

Introduction to Computer Graphics

AMES101, Lingqi Yan, UC Santa Barbara

Lecture 14: Ray Tracing 2 (Acceleration & Radiometry)



Announcements

- Grading of resubmissions — we're working on that
- GTC news: DLSS 2.0
 - <https://zhuanlan.zhihu.com/p/116211994>
- GTC news: RTXGI
 - <https://developer.nvidia.com/rtxgi>
- Personal feeling
 - Offline rendering techniques will soon become real-time
 - Current real-time rendering techniques will still be useful
- Next lectures won't be easy

Last Lecture

- Why ray tracing?
- Whitted-style ray tracing
- Ray-object intersections
 - Implicit surfaces
 - Triangles
- Axis-Aligned Bounding Boxes (AABBs)
 - Understanding — pairs of slabs
 - Ray-AABB intersection

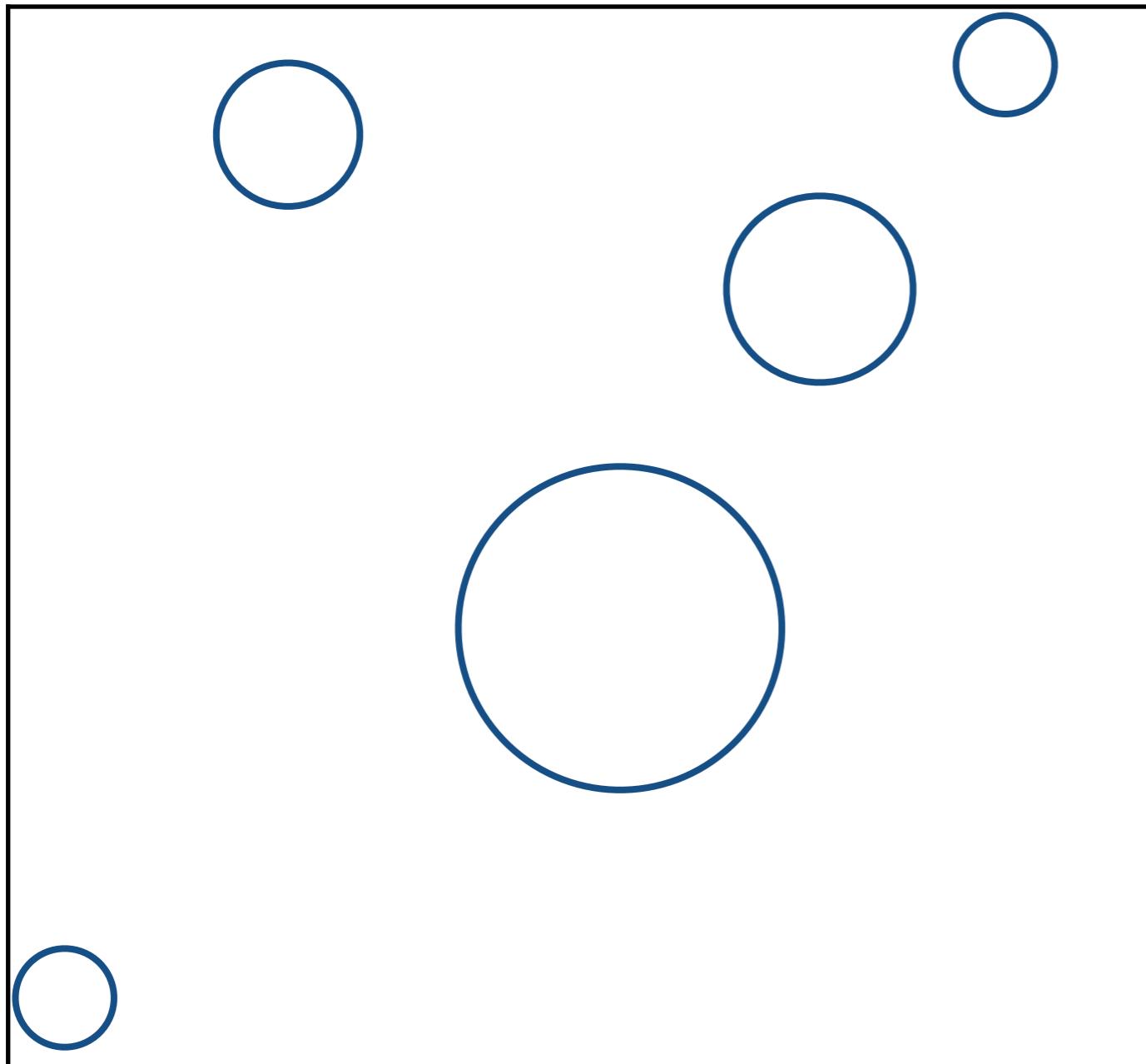
光线如果和BB不相交，就不用考虑BB里面的所有三角形了

Today

- Using AABBs to accelerate ray tracing
 - Uniform grids 均匀格子
 - Spatial partitions 空间划分
- Basic radiometry (辐射度量学)

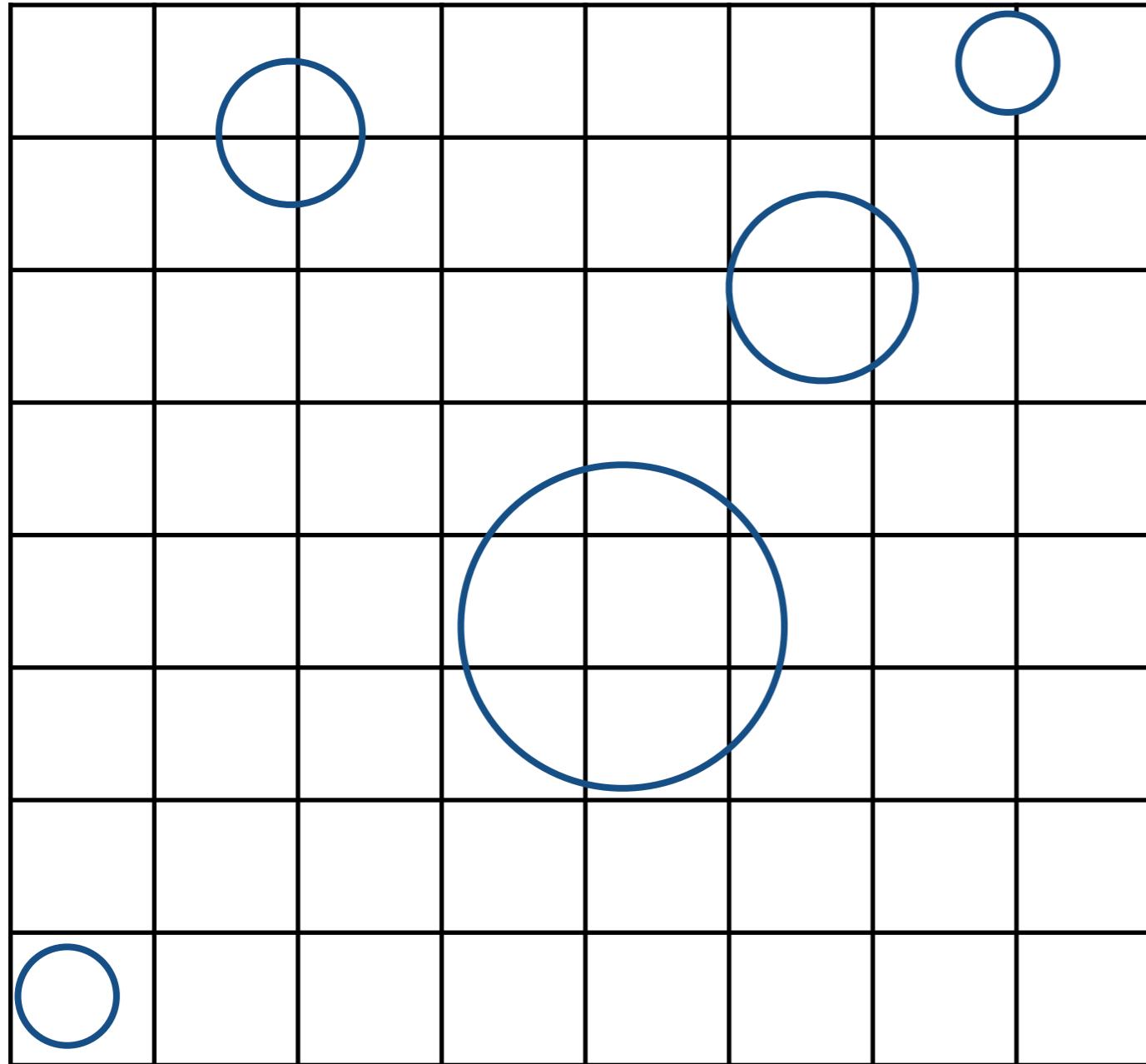
Uniform Spatial Partitions (Grids)

