Parallel Ray Tracing

See T. Plachetka: Event-Driven Message Passing and Parallel Simulation of Global Illumination, Chapter 4
http://ubdata.upb.de/ediss/17/2003/plachetk/disserta.pdf

Global illumination [Kajiya 1986]

Object geometry (set of surface points *x*)

Object materials: *BSDF(x,ω’,ω)*

Light sources: $L_e(x,\omega)$

Measuring sensors in camera: $W_e(x,\omega')$

RT(x,ω) denotes the ray tracing operation which returns the first surface point from point *x* in direction *ω*

$$L(x,\omega) = L^e(x,\omega) + \int_\Omega BSDF(x,\omega',\omega) L(RT(x,-\omega'),\omega') \cos(\theta') d\omega'$$

$$W(x,\omega') = W^e(x,\omega') + \int_\Omega BSDF(x,\omega',\omega) W(RT(x,\omega),\omega) \cos(\theta) d\omega$$

Radiance *L(x,ω)* at least for all points *x* and directions *ω* which contribute to the response of some camera sensor

Potential *W(x,ω)* at least for all light surface points *x* and all directions *ω*.

Global illumination [Kajiya 1986]

$$L(x,\omega) = \Re\left(L^i_{\text{direct}}(x,\omega'), L^i_{\text{reflected}}(x,\omega'), L^i_{\text{refracted}}(x,\omega'), L^i_{\text{ambient}}(\mathrm{x})\right)$$

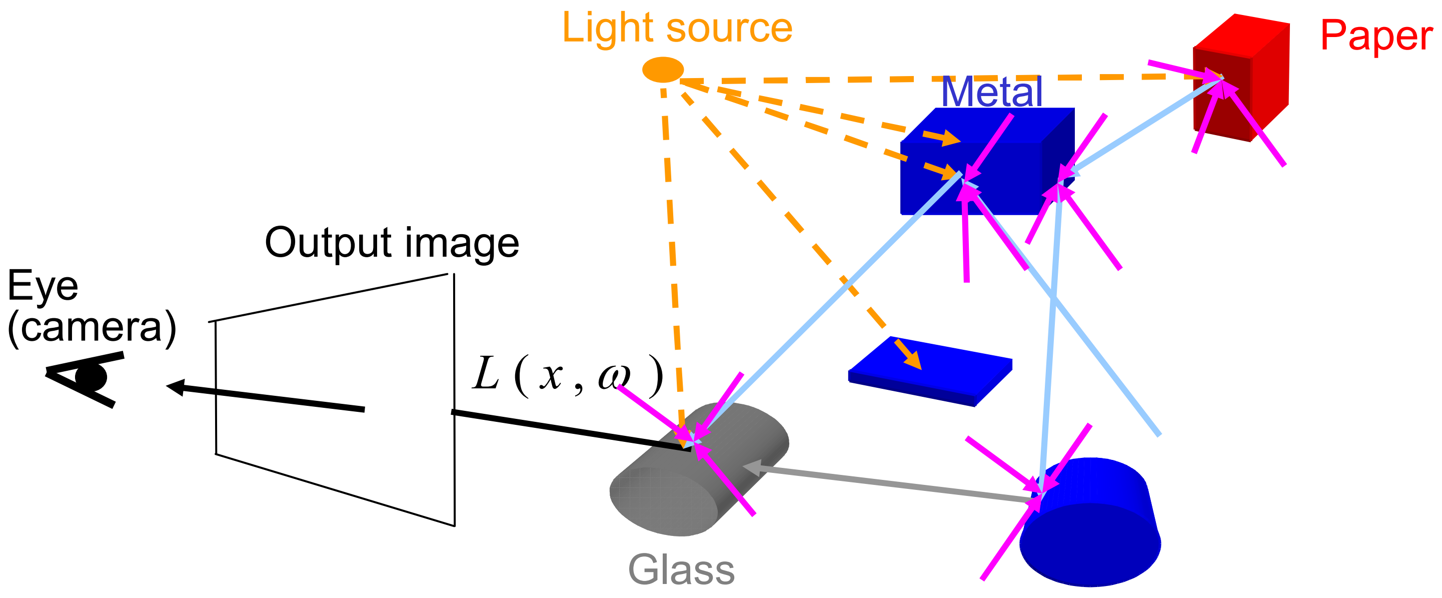
$$= m_{diff} \int L_e(RT(x,-\omega_{light}), \omega_{light})$$

$$+ m_{spec} L(RT(x,-\omega_{spec}), \omega_{spec})$$

$$+ m_{transm} L(RT(x,-\omega_{transm}), \omega_{transm})$$

$$+ m_{diff}(x) \int L(RT(x,-\omega), \omega) \cos\theta \, d\omega$$

These terms are further simplified in ray tracing



Global illumination [Kajiya 1986]

$$L(x,\omega) = \Re\left(L^i_{\text{direct}}(x,\omega'), L^i_{\text{reflected}}(x,\omega'), L^i_{\text{refracted}}(x,\omega'), L^i_{\text{ambient}}(\text{x})\right)$$

