Dependency Graph Scheduling in a Ray Tracing Architecture

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Why use ray tracing?

- + Global illumination
- + Unifying technique for volumes
  - + Processing and rendering
  - + Triangles, points, implicit surfaces etc.
- + Early ray termination
- + Scene complexity independence
- + Inherently parallel

Why not use ray tracing?

- Non-uniform memory access
- Need spatial coherence

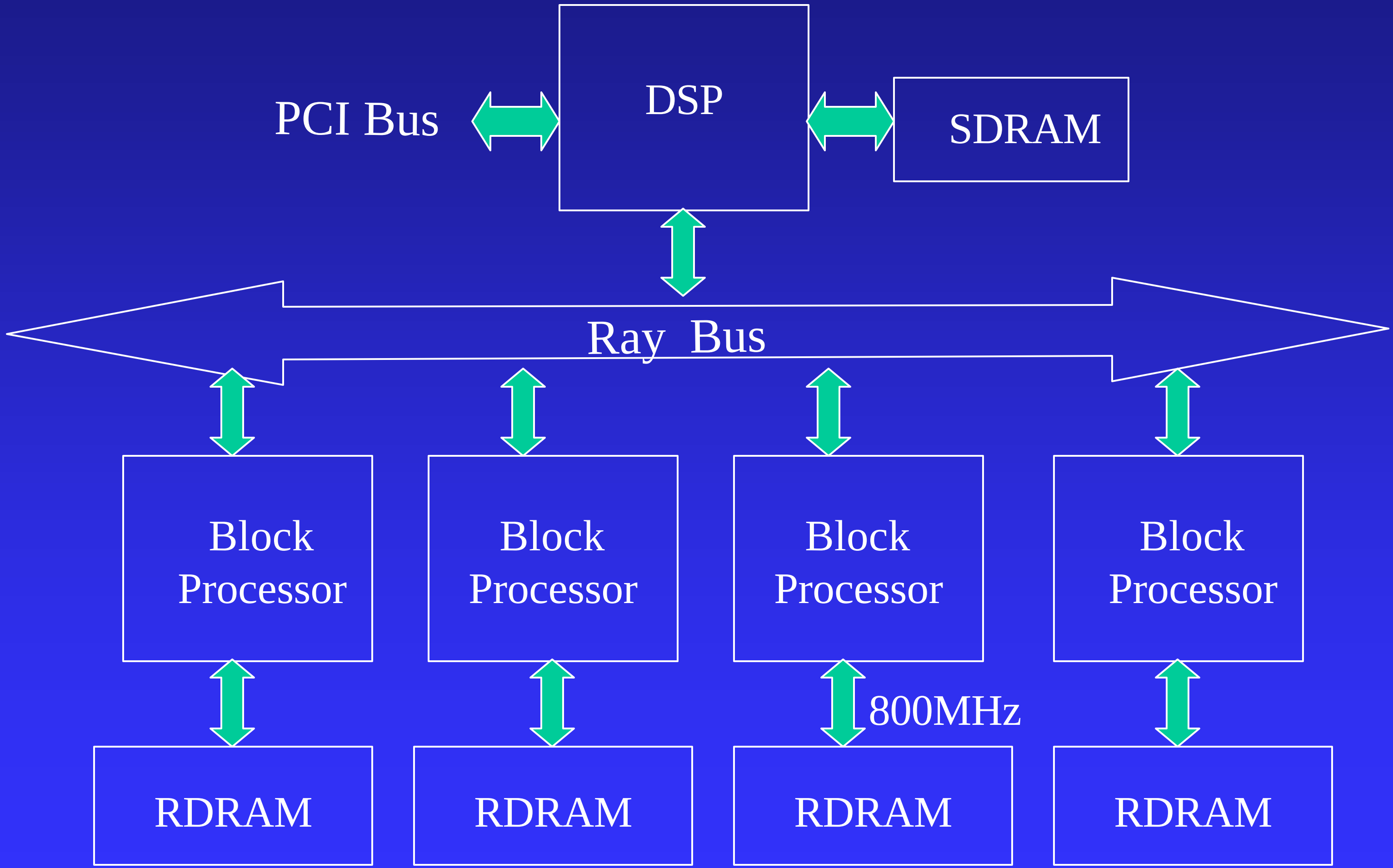
Ray Tracing Systems

- Ray Queues [Pharr et al. ‘97]
- GI-Cube [Dachille, Kaufman ’00]
- Pyramid clipping and octree subdivision [Reinhard et al. ’99]
- Kilauea system [Nishimura et al. ’01]
- AR250 [ART ’99]
- Coherent Ray Tracing [Wald, et al. 2001]

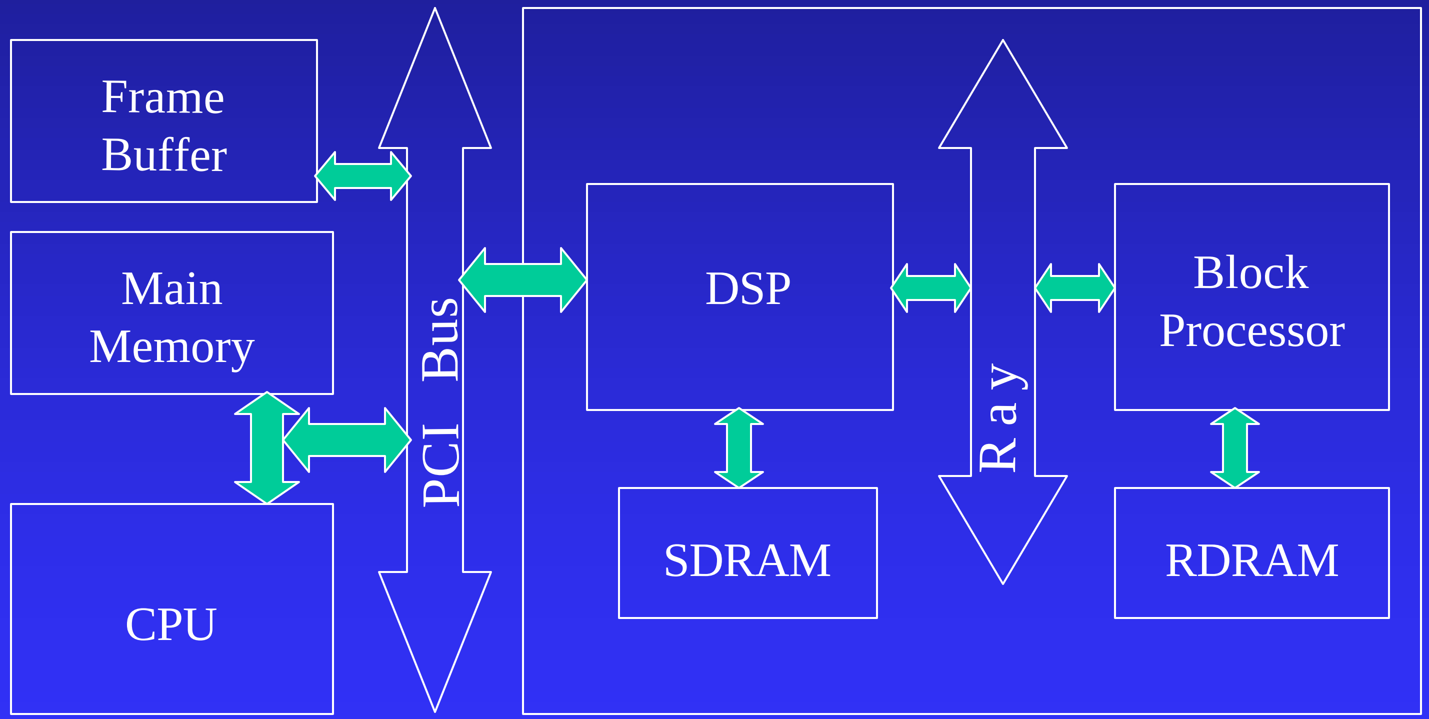
Outline

- **Our System**
- Cell Tree
- Dependency Graph Scheduling
- Peel Algorithm
- Results

GI-Cube Architecture

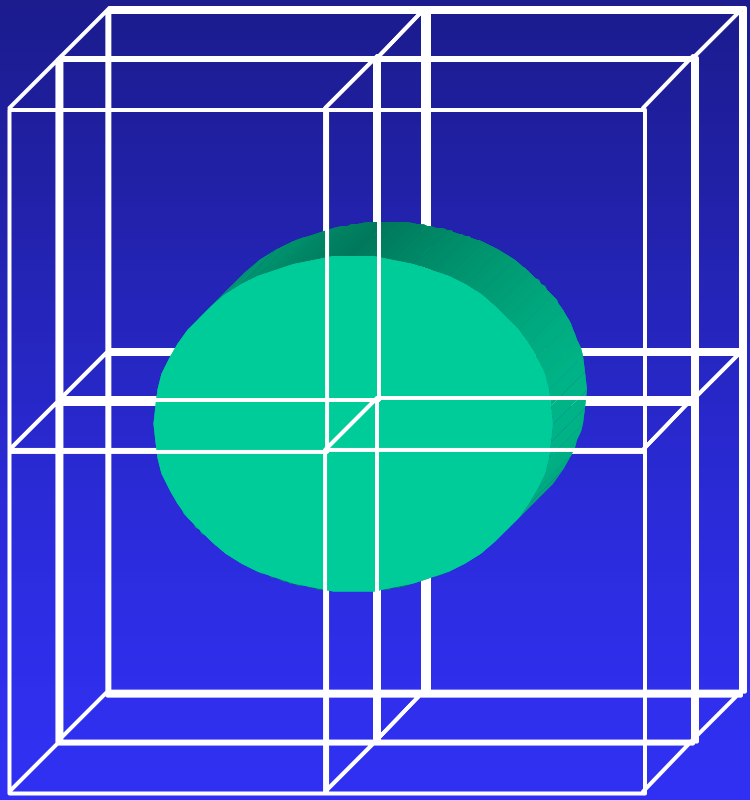


Single Processor



Ray Queues

- Maintain ray queue for each cell
- Process all rays while a cell is in cache
- Spawned rays added to queue of next intersected cell



Subdivide Volume Into Cells

Our Scheduling Schema

- Cell Tree
  - Ray-cell dependencies from frame i used to create schedule for frame i+1
- Max Work
  - First frame (ray dependencies unknown) and if rays remain after Cell Tree schedule
- Any level of the memory hierarchy
- Cell size set to memory size

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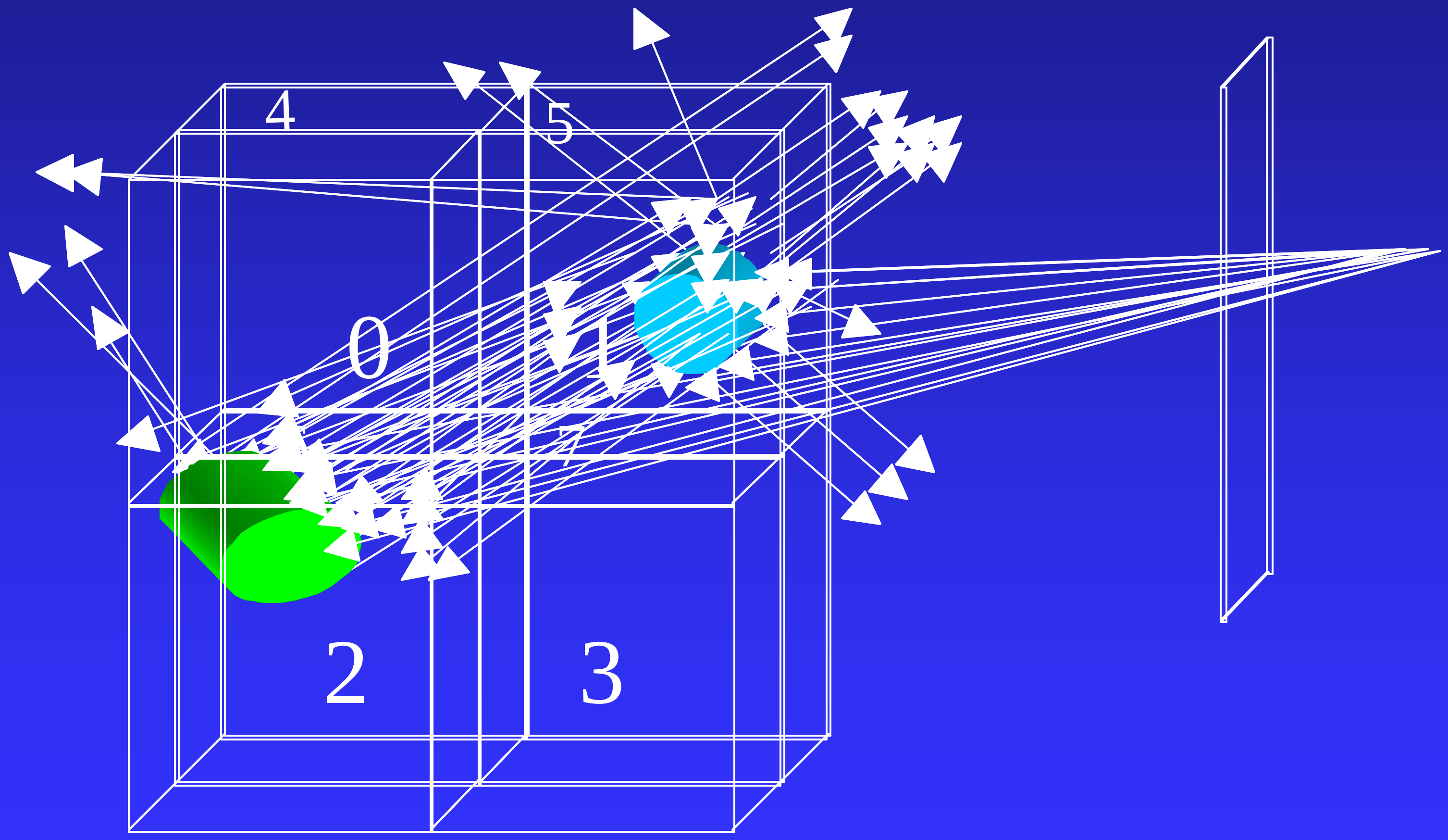
Psuedo-Random Ray Traversal



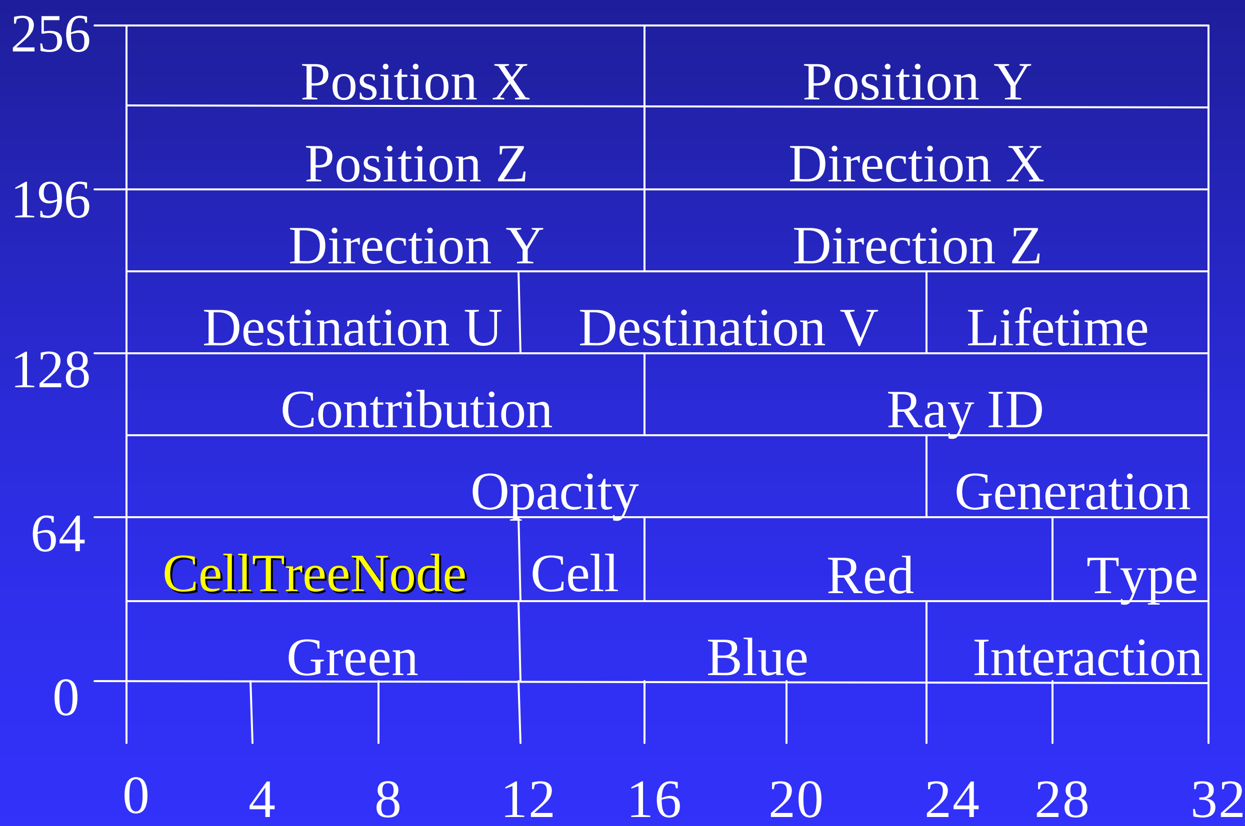
Cell Tree

- Gathers clusters of rays as they're generated
- Concisely describes all ray-cell dependencies of completed frame
  - 100 times fewer nodes than rays represented
- Predict better schedule for next frame