Preprocess – Build Acceleration Grid



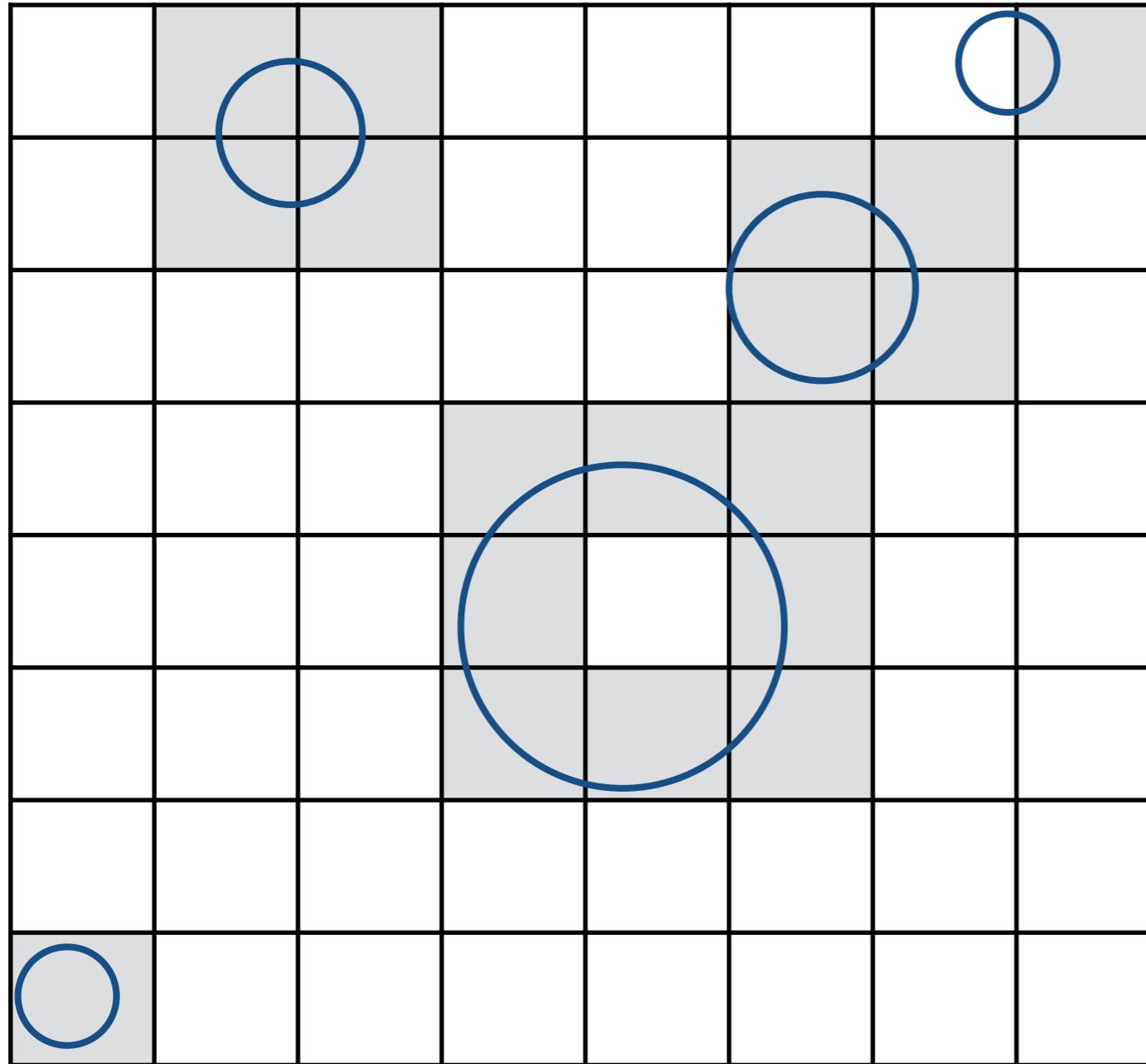
1. Find bounding box

Preprocess – Build Acceleration Grid



1. Find bounding box
2. Create grid

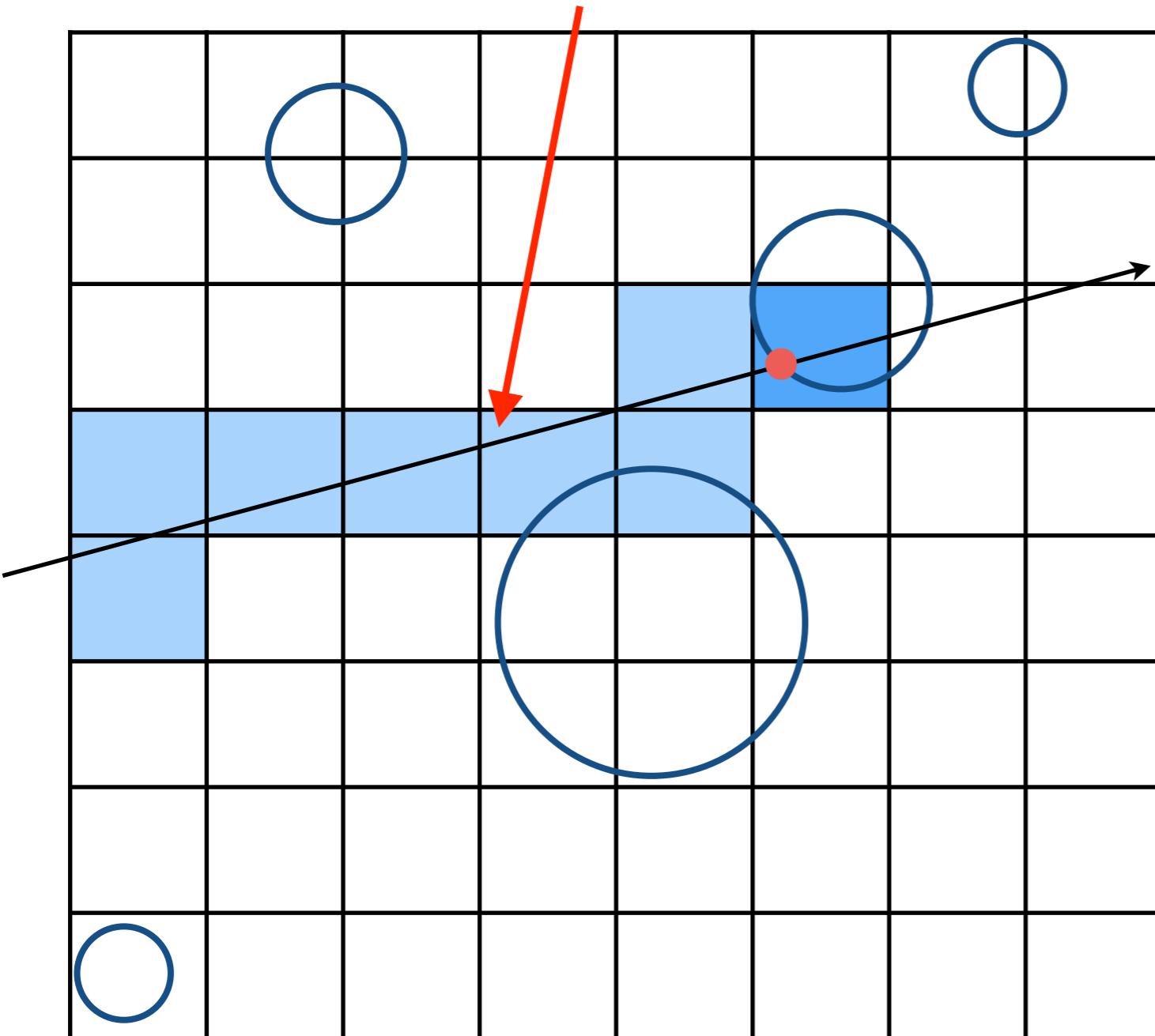
Preprocess – Build Acceleration Grid



1. Find bounding box
2. Create grid
3. **Store** each object
in overlapping cells

Ray-Scene Intersection

光线与盒子相交，所以光线有可能和盒子里的物体相交；
进一步将光线与物体求交，判断是否有交点

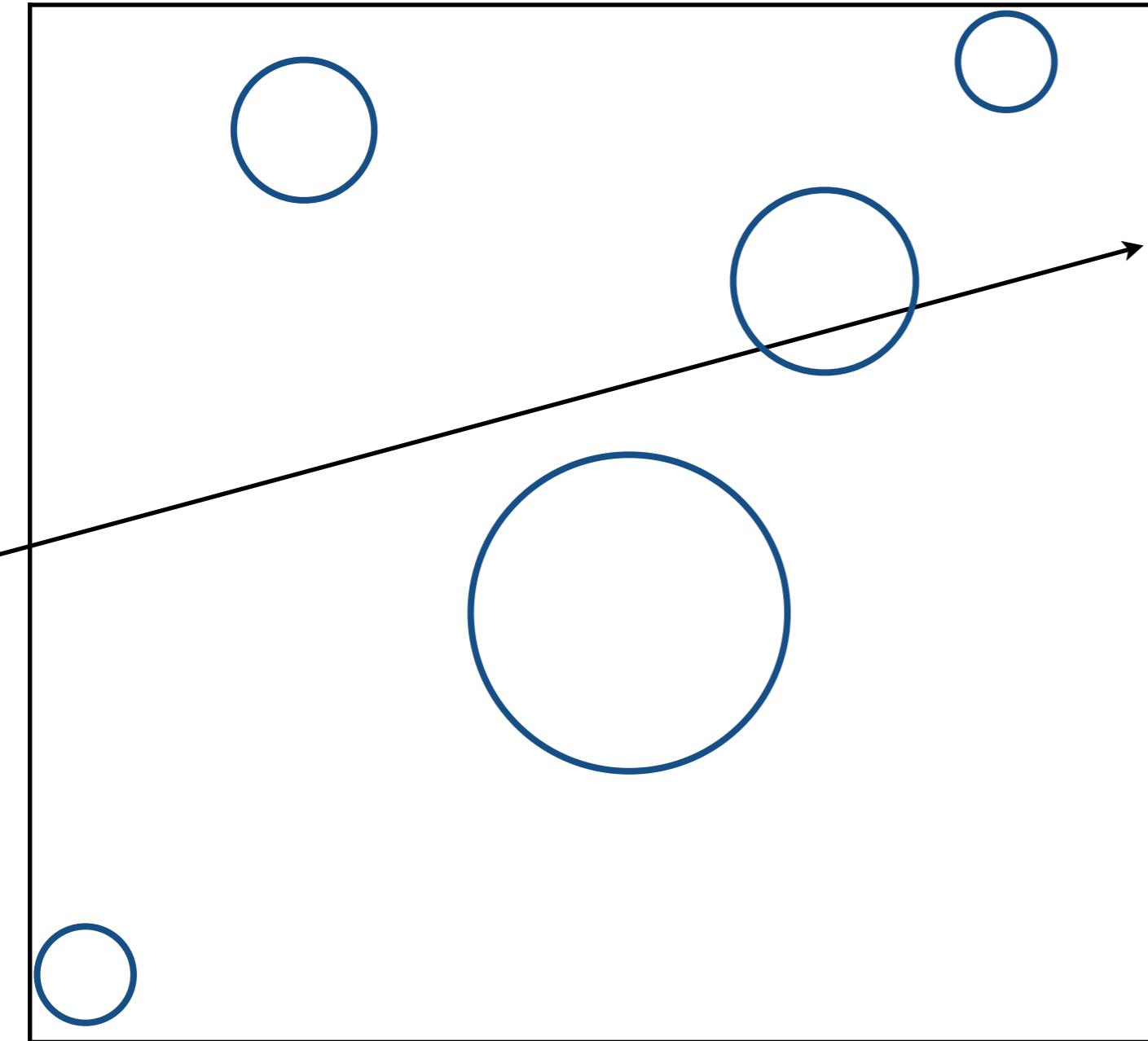


认为光线和盒子求交是简单的

Step through grid in ray traversal order

For each grid cell
Test intersection
with all objects
stored at that cell

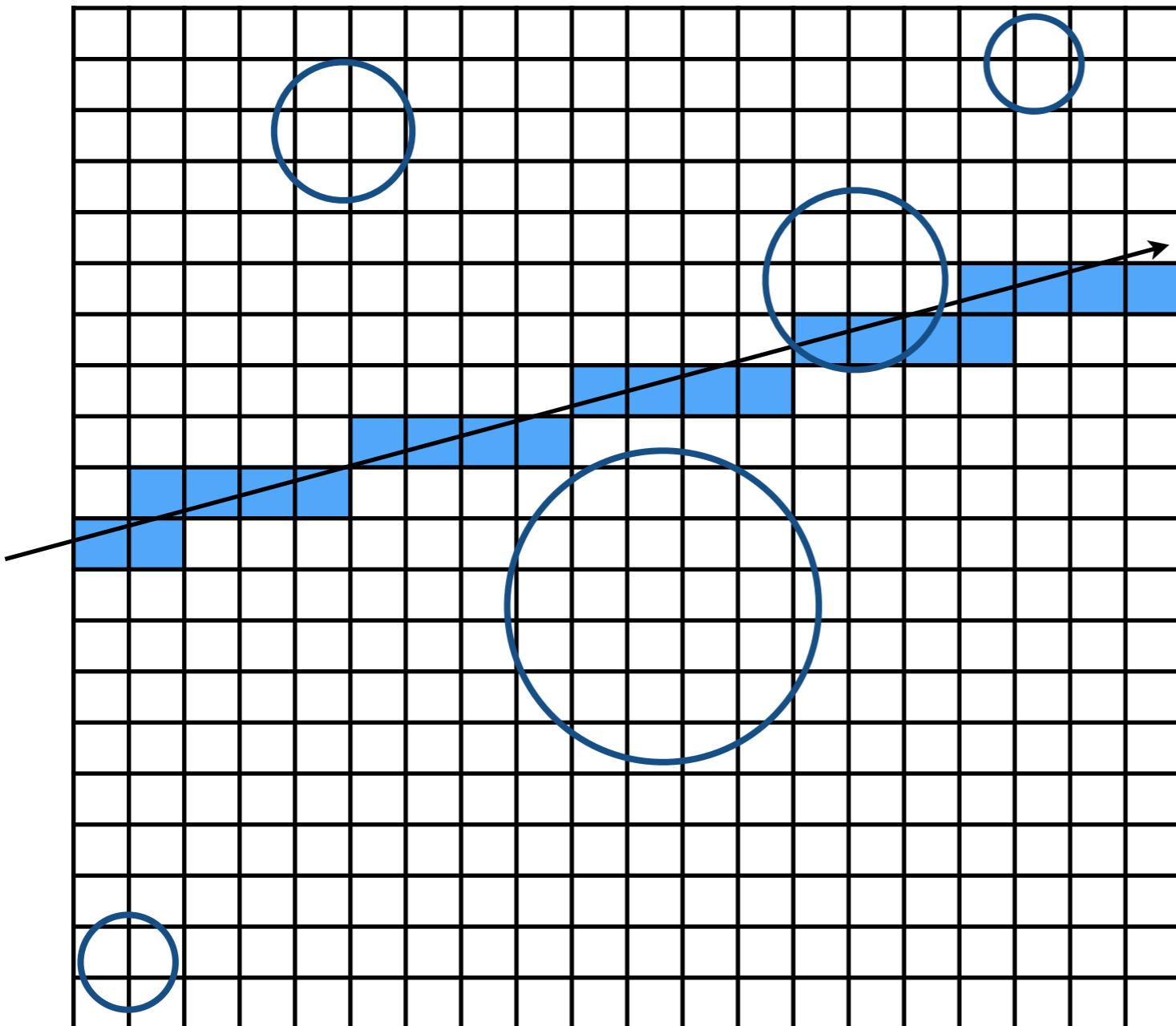
Grid Resolution?



One cell

- No speedup

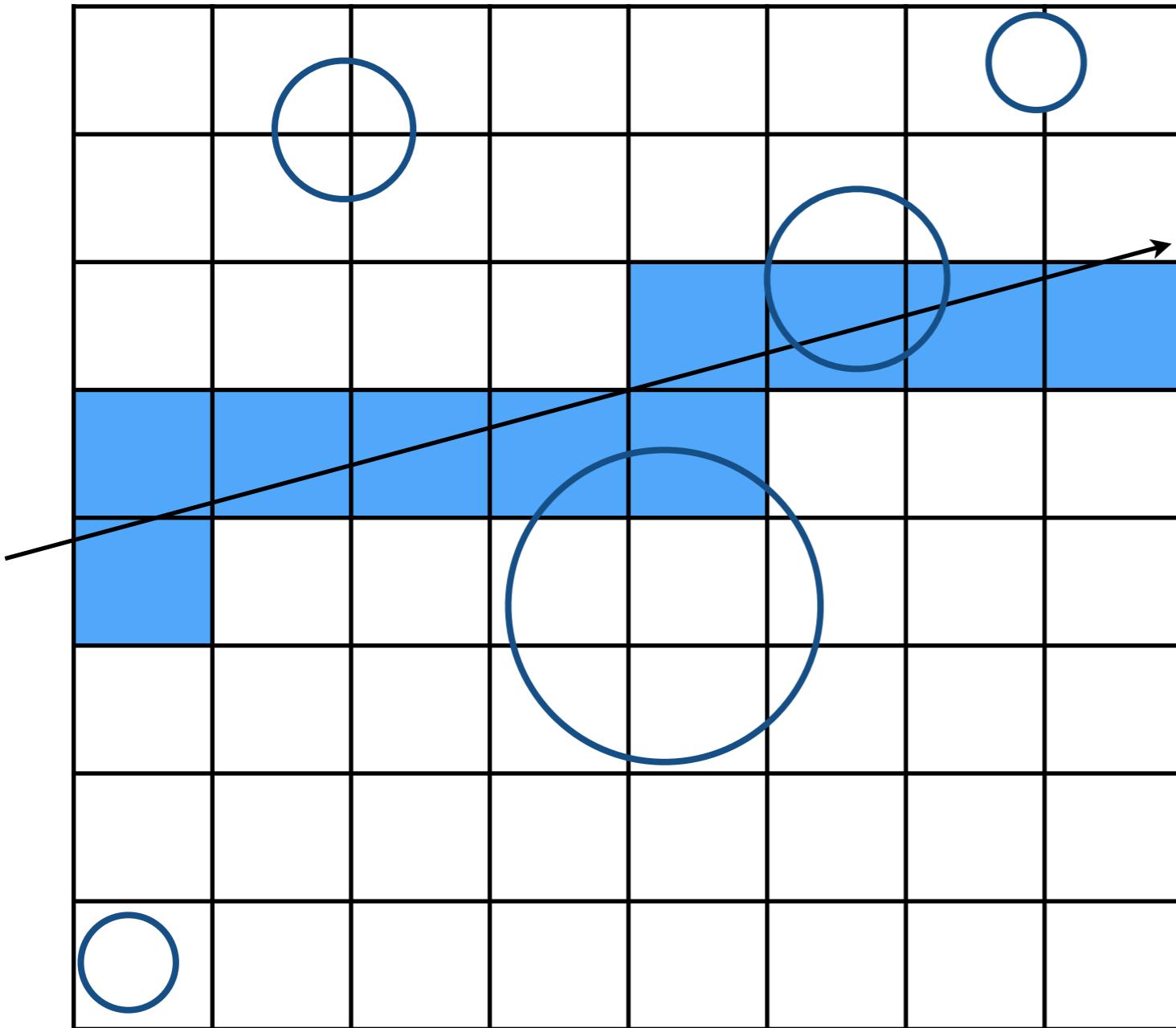
Grid Resolution?



Too many cells

- Inefficiency due to extraneous grid traversal

Grid Resolution?



Heuristic:

- $\# \text{cells} = C * \# \text{objs}$
- $C \approx 27$ in 3D

Uniform Grids – When They Work Well



Deussen et al; Pharr & Humphreys, PBRT

Grids work well on large collections of objects
that are distributed evenly in size and space

场景分布均匀

Uniform Grids – When They Fail

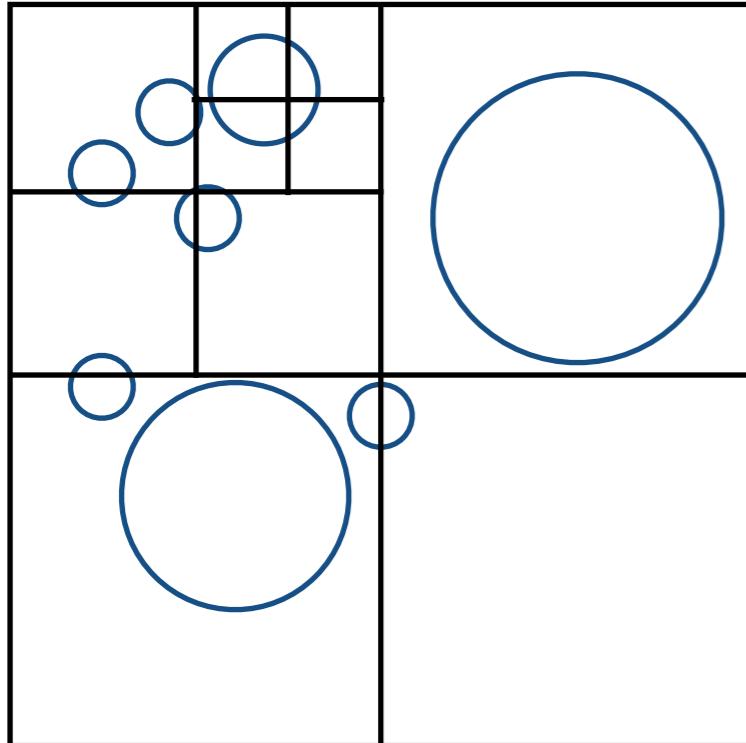


Jun Yan, Tracy Renderer

“Teapot in a stadium” problem
场景分布不均匀

Spatial Partitions

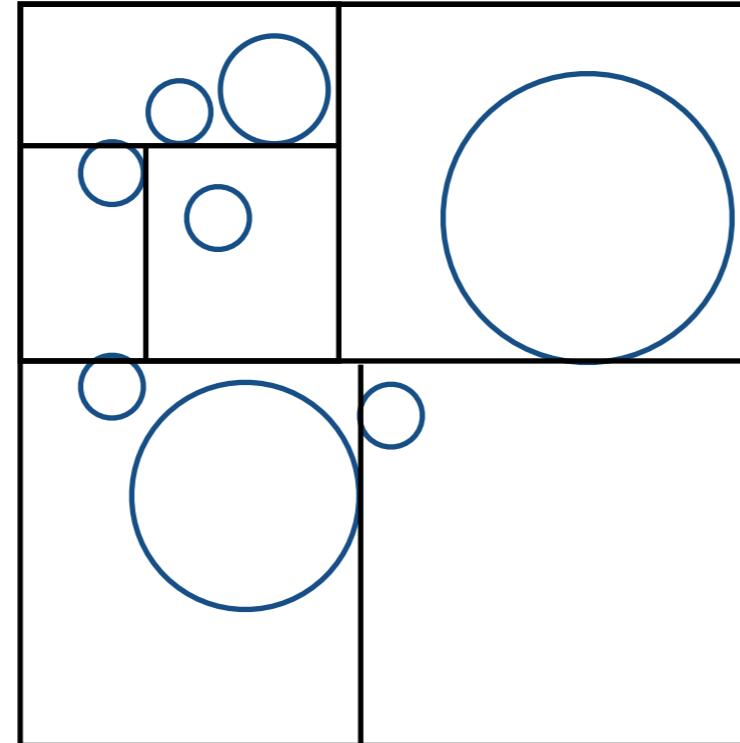
Spatial Partitioning Examples



Oct-Tree

3D, 所以是切成八份

是否继续切看物体的分布
(某个格子有空物体停止)

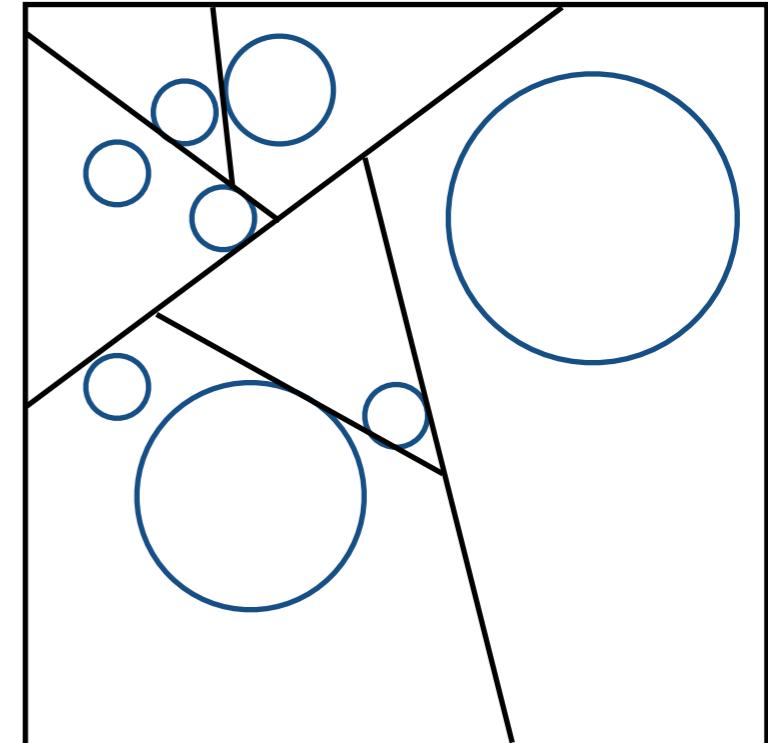


与维度无关

KD-Tree

切的时候水平和竖直交替
(保证空间划分基本均匀)

可以直接沿着垂直坐标轴方向切



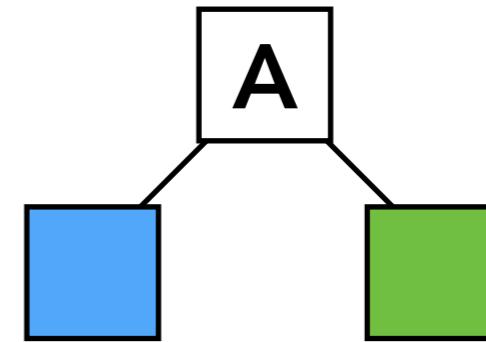
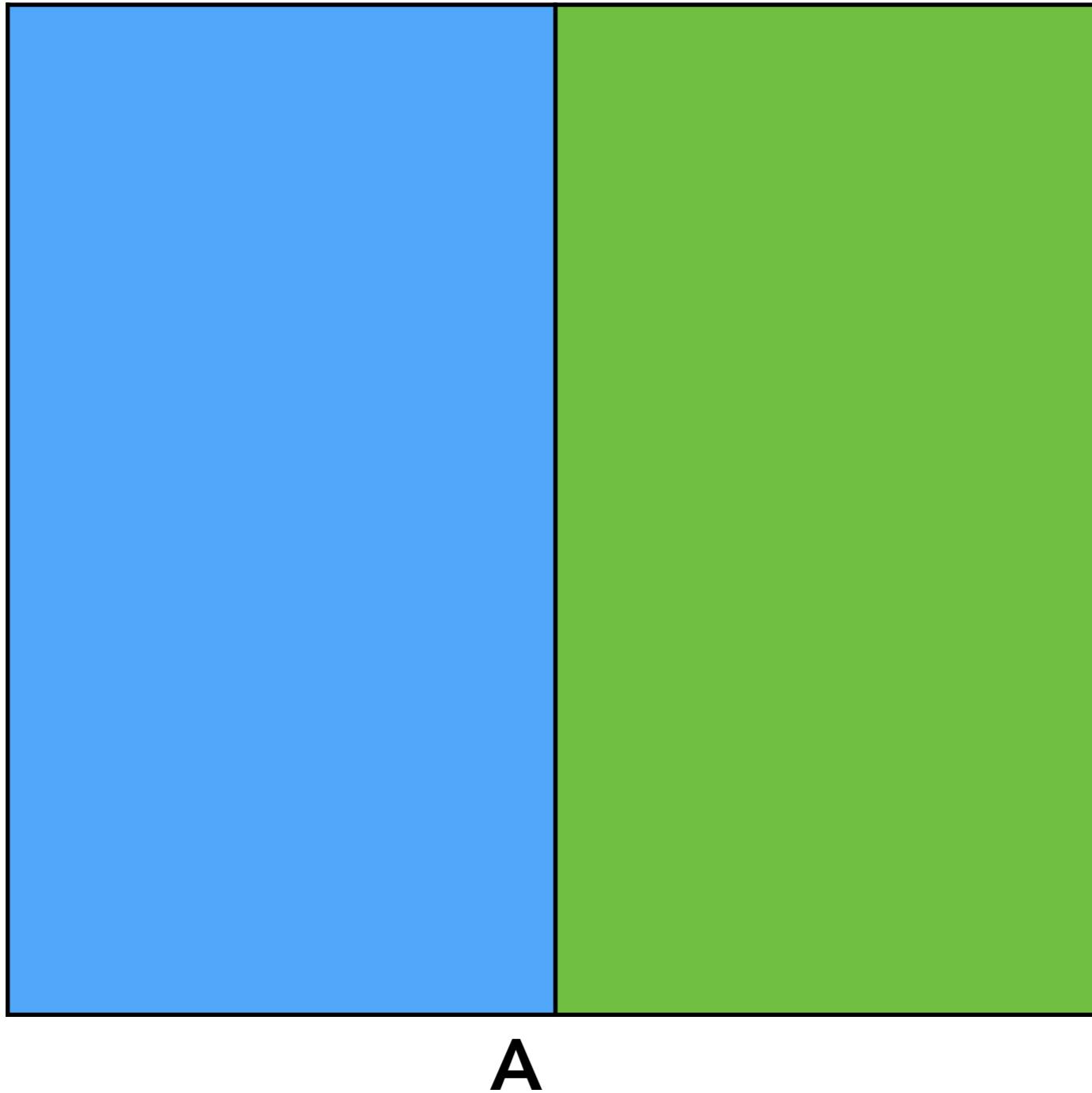
BSP-Tree

对空间二分，每次给定一个方向
(不是横平竖直的)

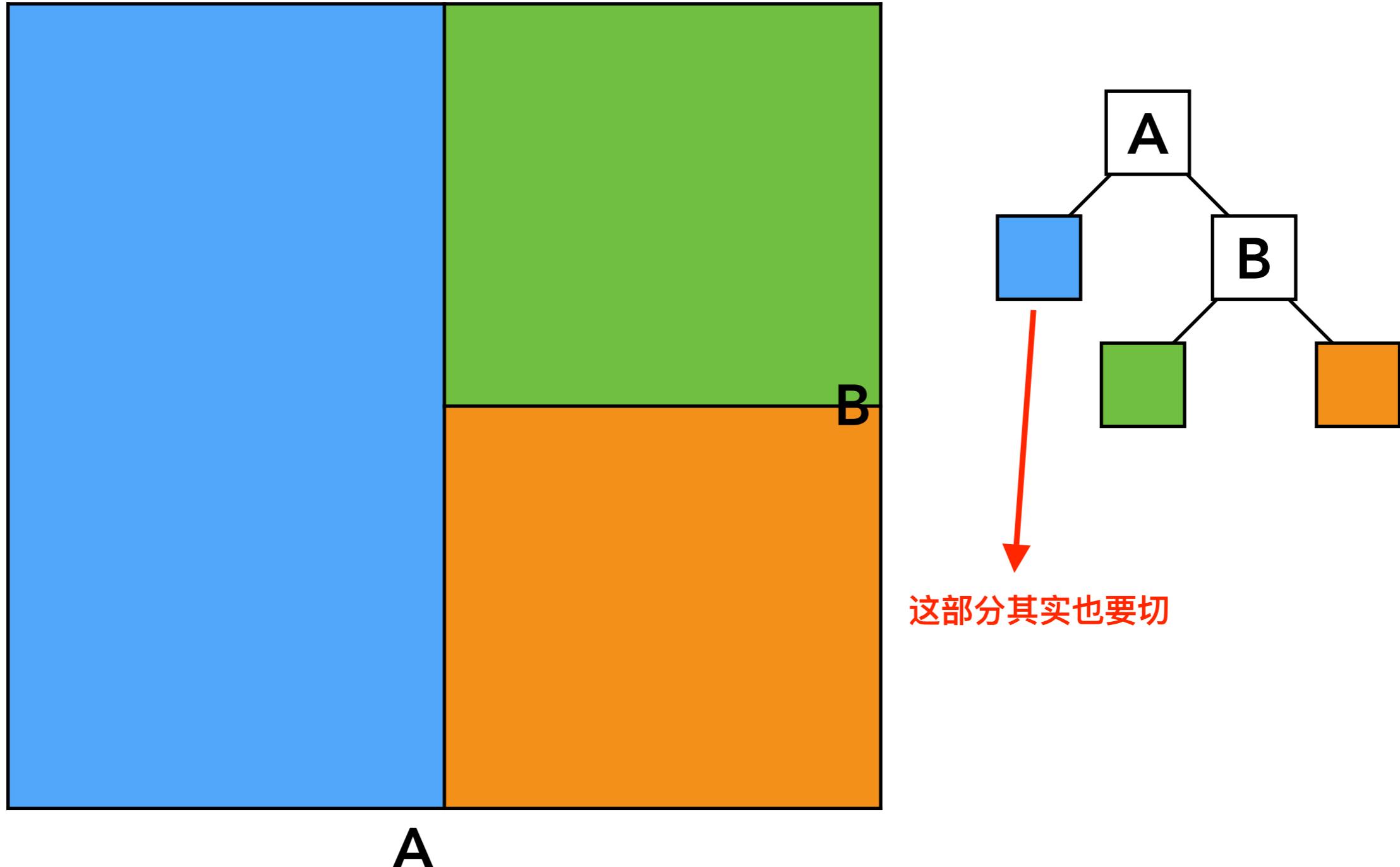
高维度不好计算

Note: you could have these in both 2D and 3D. In lecture we will illustrate principles in 2D.