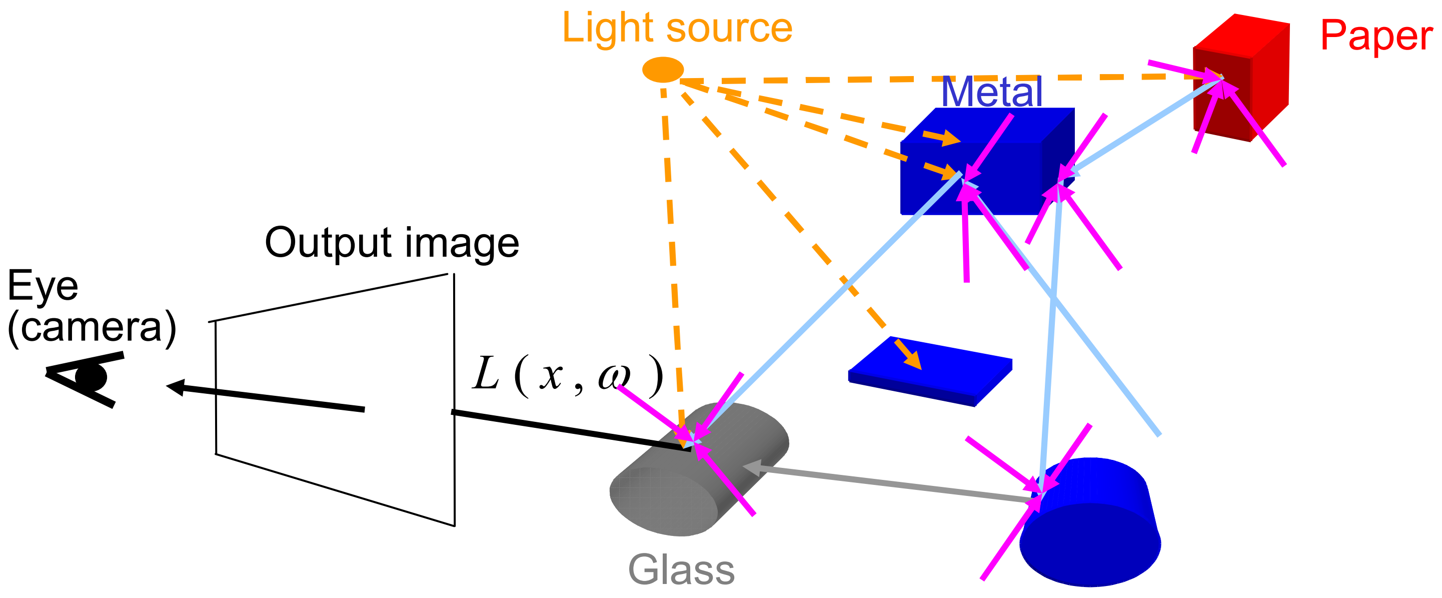
$$= m_{diff} \sum L_e(RT(x,-\omega_{light}),\omega_{light})$$

$$+ m_{spec} L(RT(x,-\omega_{spec}),\omega_{spec})$$

$$+ m_{transm} L(RT(x,-\omega_{transm}),\omega_{transm})$$

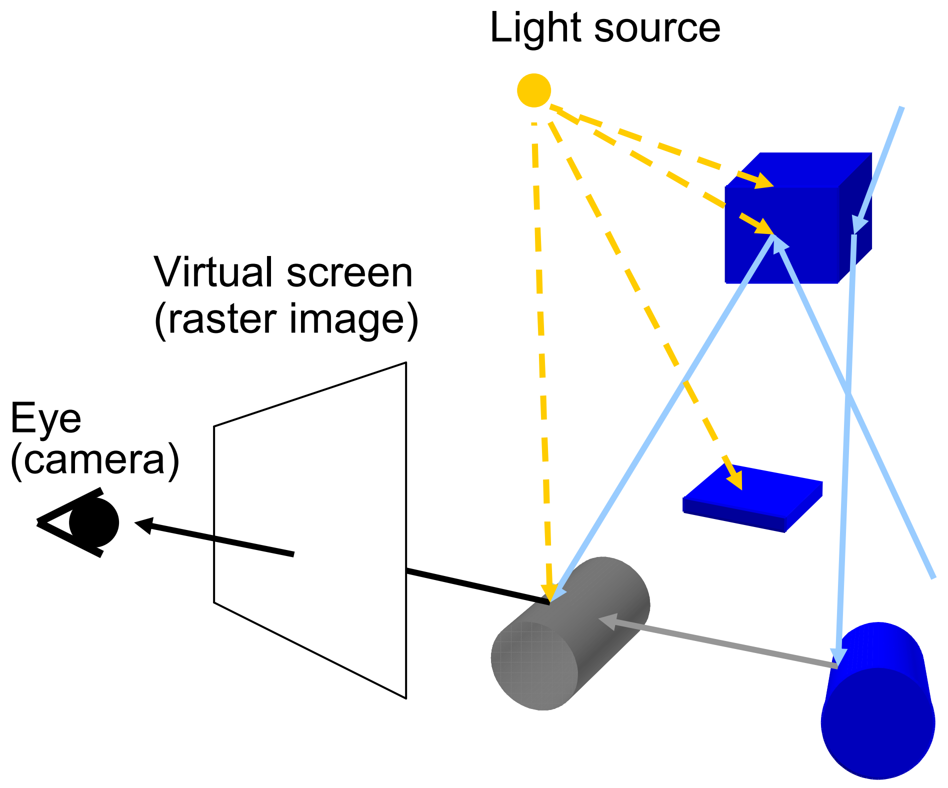
$$+ const_{ambient}$$

These terms are further simplified in ray tracing



How ray tracing works [Whitted, 1979]

We start with a 3D scene and a camera. What does the camera see?
The blue objects below are specularly reflective but not transparent (opaque mirror-like).
The grey object below is both transparent and specularly reflective (glass-like).