Cell Tree Creation

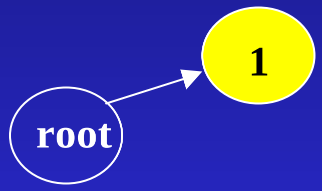
1. Initialize
2. Maintain *CellTreeNode* in Ray Packet
3. Add nodes to Cell Tree as needed to represent ray-cell dependencies

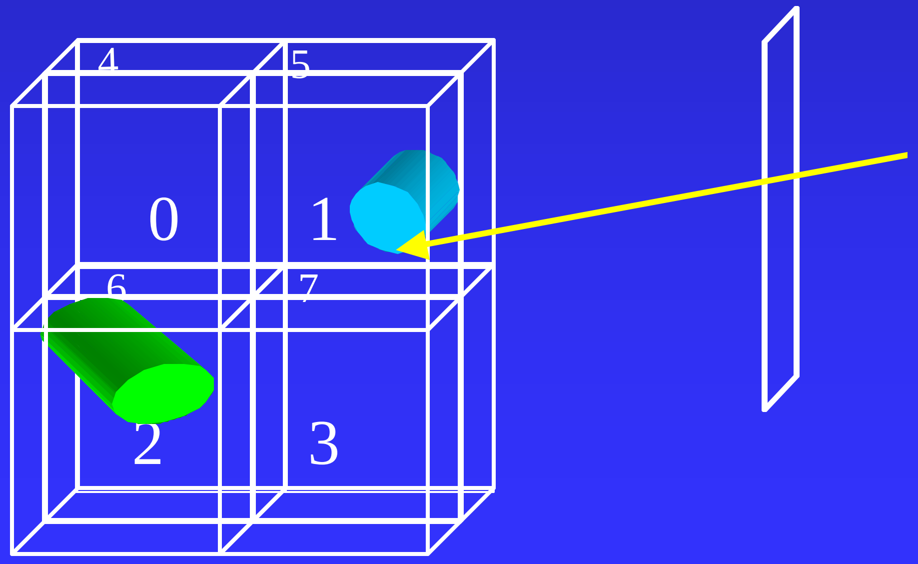
Ray Packet



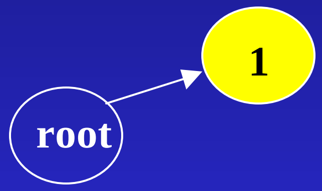
256
Position X
Position Y
Position Z
Direction X
196
Direction Y
Direction Z
Destination U
Destination V
Lifetime
128
Contribution
Ray ID
Opacity
Generation
64
CellTreeNode
Cell
Red
Type
Green
Blue
Interaction
0
0
4
8
12
16
20
24
28
32

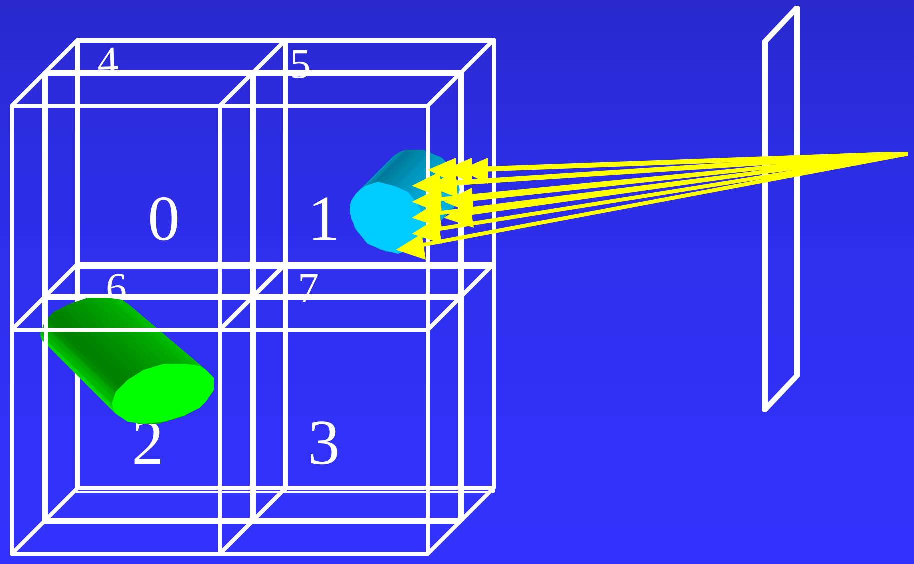
Initialization



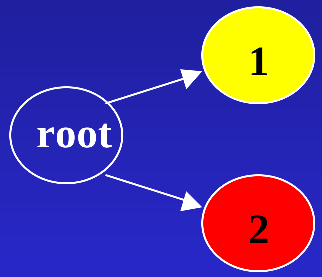


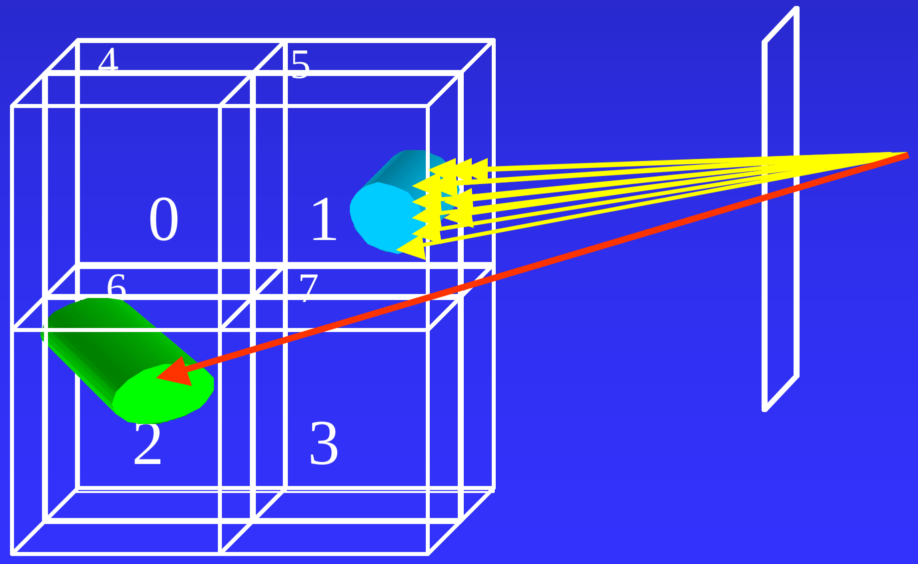
Initialization



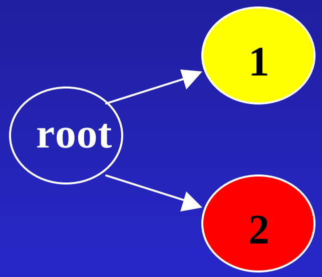


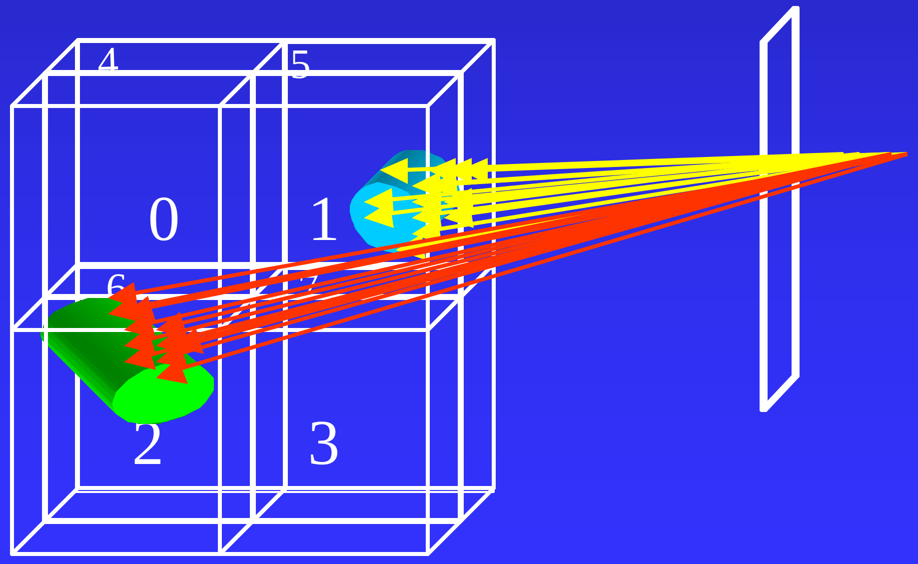
Initialization



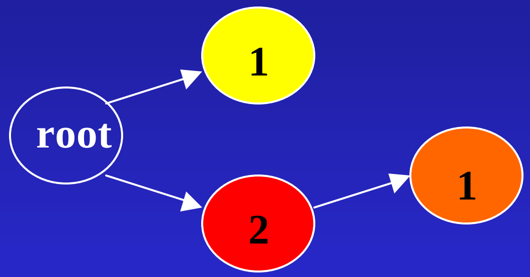


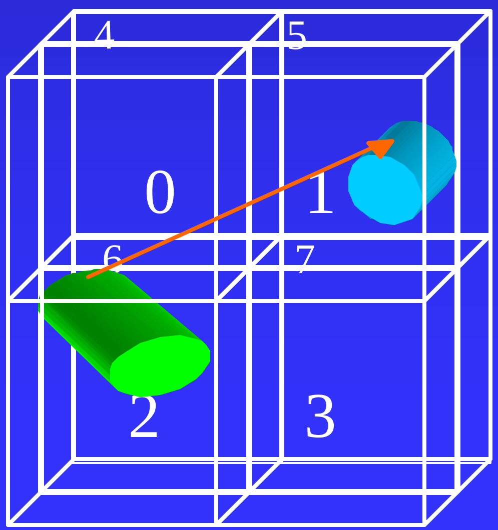
Initialization





Reflections Refractions and Shadows





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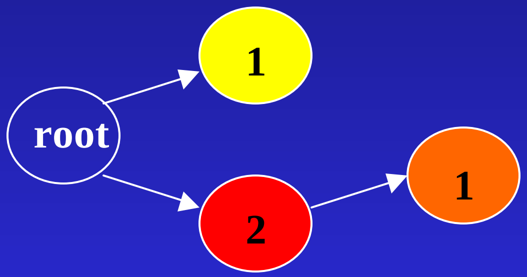

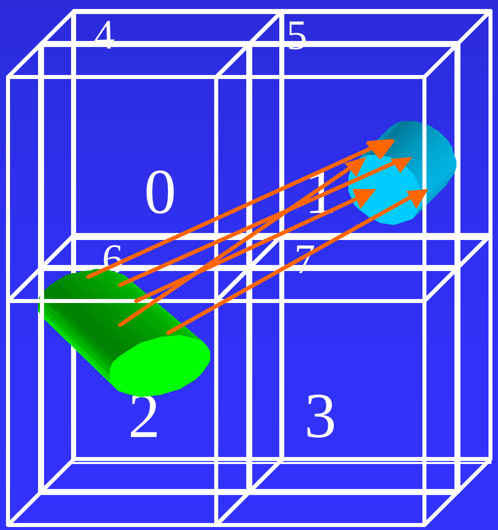

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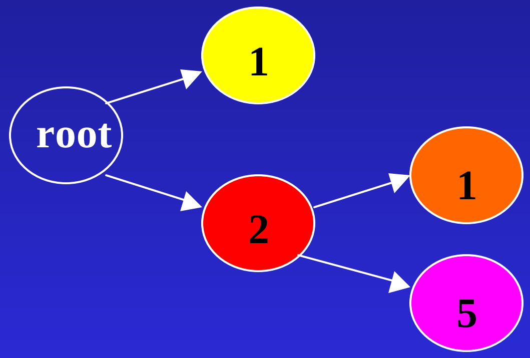

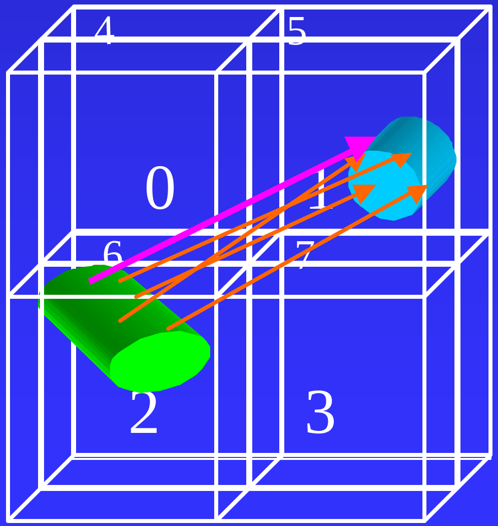

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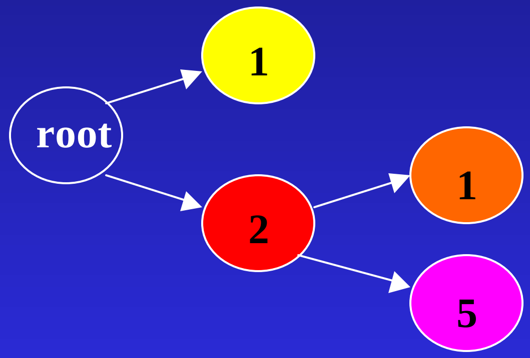

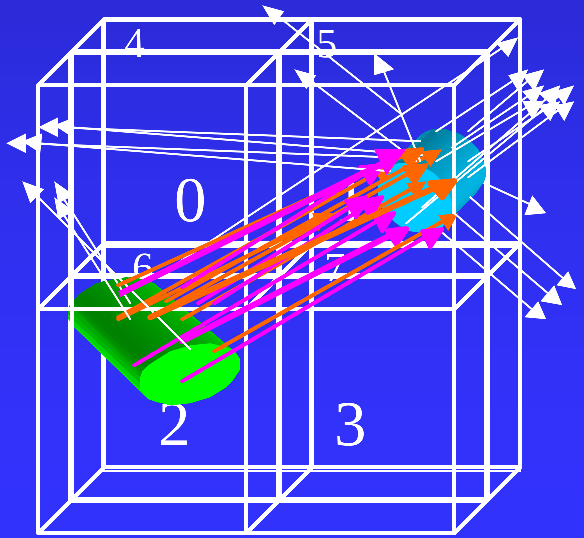

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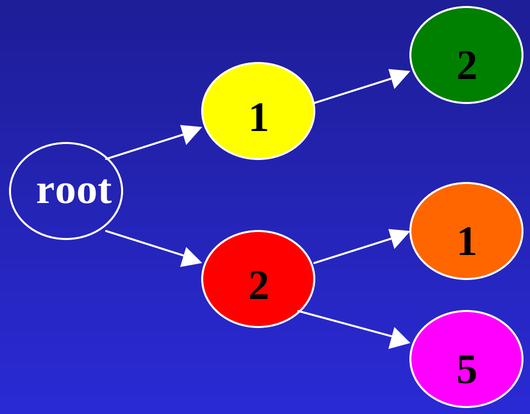
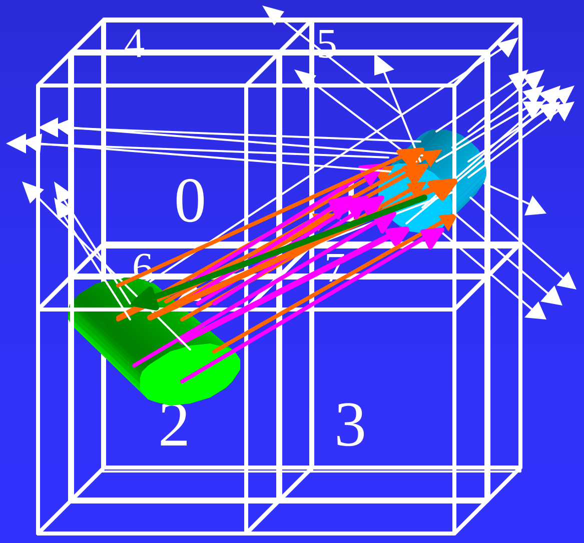
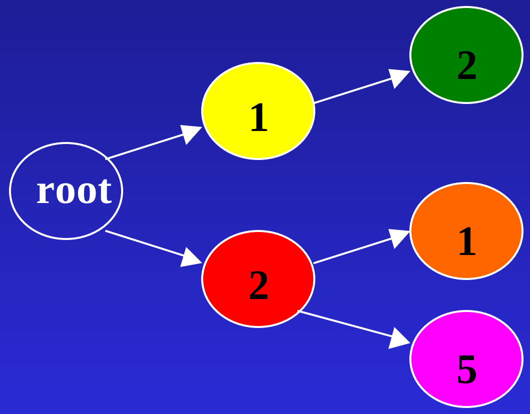
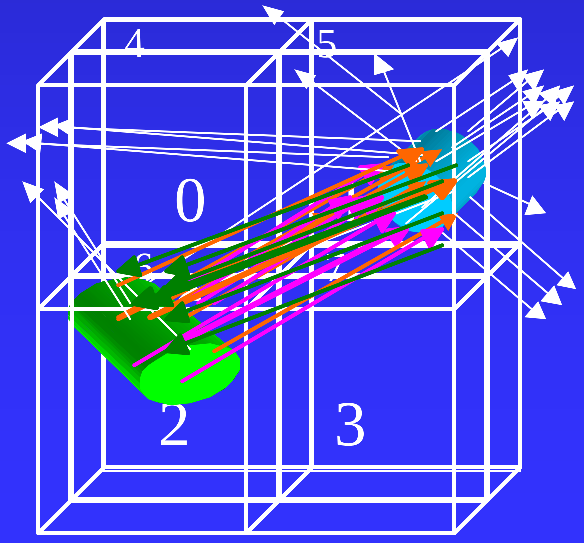


