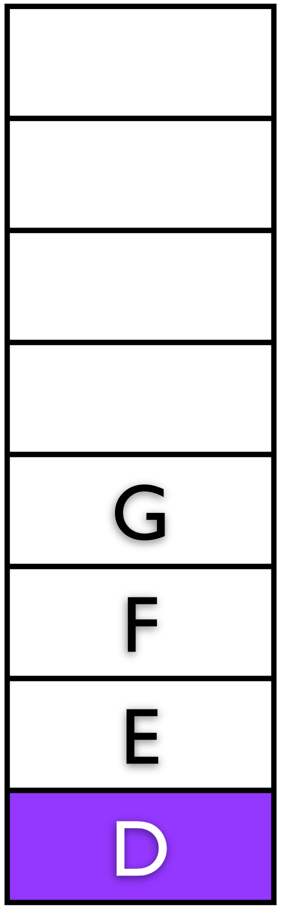

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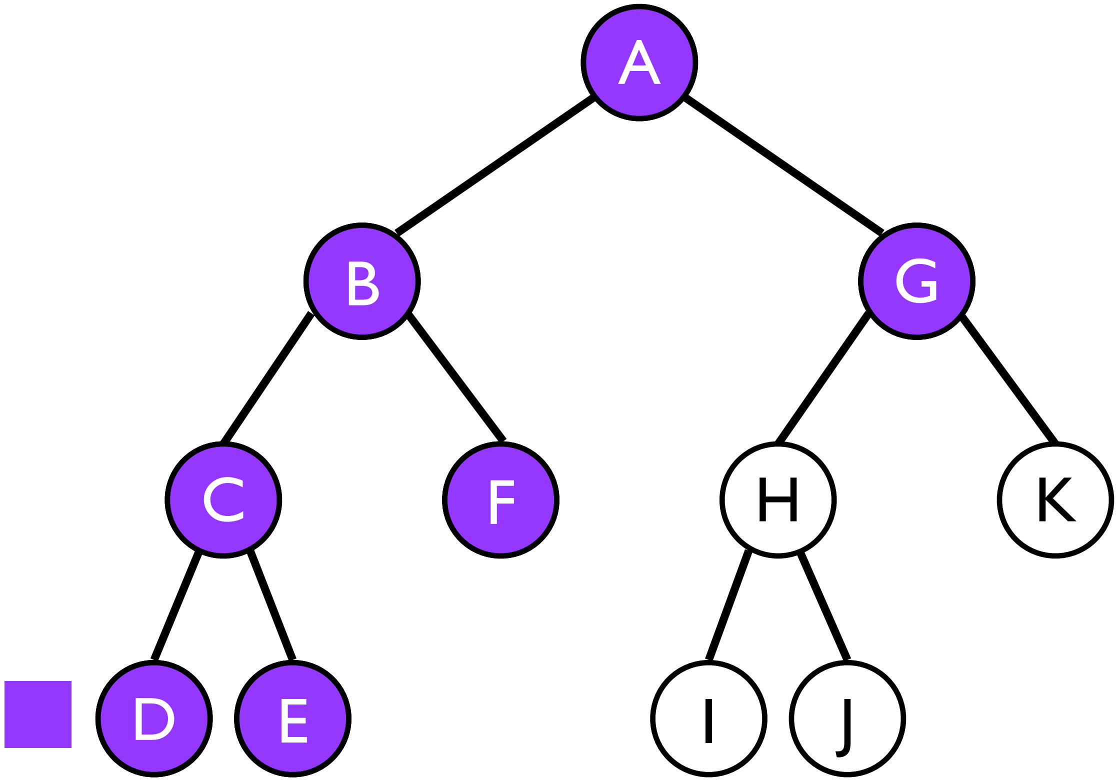

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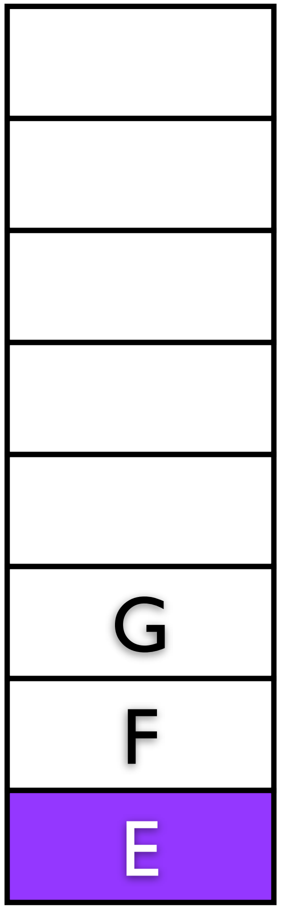

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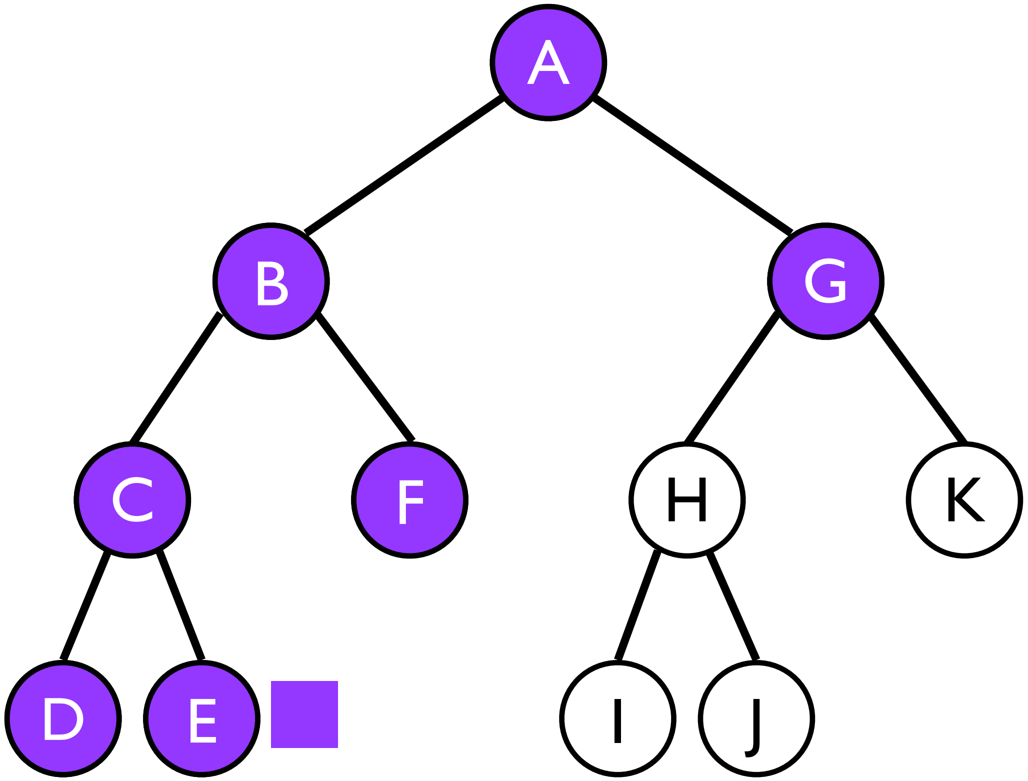