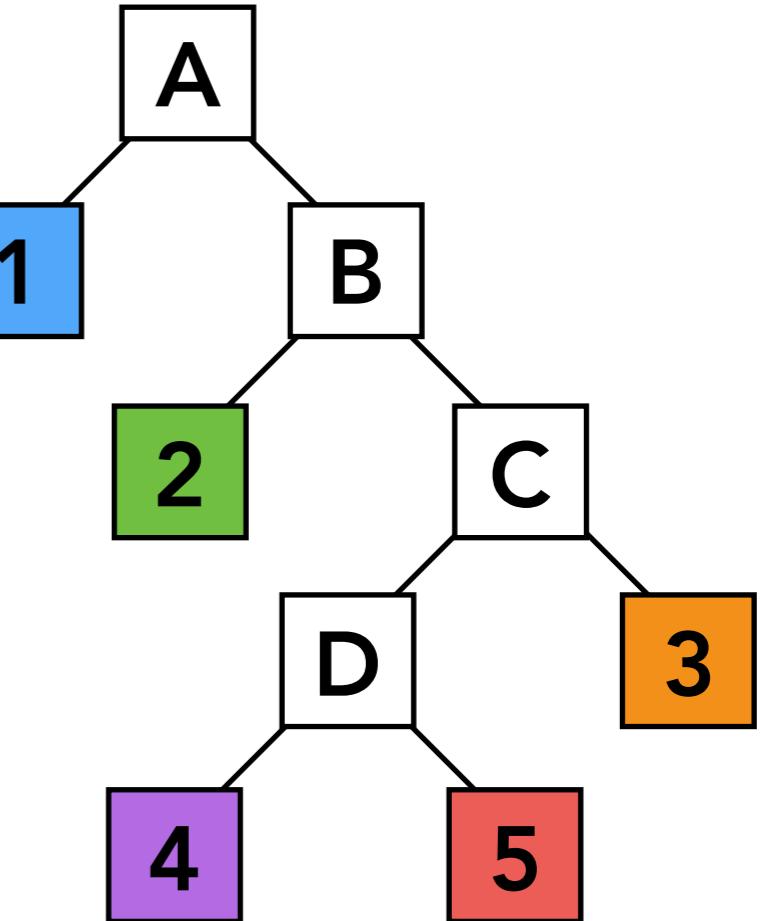
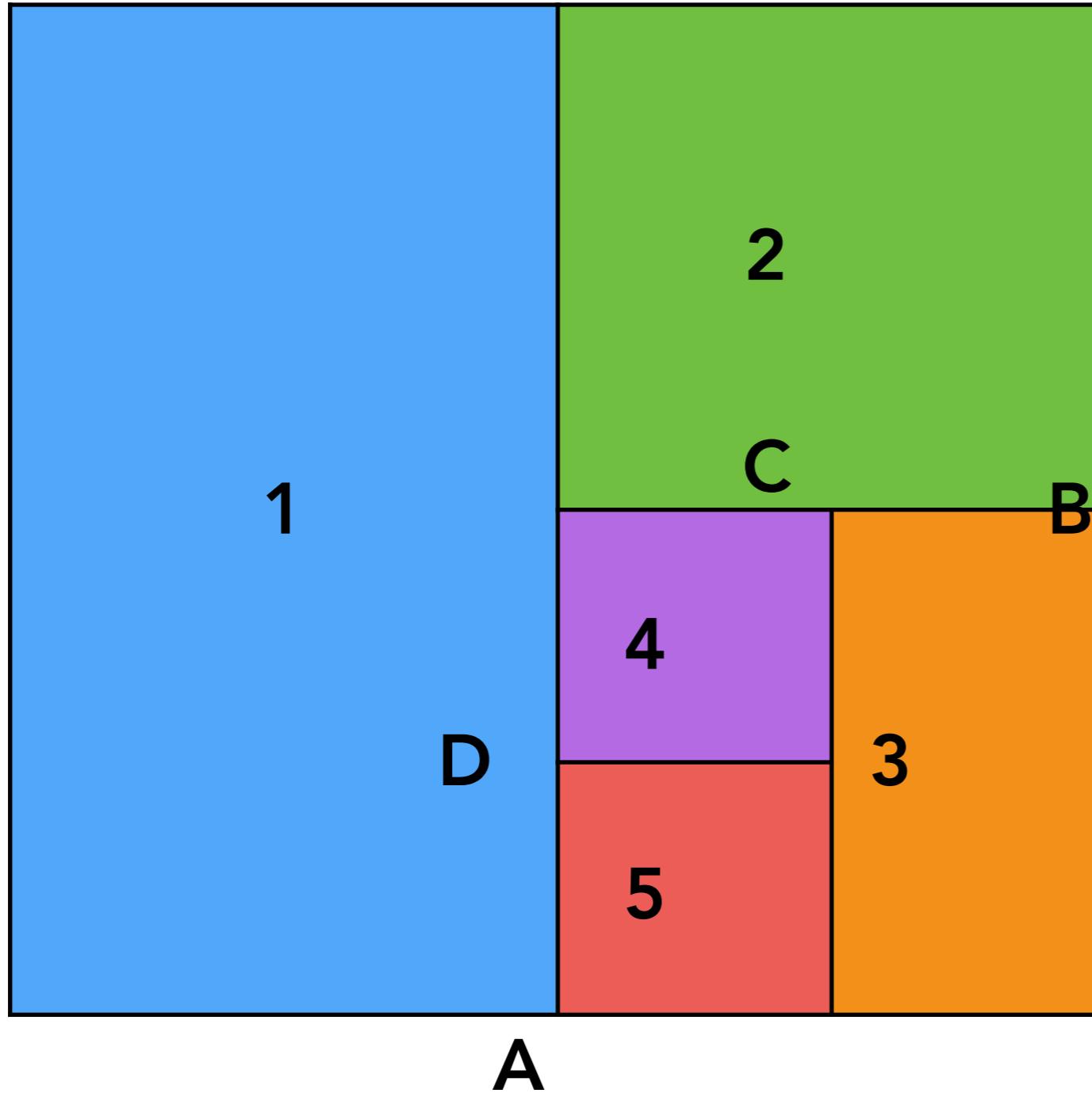
KD-Tree Pre-Processing



KD-Tree Pre-Processing



KD-Tree Pre-Processing



Note: also subdivide nodes 1 and 2, etc.

将与格子相交的几何objects存储在叶子结点上

Data Structure for KD-Trees

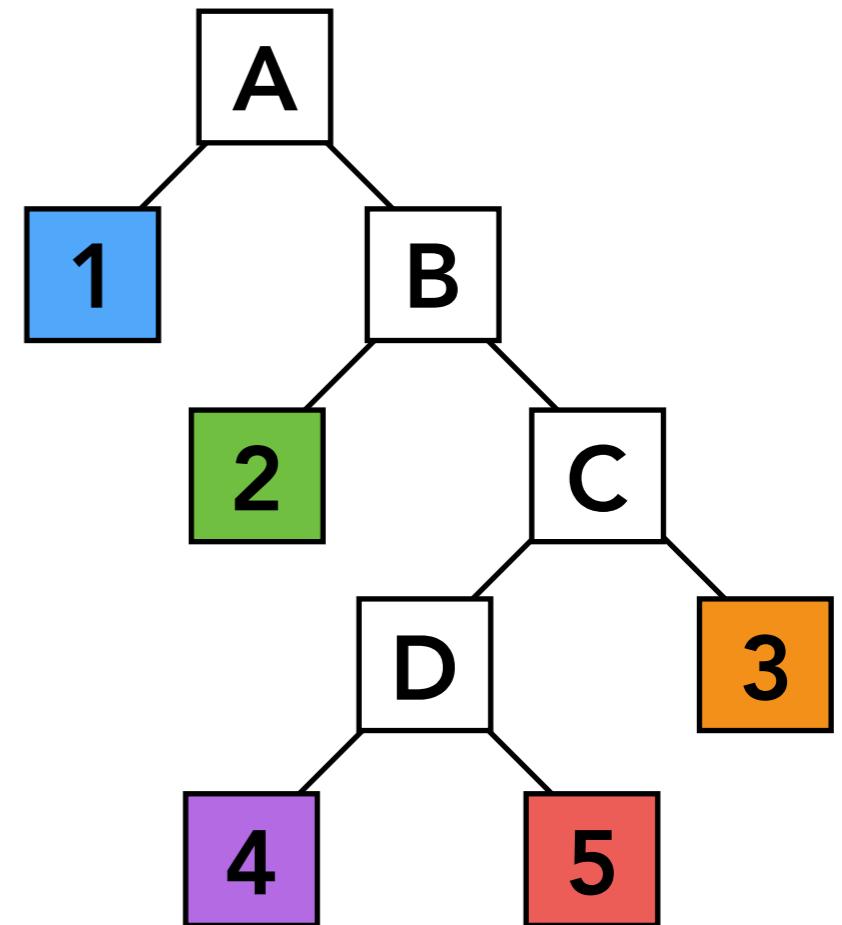
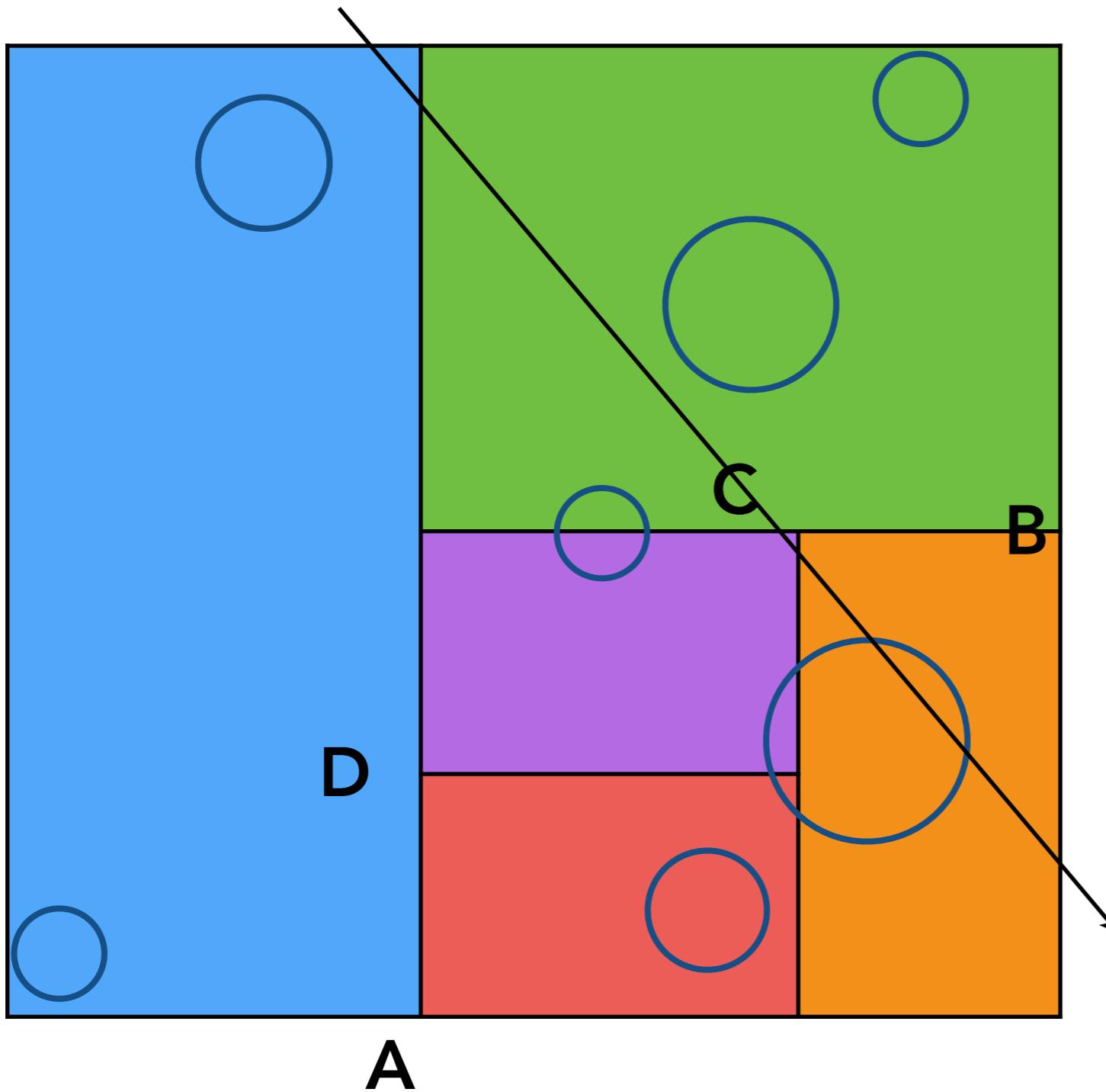
Internal nodes store

- split axis: x-, y-, or z-axis
- split position: coordinate of split plane along axis
- children: pointers to child nodes
- **No objects are stored in internal nodes**

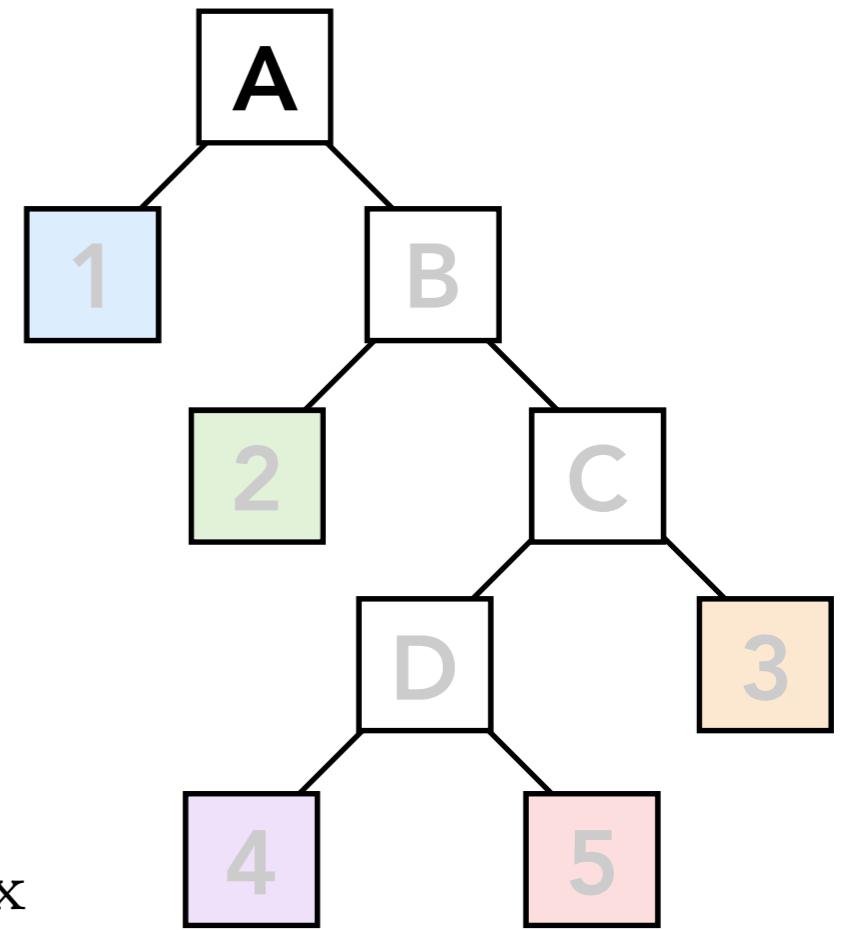
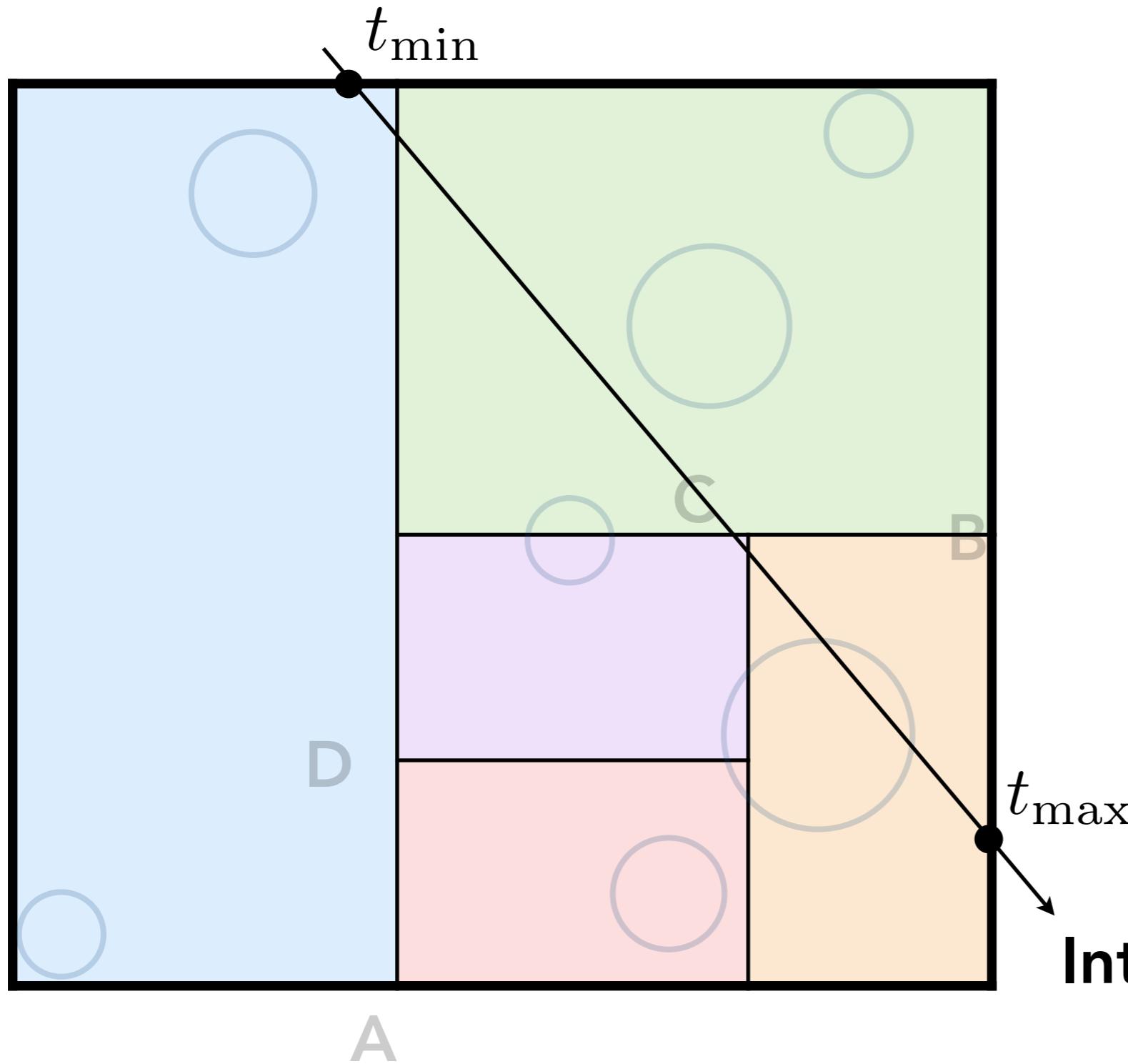
Leaf nodes store

