COMP3421

Ray Tracing

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Recap: Global Lighting

- The lighting equation we looked at earlier only handled direct lighting from sources:

$$I = \boxed{I_a \rho_a} + \sum_{l \in \text{lights}} I_l \left(\rho_d (\hat{\mathbf{s}}_\mathbf{l} \cdot \hat{\mathbf{m}}) + \rho_{sp} \left(\hat{\mathbf{r}}_\mathbf{l} \cdot \hat{\mathbf{v}} \right)^f \right)$$

- We added an ambient fudge term to account for all other light in the scene.

- Without this term, surfaces not facing a light source are black.

Recap: Global lighting

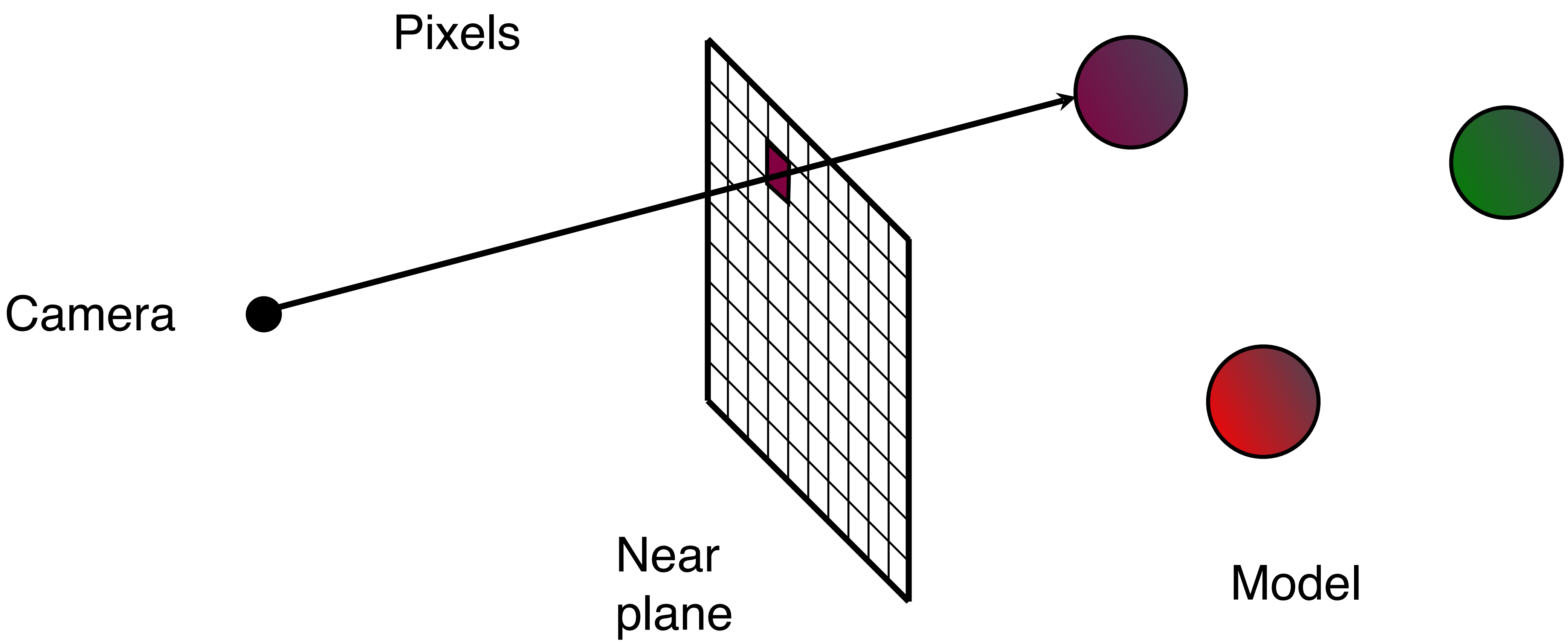
- In reality, the light falling on a surface comes from everywhere. Light from one surface is reflected onto another surface and then another, and another, and...

- Methods that take this kind of multi-bounce lighting into account are called global lighting methods.

Raytracing and Radiosity

- There are two main methods for global lighting:
  - Raytracing models specular reflection and refraction.
  - Radiosity models diffuse reflection.
- Both methods are computationally expensive and are rarely suitable for real-time rendering.