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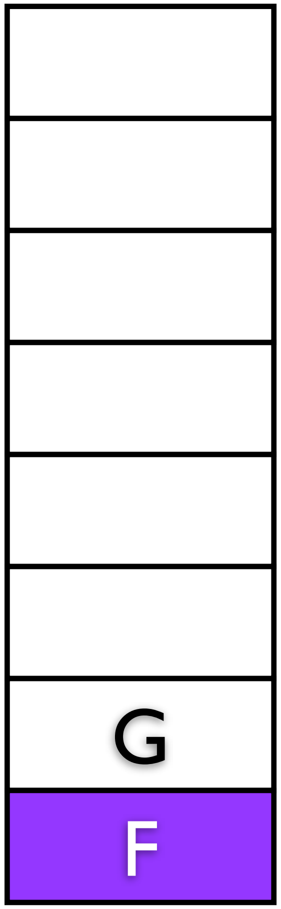

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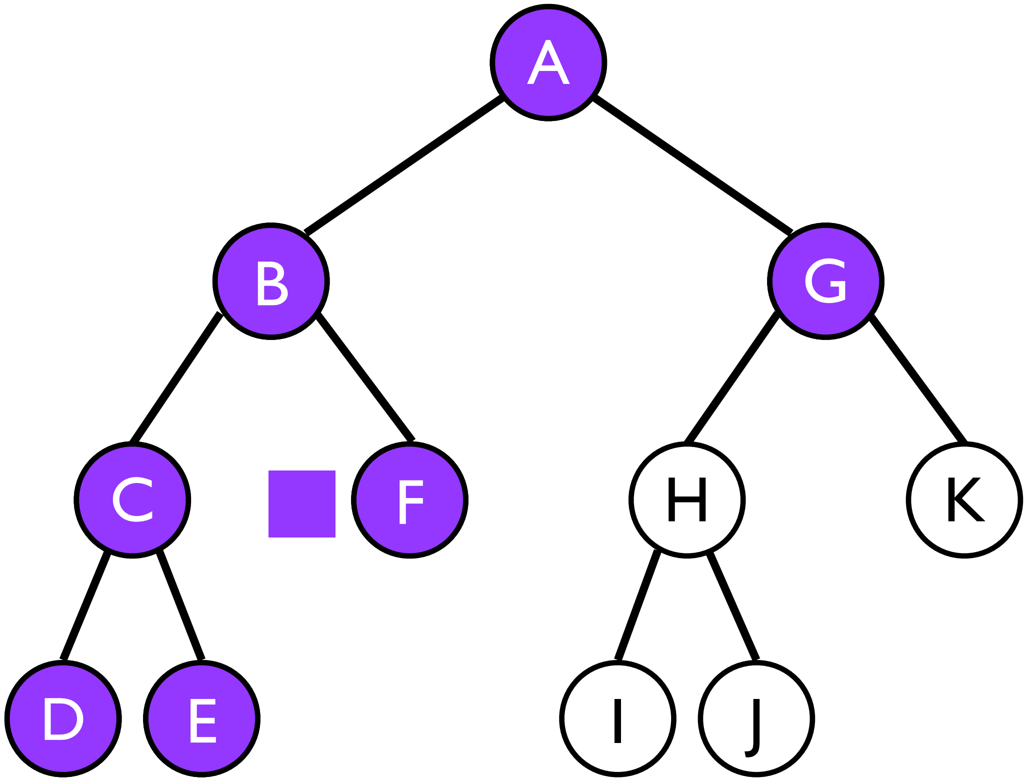
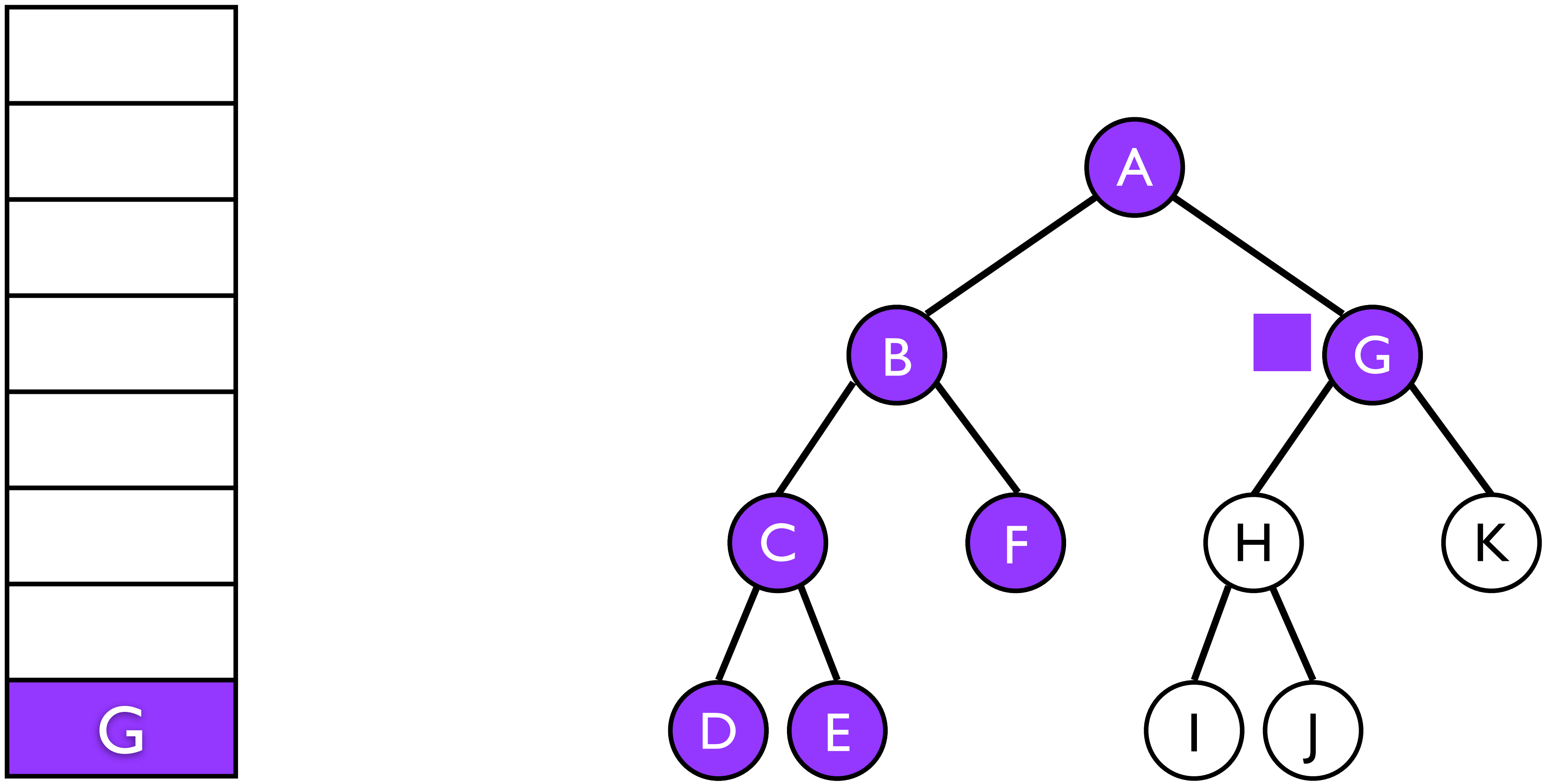


Autoropes



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

Autoropes

Simple compiler transformation converts recursive code into iterative autoropes code