We send a ray from the eye through each pixel on the virtual screen to compute the colour of the pixel. Where does the light travelling along this ray to the eye come from?

OK, now we know where from. Let´s see whether this point is directly illuminated.This one is.

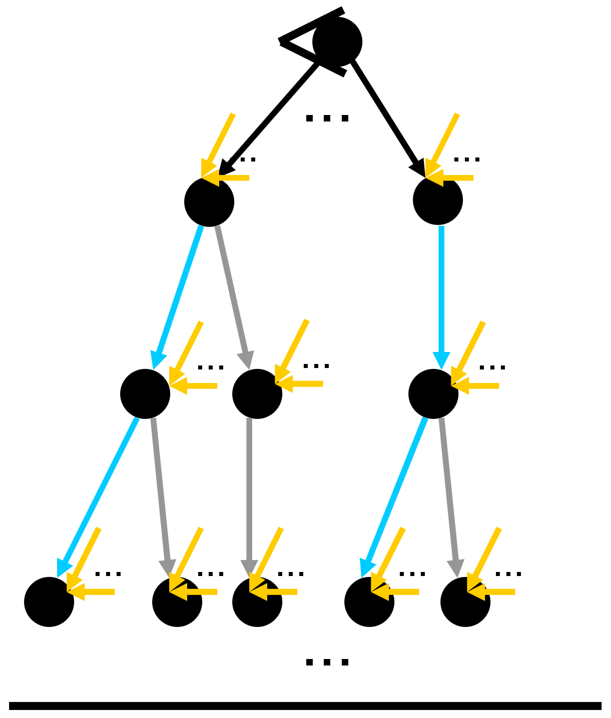
But some light could also have been reflected or refracted by this object. Where does *this* light come from?

Are those new points directly illuminated? Not both are, only one is. The other light ray is blocked by another object.

What about multiple reflection or refraction? We trace (recursively) the reflected and refracted rays until they do not hit any object in our scene.

Finally we add energy contributions of all rays to get the colour of the screen pixel.

Complexity of ray tracing



eye

eye rays

ray-object intersections

reflected and refracted rays

ray-object intersections

reflected and refracted rays

ray-object intersections

...

recursion limit

Complexity of ray tracing: number of rays, number of intersections tests.

Estimation: #Rays = #Eye_Rays * N^{D-1} / (N - 1) * (1 + #Lights)

D is the recursion depth

N is the average number of rays spawned by a ray-object intersection

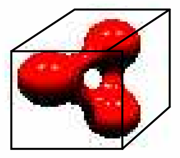
*Example: #Rays = 640 x 480 x 1.2^5 / (1.2 - 1) * (1 + 20) ≅* ***80,260,000***

Sequential speedup techniques

The most of the of ray tracing time (90%) is spent in computing ray-object intersections.

(Sequential) speedup techniques

- Faster ray-object intersections
    - intersection code optimisations
    - bounding volumes
    - bounding volume hierarchies (building BSP trees or octrees from the bounding volumes in the pre-processing phase)
- Tracing fewer rays
    - adaptive recursion depth control
    - vista buffer (saving eye rays by projecting bounding volumes onto the virtual screen in the pre-processing phase)
    - light buffers (saving illumination rays by projecting objects onto a cube around a light source in the pre-processing phase)
- Exploitation of ray coherence
- Tracing more rays at once (tracing cones or cylinders, etc.)



If a simple bounding volume (e.g. a cube) is not intersected, it is not necessary to intersect a more complex shape

Parallel ray tracing, previous work

Screen subdivision techniques

Idea: eye rays are independent, therefore can be computed in parallel without a need of communication between processors

+ easy to implement, sequential speedup techniques can be directly applied

- load balancing, replication of the scene, antialiasing

Object space subdivision techniques

Idea: geometrical distribution of objects onto processors, rays or objects are exchanged between processors

+ no scene replication

- difficult to implement, problems with using the sequential speedup techniques, load balancing

Functional decomposition techniques

Idea: decomposition of the ray tracing algorithm into subtasks like “ray-object intersection”, “shading” etc. which can be implemented in the client-server way

+ modularity, combination with the previous techniques

- difficult to implement, problems with using the sequential speedup techniques, load balancing

Parallel ray tracing, previous work

Functional decomposition techniques

[Scherson, Caspary, 1988]

• Hierarchical bounding volumes

• Storing the upper part of the tree in *every* processor; distributing lower parts.

• 2 kinds of tasks on every processor: 1.intersection of a ray with the upper part of the tree; 2.intersection of a ray with the lower part of the tree.

• Idea: the first task will not be running on a processor if workload on the processor is heavy.

• When a ray is to be processed, *any* processor can take care about the ray. It performs the task 1, then sends a task 2 to the appropriate processor.