- list of objects

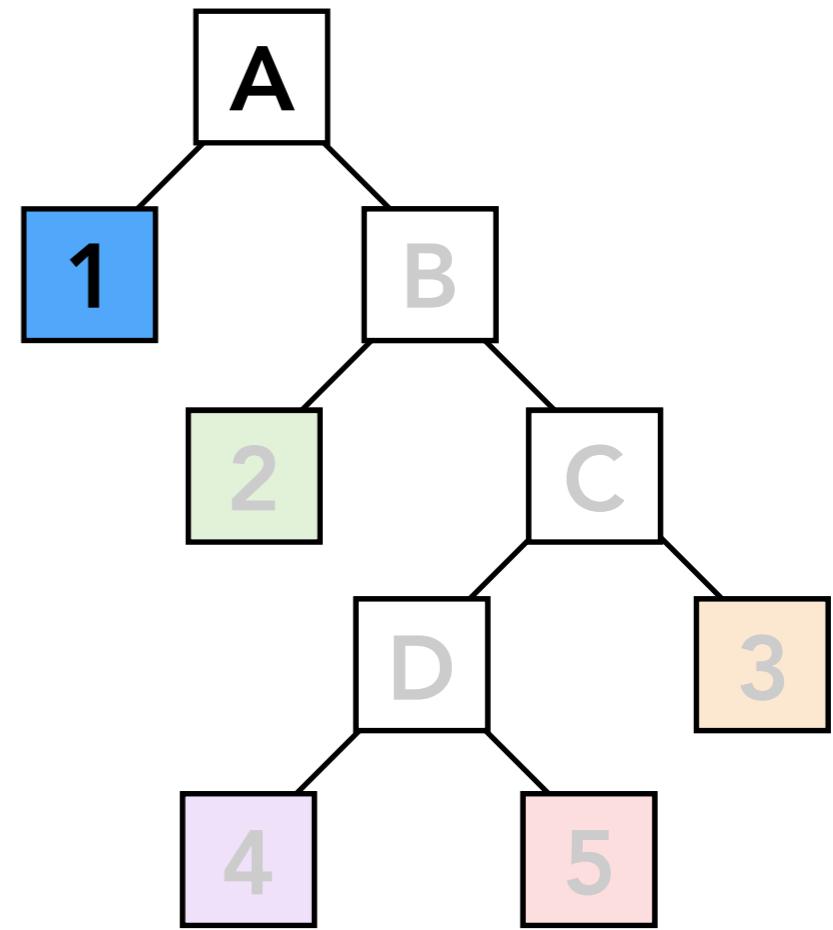
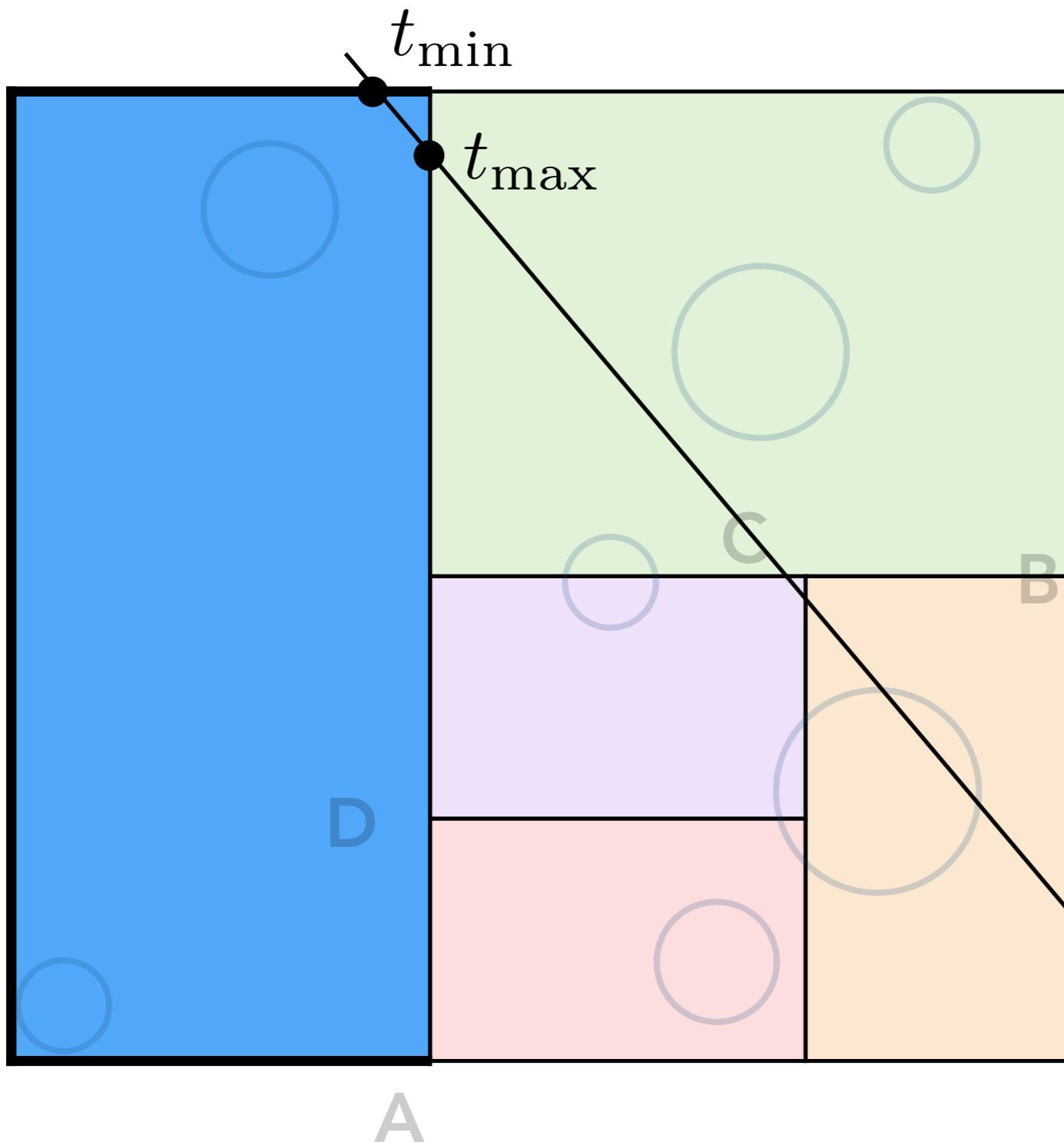
Traversing a KD-Tree



Traversing a KD-Tree

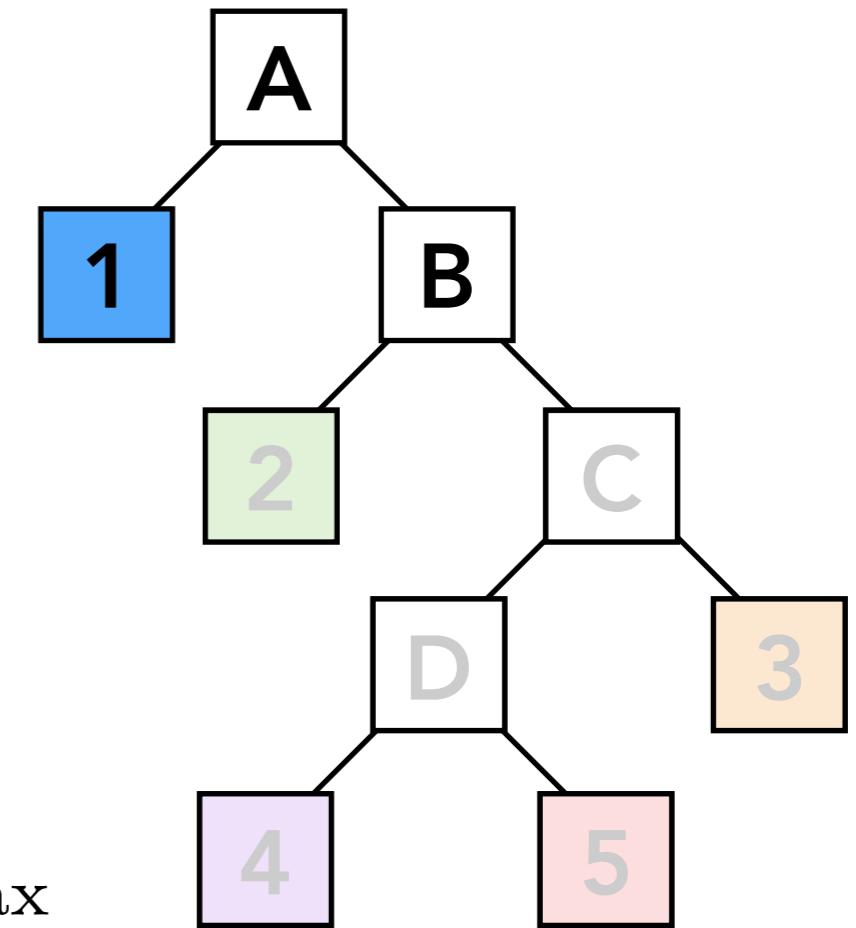
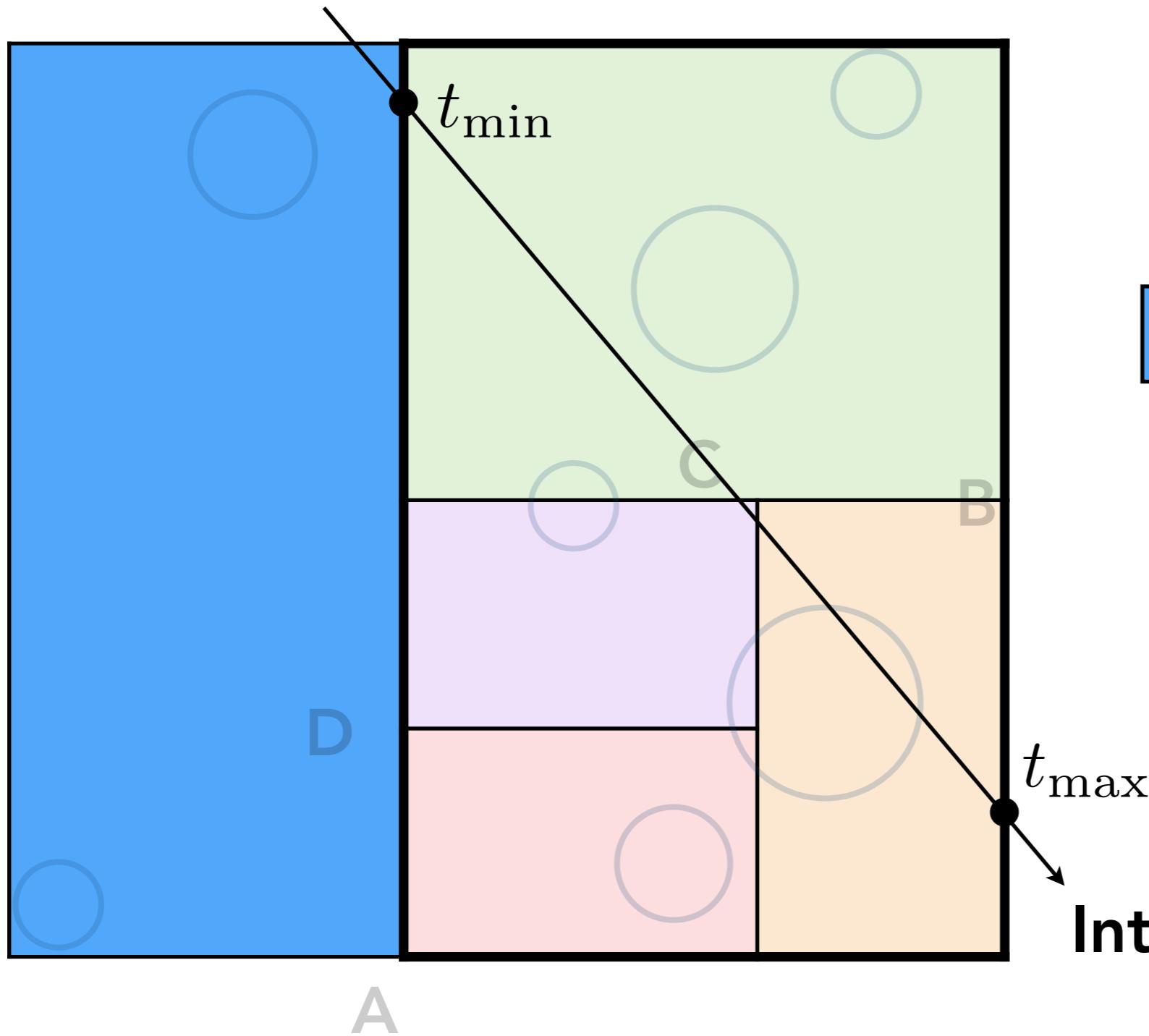


Traversing a KD-Tree



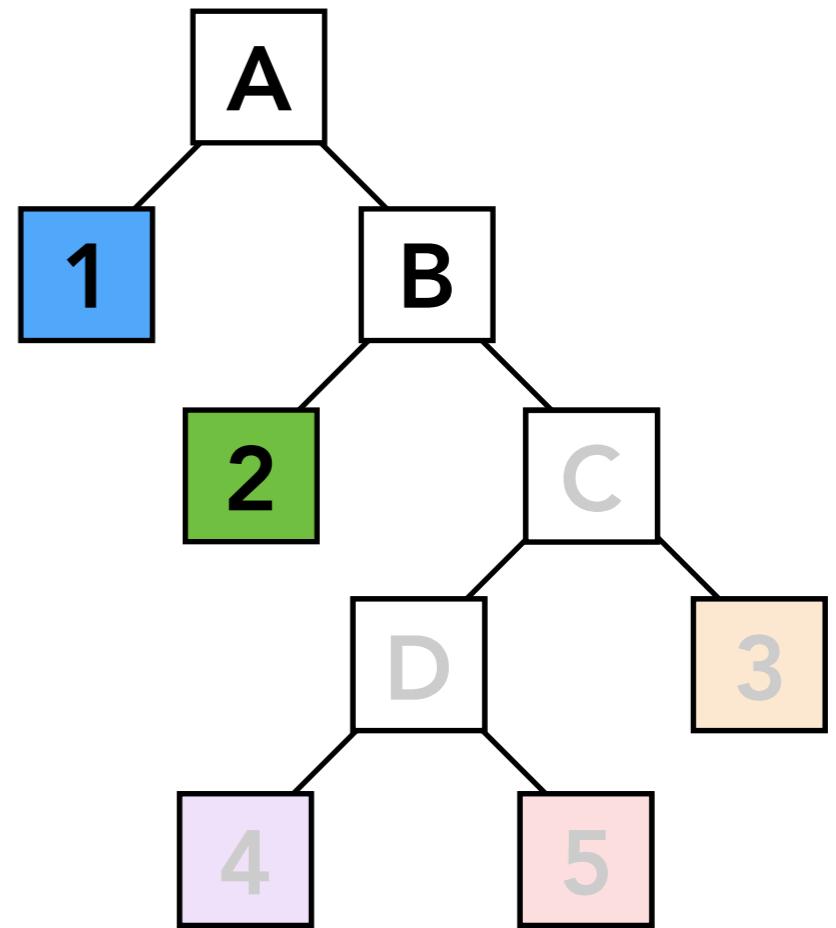
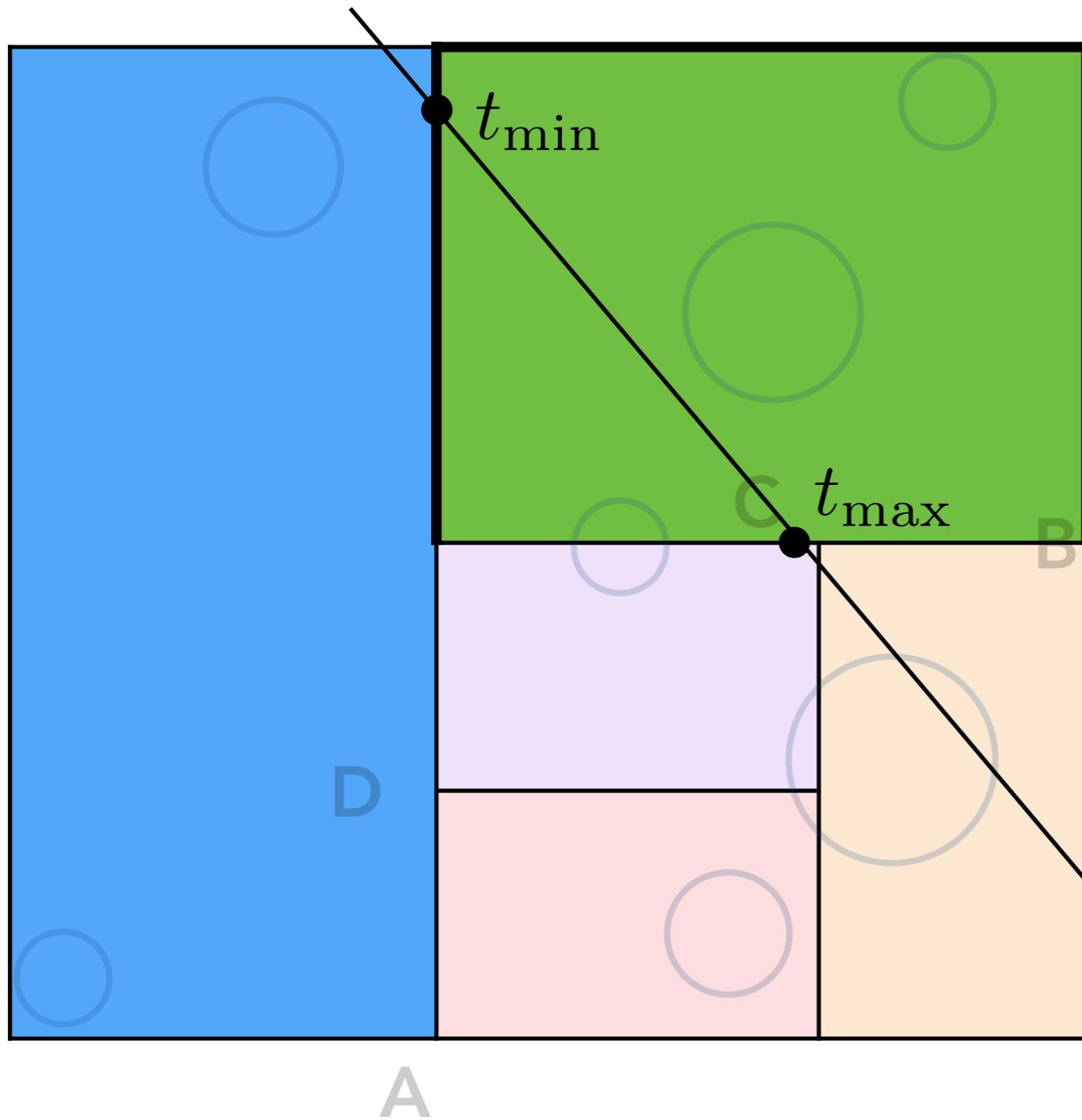
**Assume it's leaf node:
intersect all objects**