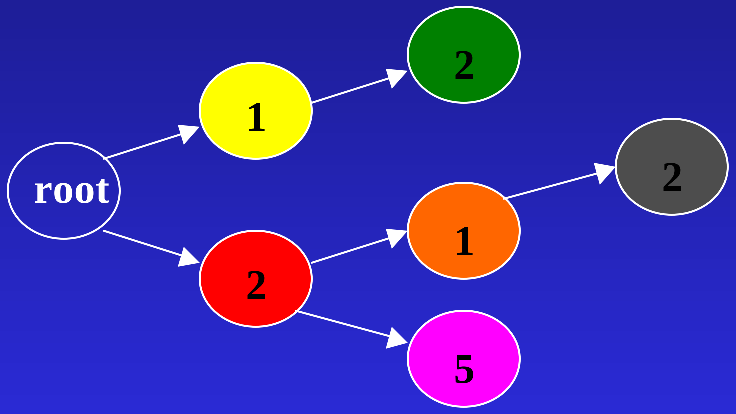


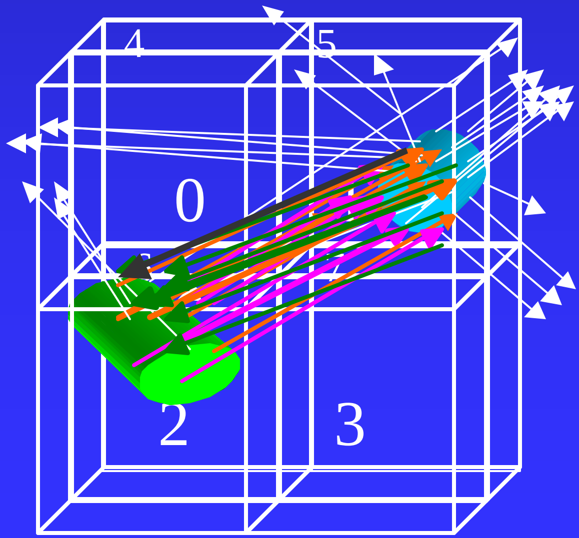
Reflections Refractions and Shadows



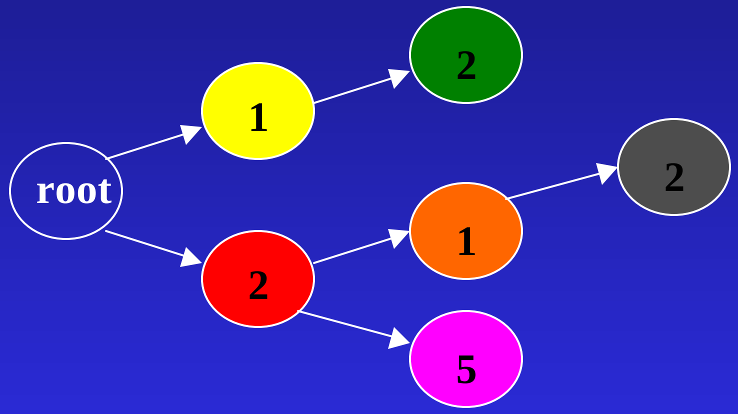


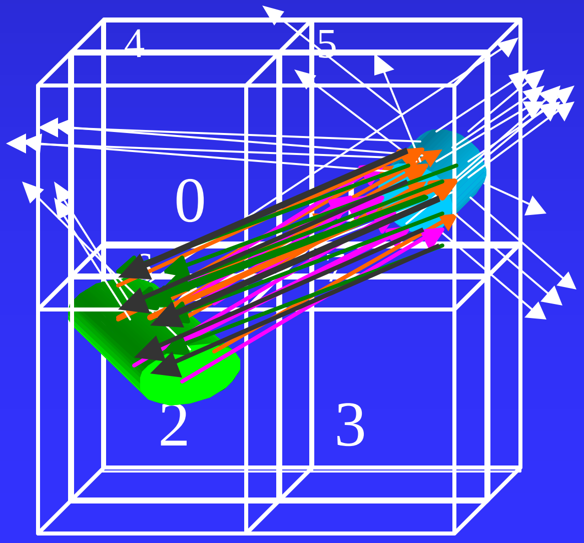
Secondary Reflections





Secondary Reflections





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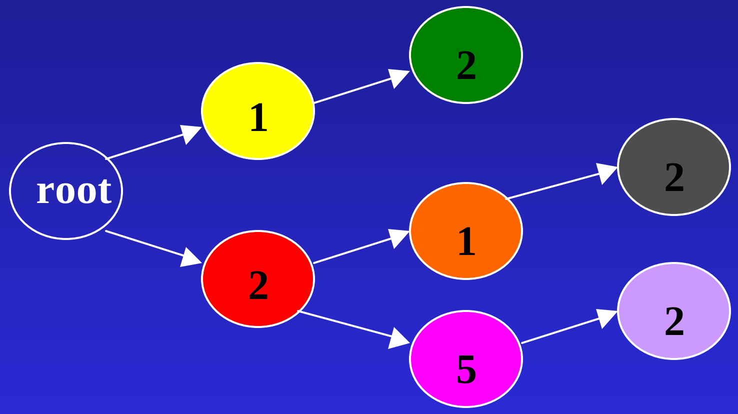

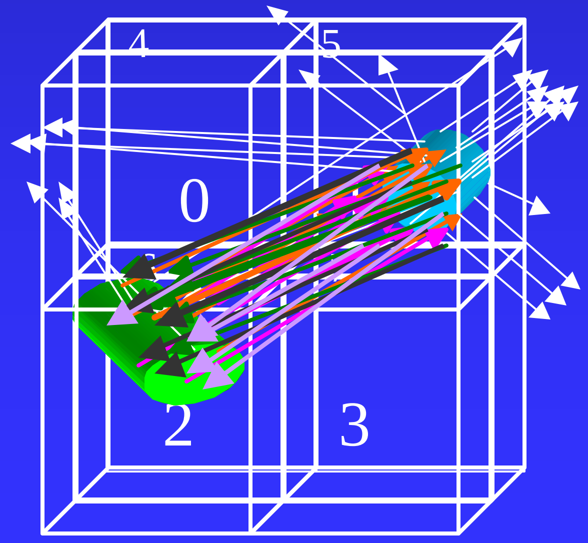

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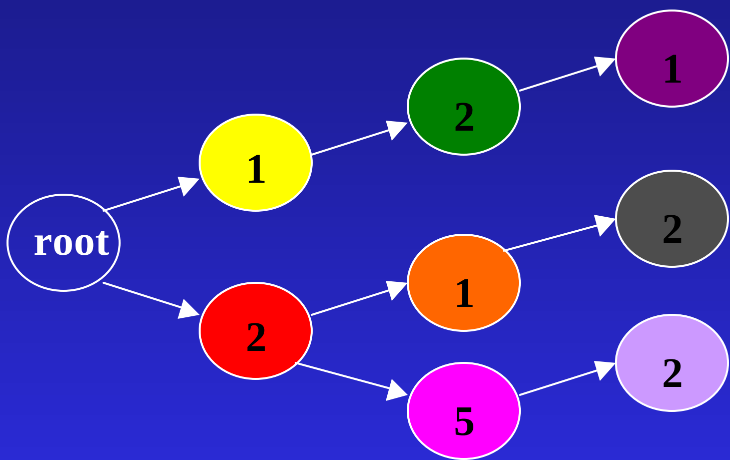

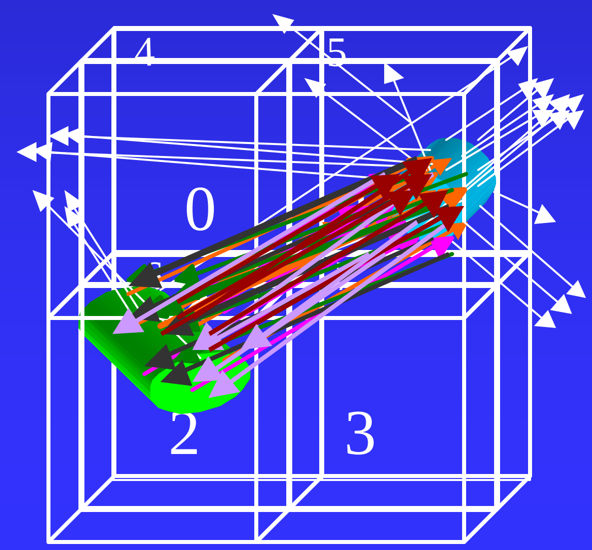

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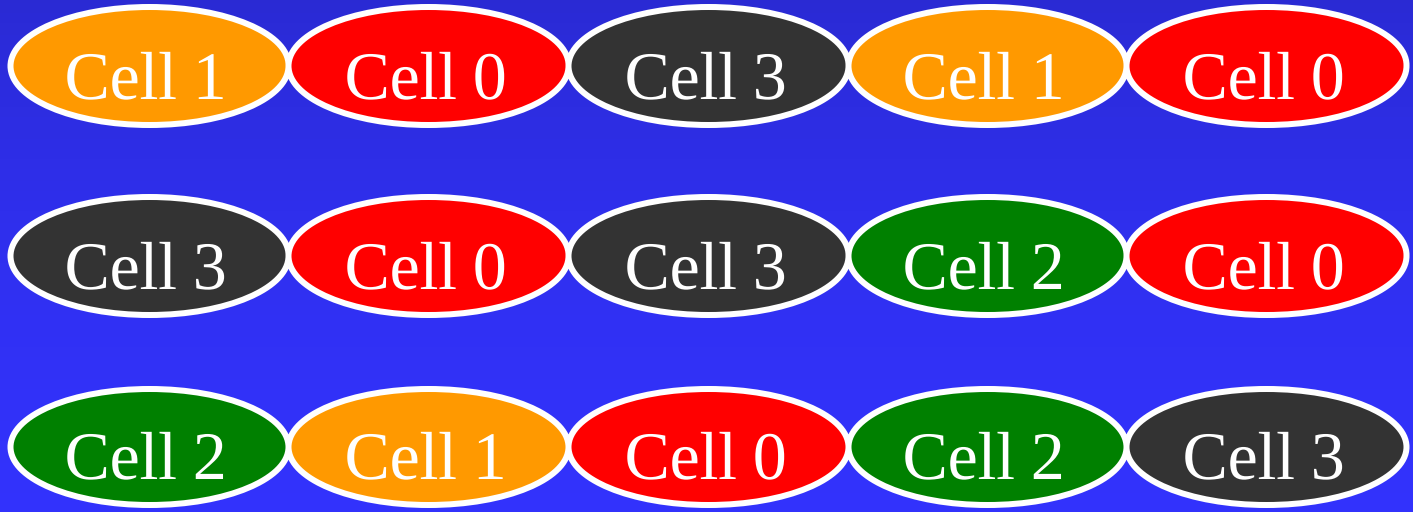
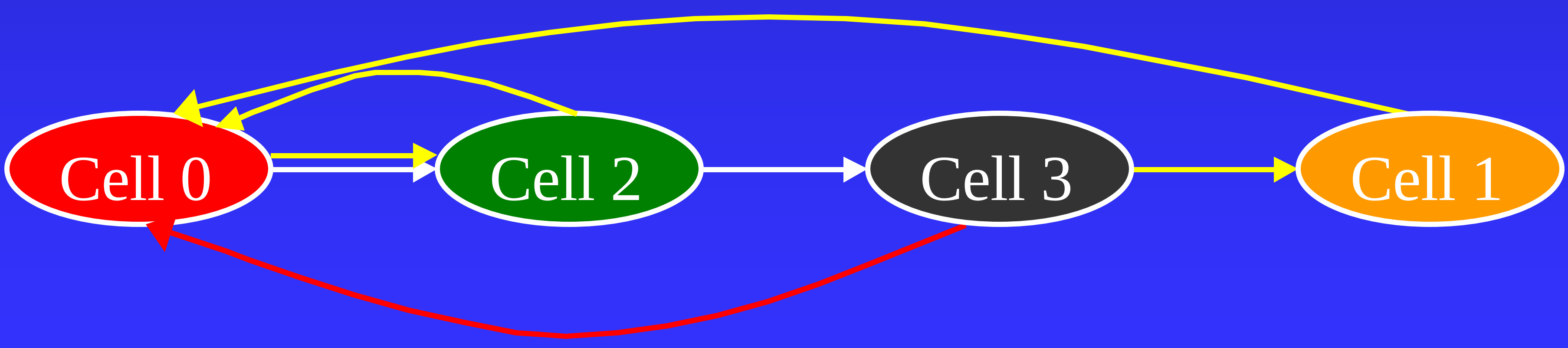
Task Scheduling Problem

- Goal - minimize memory fetches
- Equivalently - minimize color changes in super sequence which contains all sequences

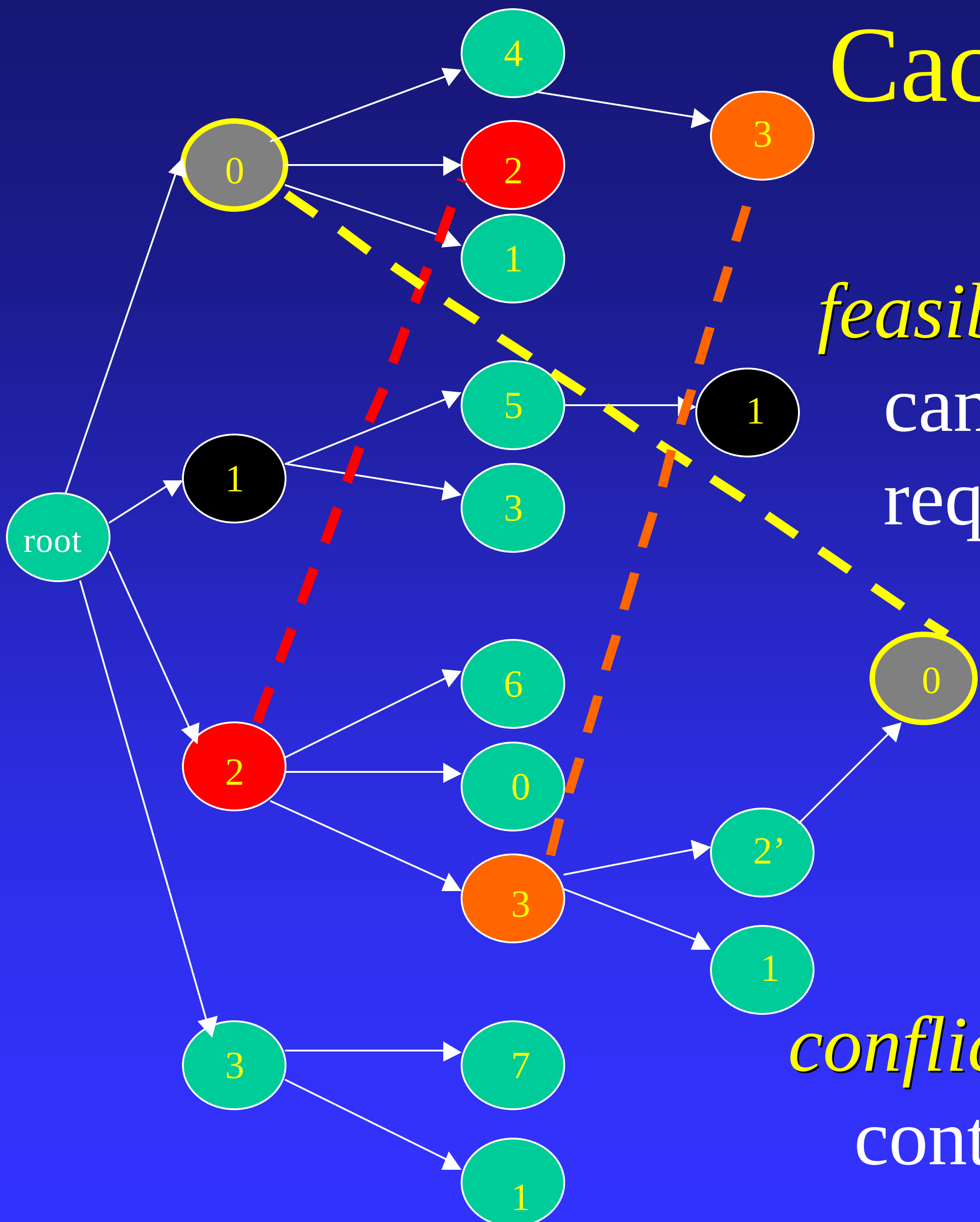


Cyclic Dependency Graphs

- Rays must visit cells in a particular order
- A ray may revisit a cell several times
- Sub-volume must be cached each time