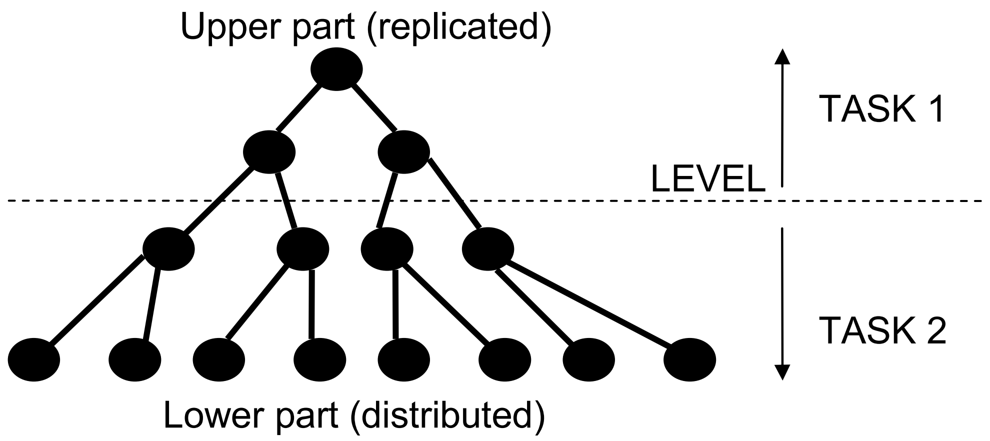
• Problem: choosing the level dividing the tree into the upper and lower parts.

[Lefer, 1994]

• A similar approach with more task types

• Implementation on Meiko transputer machine with 8 processors

• Speedup 5.5 - 7 with 8 processors



Parallel ray tracing, previous work

Object space subdivision techniques

[Dippé, Svensen, 1984]

• An algorithm and a parallel computer architecture (3D grid) which fit well together.

• Idea of the algorithm: subdividing the 3D space geometrically into 3D sub-regions (parallelpipeids, general "cubes", tetrahedra); mapping 1 sub-region onto 1 processor; exchanging rays between processors.

• Motivation: a mathematical model showing an expected speedup of $O(S^{2/3})$ over the "classical" algorithm (S being the number of sub-regions; the complexity measure was number of ray-object intersections). A sequential testing of all objects against the ray is understood under the "classical" algorithm. *No object hierarchy is considered.*

• Suggestion for tackling the problem of work imbalance: moving sub-region boundaries.

• Many non-trivial problems, no implementation.

[Cleary, Wywill, Birtwistle, Vatti, 1986]

• The idea of parallelization similar to [Dippé, Svensen, 1984].

• Extended theoretical analysis: $T = T_R + T_P$, where is T_R the time taken to compute the longest ray and T_P is the time taken by the busiest processor; exact analysis for an empty scene.

• No implementation, no object hierarchy is considered.

Parallel ray tracing, previous work

Object space subdivision techniques (continued)

[Priol, Boutatouch, 1988]

• A similar algorithm as in previous papers. Improvement: using pyramidal shapes for regions (by doing so it is guaranteed that the primary rays never leave their initial regions).

• Implementation on an iPSC Hypercube, however, no measurements reported.

[Kobayashi, Nakamura, Shigei, 1988]

• An efficient mapping of 3D sub-regions onto the hypercube. The distance on the hypercube is proportional to the size of the sub-regions.

[Jevans, 1989]

• Idea: an optimistic firing of rays into neighbouring voxel processors before actually computing intersections in the current voxel (and cancelling the rays which should not have been fired).

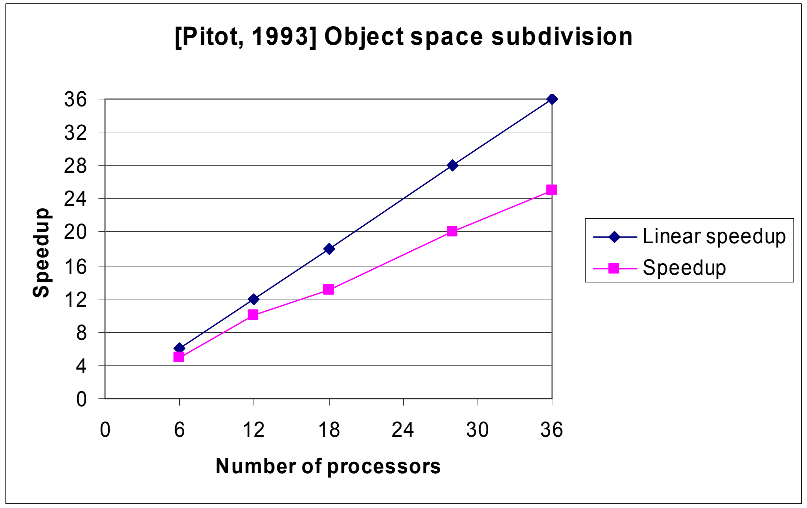
[Pitot, 1993]