```
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);
   }
}
```

Autoropes

```
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

```
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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      p.co
  else {
   ropeStack.push(node.right);
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  }
}
```
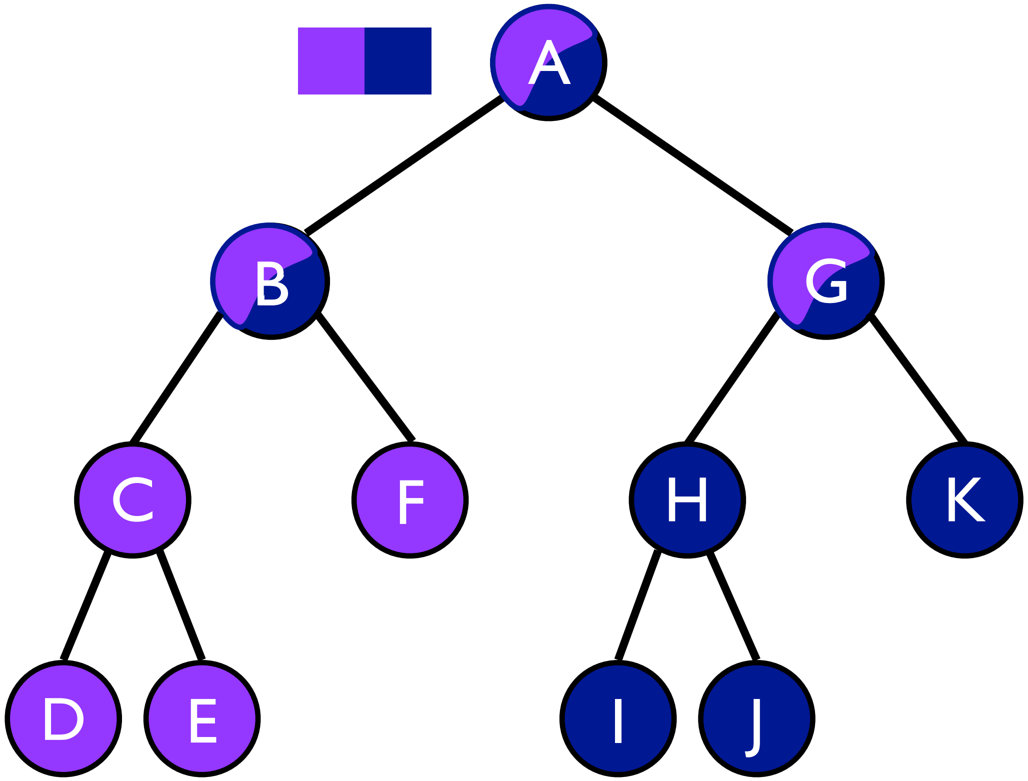
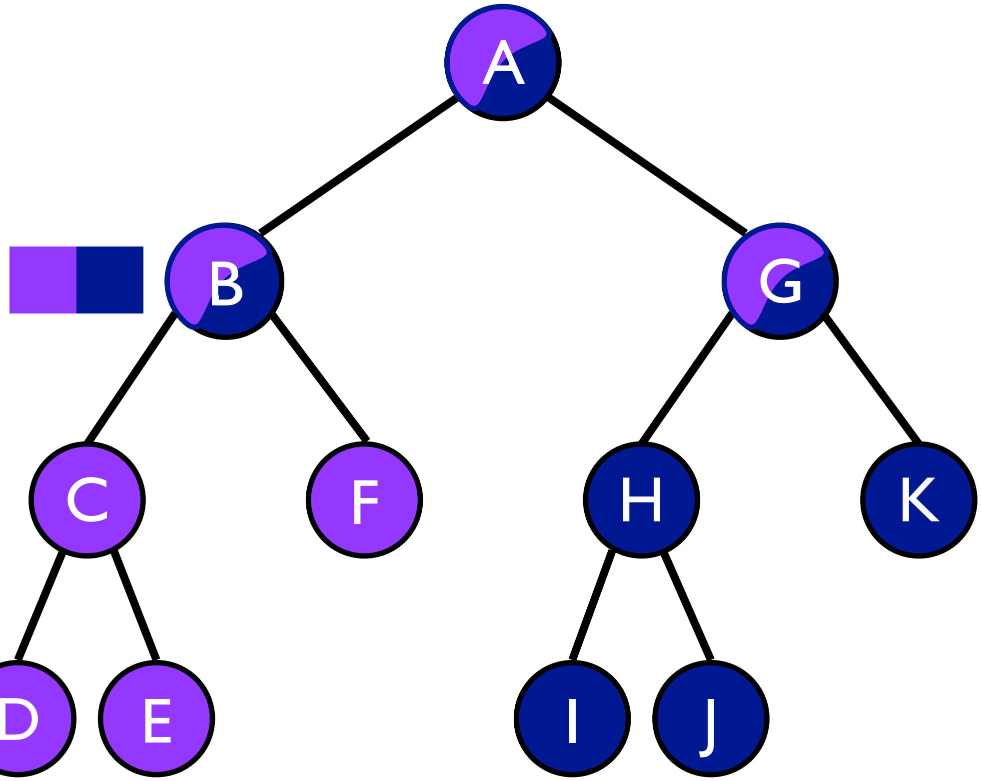

formerly return

formerly recursion

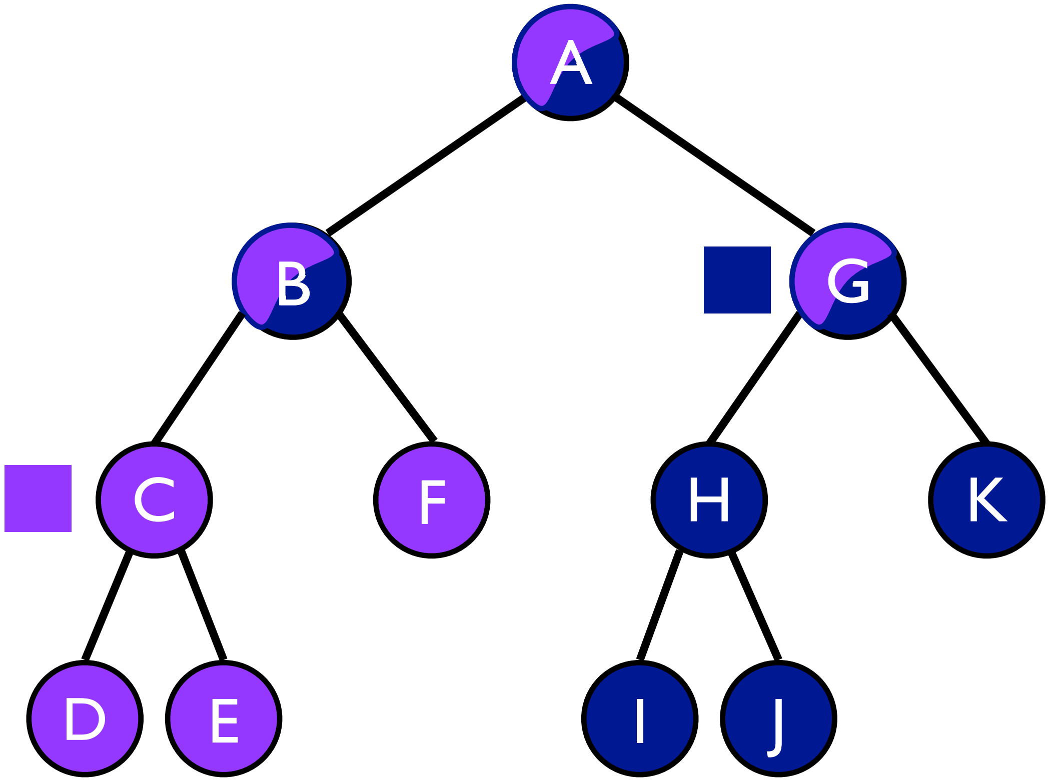
Autoropes on GPU



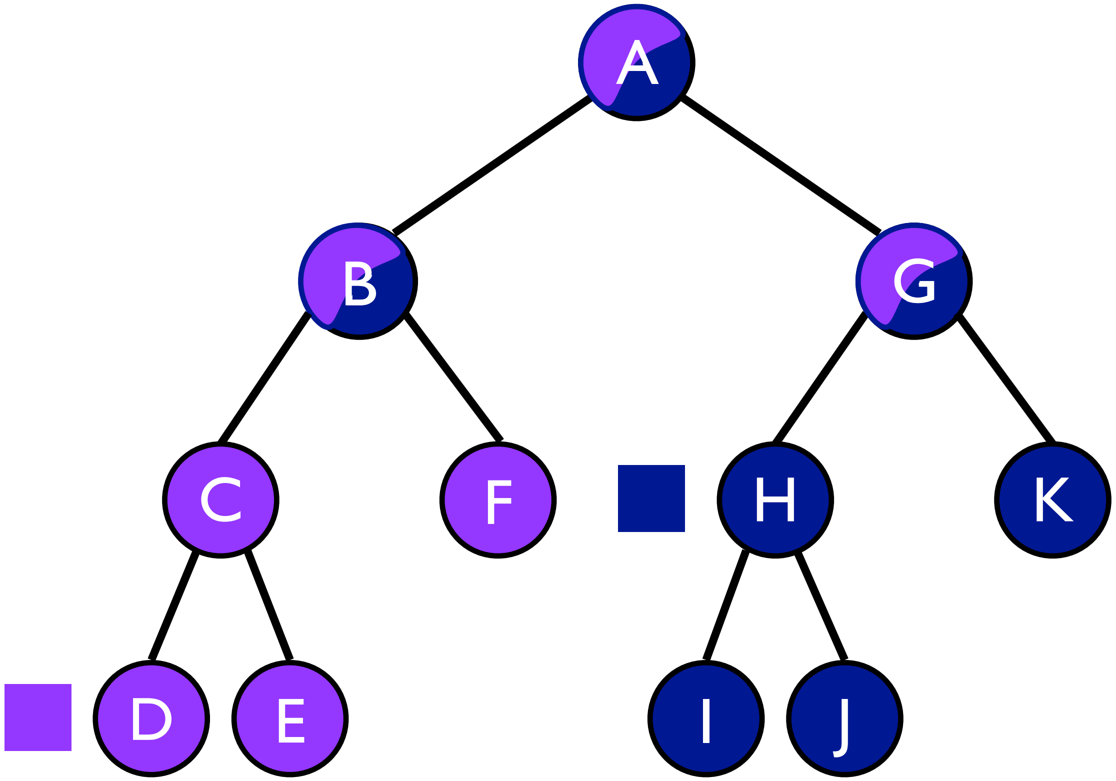
Autoropes on GPU



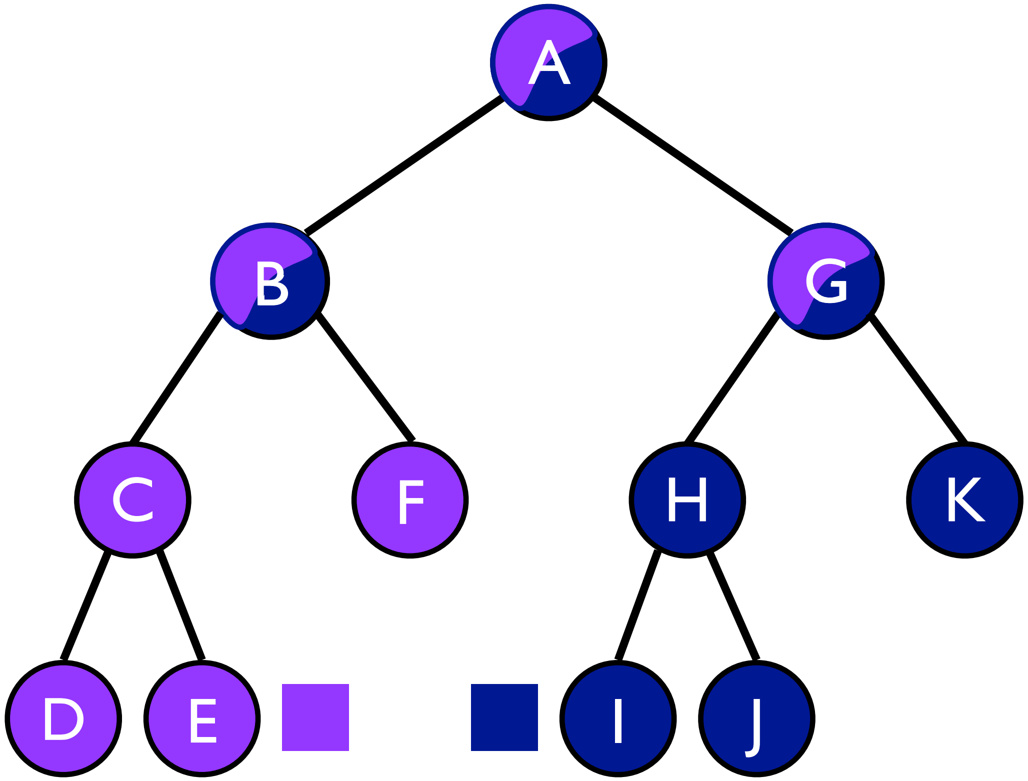