Traversing a KD-Tree

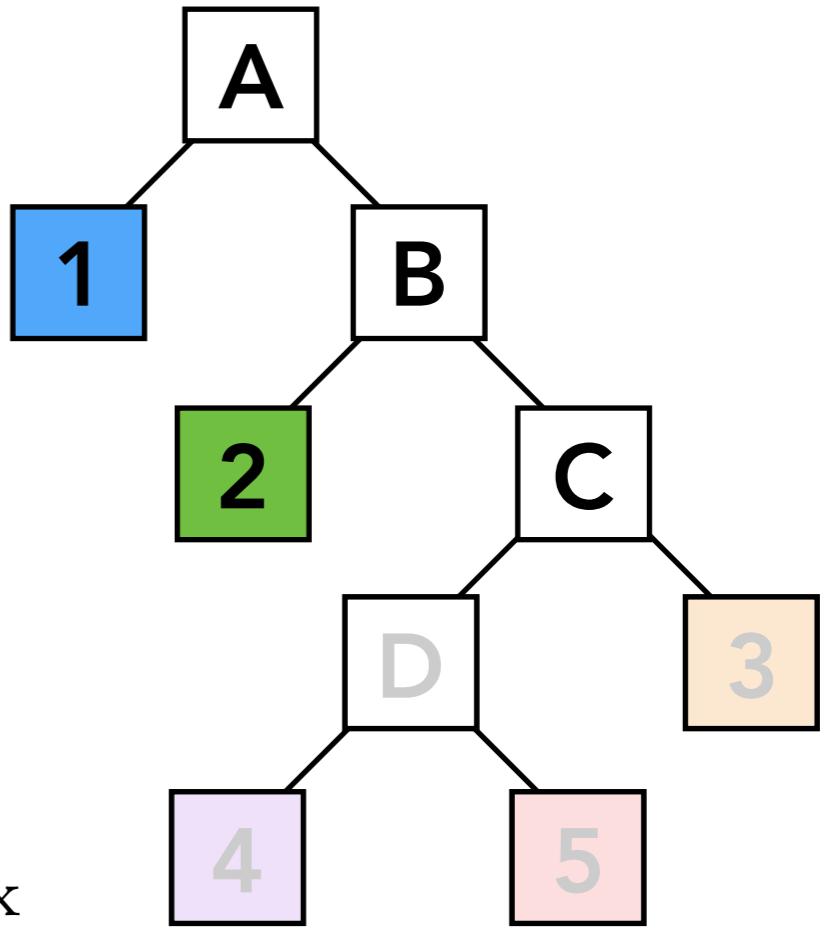
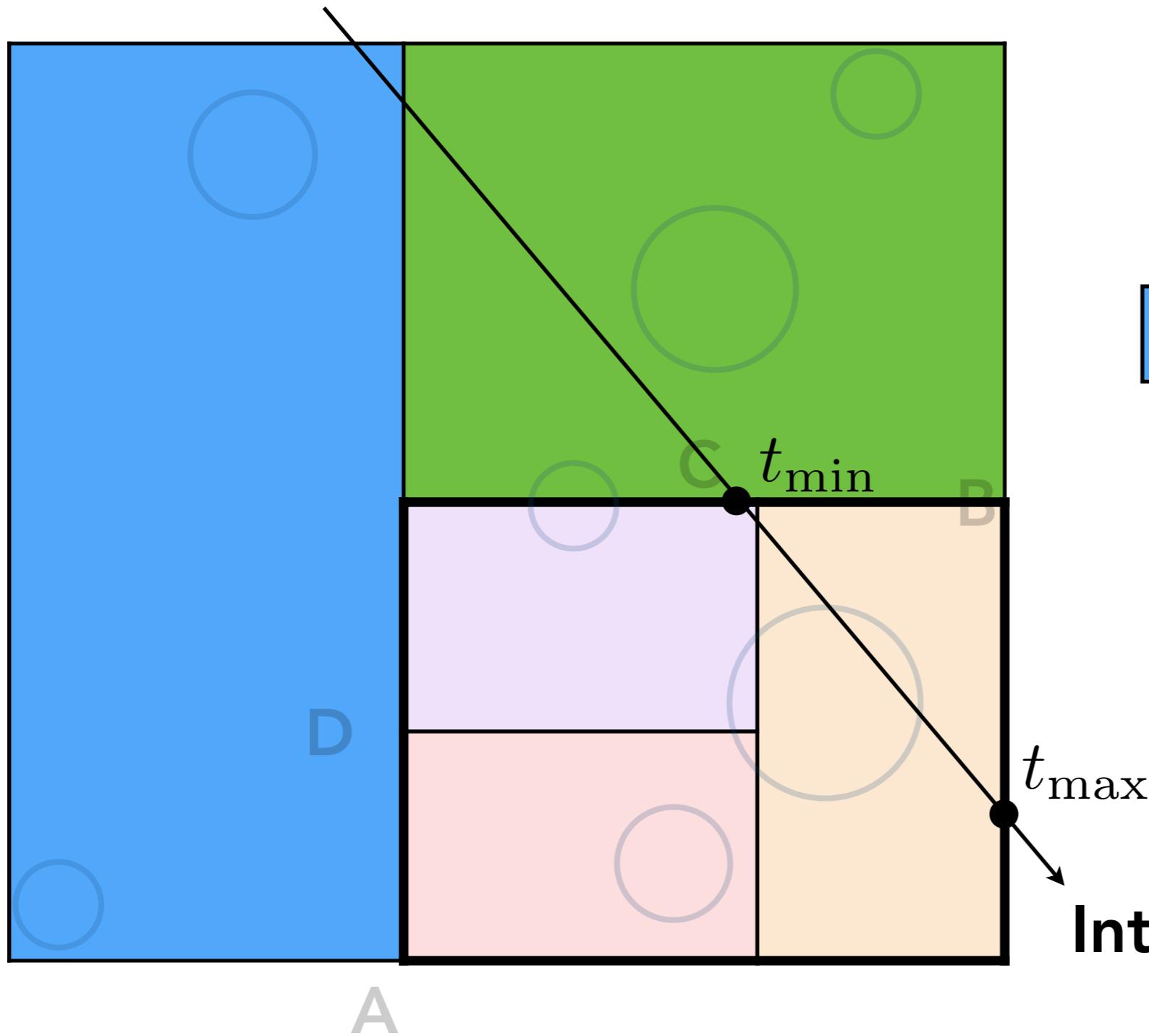


Internal node: split

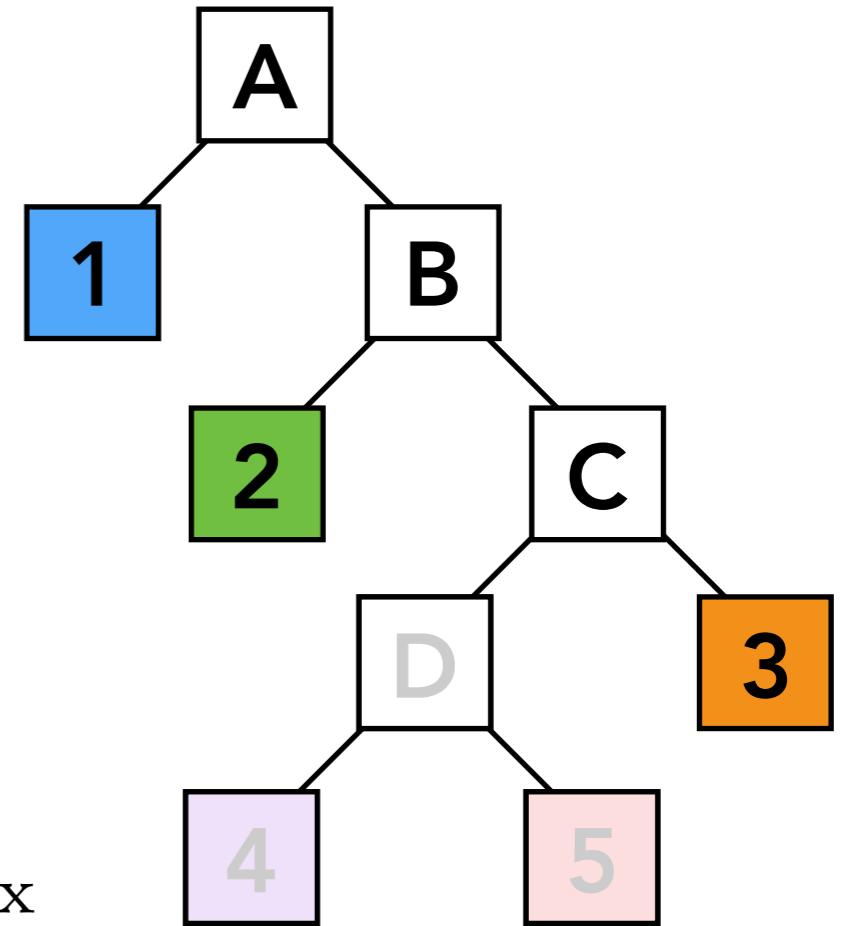
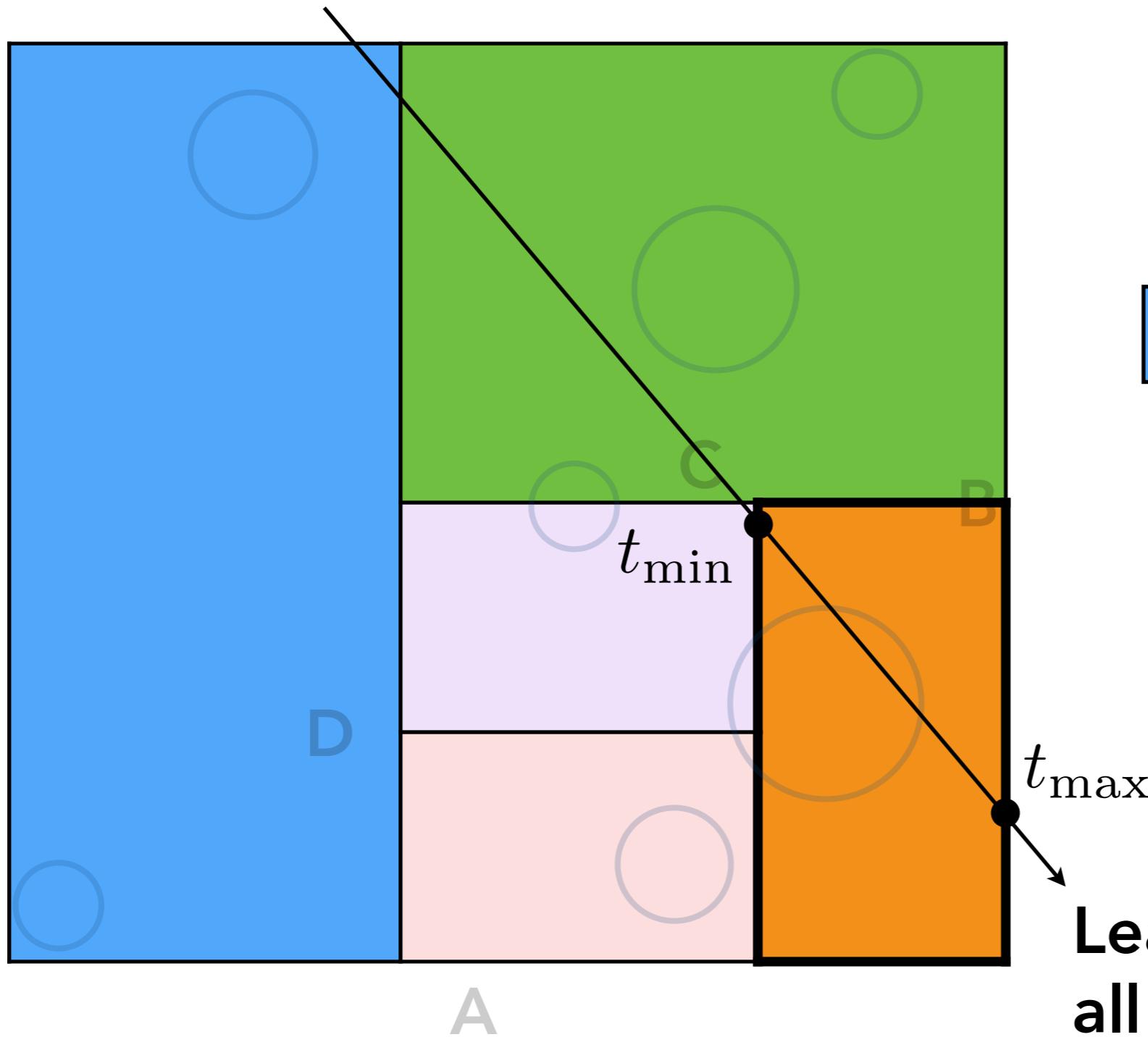
Traversing a KD-Tree



Traversing a KD-Tree



Traversing a KD-Tree

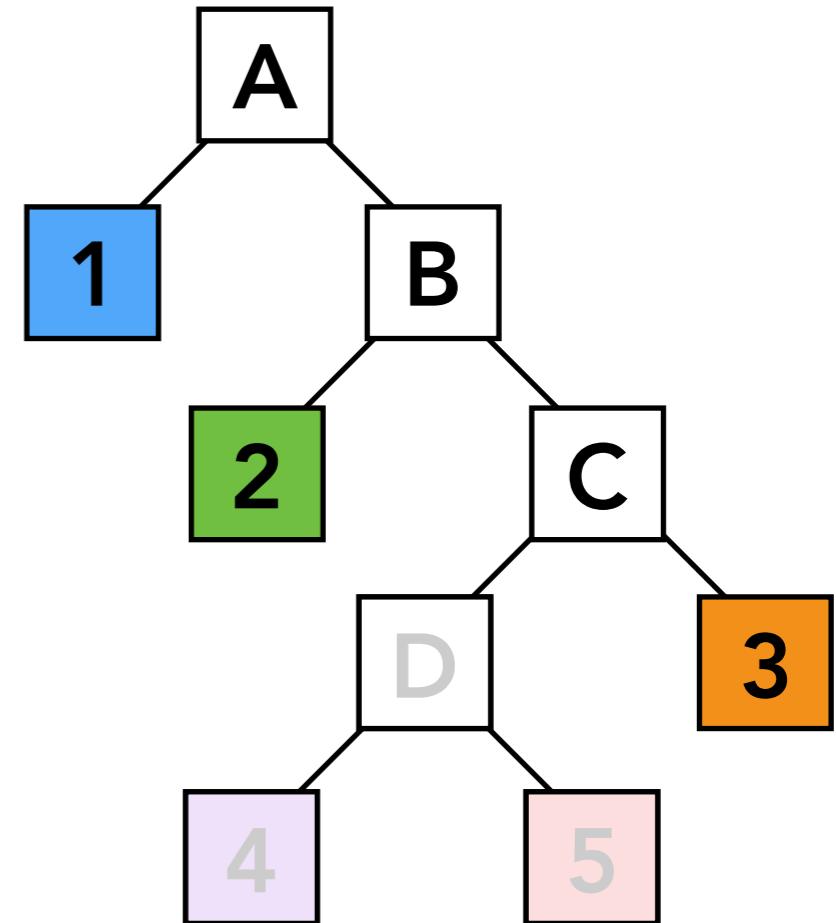
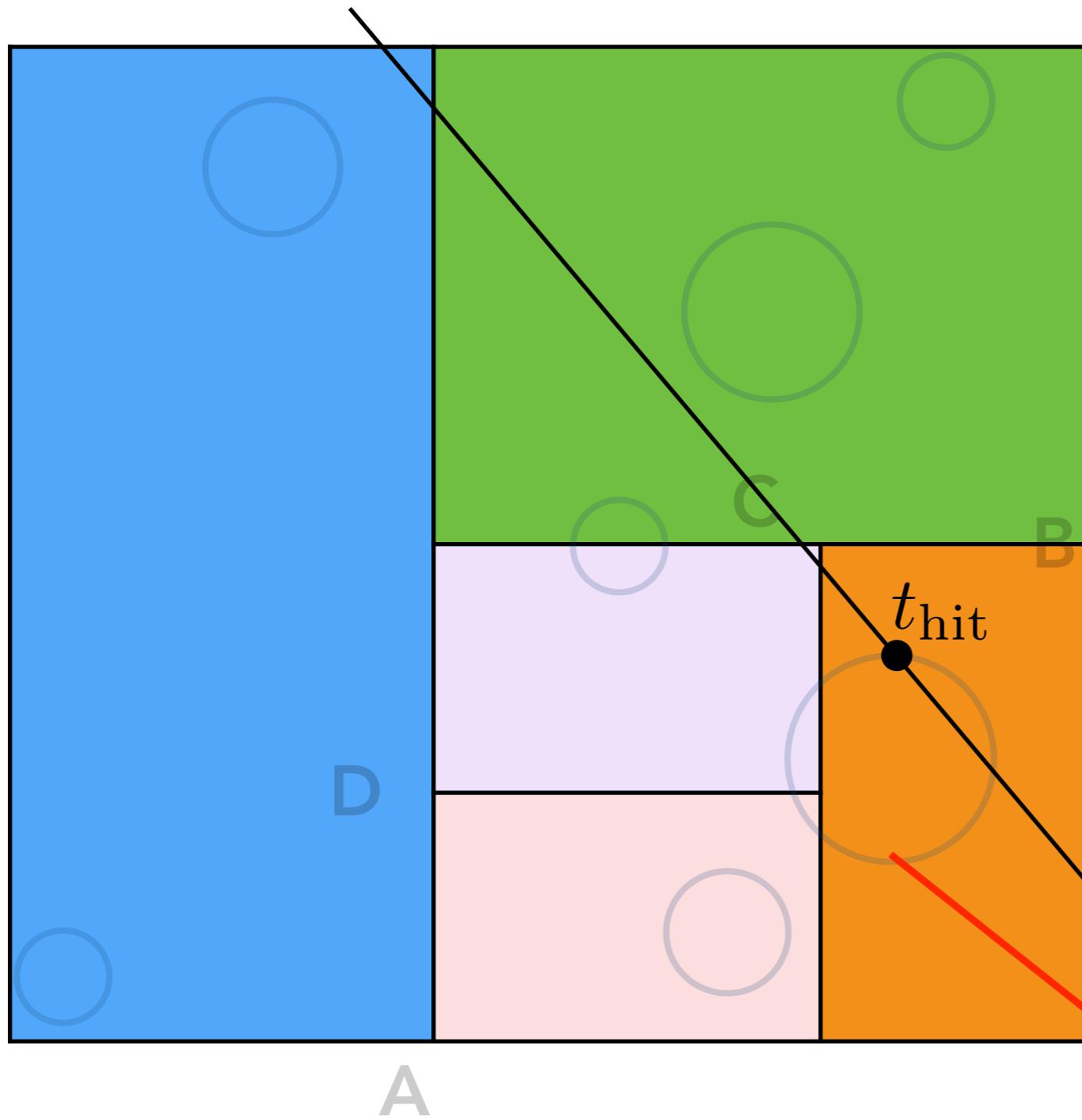