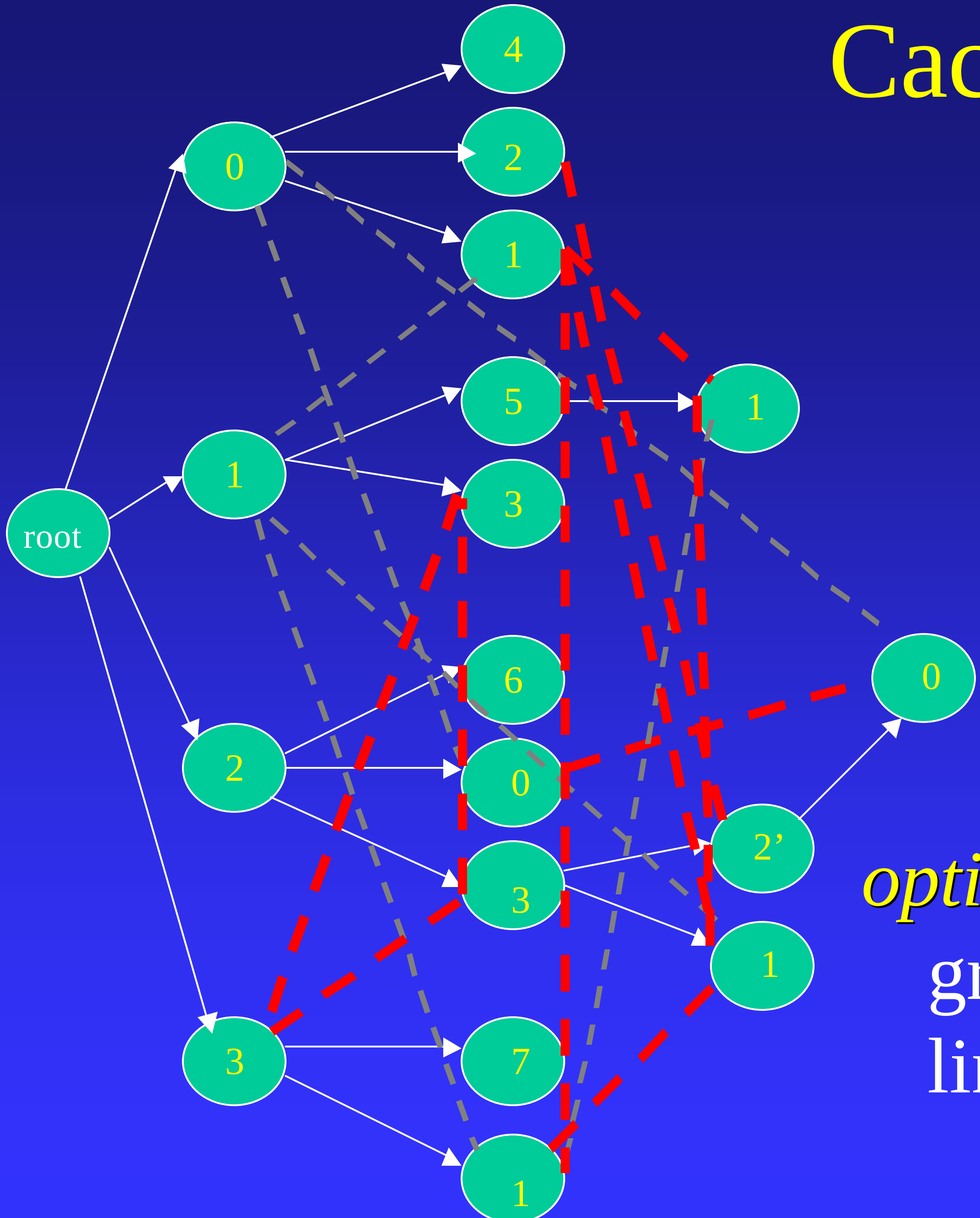
Cache Saving Links



feasible schedule - all rays can be processed in required order

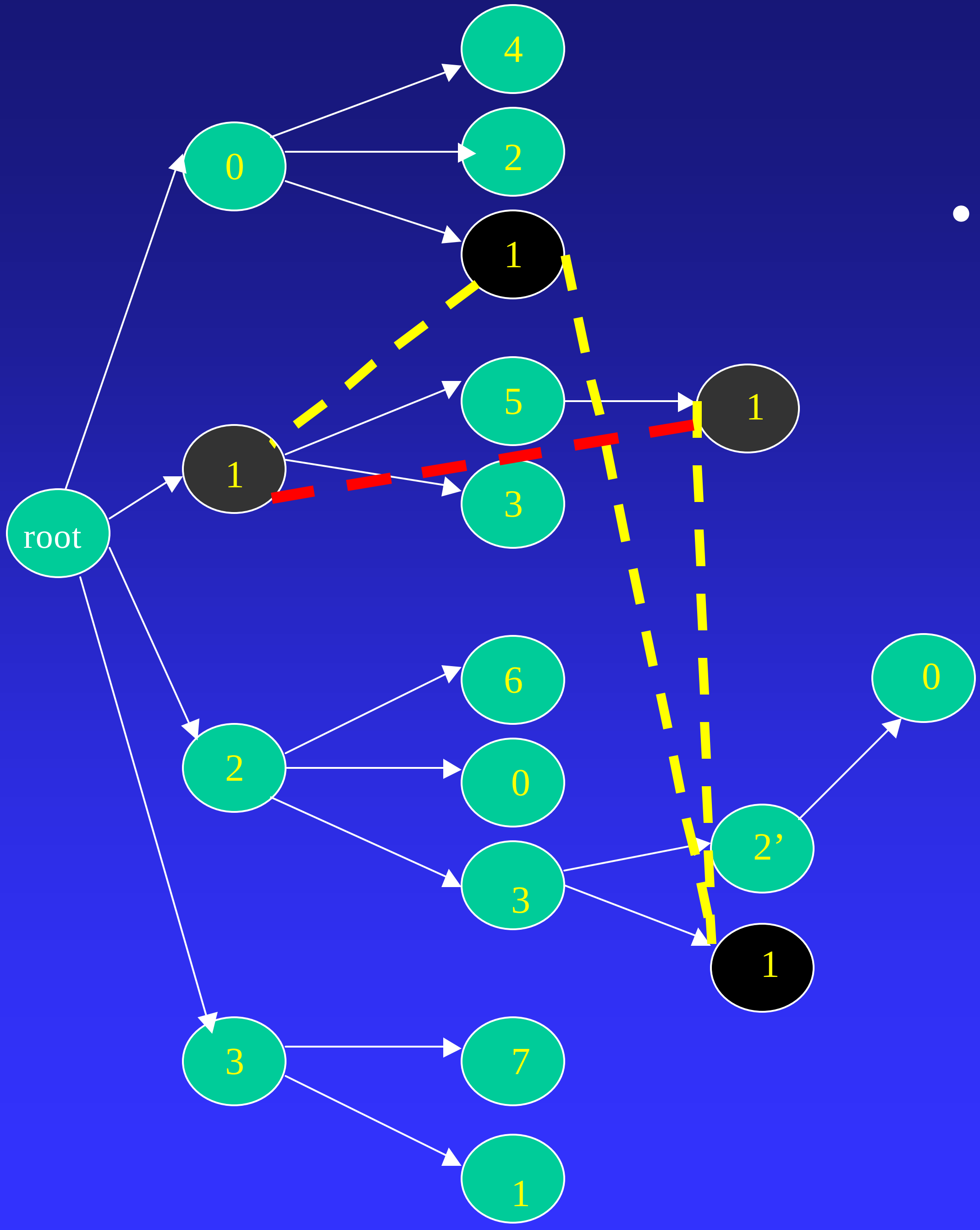
conflict - no feasible schedule contains both links

Cache Saving Links



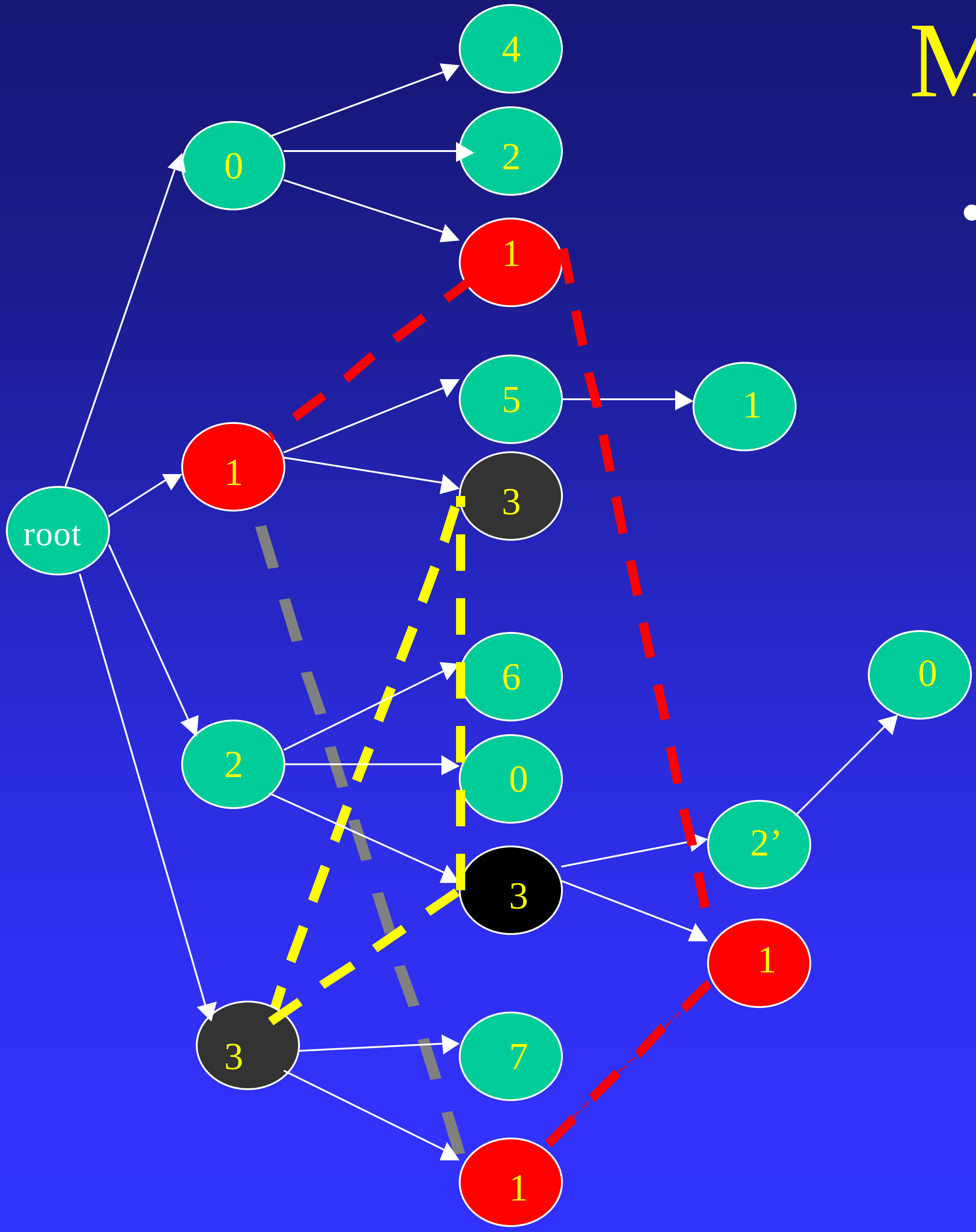
optimal schedule - maximal group of non-conflicting links

Chains



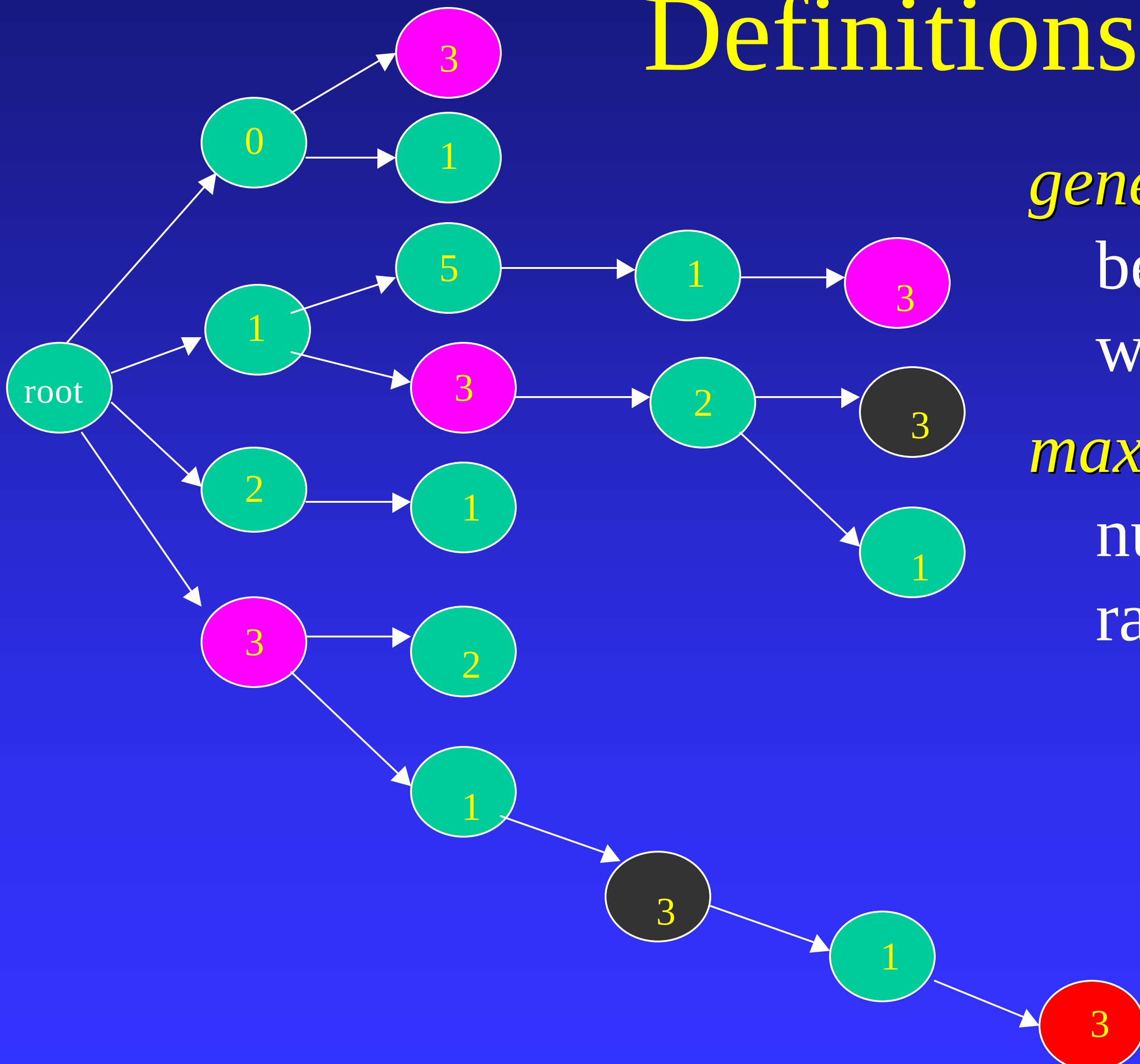
- Chain of non-conflicting links may produce a non-feasible schedule