Autoropes on GPU



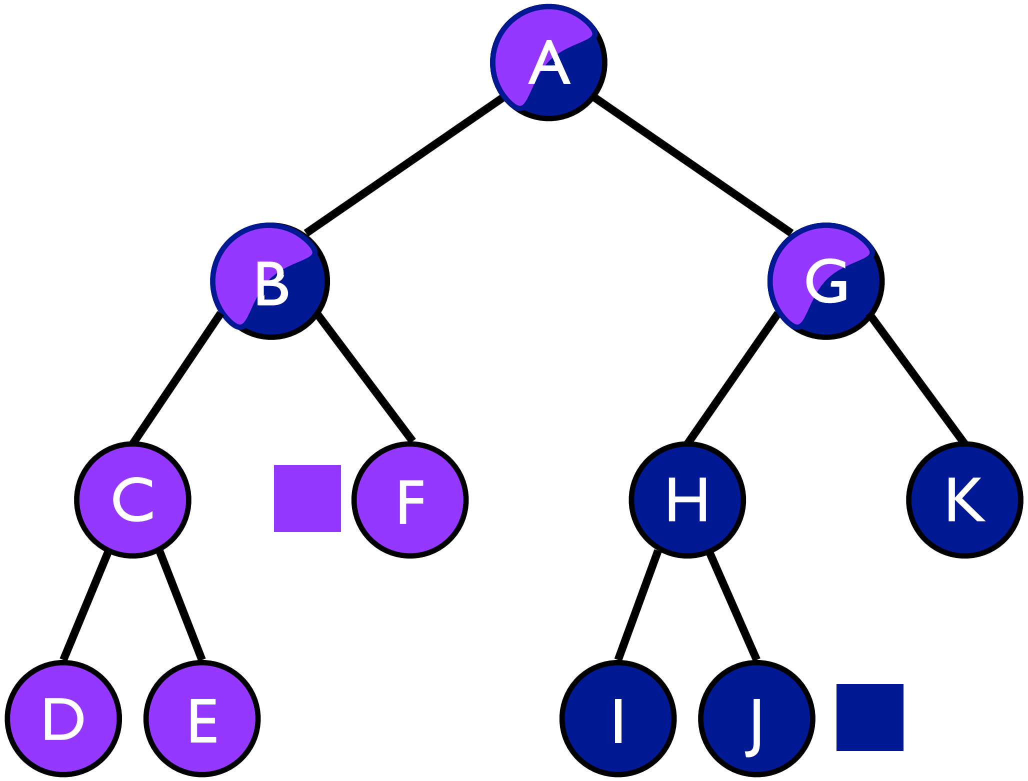
Autoropes on GPU



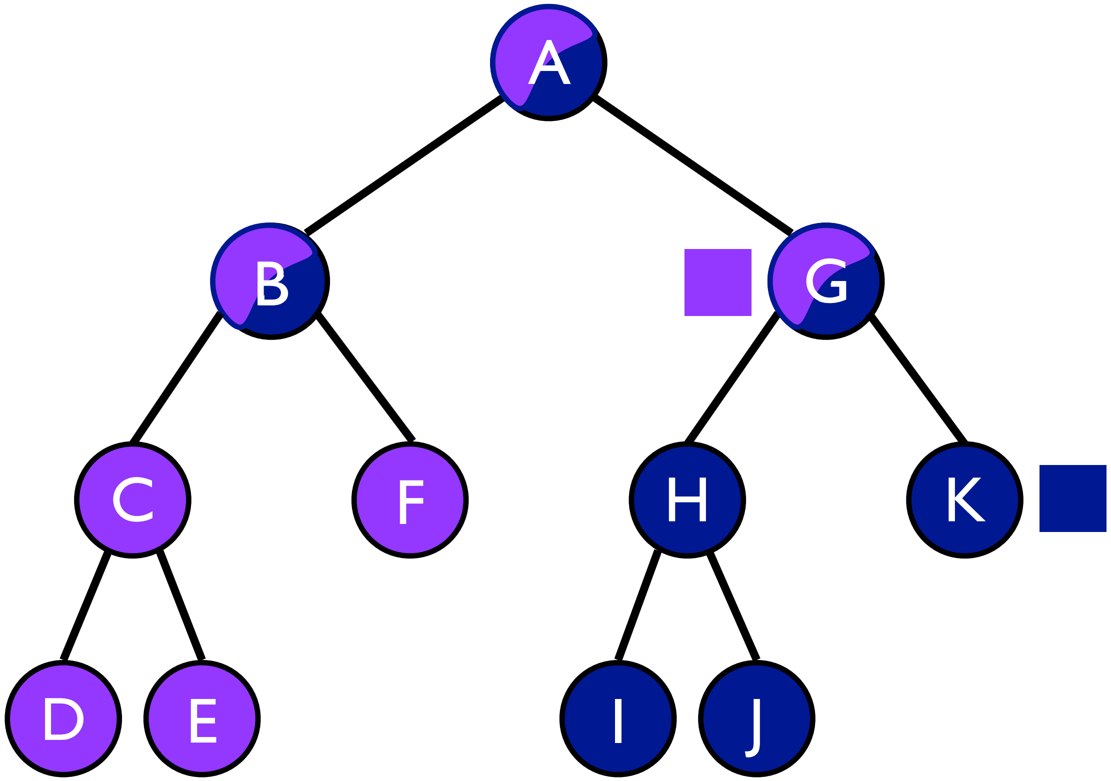
Autoropes on GPU



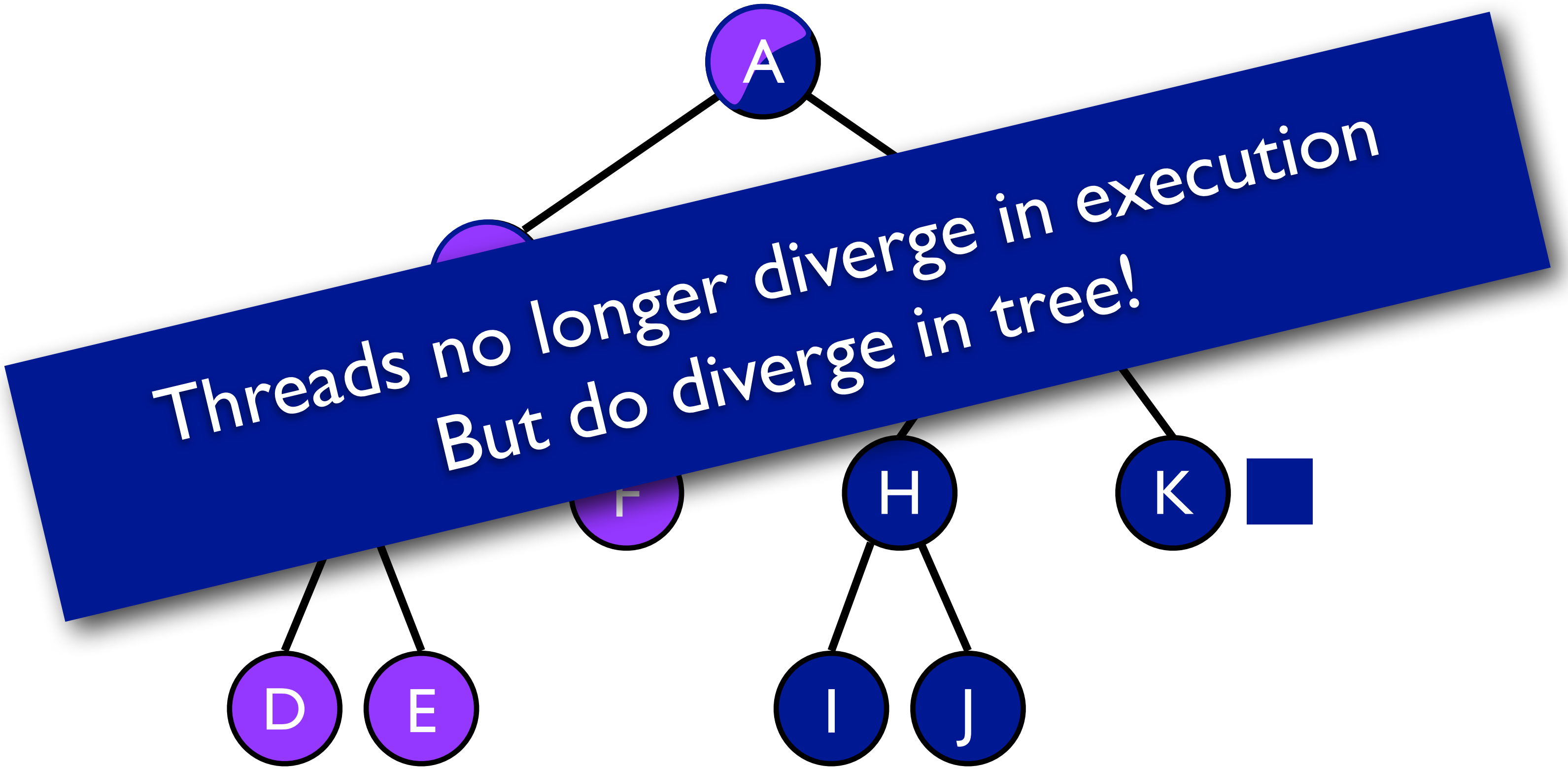
Autoropes on GPU



Autoropes on GPU



Autoropes 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

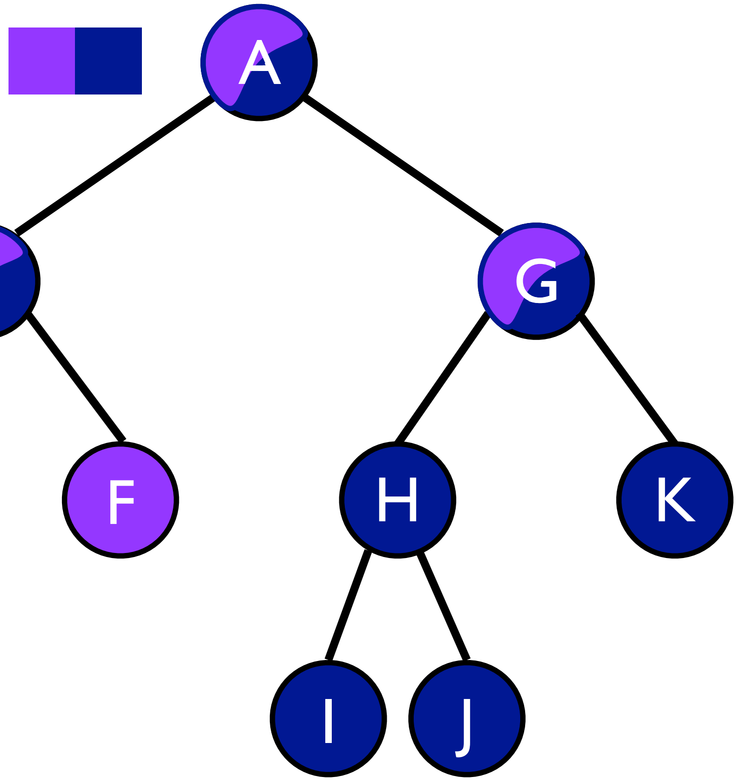
Lockstepping