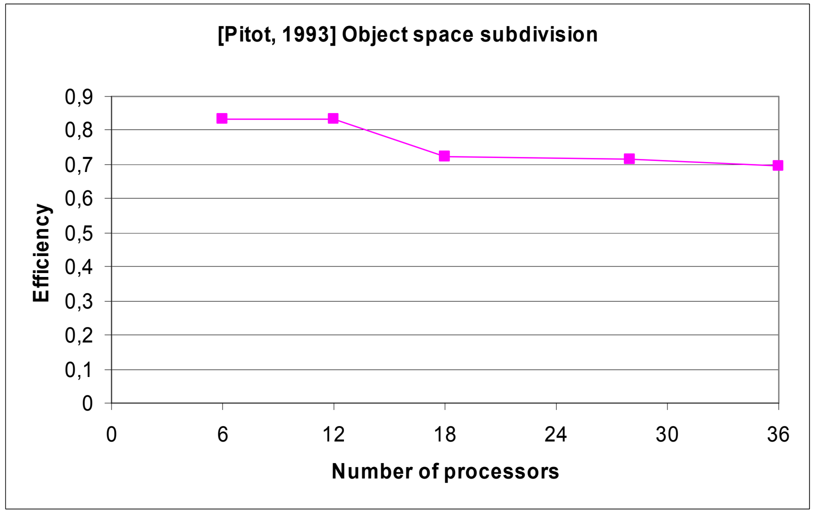
• Implementation of Cleary’s algorithm and experiments on a transputer machine.

• Static load distribution (meta-voxels mapped onto processors, subdividing meta-voxels into voxels on all processors).

Parallel ray tracing, previous work

Object space subdivision techniques (continued)



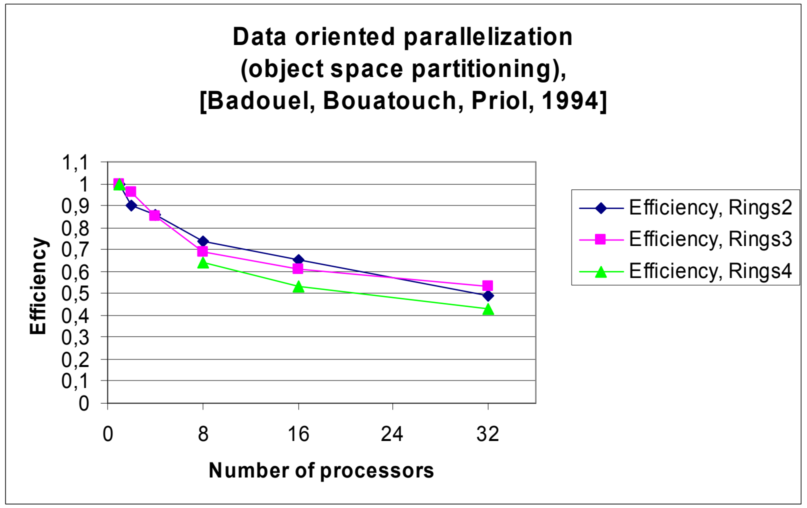


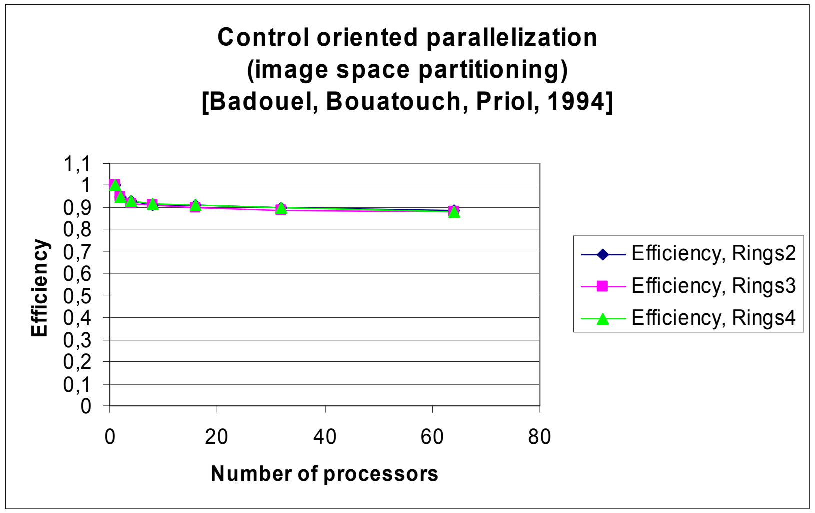
[Badouel, Boutatouch, Priol, 1994]

- Experiments with *data-oriented parallelization* (object space subdivision):
  - The algorithm depends on empirical choices (size of the sampling grid, etc.)
  - Several regions may share the same object (repeated ray-object computation occur).
  - Processors with light sources are overloaded.
- Experiments with control-oriented parallelization (image space subdivision):
  - Work stealing in a logical processor ring; object cache (inspired by Paddon and Green).

Parallel ray tracing, previous work

Object space subdivision techniques (continued)





[Keates, Hubbold, 1995]

• Experiments with Kendal Square Research Machine (KSR1)

• Distributed memory, virtual shared memory supported by hardware, pthread programming model.

• A very good characteristics: efficiency 75% on 200 processors, 70% on 230 processors.

Parallel ray tracing, previous work

Screen subdivision techniques

[Green, Paddon, 1989]

A virtual memory management system (on every worker processor)

• Resident object set (always in local memory)

• Object cache (used during the computation for storing non-resident objects in order to minimize the communication)

• Additional processors with enough memory acting as object database server(s)

The resident object sets are determined by tracing a very low resolution picture in the pre-processing phase.