Multiple Chains



- A combination of chains may also produce a non-feasible schedule

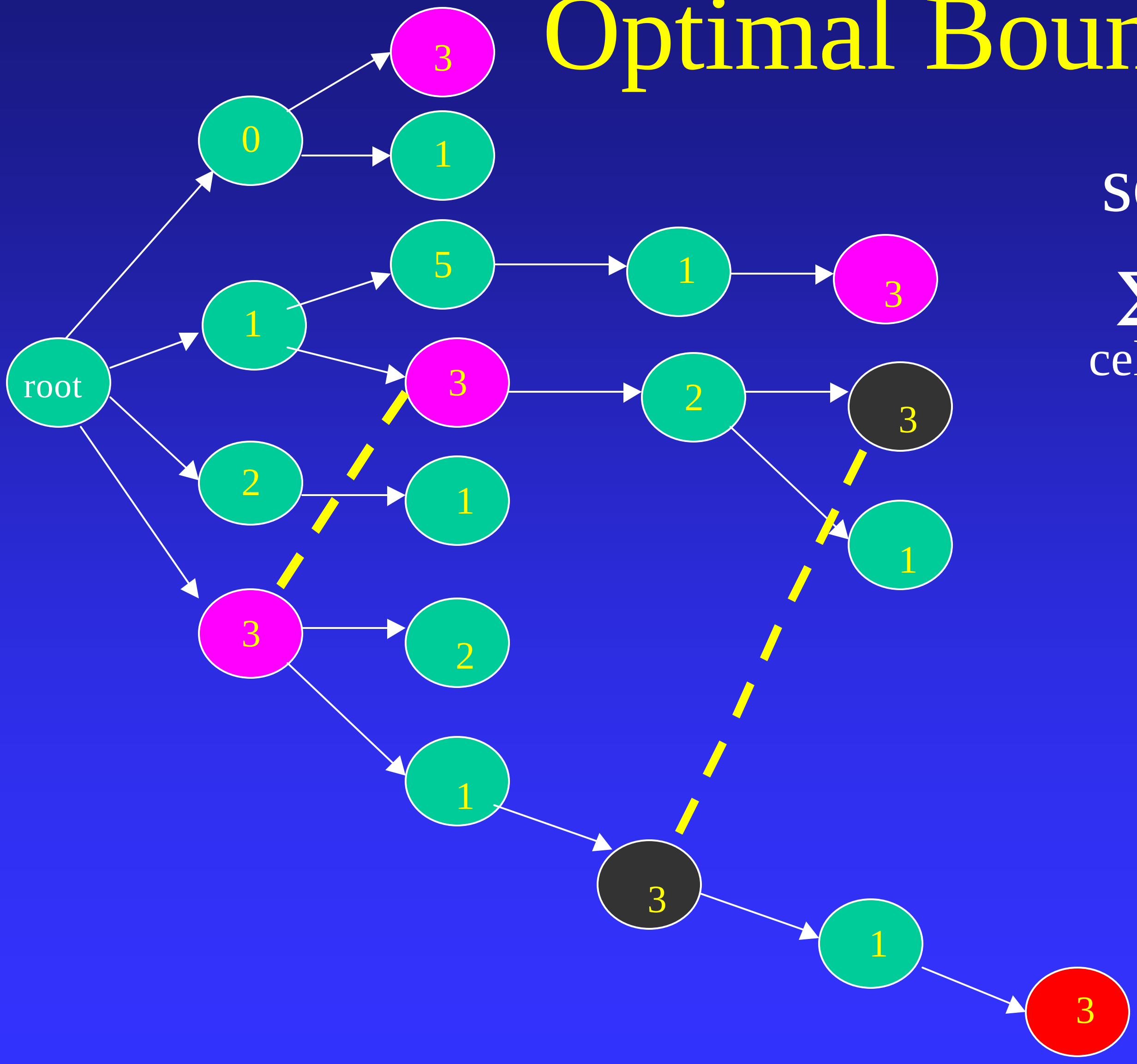
Definitions



generation(node) - nodes between root and *node* with same cell as *node*

maxGen(cell) - max number of times *any* ray enters *cell*

Optimal Bound



schedule size >=

$$\sum_{cells} \text{maxGen(cell)}$$

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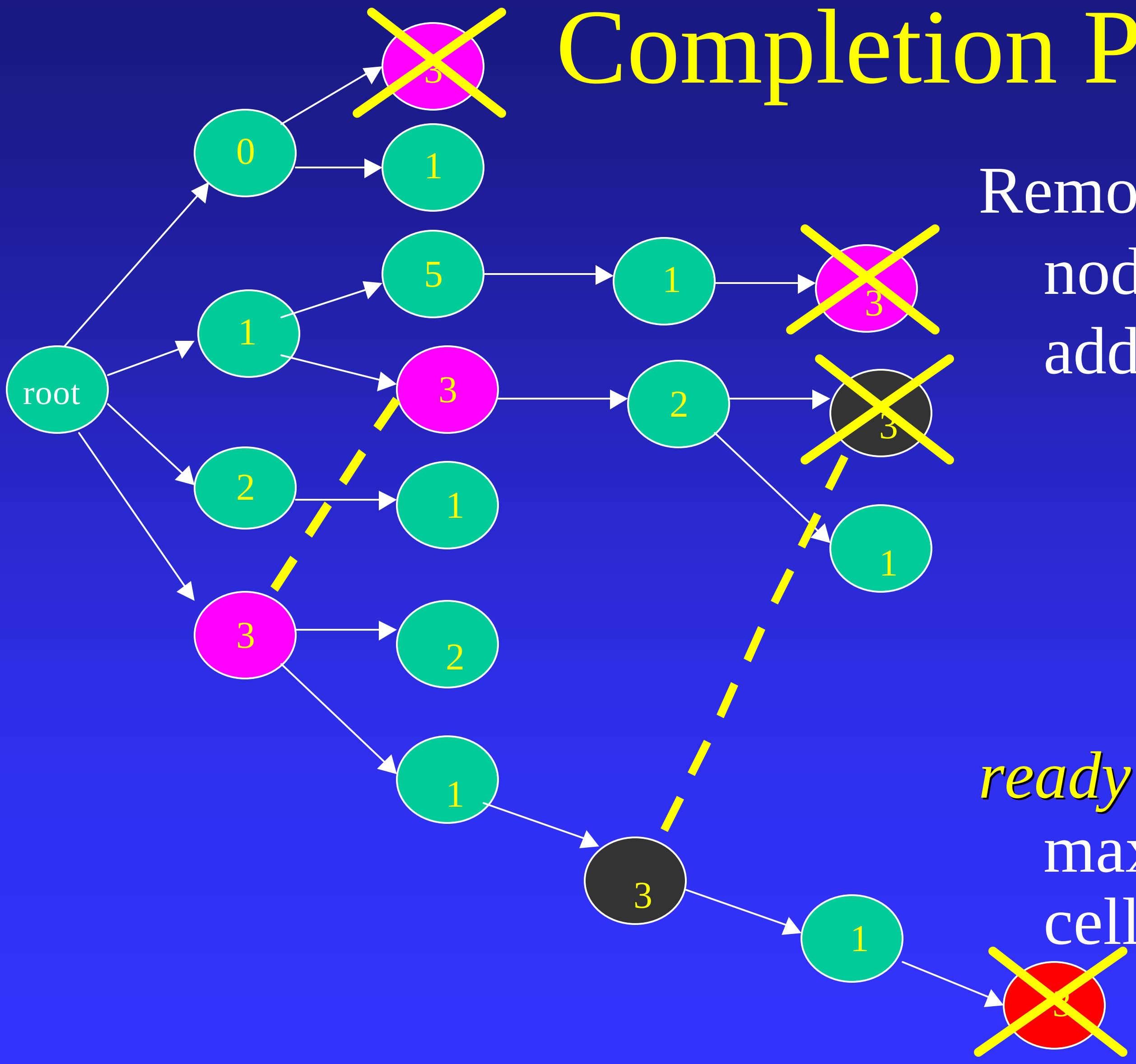
Peel Algorithm

- Peel tree leaves to create reverse schedule
- Gather cache savings links

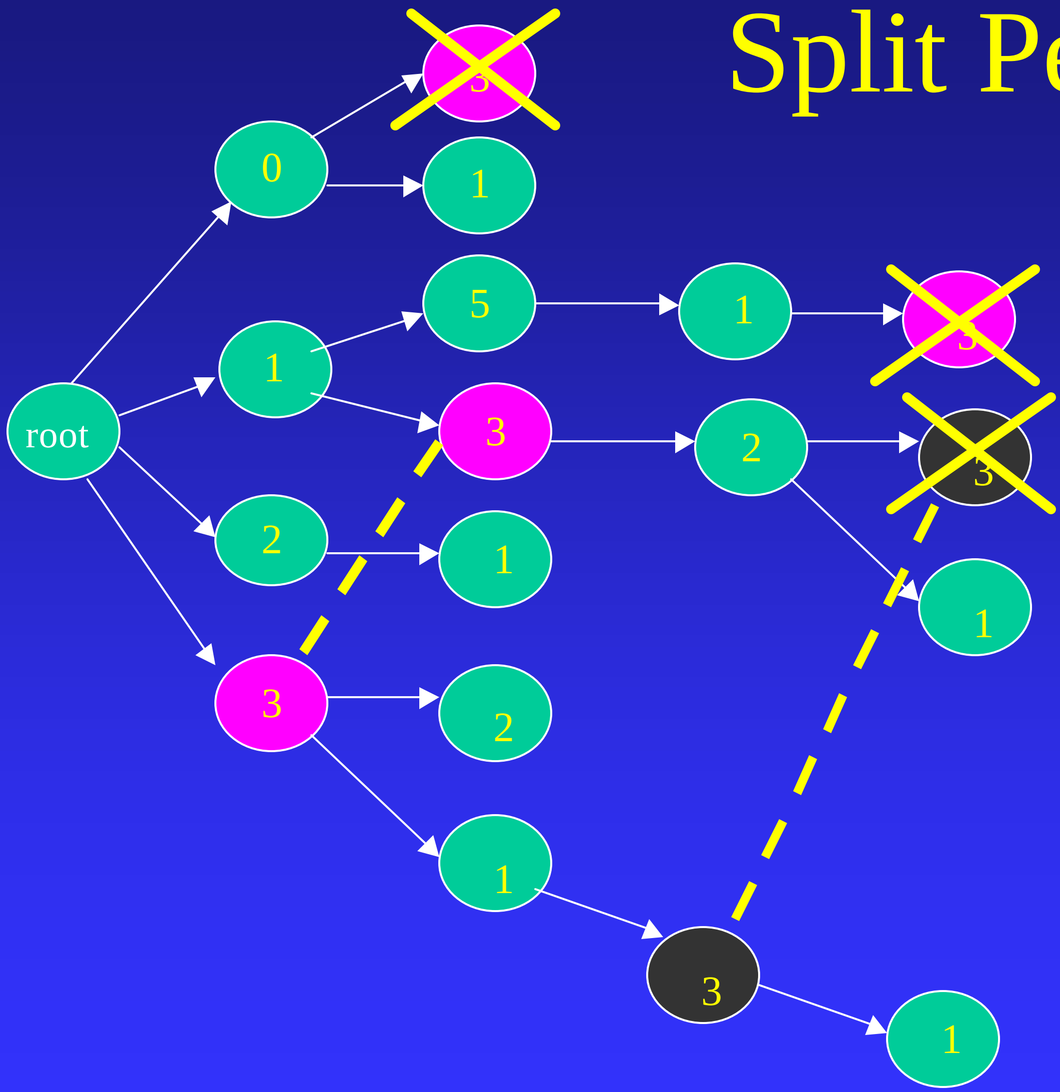
Completion Peel



Remove *ready cell* leaf nodes from tree and add it to schedule

ready cell - all the maxGen nodes of a cell are leaf nodes

Split Peel



Remove non-ready cell leaf nodes from tree and add it to schedule

Peel (***tree***)

While *tree* has any nodes…

Does *tree* have a ready cell *c*?

yes - add *c* to *schedule* and peel *c* leaf nodes

no - Find $cell_{max}$ with most leaf nodes

Peel $cell_{max}$ and add it to *schedule*

Return *schedule*

Peel (***tree***)

While *tree* has any nodes…

Does *tree* have a ready cell *c*?

yes - add *c* to *schedule* and peel *c* leaf nodes

no - Find $cell_{max}$ with most leaf nodes

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Peel (***tree***)

While *tree* has any nodes…

Does *tree* have a ready cell *c*?

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Peel $cell_{max}$ and add it to *schedule*

Return *schedule*

Peel (*tree*)

While *tree* has any nodes…

Does *tree* have a ready cell *c*?

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Peel $cell_{max}$ and add it to *schedule*

Return *schedule*

Peel (***tree***)

While *tree* has any nodes…

Does *tree* have a ready cell *c*?

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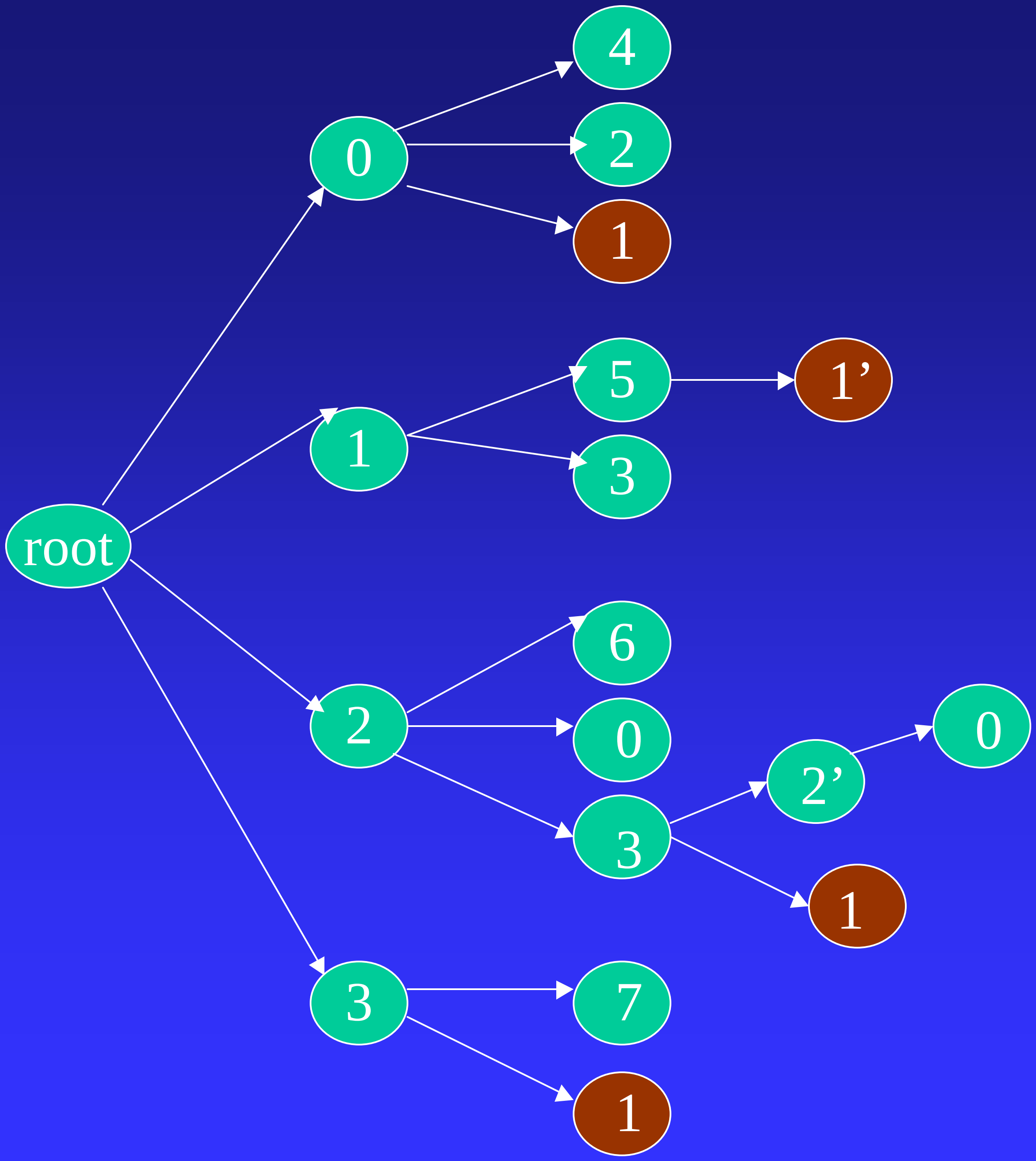
Peel $cell_{max}$ and add it to *schedule*