- 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

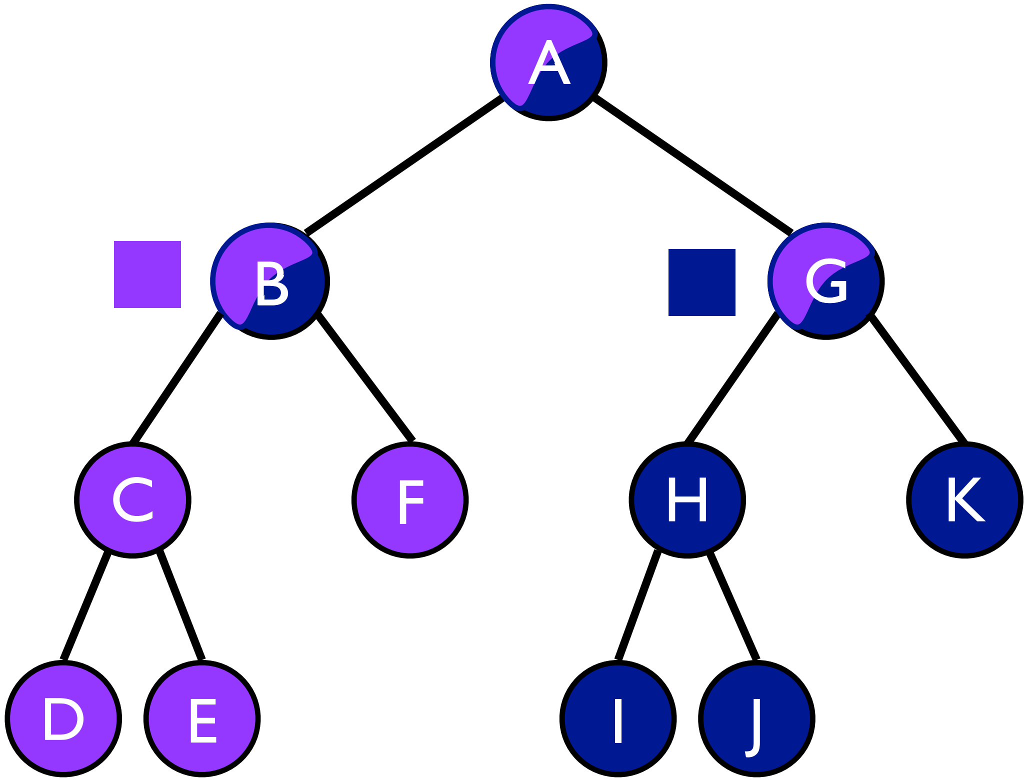
Dynamic lockstepping

- 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

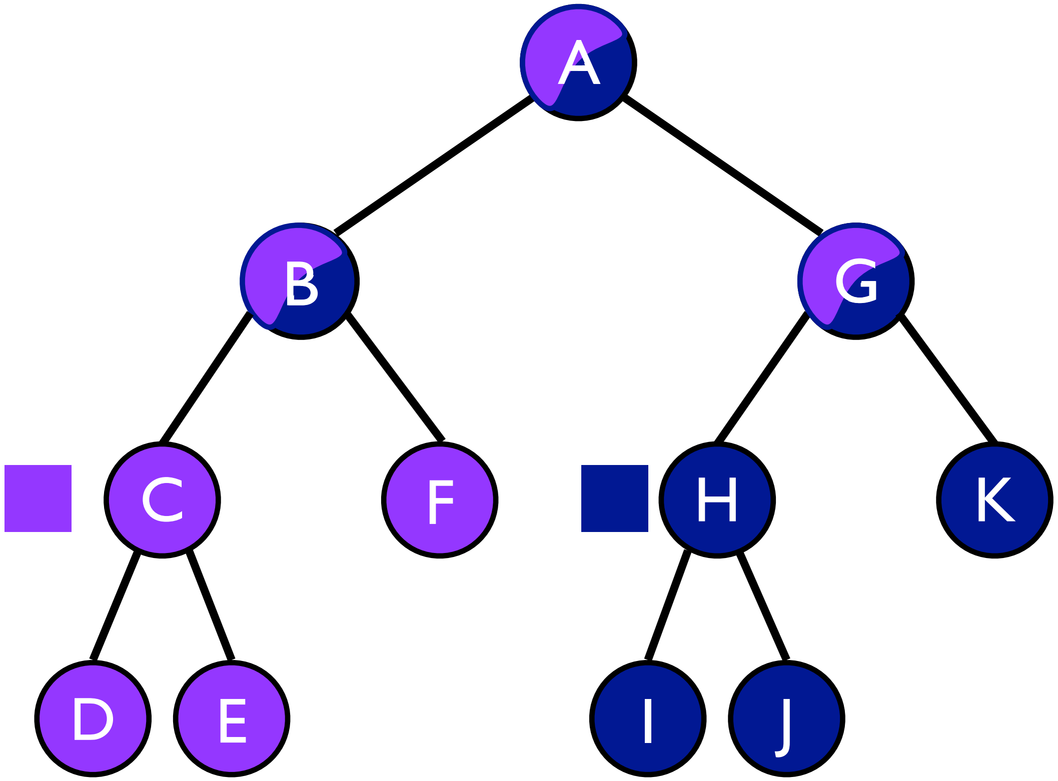
Dynamic lockstepping



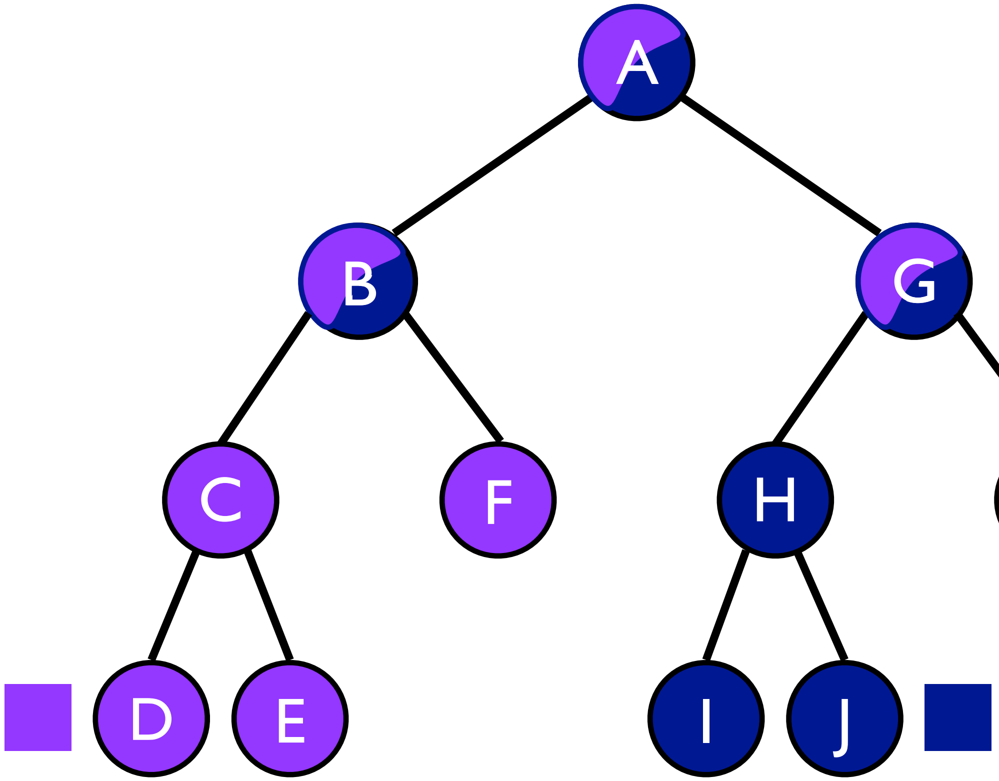
Dynamic lockstepping



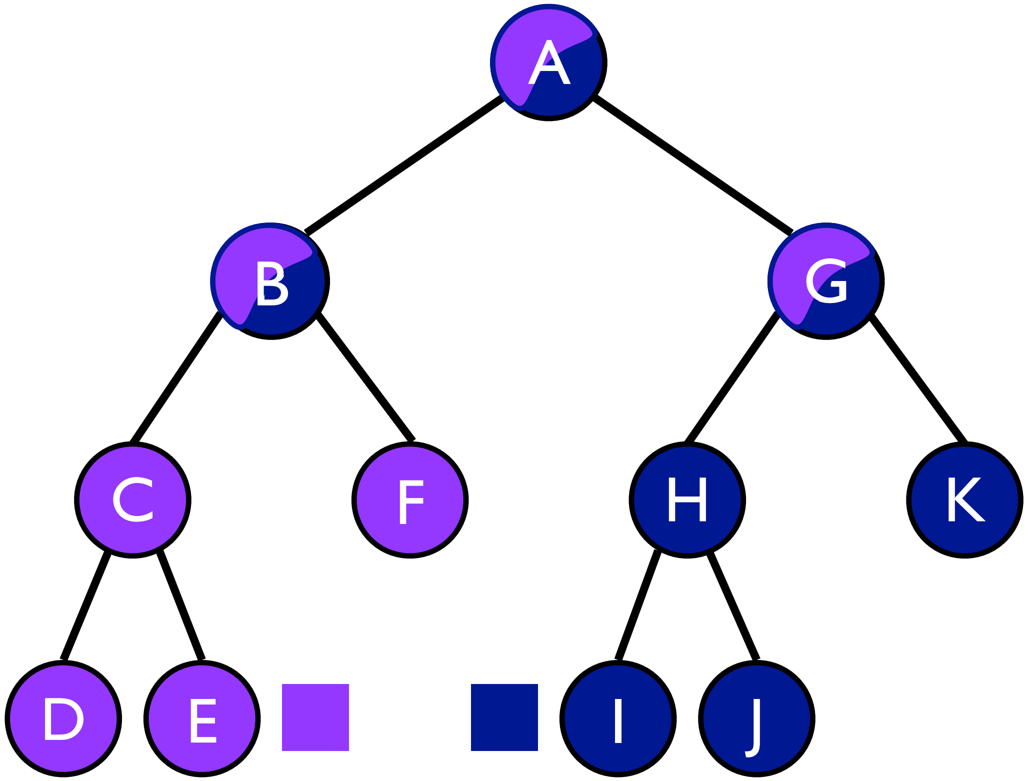