Implementation: a simple ray tracer (4-vertex polygons, octree object hierarchy), up to 10 T800 Transputers, LRU cache, static load balancing.

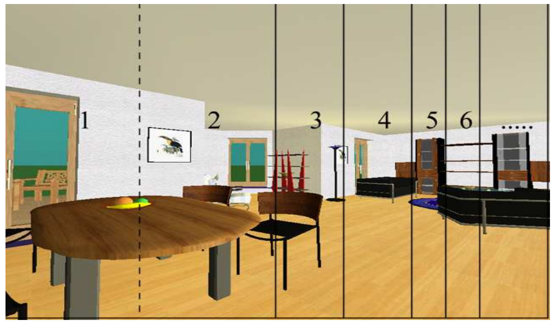
```
if (cached object needed) {
  if (the object is in permanent database or in the local cache)
    return(object)
  else {
    send request to the processor owning the object()
    wait for the object()
     return(object)
  }
}
```

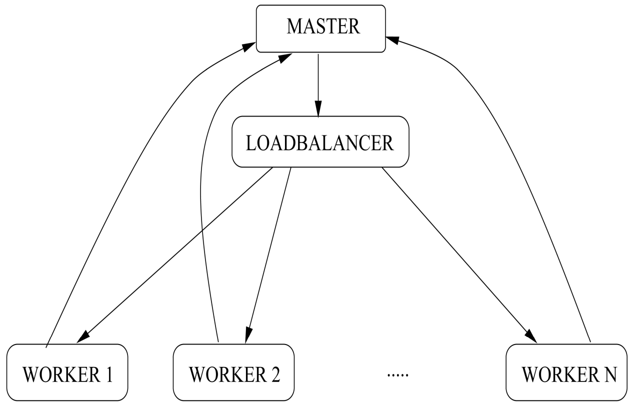
POV||Ray: Persistence Of Vision Parallel Ray Tracer

(Plachetka, 2003)

Screen subdivision

Dynamic load balancing





Data parallelism

• Caching *mesh objects* only; bounding box hierarchy is kept intact, only data (vertices, normals, etc.) are distributed.

• Checking for the local presence of the data and eventual fetching the missing data from another processor occurs only in one place in the source code (intersection calculations).

• Pre-computing information needed later during the lighting calculations and associating it with the intersection point (normal, mapped bitmap colour, etc).

• A call-back mechanism is used for answering OBJECT_REQ messages. These messages can be processed directly in an application-independent thread.

• LRU caching strategy was selected as the best one (previous experiments also with other strategies, LRU_COUNTER, RANDOM, AGING).

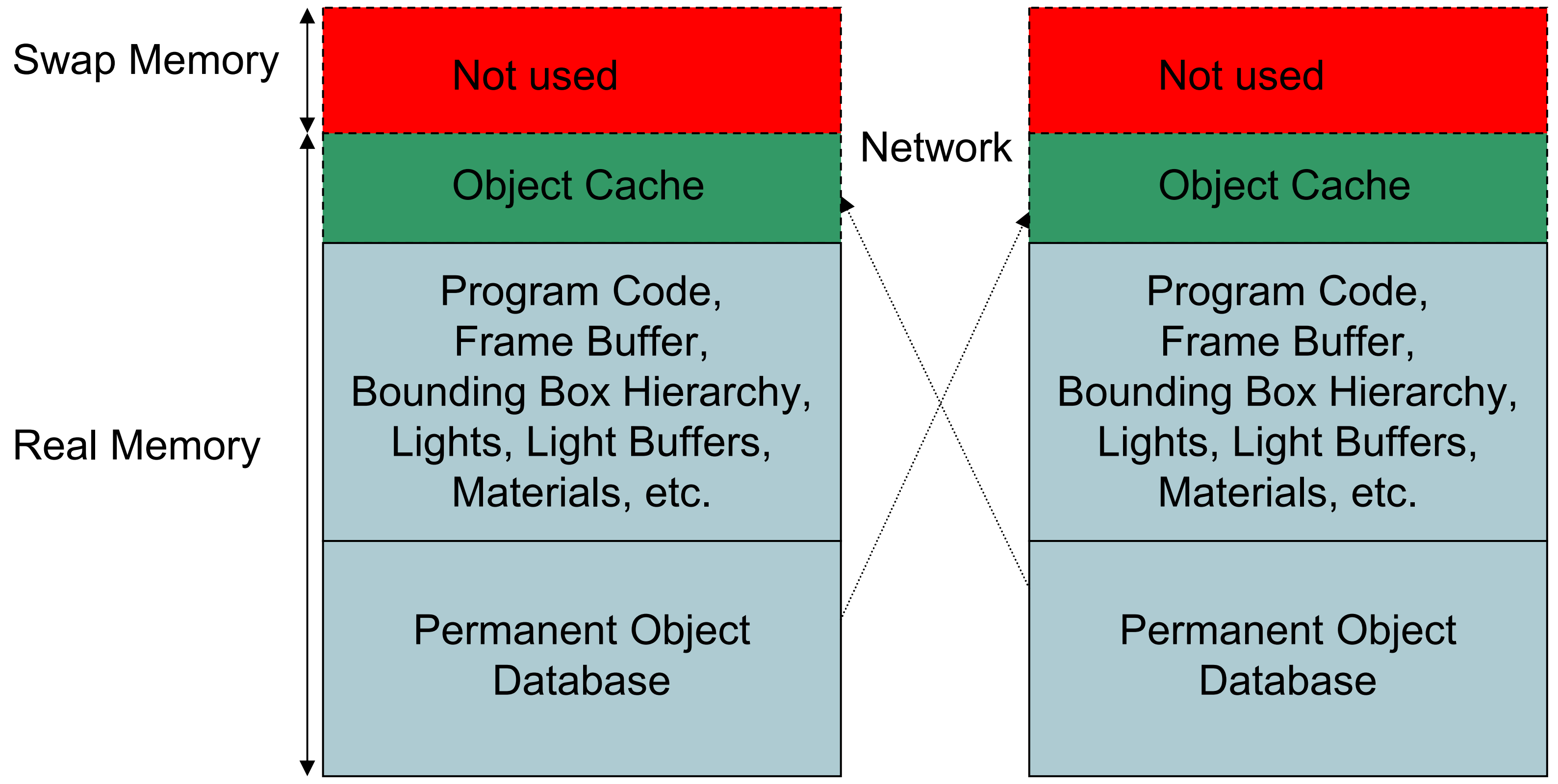
POV||Ray: Persistence Of Vision Parallel Ray Tracer