Return *schedule*



root
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2’
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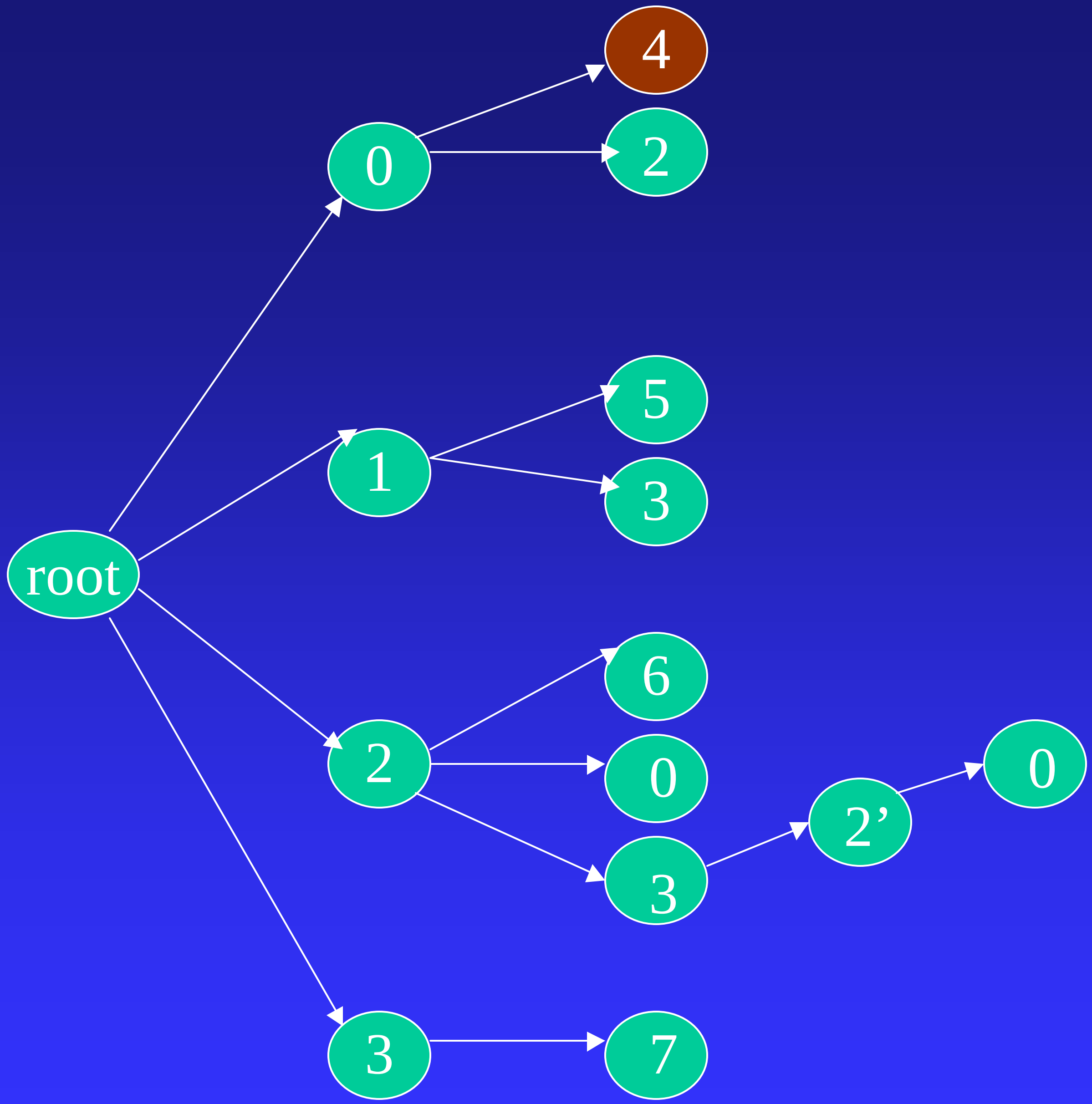
1
7
1


4
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root
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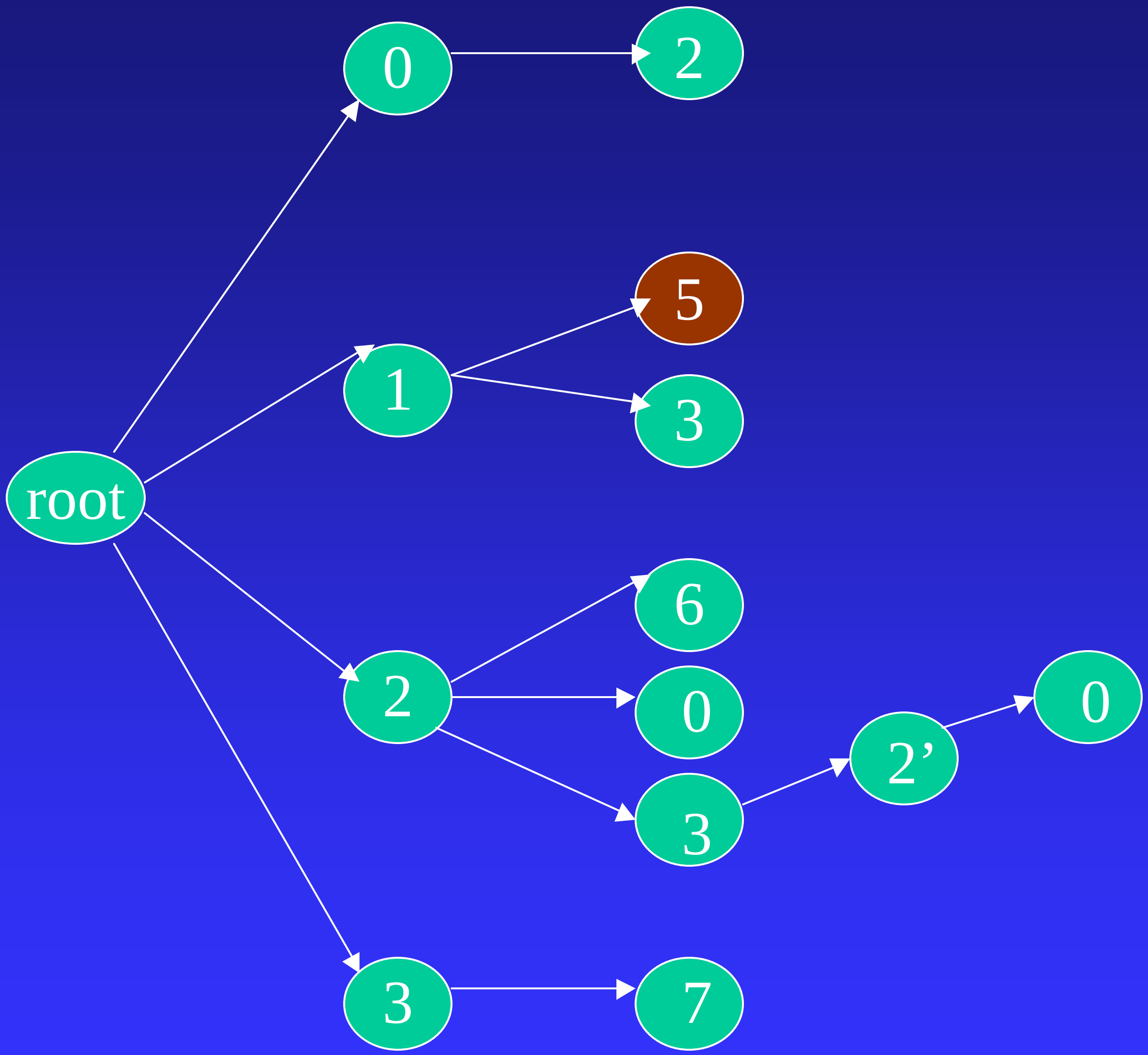
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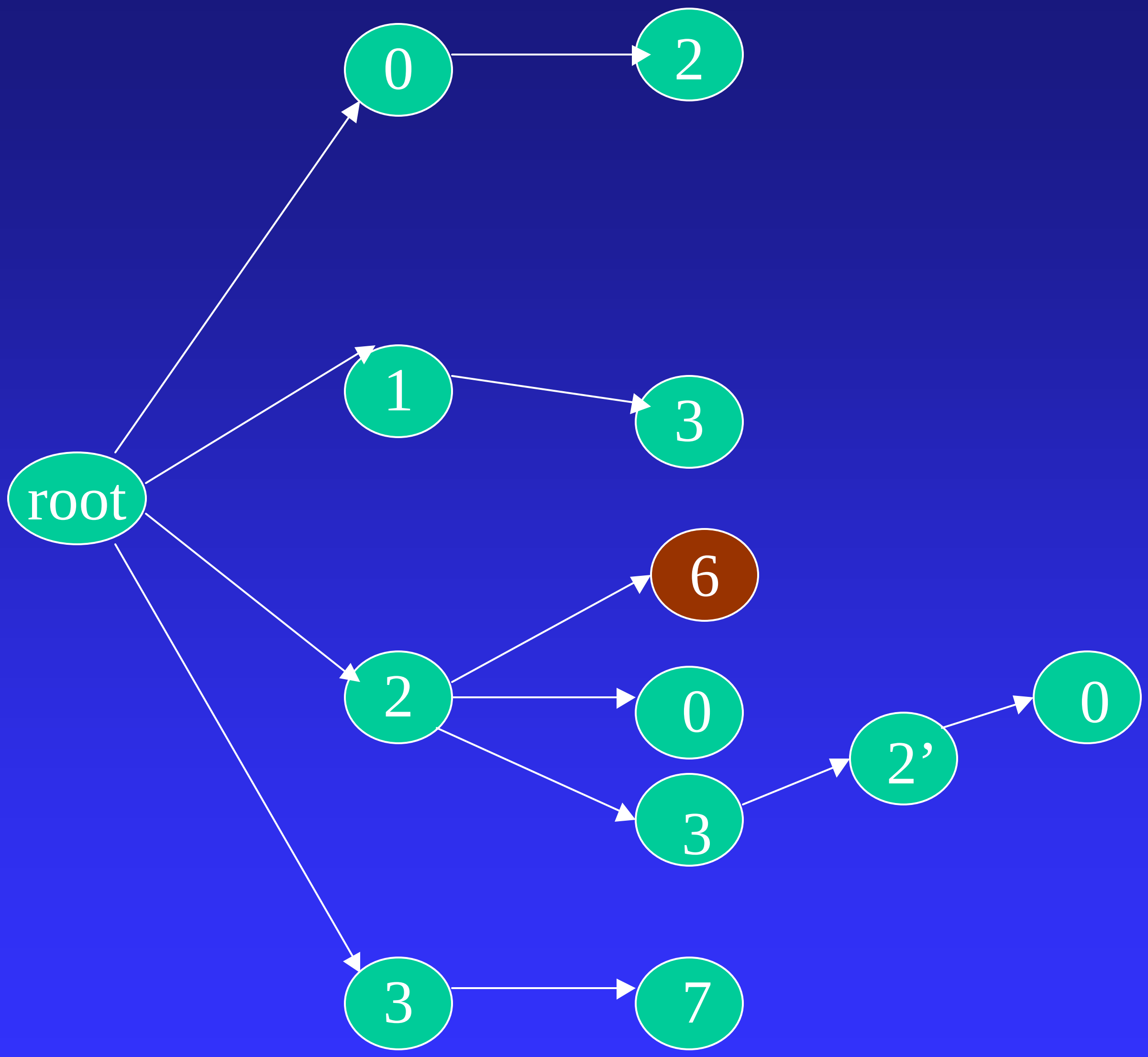
root
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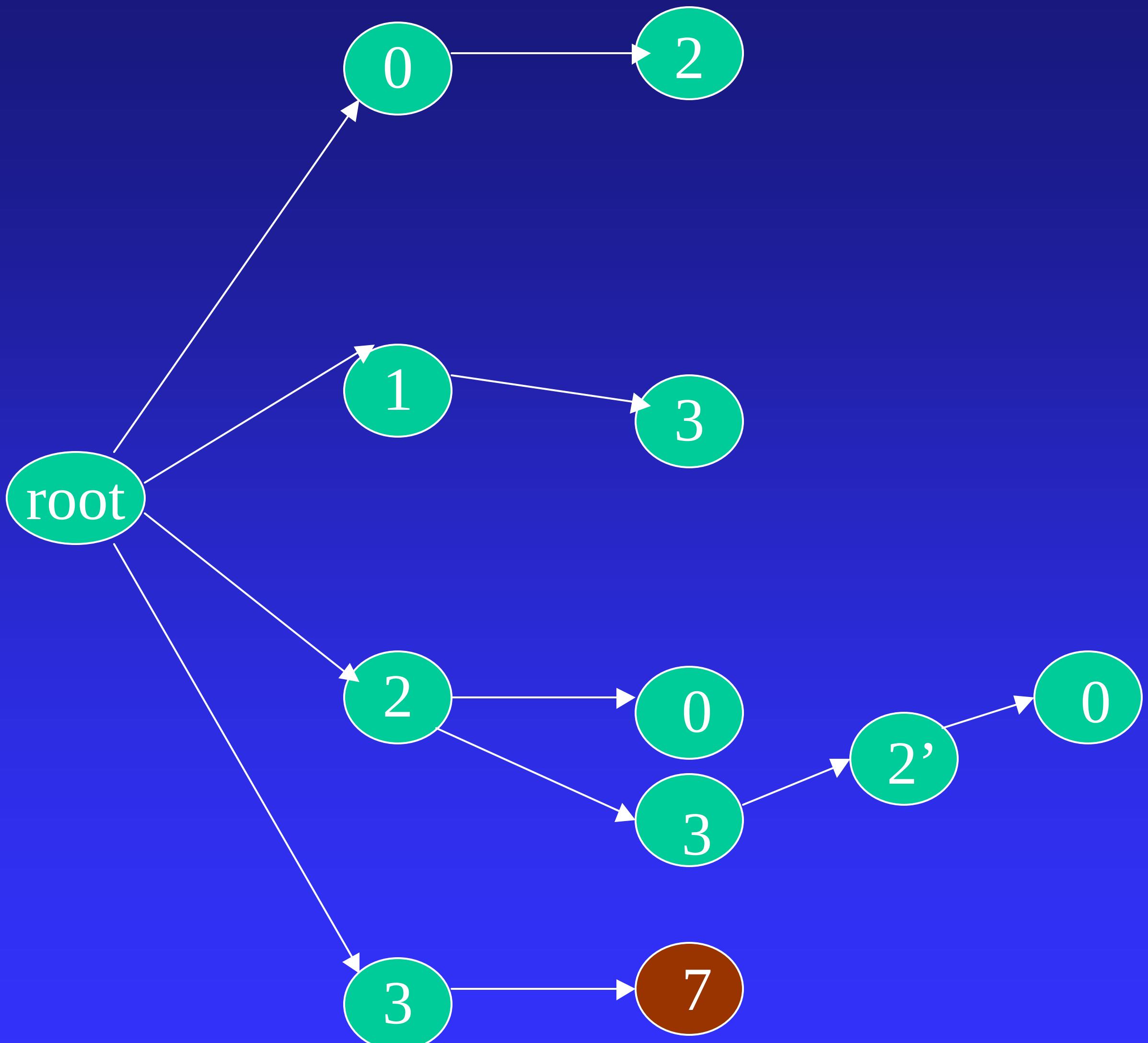