**Leaf node: intersect
all objects**

Traversing a KD-Tree

if光线和某个盒子没有交点: pass

else则可能与这个盒子的两个子结点都有交点, 判断直到光线到达叶子结点, 和叶子结点中的所有物体求交

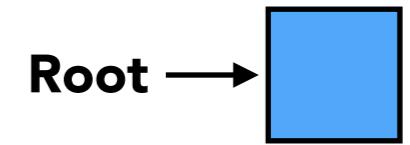
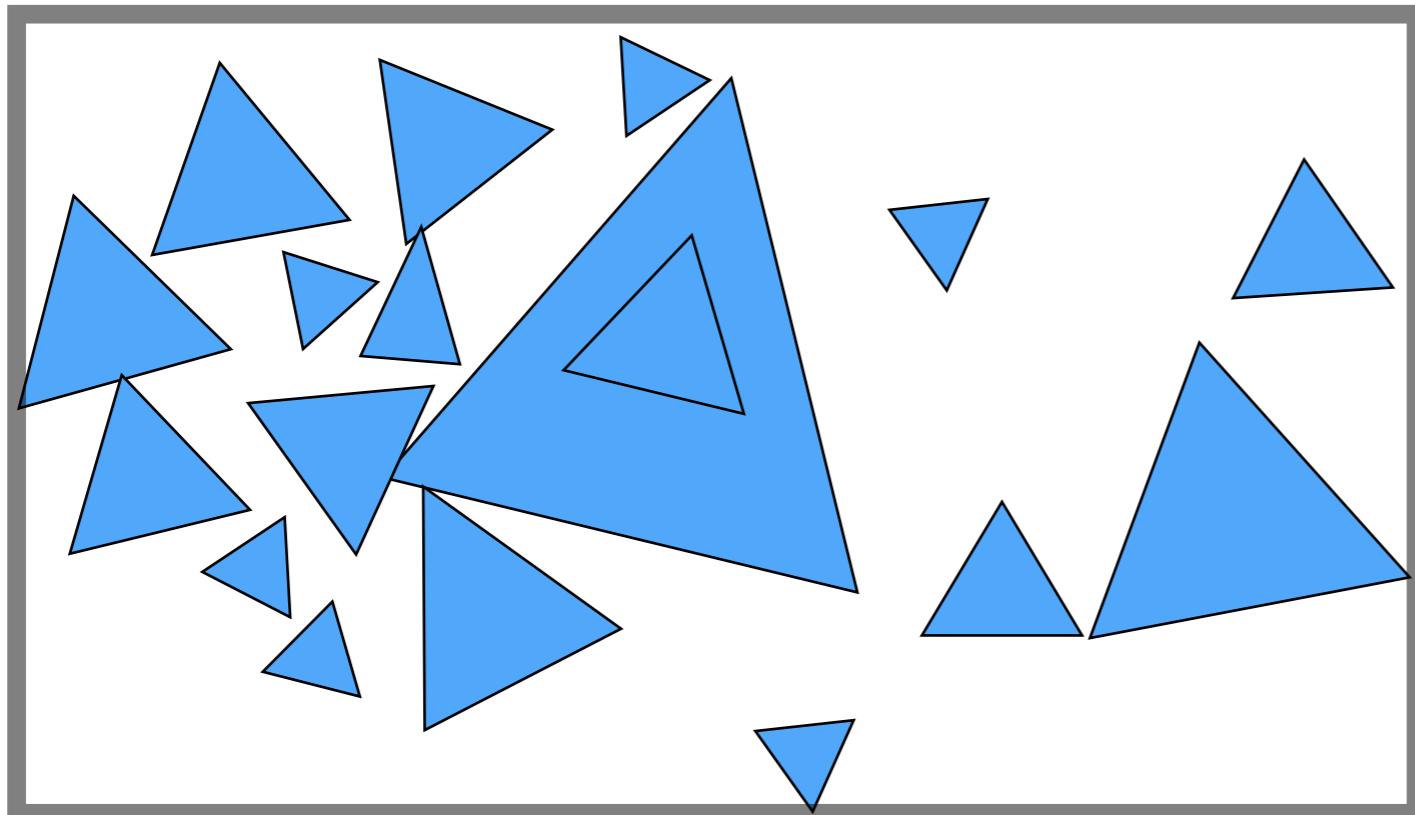


一个物体可能出现在多个叶子结点里

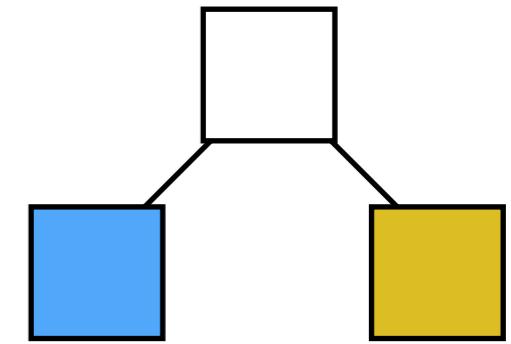
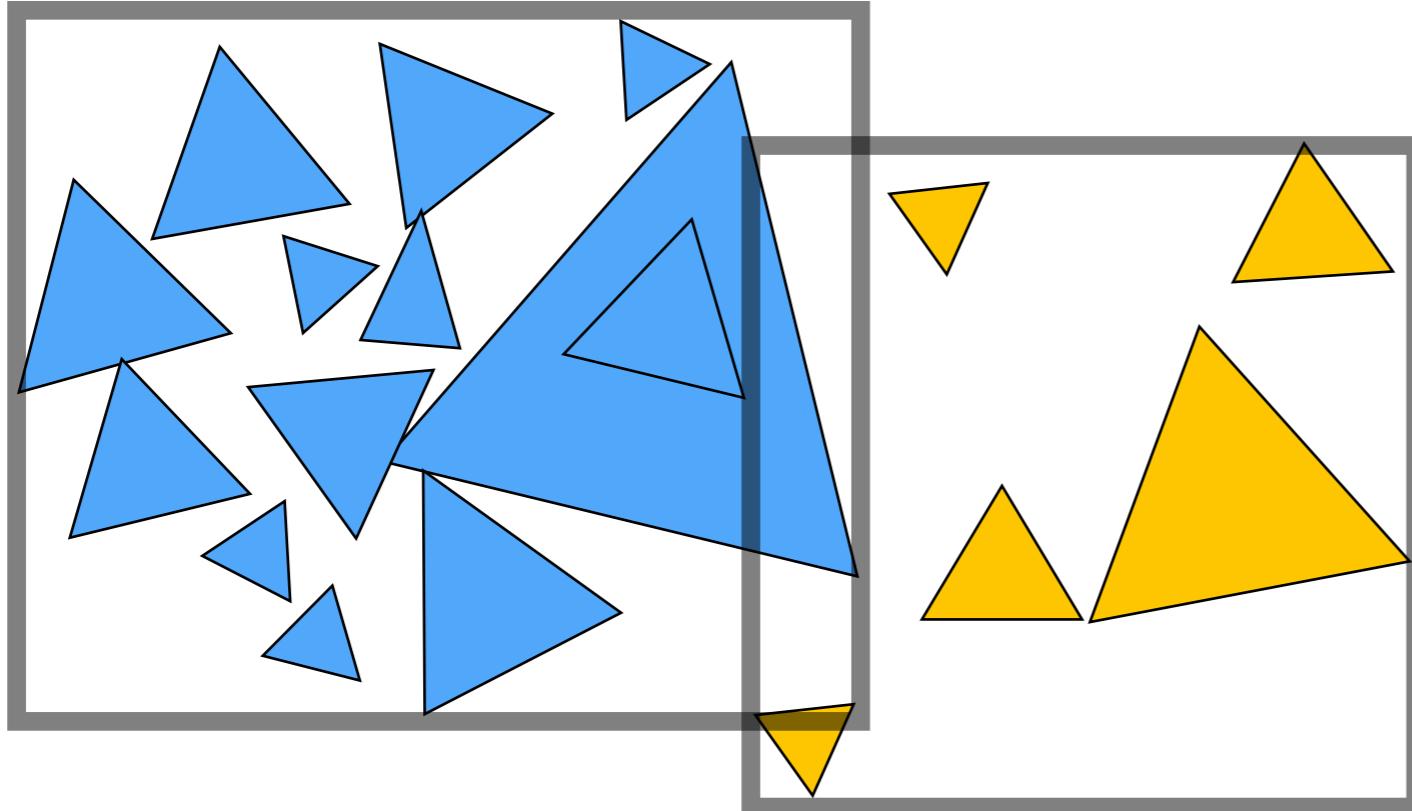
难以判定: 给定一个subBB, 需要知道所有与该BB相交的三角形

Object Partitions & 通过物体来划分，而不是直接划分空间 Bounding Volume Hierarchy (BVH)

Bounding Volume Hierarchy (BVH)

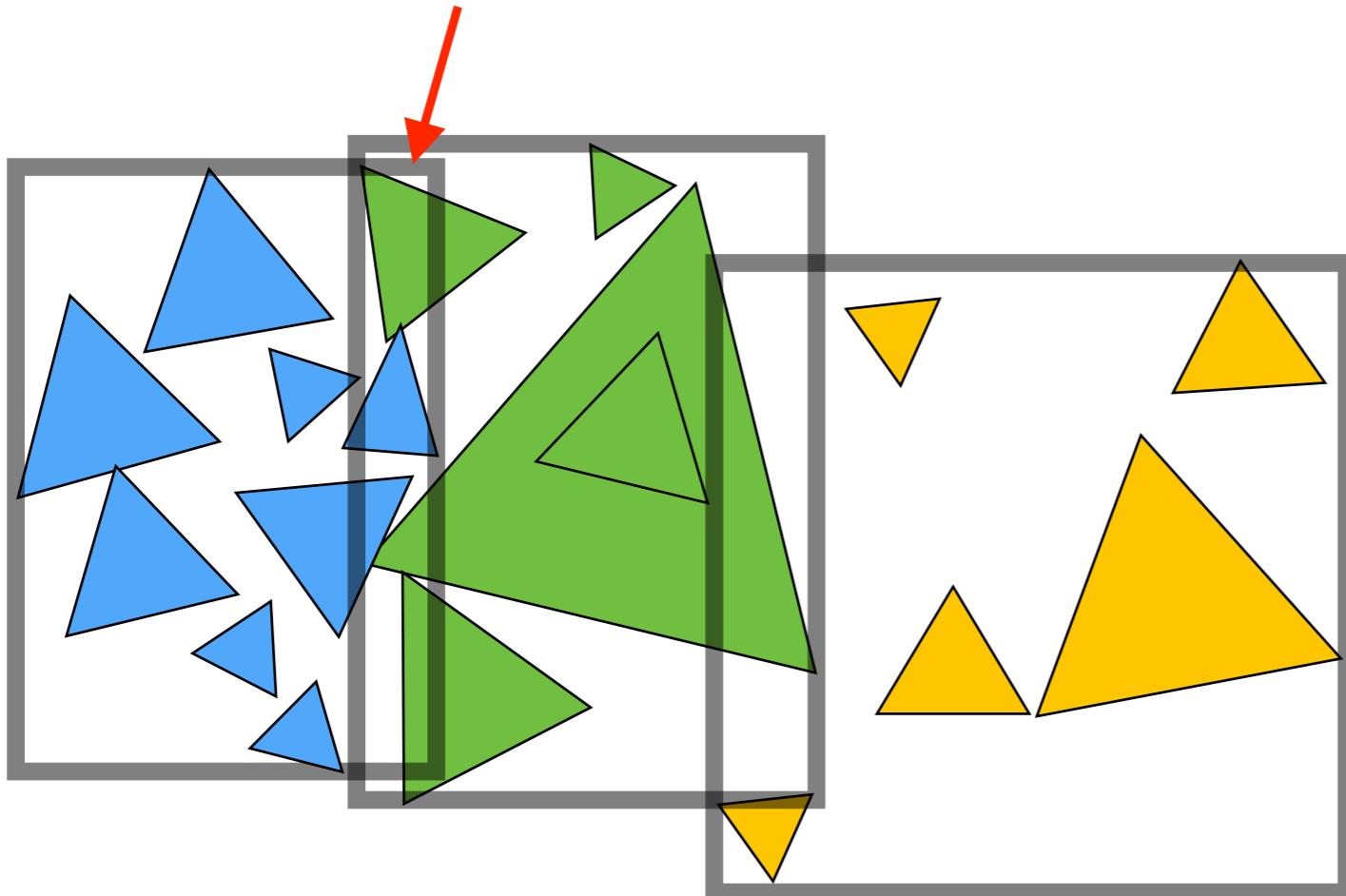


Bounding Volume Hierarchy (BVH)

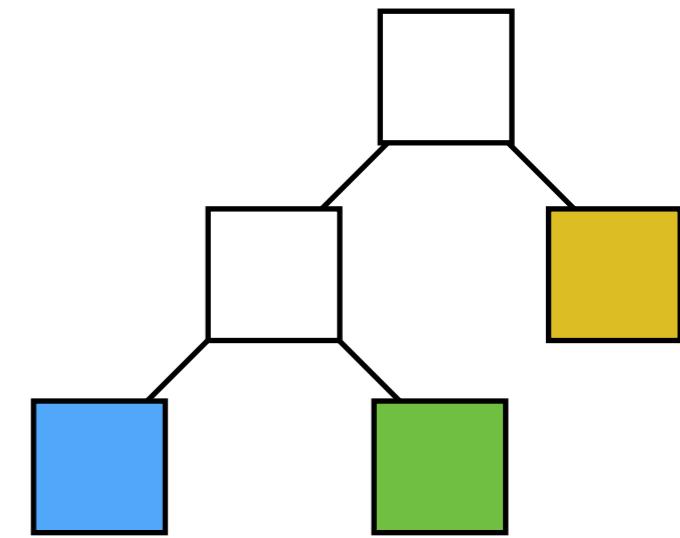


Bounding Volume Hierarchy (BVH)

需要让不同包围盒之间的重叠尽量小



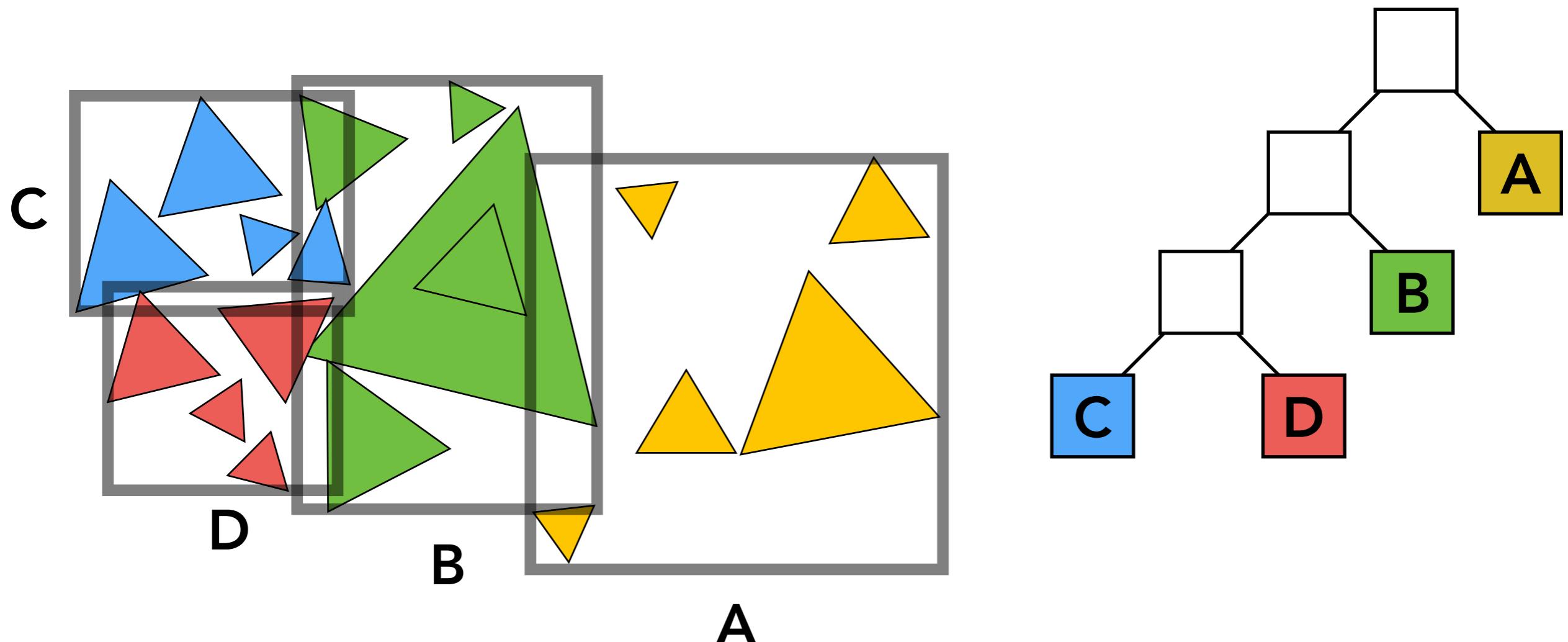
KD-Tree 直接划分空间，不重新计算包围盒



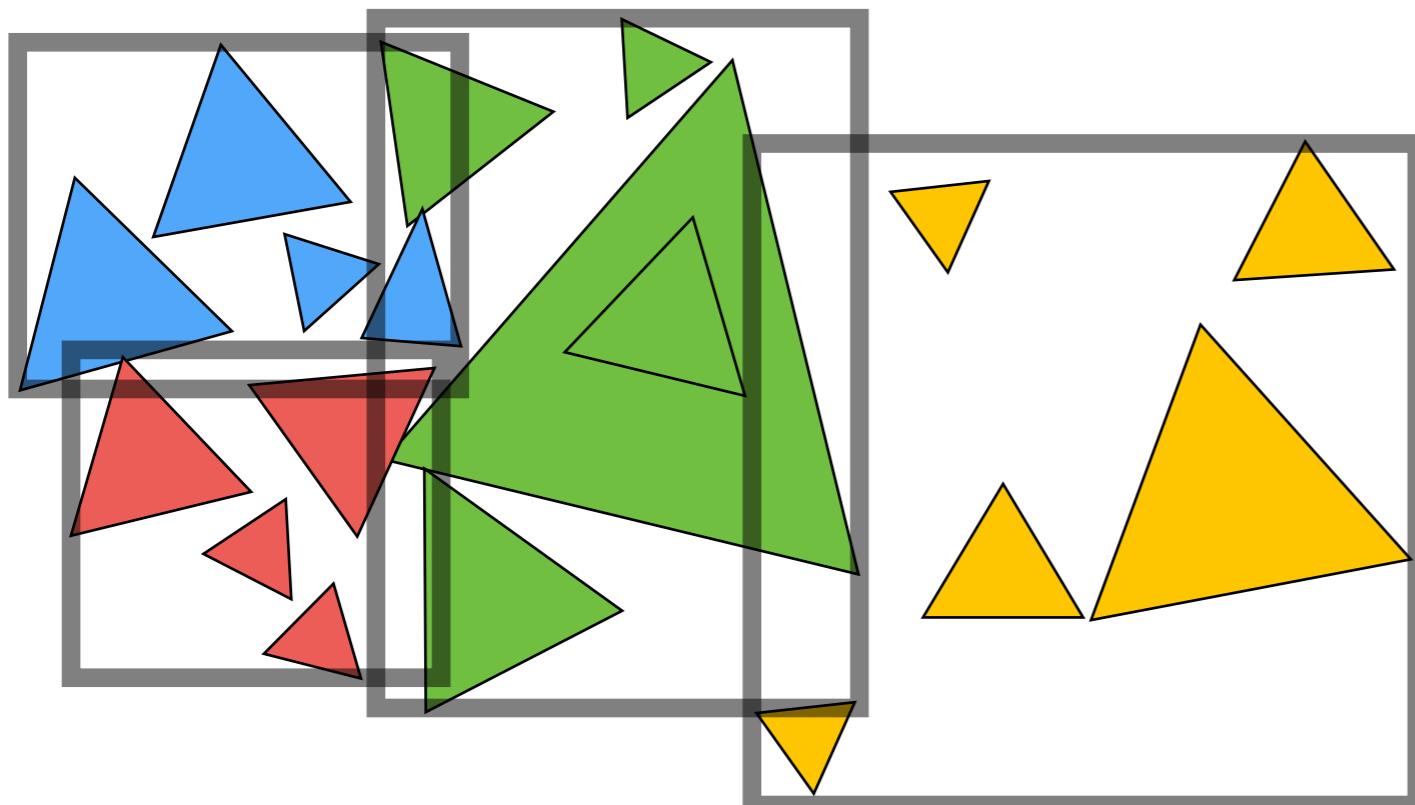
BVH：将物体分成两堆，重新计算包围盒
一个三角形只出现在一个叶子结点里

不涉及三角形和包围盒求交的过程

Bounding Volume Hierarchy (BVH)



Summary: Building BVHs



- Find bounding box
- Recursively split set of objects in two subsets
- Recompute the bounding box of the subsets
- Stop when necessary
- Store objects in each leaf node

Building BVHs

How to subdivide a node?

- Choose a dimension to split 垂直于最长轴划分物体
- Heuristic #1: Always choose the longest axis in node
- Heuristic #2: Split node at location of median object
先编号, 找第中位数个三角形 (st三角形数量在两边差不多)
让树的搜索深度小 O(n)复杂度: 快速选择算法

Termination criteria?