Motivations for a data-parallel implementation:

• No limit on the maximum scene size.

• By large scenes, in order to avoid swapping on processors, the *total* local memory should be limited.

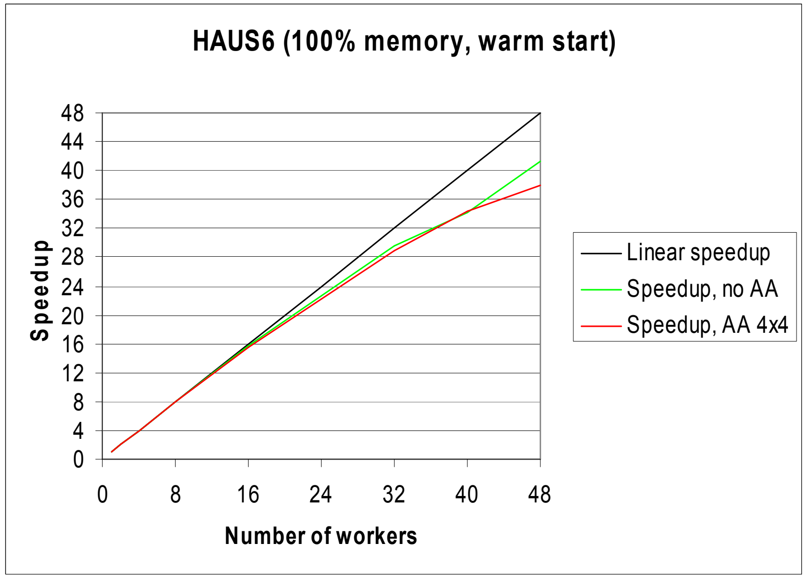
Solution: central memory management, dynamic (run-time) cache size adjustment.

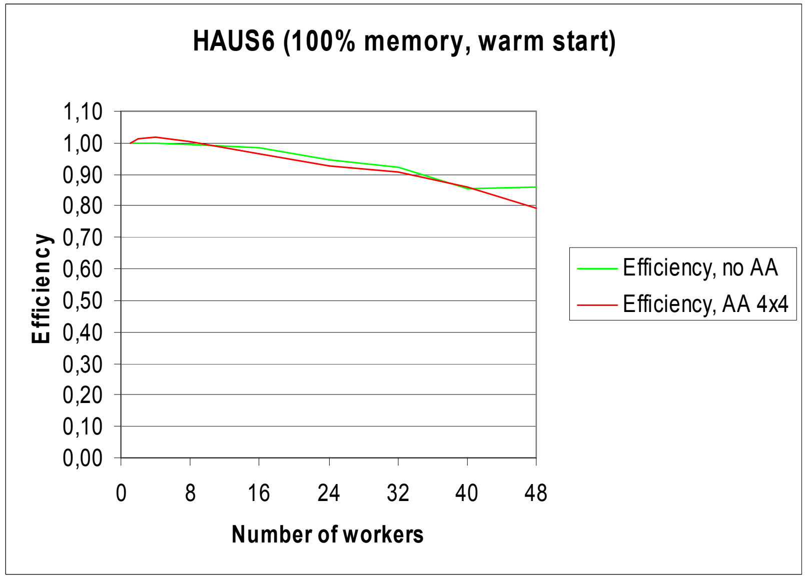

Swap Memory
Real Memory
Not used
Object Cache
Program Code, Frame Buffer, Bounding Box Hierarchy, Lights, Light Buffers, Materials, etc.
Permanent Object Database
Network
Not used
Object Cache
Program Code, Frame Buffer, Bounding Box Hierarchy, Lights, Light Buffers, Materials, etc.
Permanent Object Database

POV||Ray: Persistence Of Vision Parallel Ray Tracer

hpcLine: HAUS6 (Arcon), 614 objects (72,621 triangles), 22 point lights (640x480)