0
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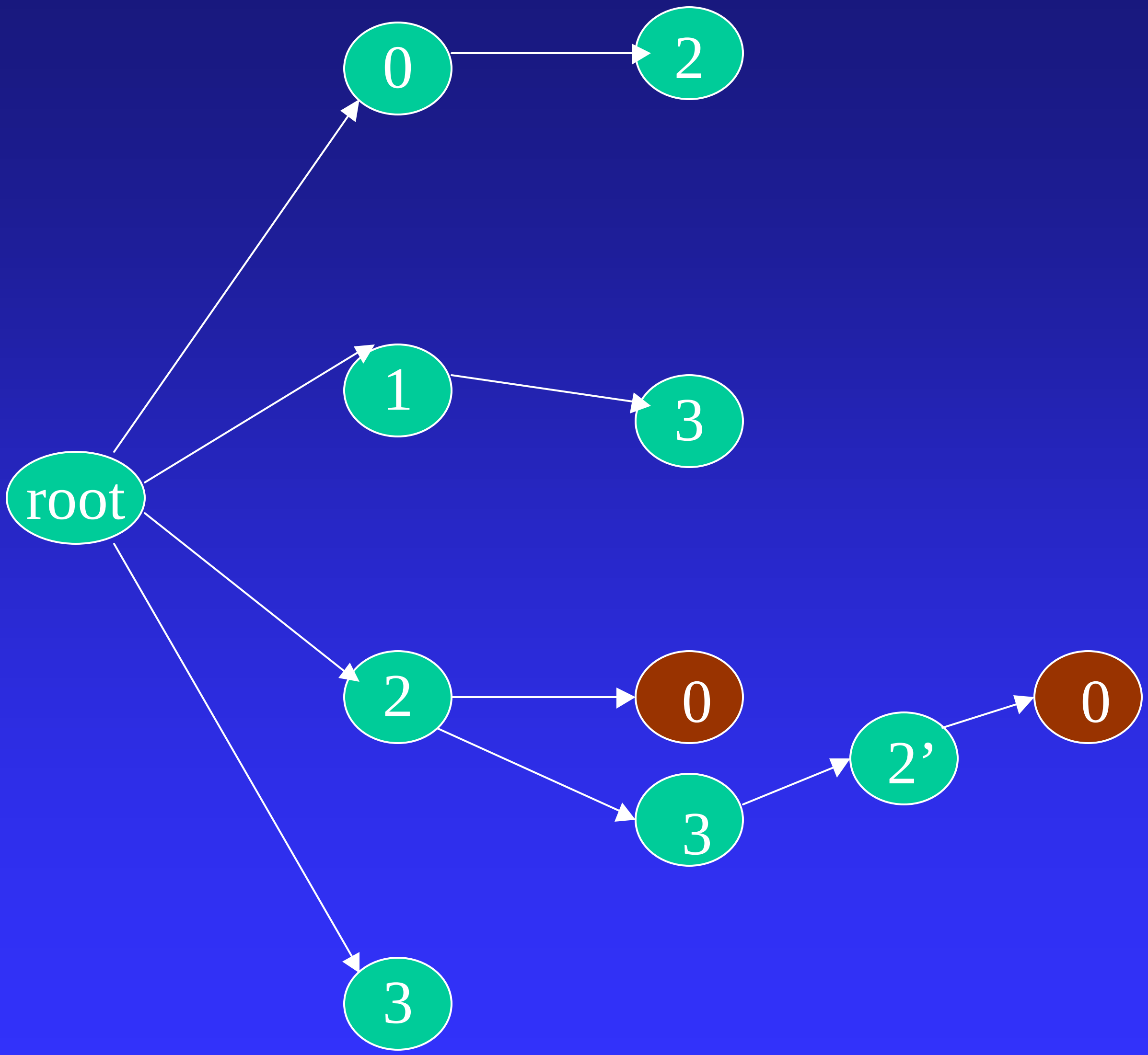
root
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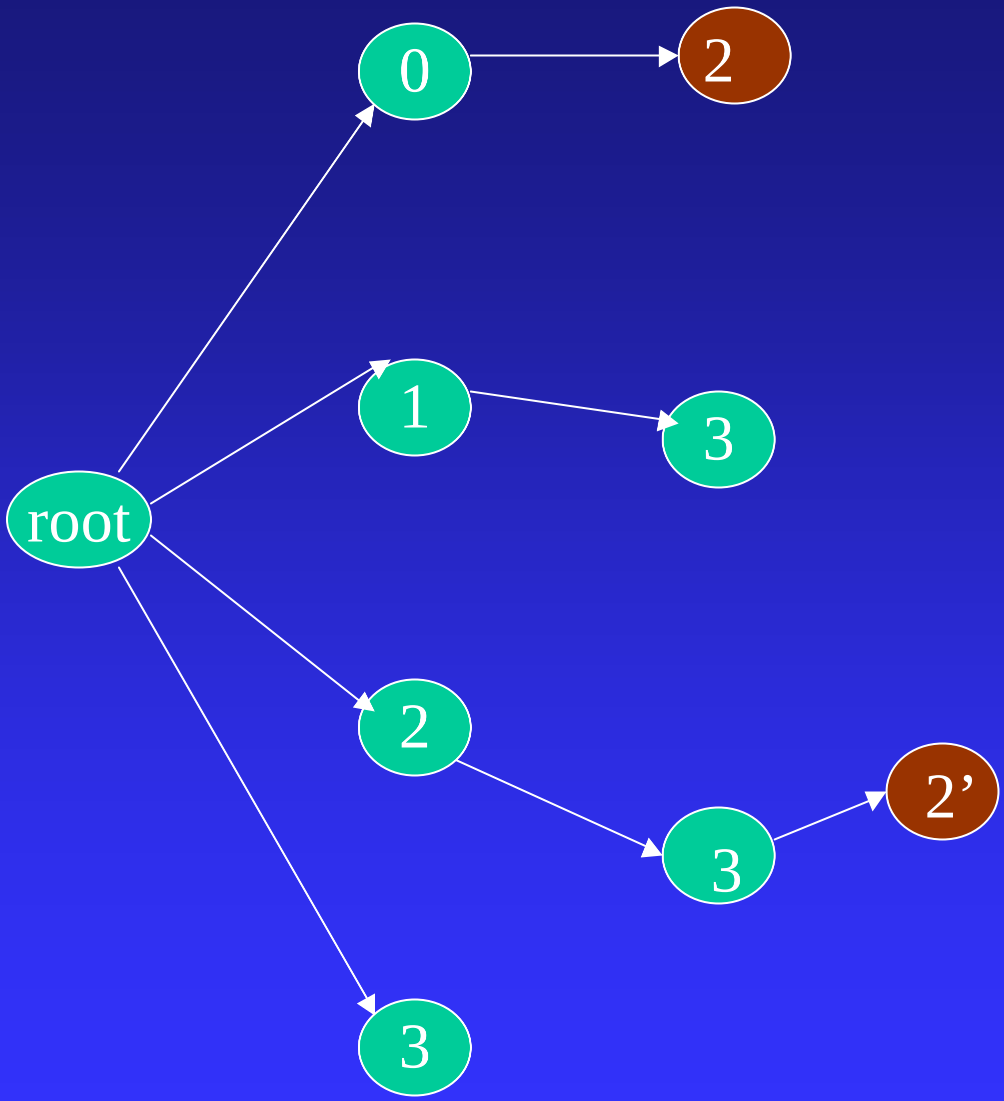

root
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2'
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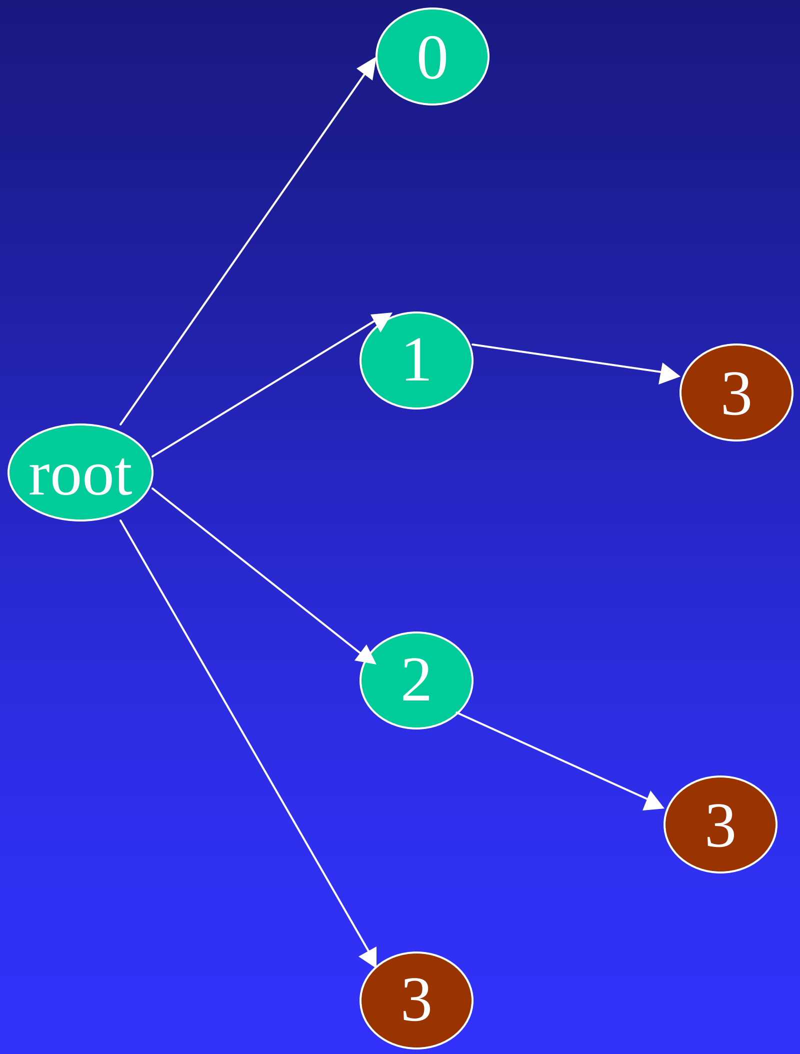
0
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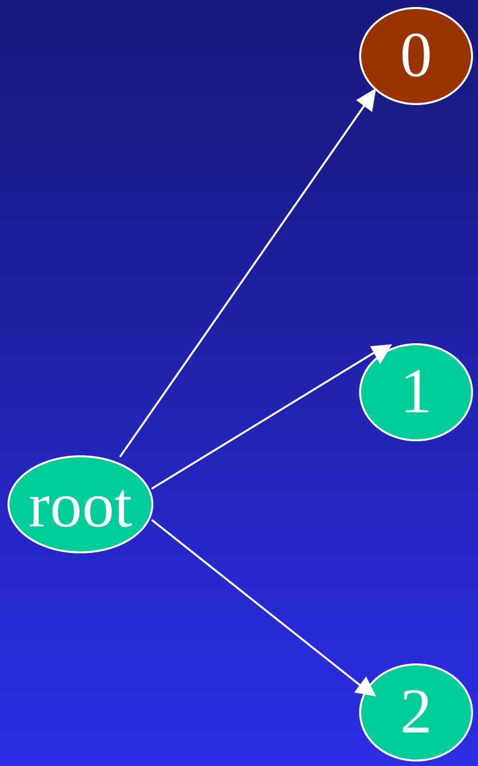
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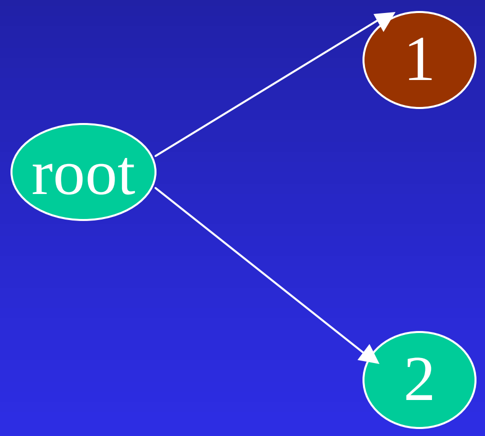
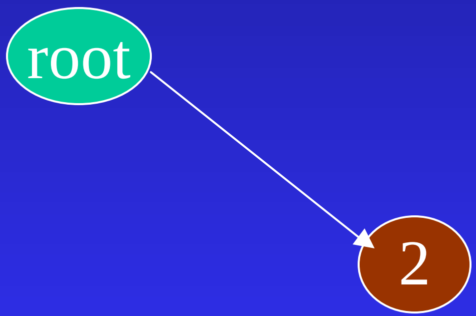

root
1
2


root
2

Algorithm Performance

- Guaranteed feasible
- Not guaranteed optimal
- Worst time O(n)
- Improvement over Max Work
- Hardware implementation reasonable