- Heuristic: stop when node contains few elements (e.g. 5)

Data Structure for BVHs

Internal nodes store

- Bounding box
- Children: pointers to child nodes

Leaf nodes store

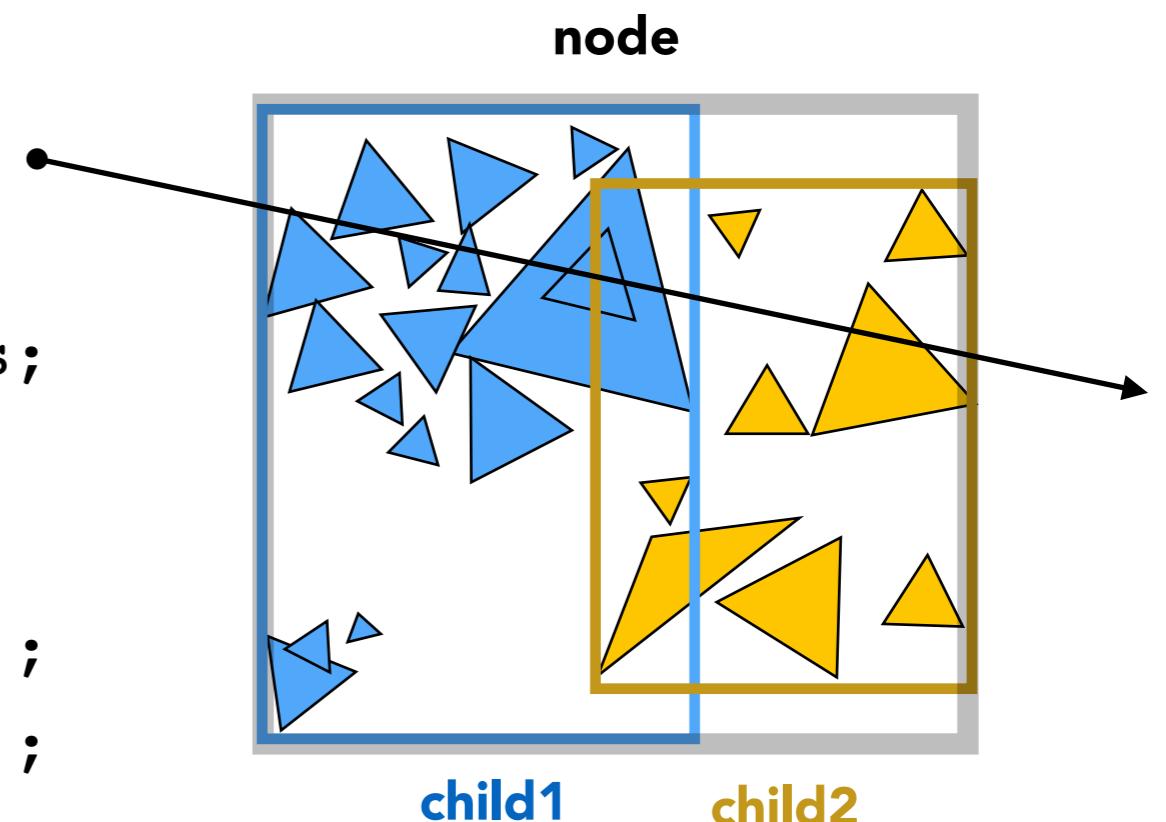
- Bounding box
- List of objects

Nodes represent subset of primitives in scene

- All objects in subtree

BVH Traversal

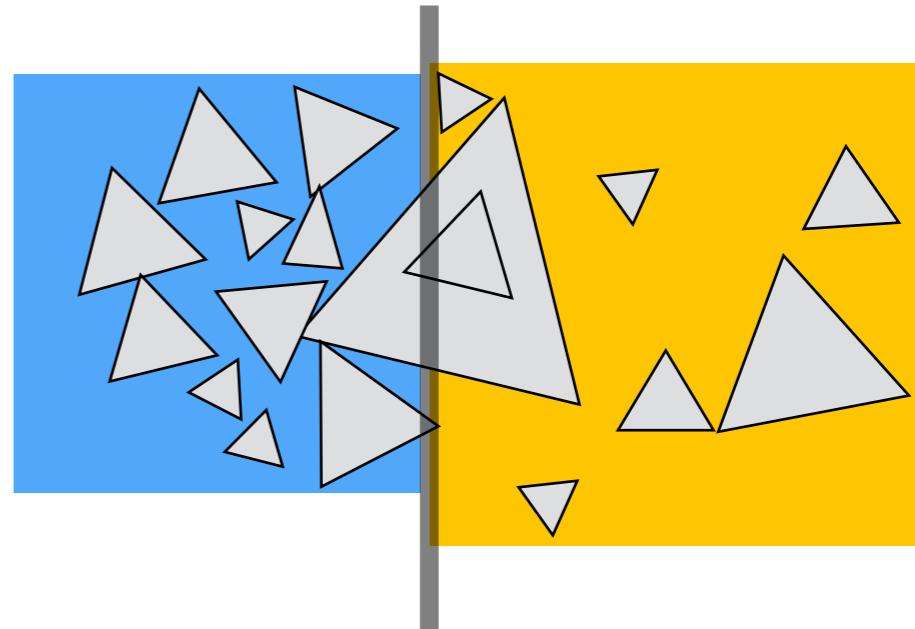
```
Intersect(Ray ray, BVH node) {  
    if (ray misses node.bbox) return;  
  
    if (node is a leaf node)  
        test intersection with all objs;  
        return closest intersection;  
  
    hit1 = Intersect(ray, node.child1);  
    hit2 = Intersect(ray, node.child2);  
  
    return the closer of hit1, hit2;  
}
```



Spatial vs Object Partitions

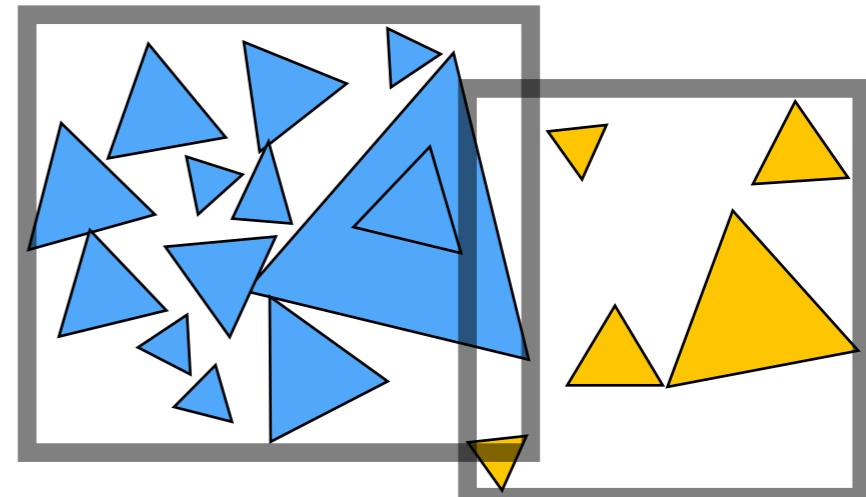
Spatial partition (e.g.KD-tree)

- Partition space into non-overlapping regions
- An object can be contained in multiple regions



Object partition (e.g. BVH)

- Partition set of objects into disjoint subsets
- Bounding boxes for each set may overlap in space



Today

- Using AABBs to accelerate ray tracing
 - Uniform grids
 - Spatial partitions
- Basic radiometry (辐射度量学)
 - Advertisement: new topics from now on, scarcely covered in other graphics courses

Radiometry — Motivation

辐射度量学：如何描述光照

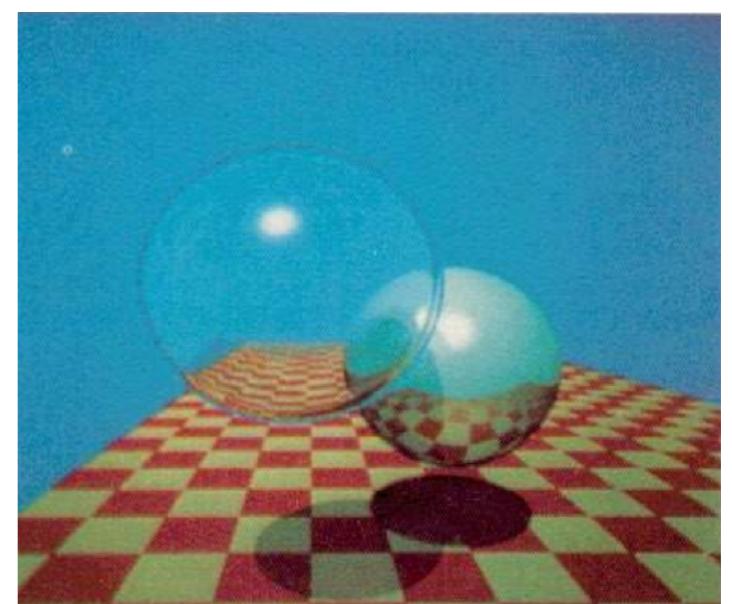
Observation

- In assignment 3, we implement the Blinn-Phong model
- Light intensity I is 10, for example
- But 10 what?

Do you think Whitted style ray tracing gives you CORRECT results?

All the answers can be found in radiometry

- Also the basics of “Path Tracing”



Radiometry

Measurement system and units for illumination

基于几何光学，不考虑波动性

Accurately measure the spatial properties of light 不考虑时间属性

- New terms: Radiant flux, intensity, irradiance, radiance

Perform lighting calculations **in a physically correct manner**

My personal way of learning things:

- WHY, WHAT, then HOW
how: less important

Radiant Energy and Flux (Power)

Radiant Energy and Flux (Power)

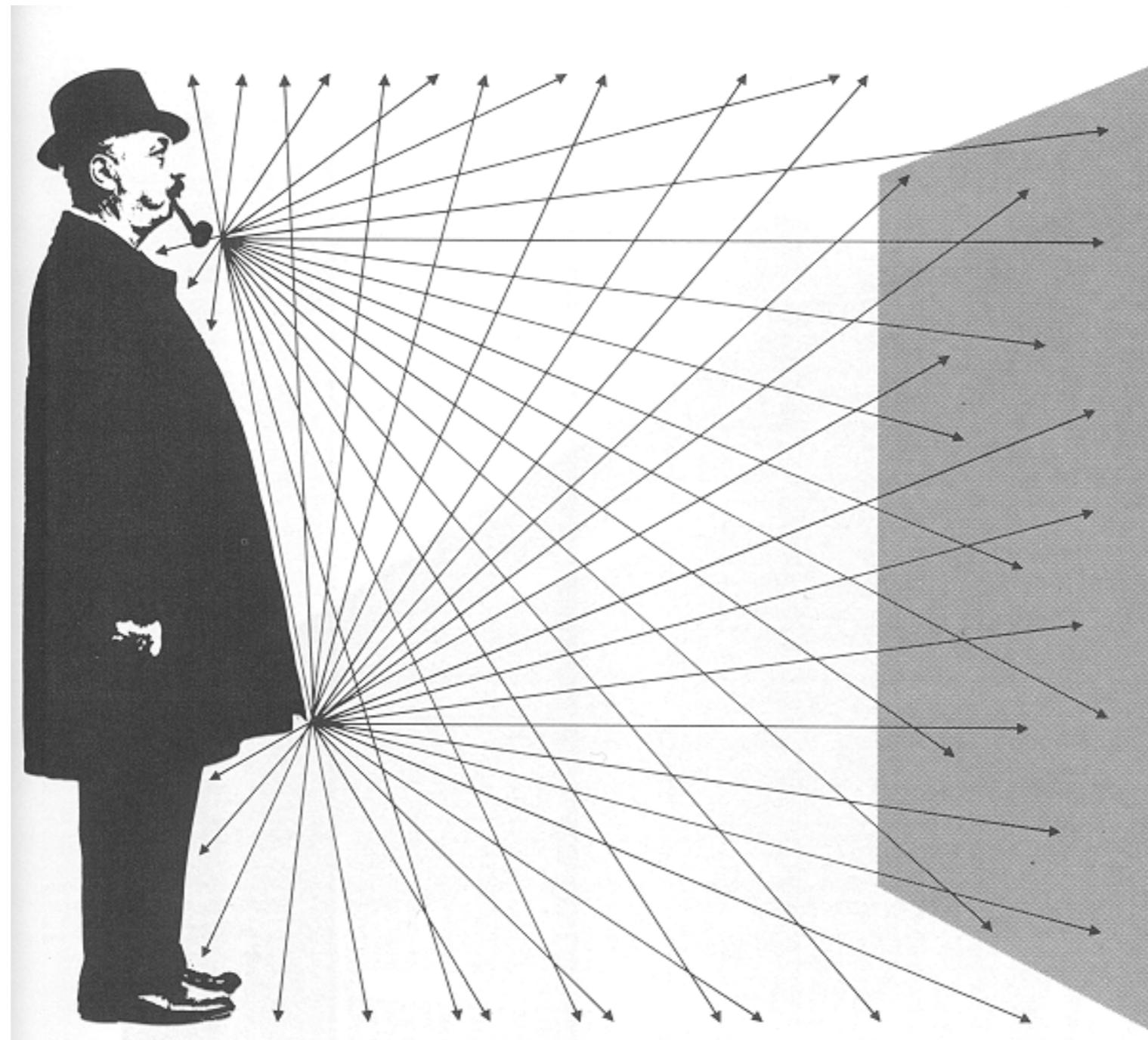
Definition: Radiant energy is the energy of electromagnetic radiation. It is measured in units of joules, and denoted by the symbol:

$$Q \text{ [J = Joule]}$$

Definition: Radiant **flux (power)** is the energy emitted, reflected, transmitted or received, per unit time.

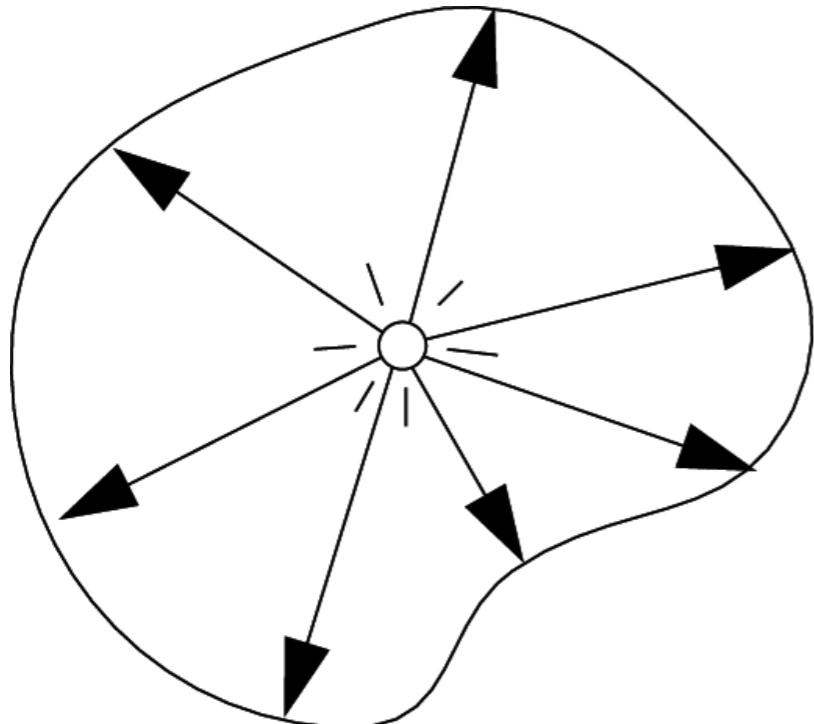
$$\Phi \equiv \frac{dQ}{dt} \text{ [W = Watt] } \underline{\text{[lm = lumen]}^*}$$

Flux – #photons flowing through a sensor in unit time



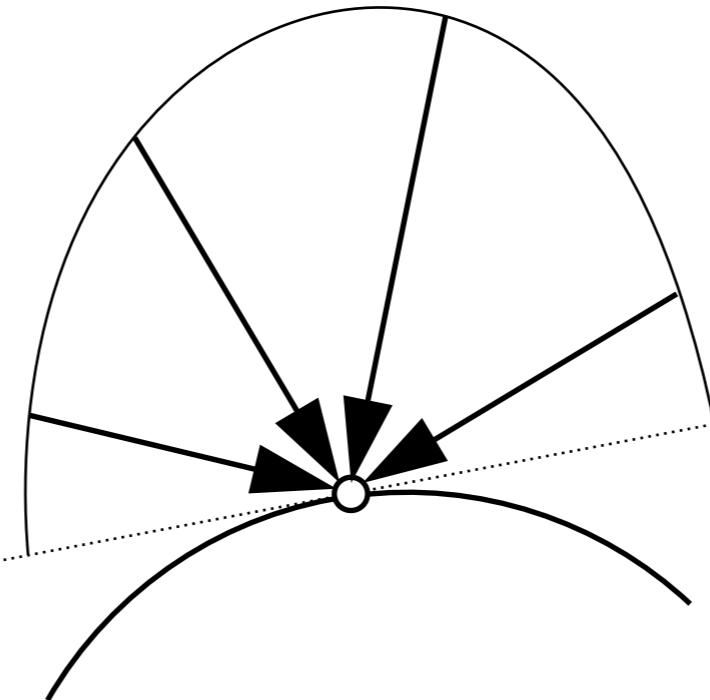
From London and Upton

Important Light Measurements of Interest



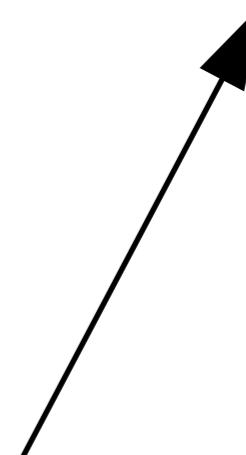
Light Emitted
From A Source

“Radiant Intensity”



收光的度量
Light Falling
On A Surface

“Irradiance”



传播中的度量
Light Traveling
Along A Ray

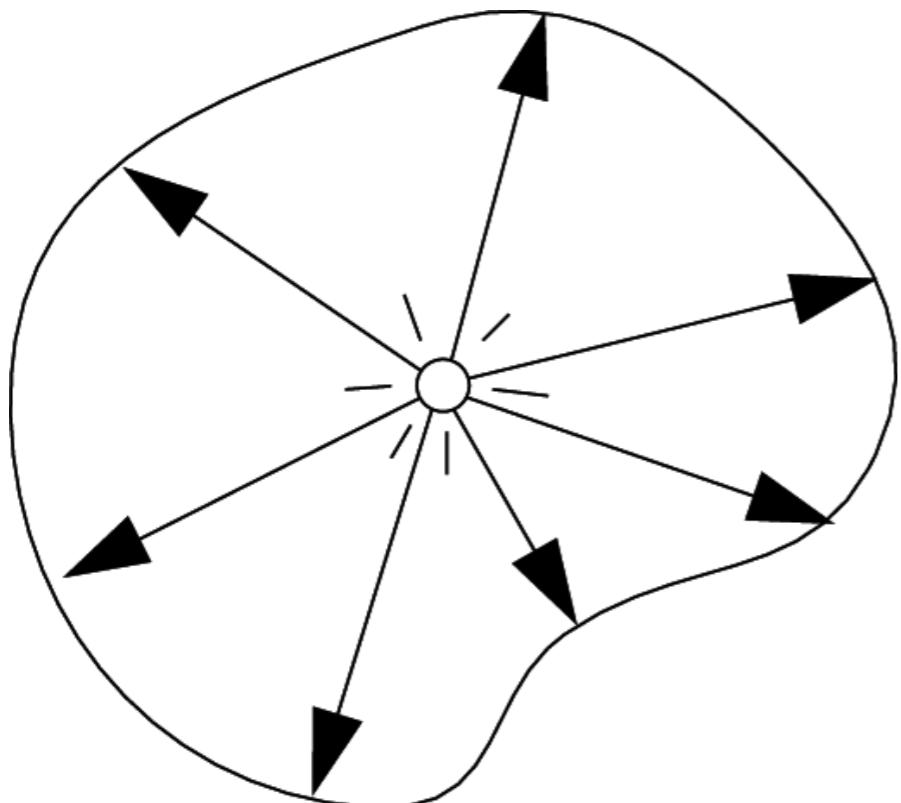
“Radiance”

Radiant Intensity

Radiant Intensity

Definition: The radiant (luminous) intensity is the **power** per unit **solid angle** (?) emitted by a point light source.