Processors	Linear speedup	Speedup, no AA	Efficiency, no AA	Speedup, AA 4x4	Efficiency, AA 4x4
1	1	1,00	1,00	1,00	1,00
2	2	2,00	1,00	2,03	1,02
4	4	4,00	1,00	4,08	1,02
8	8	7,97	1,00	8,03	1,00
16	16	15,79	0,99	15,47	0,97
24	24	22,66	0,94	22,28	0,93
32	32	29,54	0,92	28,99	0,91
40	40	34,26	0,86	34,34	0,86
48	48	41,19	0,86	38,03	0,79





POV||Ray: Persistence Of Vision Parallel Ray Tracer

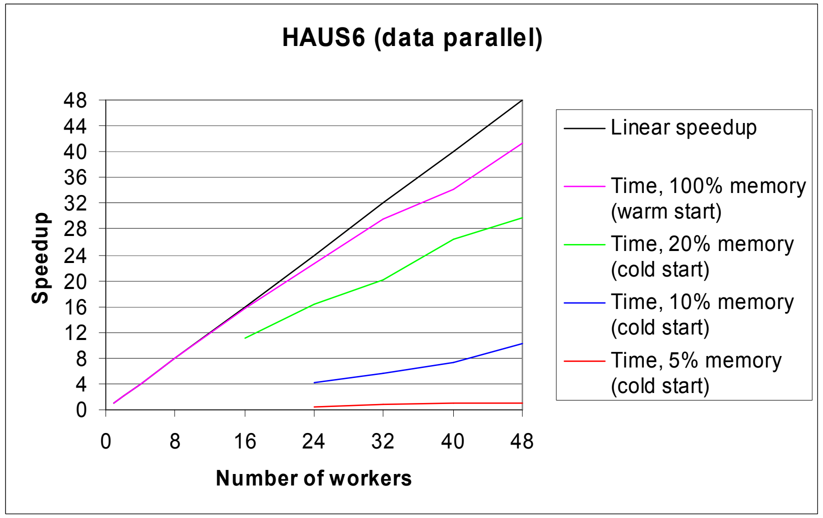
hpcLine: HAUS6 (Arcon), 614 objects (72,621 triangles), 22 point lights (640x480)

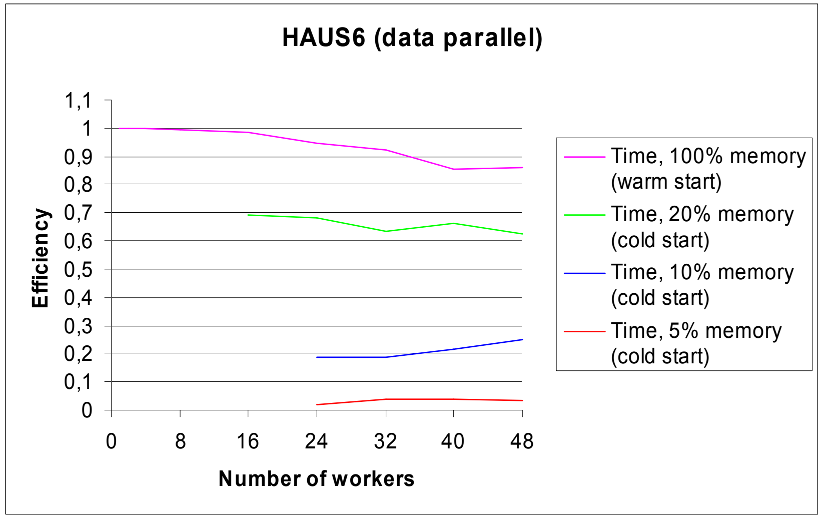
- Total object requests: ~50,000,000
- Cold start, 48 workers, 100% memory: 3392 objects exchanged (~13 MB)

	20% memory			
Processors	Obects exchanged	Bytes exchanged	Exchange time (s)	Cache hit ratio
16	2.723	11.383.104	5,5	0,9999
24	2.172	8.262.024	4,5	1,0000
32	2.457	9.686.632	5,9	1,0000
40	3.062	12.043.576	7,8	0,9999
48	3.625	14.044.532	9,3	0,9999

10% memory				
Procs	Objects exchanged	Bytes exchanged	Exchange time (s)	Cache hit ratio
16	N/A	N/A	N/A	N/A
24	713.562	inf	2.104,2	0,9860
32	501.686	2.111.045.688	1.926,0	0,9902
40	426.791	1.798.978.892	1.819,7	0,9917
48	357.778	1.517.580.352	1.466,9	0,9930

5% memory				
Procs	Objects exchanged	Bytes exchanged	Exchange time (s)	Cache hit ratio
16	N/A	N/A	N/A	N/A
24	9.764.151	inf	25.200,7	0,7671
32	7.244.288	inf	24.465,3	0,8357
40	5.539.805	inf	24.880,1	0,8799
48	5.054.140	inf	25.732,2	0,8921





POV||Ray: Persistence Of Vision Parallel Ray Tracer

- Screen parallelisation can work with a distributed object database.
  - Almost all sequential parallelisation techniques can be reused!
  - Object distribution can be treated as an independent problem
- A good screen parallelisation (process farming) algorithm and its tuning can be found in [Plachetka 2004, Tuning of Algorithms…], http://www.dcs.fmph.uniba.sk/~plachetk/PUBLICATIONS/egpgv04.pdf