Dynamic lockstepping



Dynamic lockstepping



Dynamic lockstepping



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

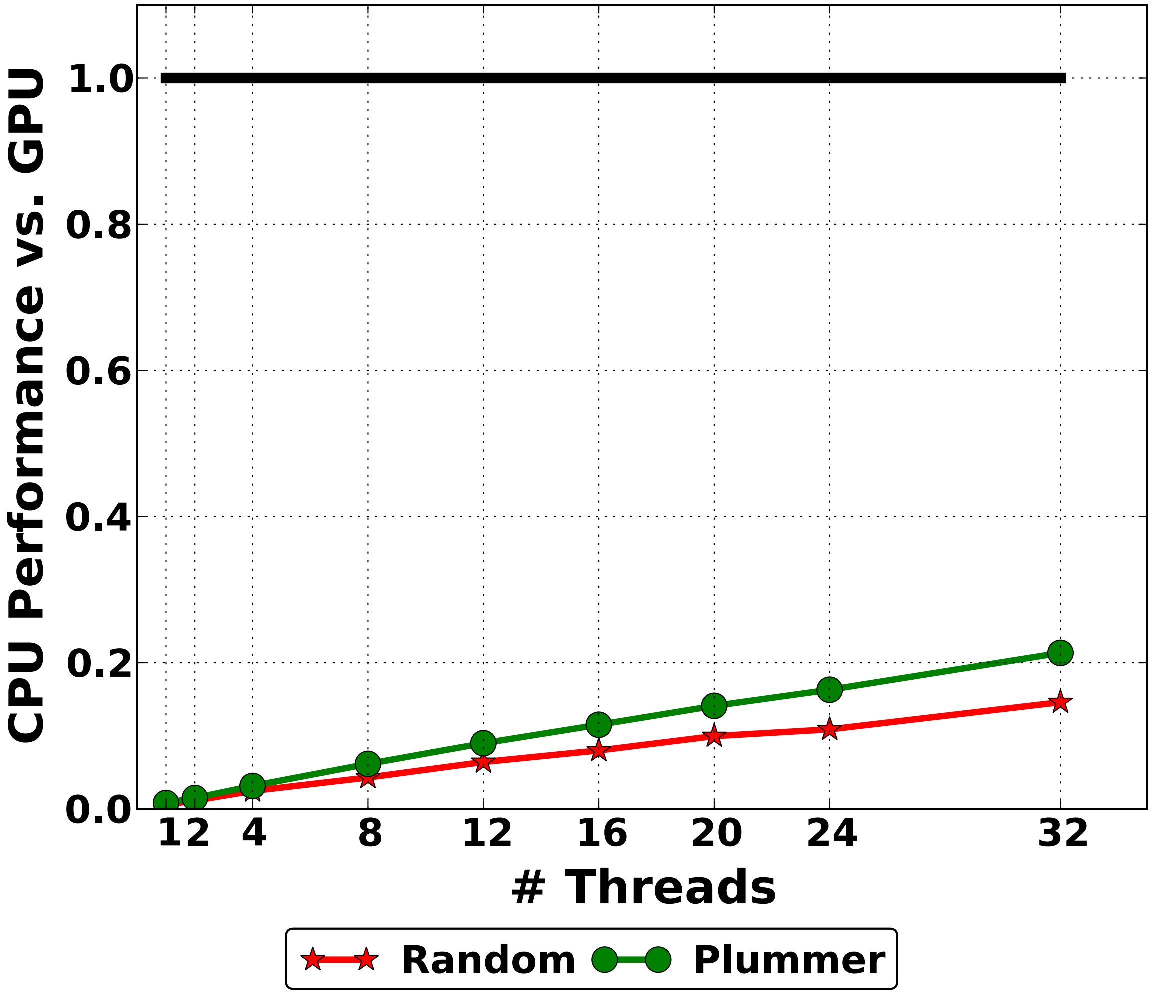
Results

- 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

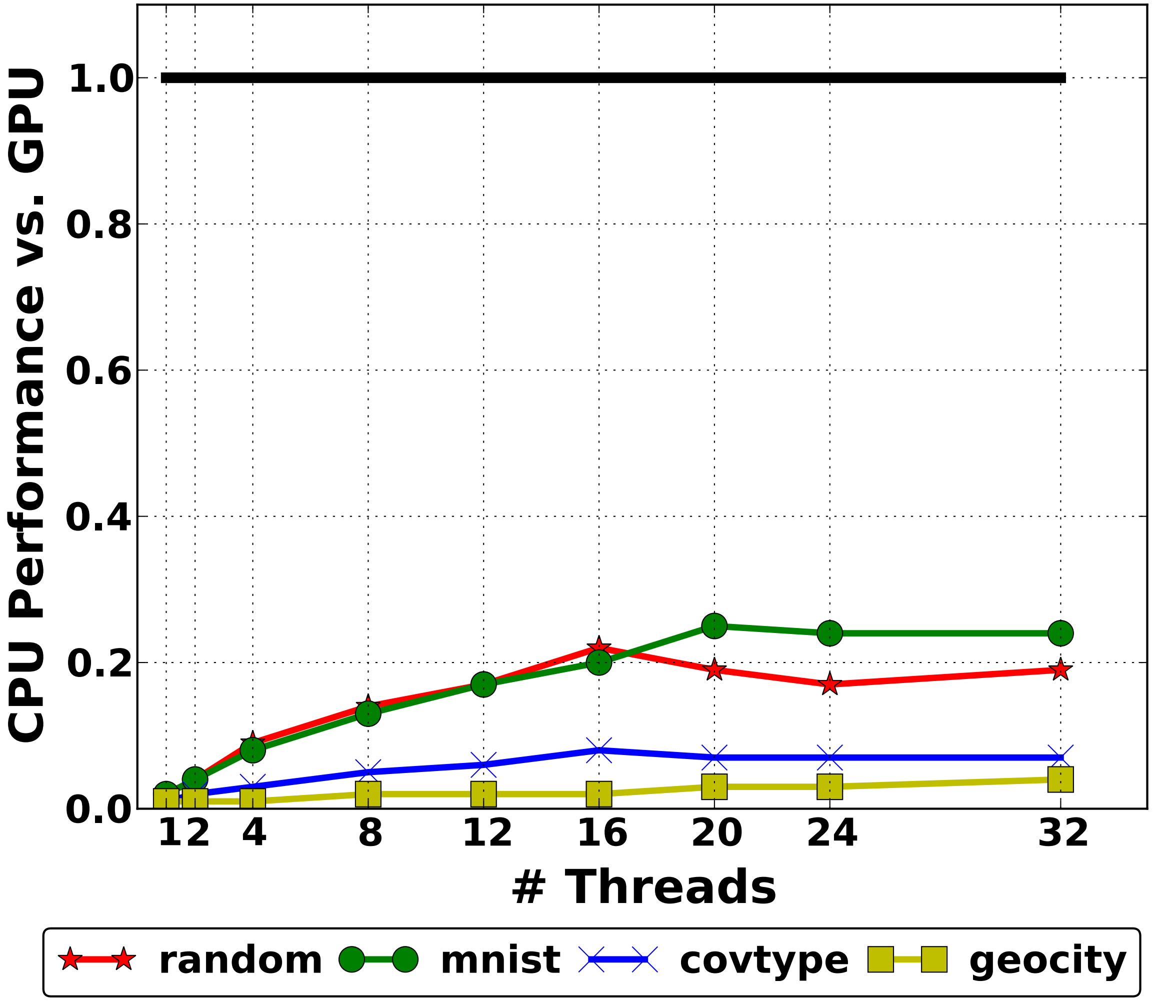
High-level takeaways

- 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