(立体角)



$$I(\omega) \equiv \frac{d\Phi}{d\omega}$$

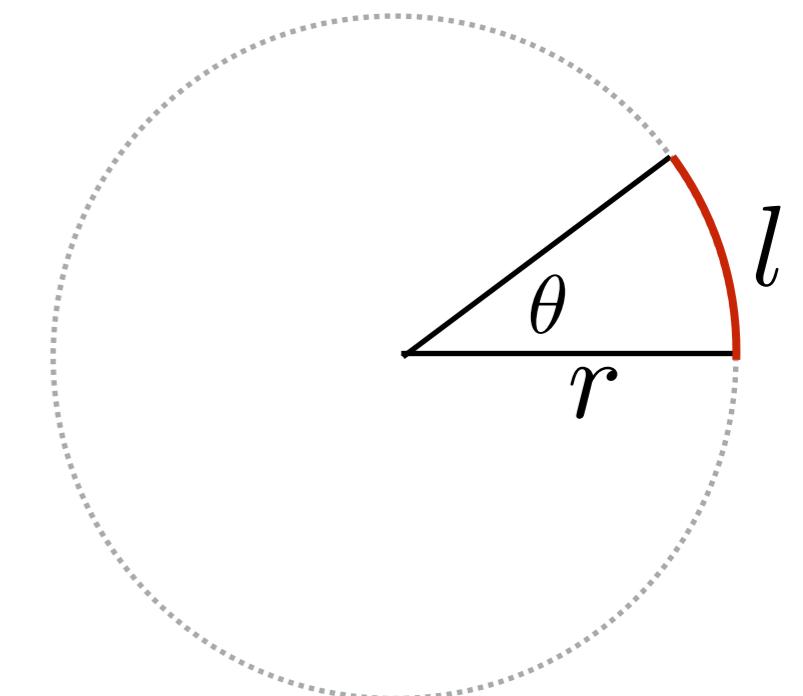
$$\left[\frac{\text{W}}{\text{sr}} \right] \left[\frac{\text{lm}}{\text{sr}} = \text{cd} = \text{candela} \right]$$

The **candela** is one of the seven SI base units.

Angles and Solid Angles

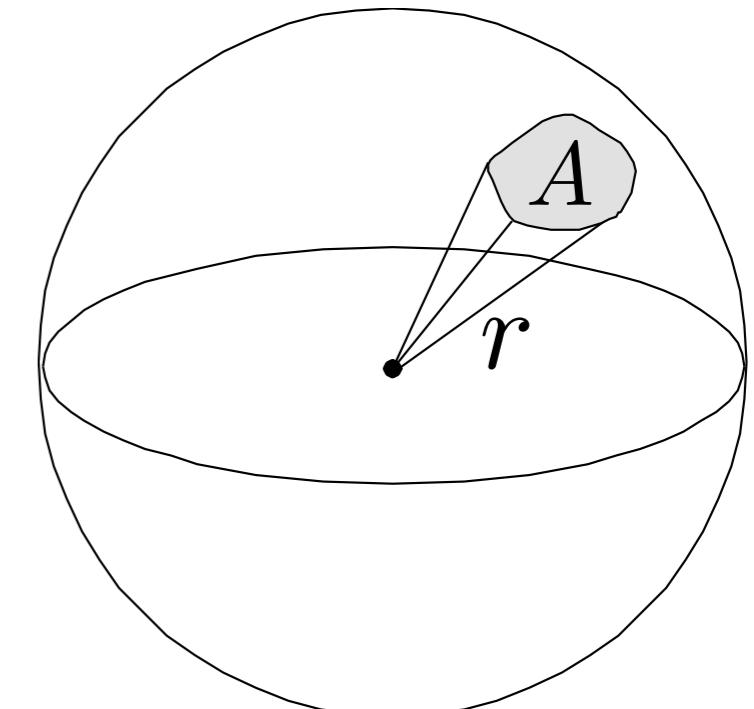
Angle: ratio of subtended arc length on circle to radius

- $\theta = \frac{l}{r}$
- Circle has 2π radians

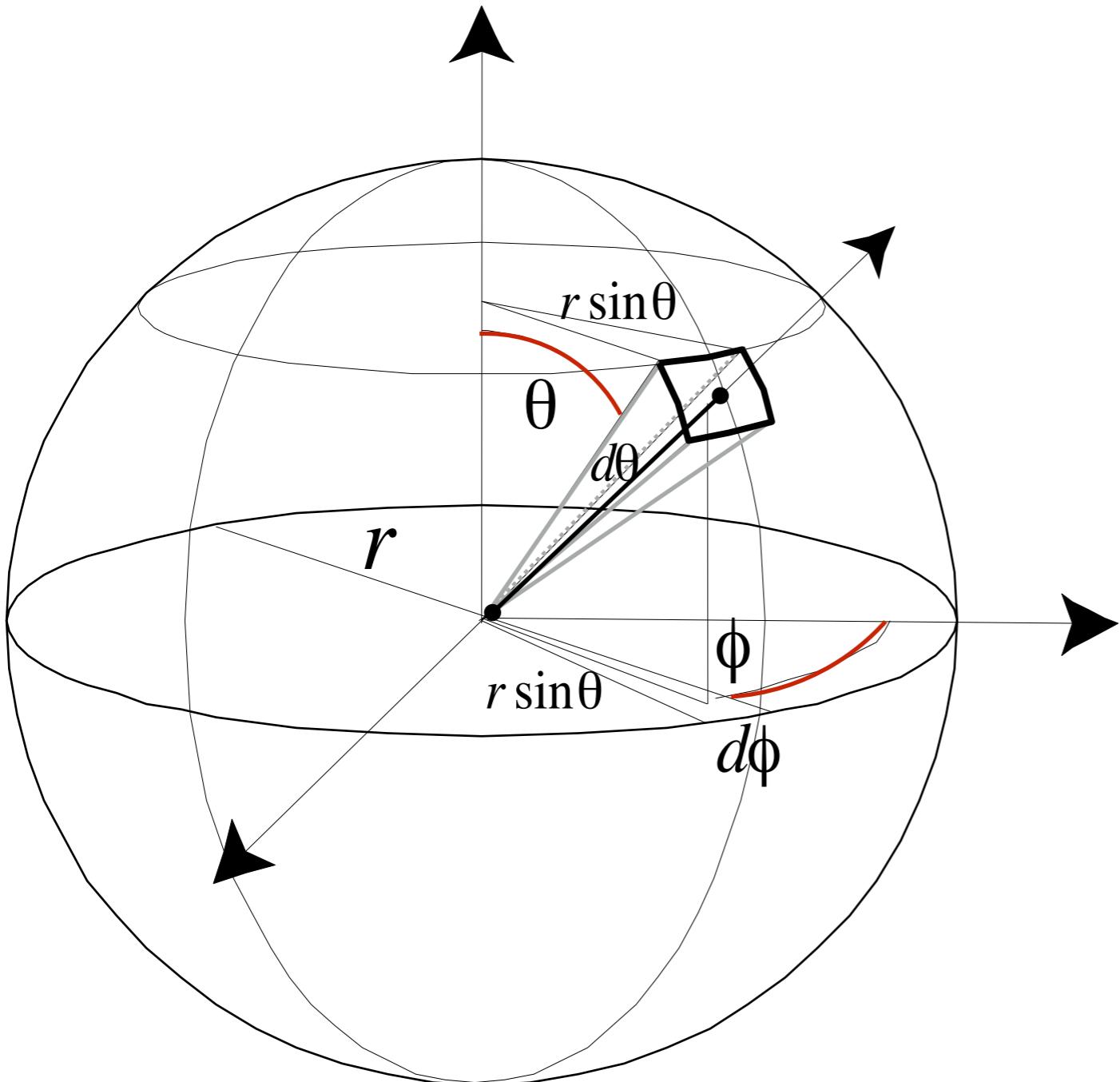


Solid angle: ratio of subtended area on sphere to radius squared

- $\Omega = \frac{A}{r^2}$
- Sphere has 4π steradians



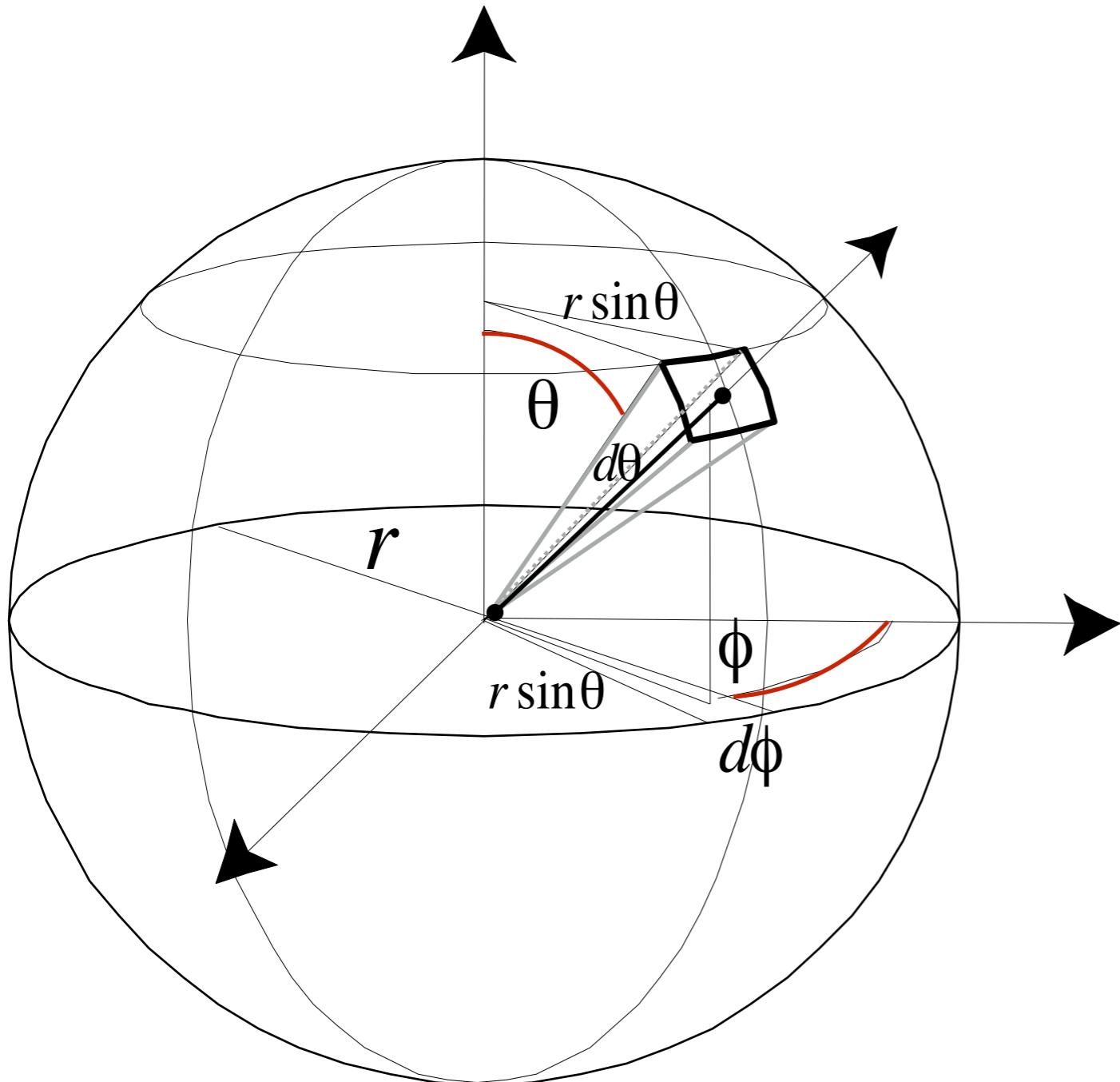
Differential Solid Angles



$$\begin{aligned} dA &= (r d\theta)(r \sin \theta d\phi) \\ &= r^2 \sin \theta d\theta d\phi \end{aligned}$$

$$d\omega = \frac{dA}{r^2} = \sin \theta d\theta d\phi$$

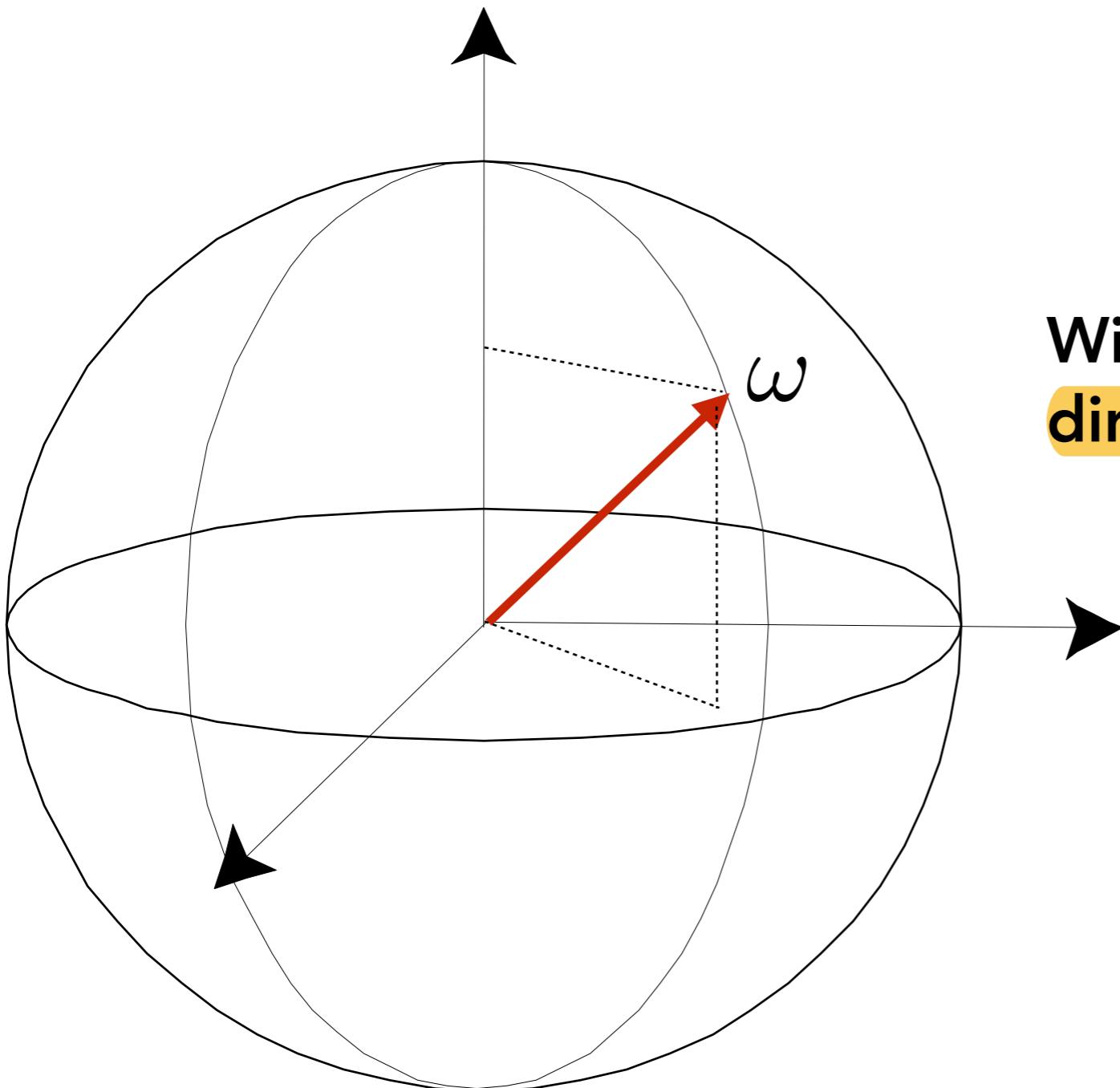
Differential Solid Angles



Sphere: S^2

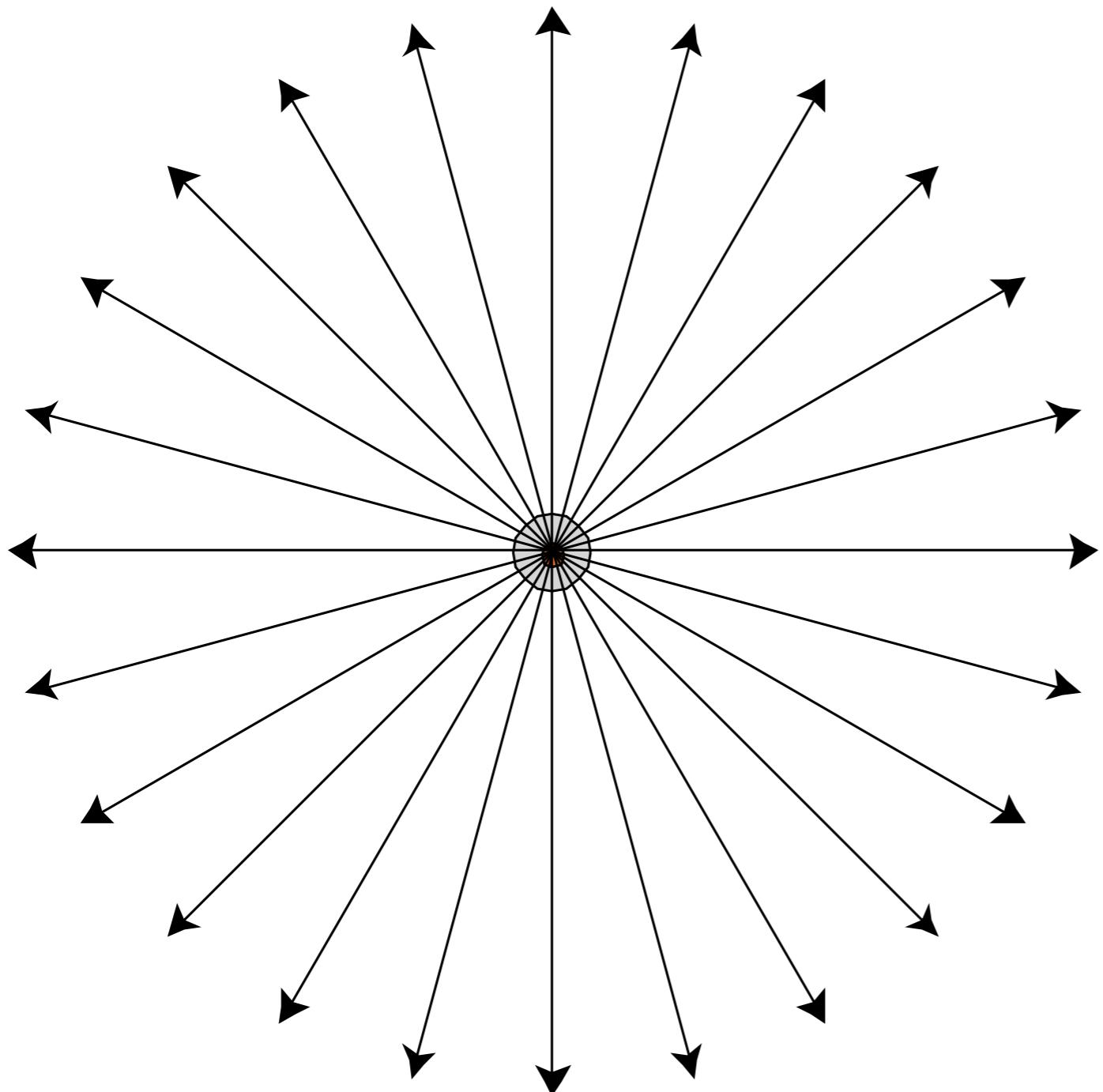
$$\begin{aligned}\Omega &= \int_{S^2} d\omega \\ &= \int_0^{2\pi} \int_0^\pi \sin \theta d\theta d\phi \\ &= 4\pi\end{aligned}$$

ω as a direction vector



Will use ω to denote a
direction vector (unit length)

Isotropic Point Source



$$\begin{aligned}\Phi &= \int_{S^2} I d\omega \\ &= 4\pi I\end{aligned}$$

$$I = \frac{\Phi}{4\pi}$$

Modern LED Light

Output: 815 lumens

(11W LED replacement
for 60W incandescent)

Radiant intensity?

相当于多少W的白炽灯
(实际上LED能耗很小)

Assume isotropic:

$$\text{Intensity} = 815 \text{ lumens} / 4\pi \text{ sr} \\ = 65 \text{ candelas}$$



Thank you!

(And thank Prof. Ravi Ramamoorthi and Prof. Ren Ng for many of the slides!)