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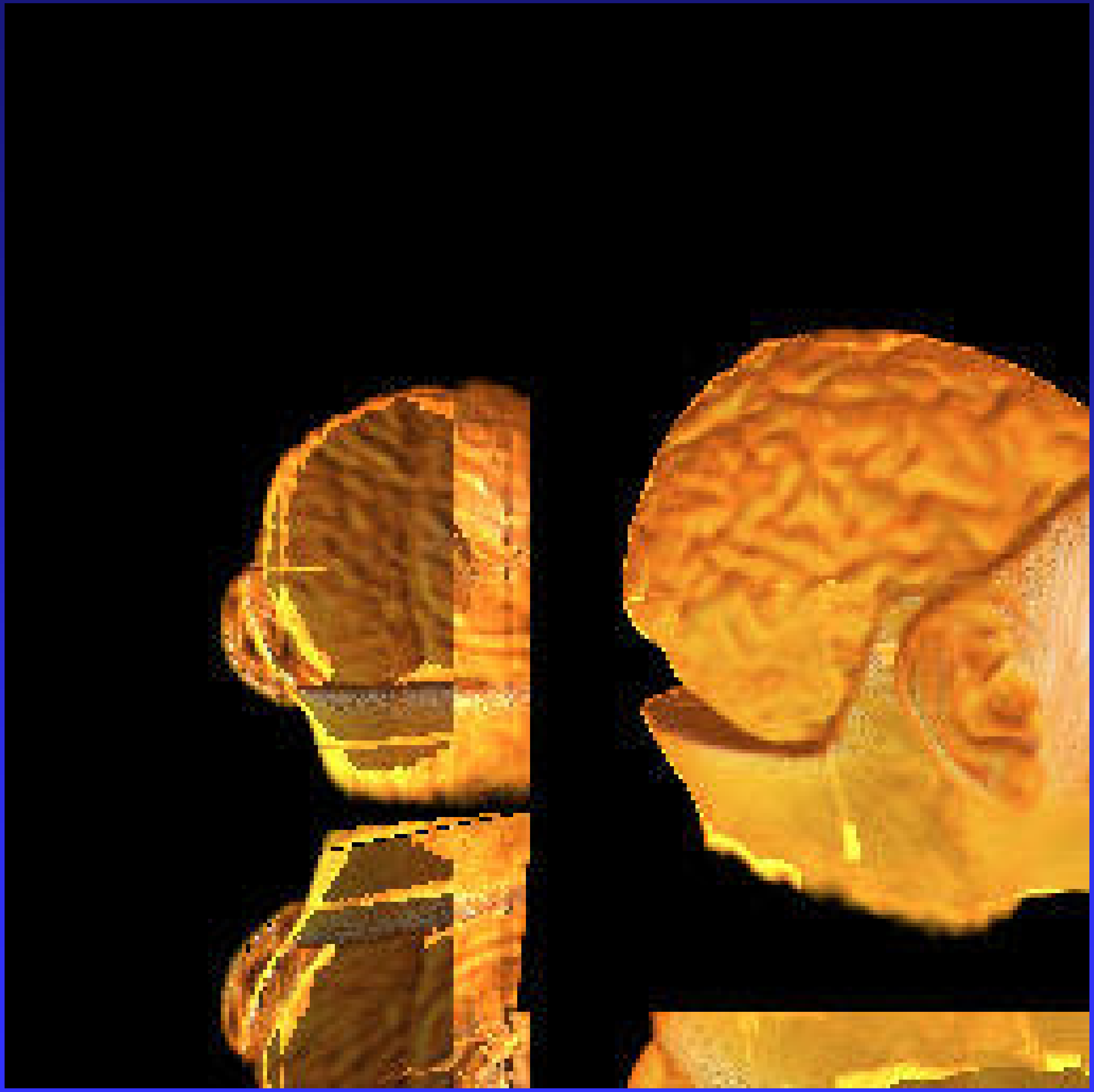
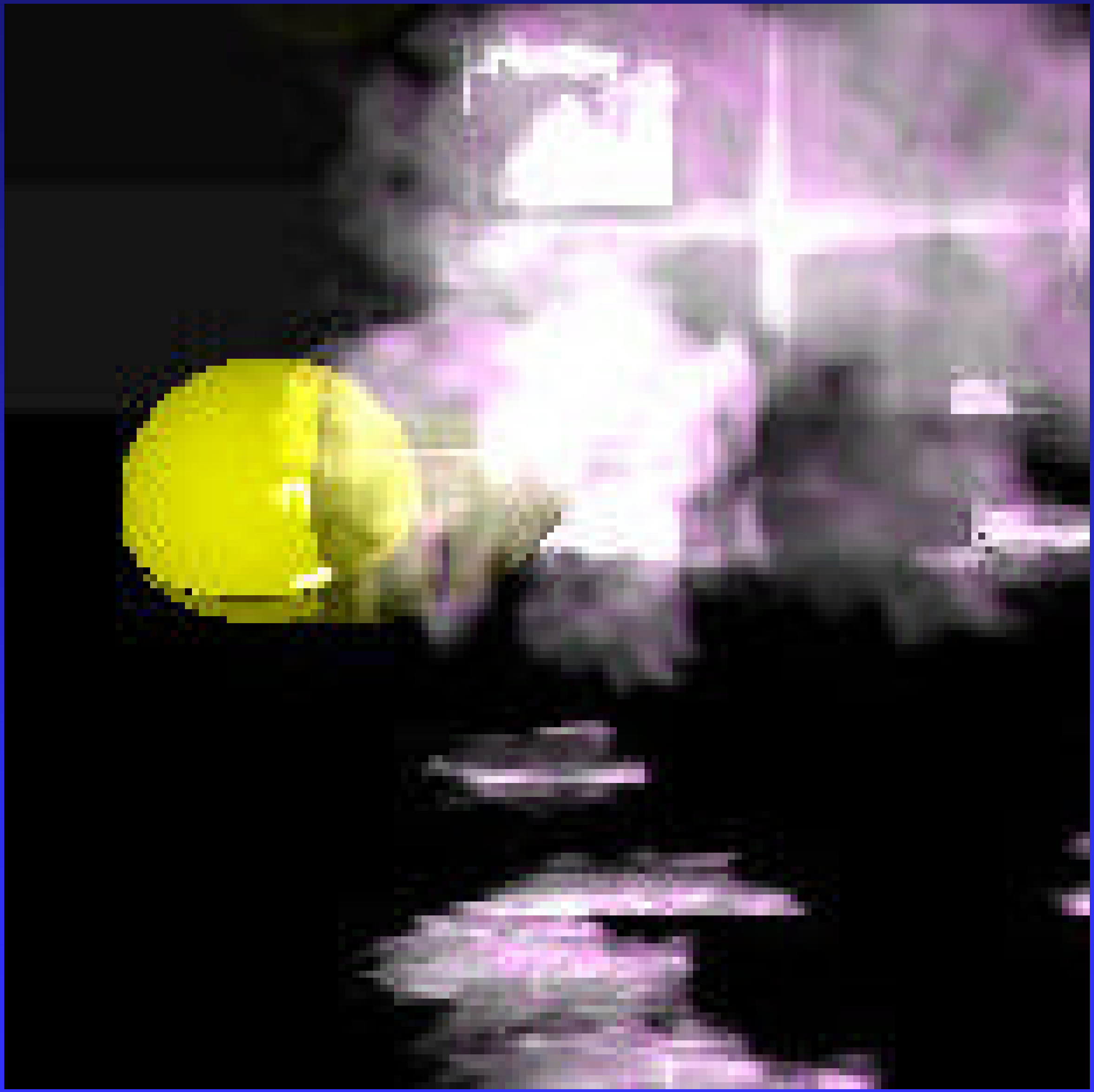
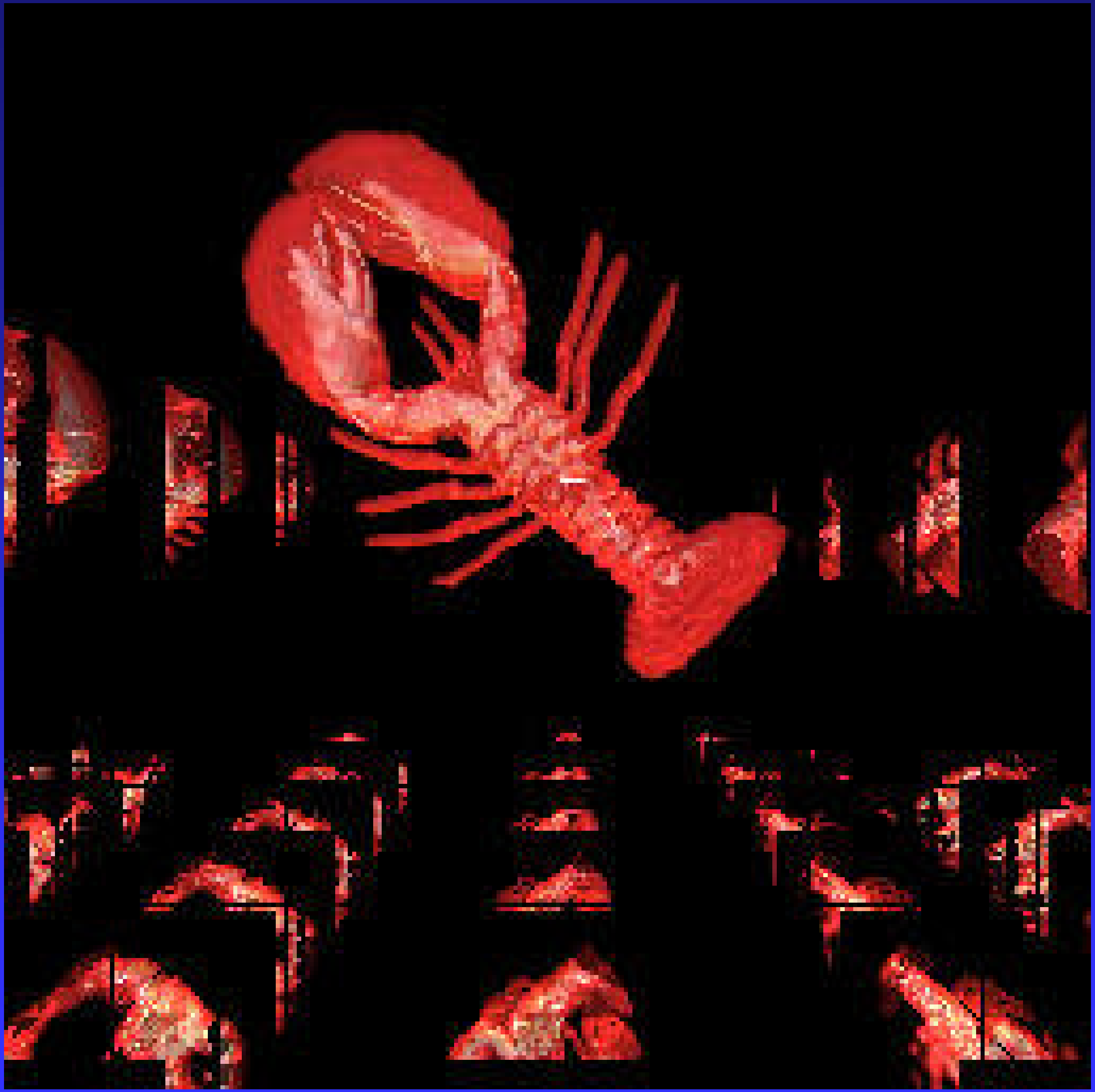
Tests

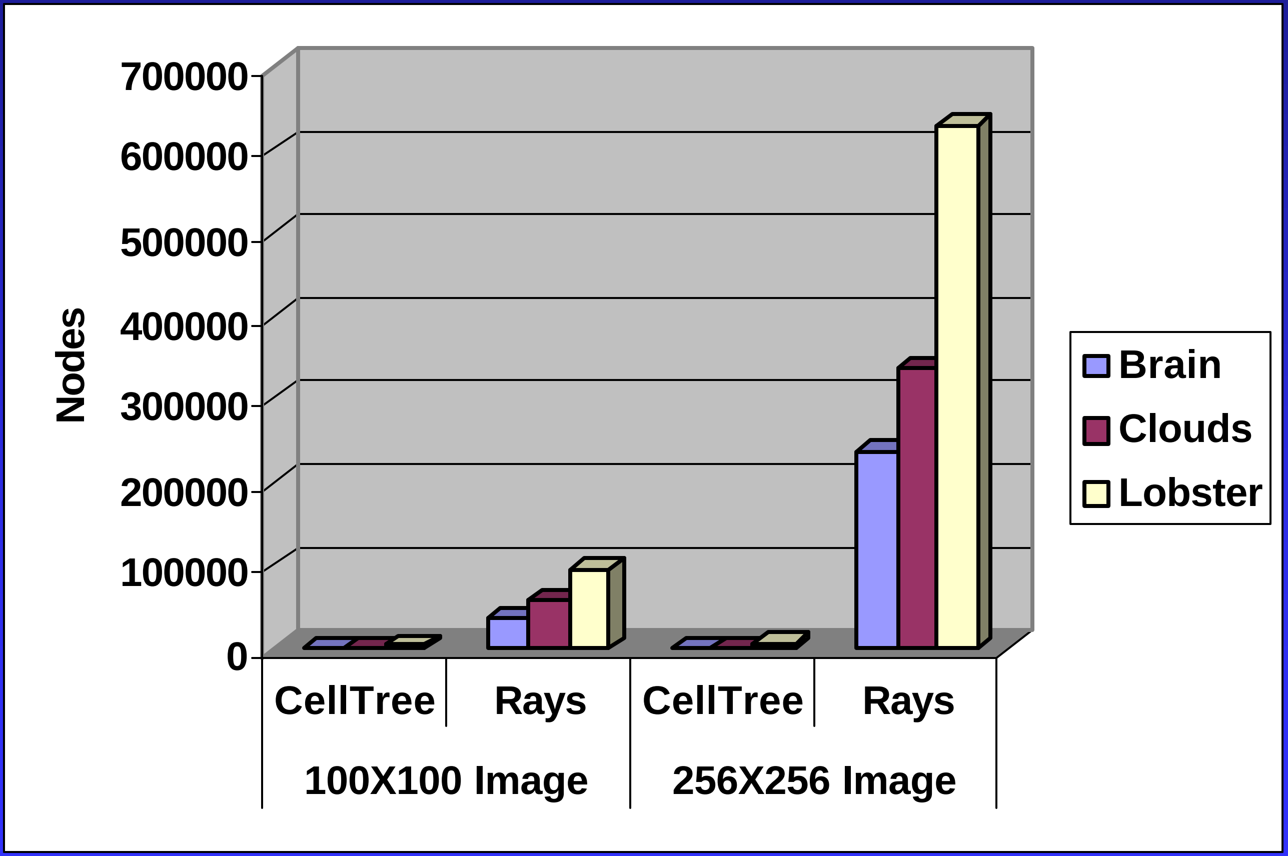
- C++ simulation
- SGI 02/RISC 10000 128MB
- Volumes split into 8 cells and 27 cells
- Image resolution 256^2



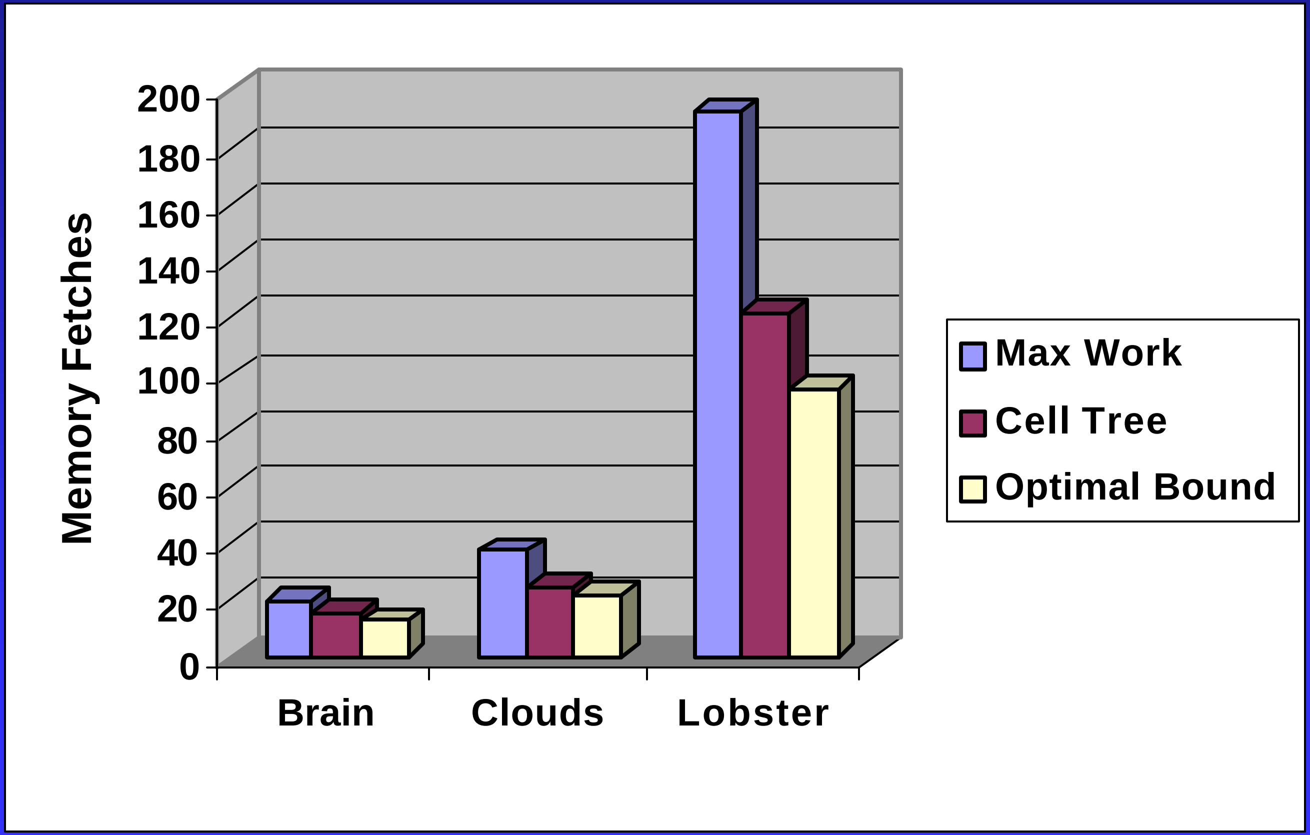




Cell Tree Sizes



30% Fewer Fetches



Conclusion

- Cell Tree captures all ray-cell dependencies
- Dependency graph based algorithm significantly improves cache performance

Future Work

- Dynamic load balance
- Dynamic volume subdivision
- Multi-level memory hierarchy
- Limited depth recursion

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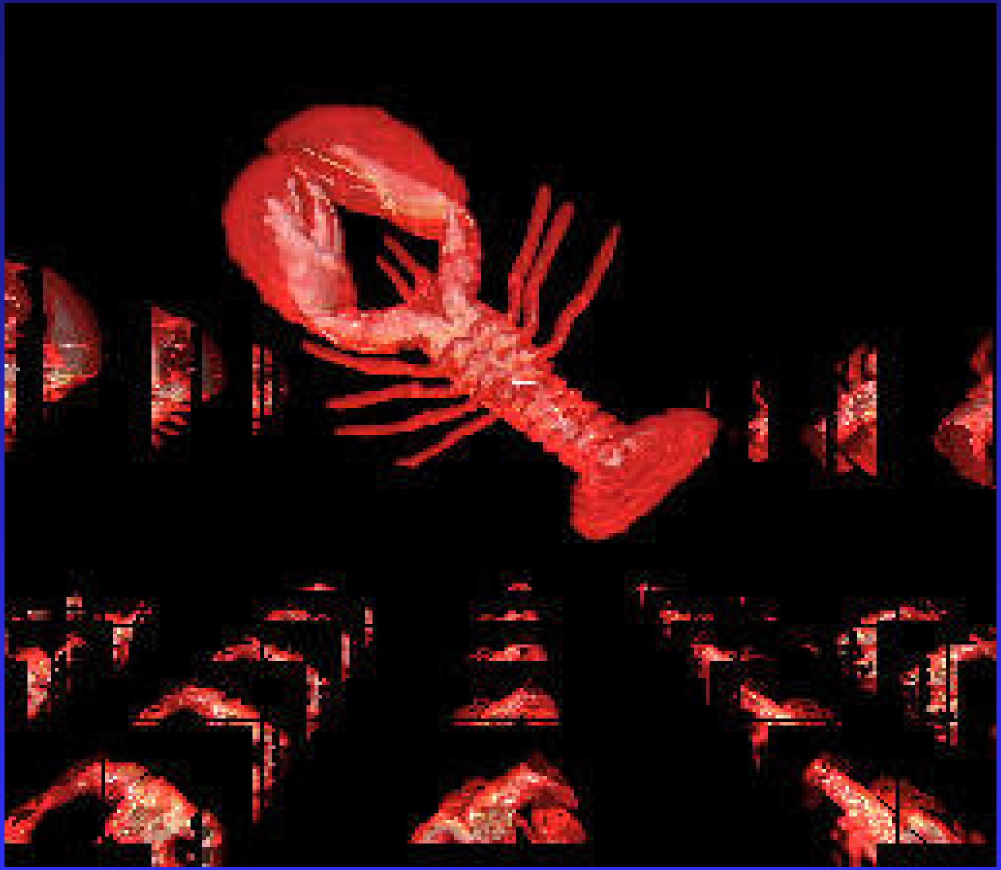

Thank you!