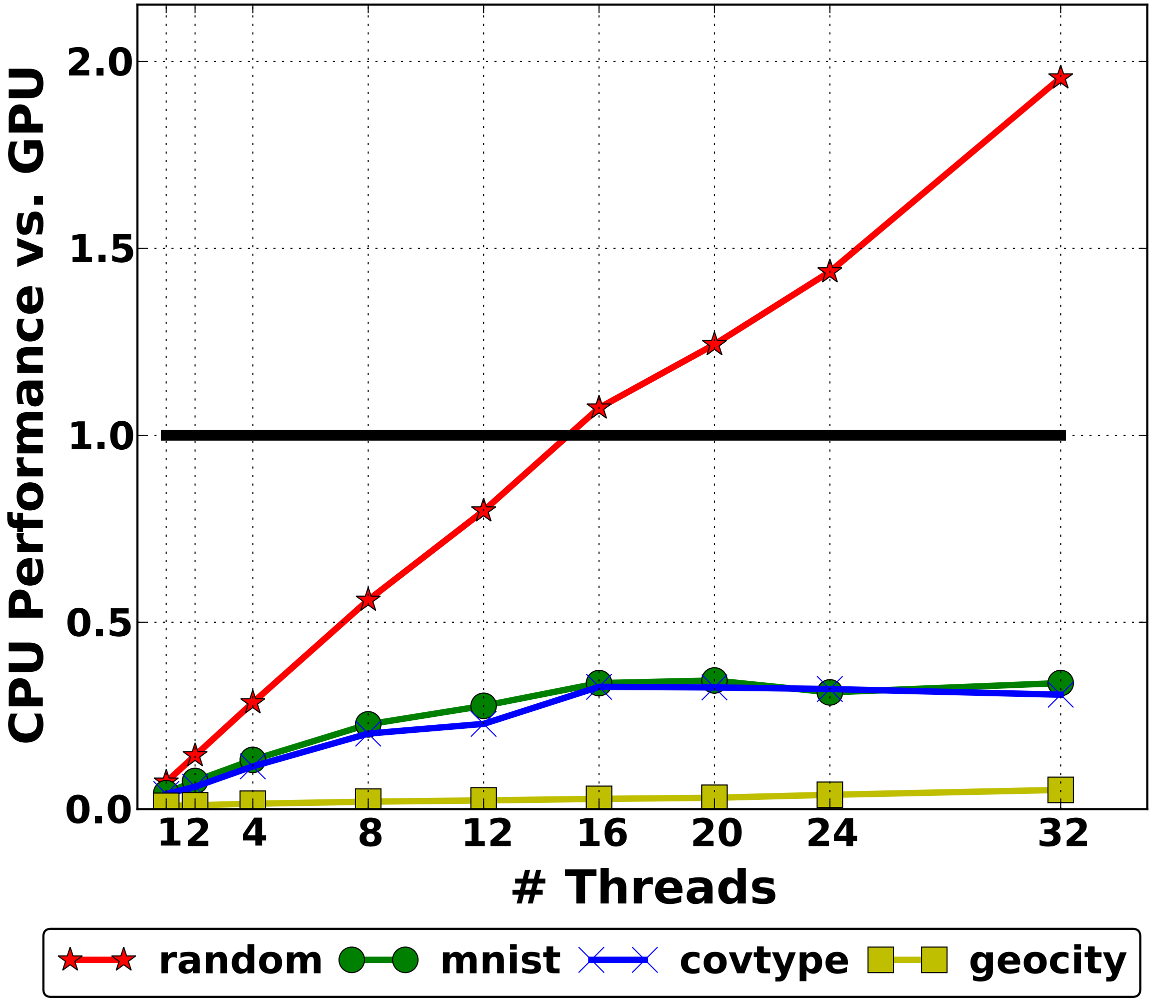
Barnes-Hut


CPU Performance vs. GPU
1.0
0.8
0.6
0.4
0.2
0.0
1
2
4
8
12
16
20
24
32
Threads
Random
Plummer

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

General Transformations for GPU Execution of Tree Traversals

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