Rays



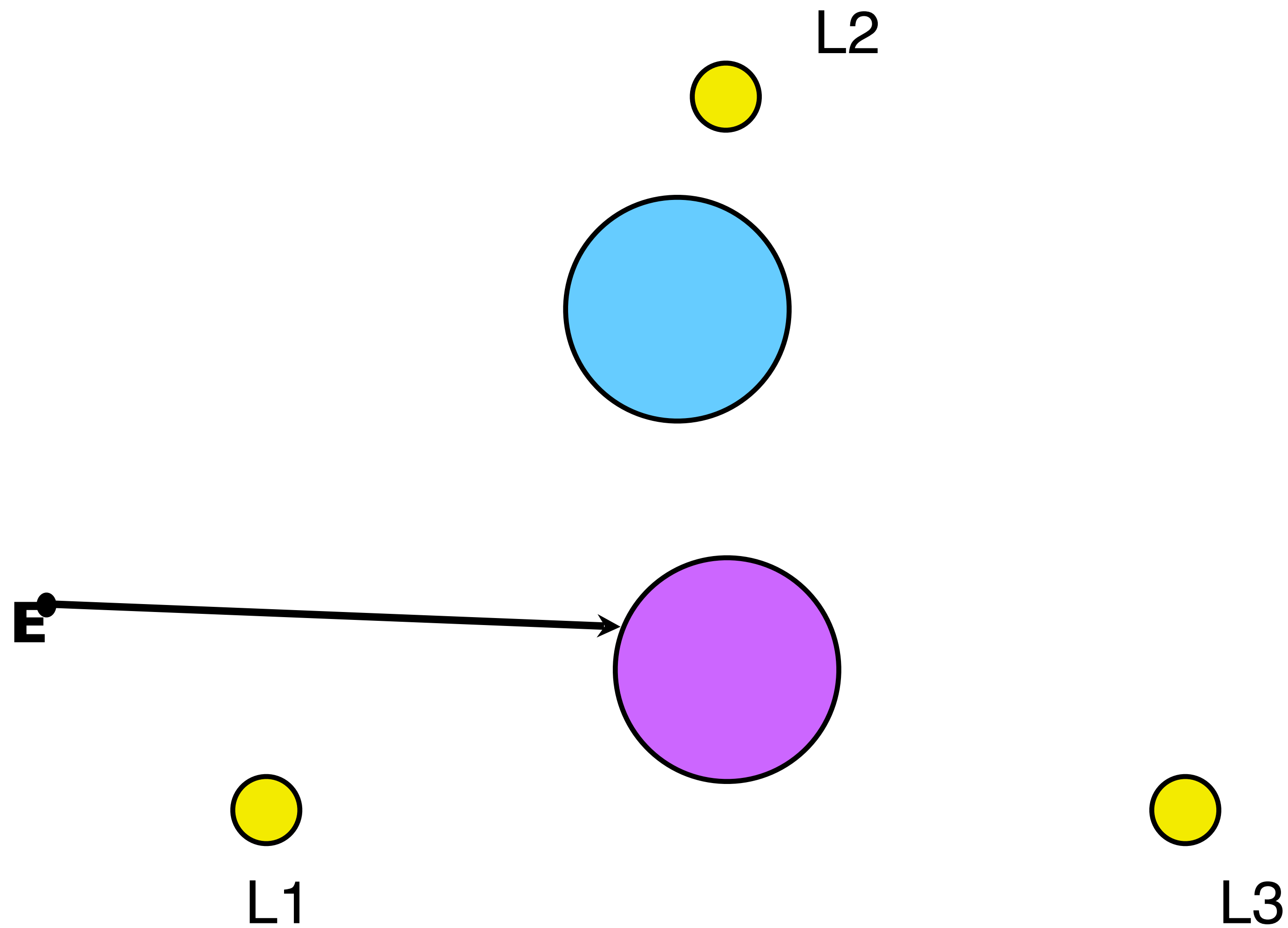
Shadows

- We can add shadows very simply.
- At each hit point we cast a new ray towards each light source. These rays are called shadow feelers.
- If a shadow feeler intersects an object before it reaches the source, then omit that source from the illumination equation for the point.

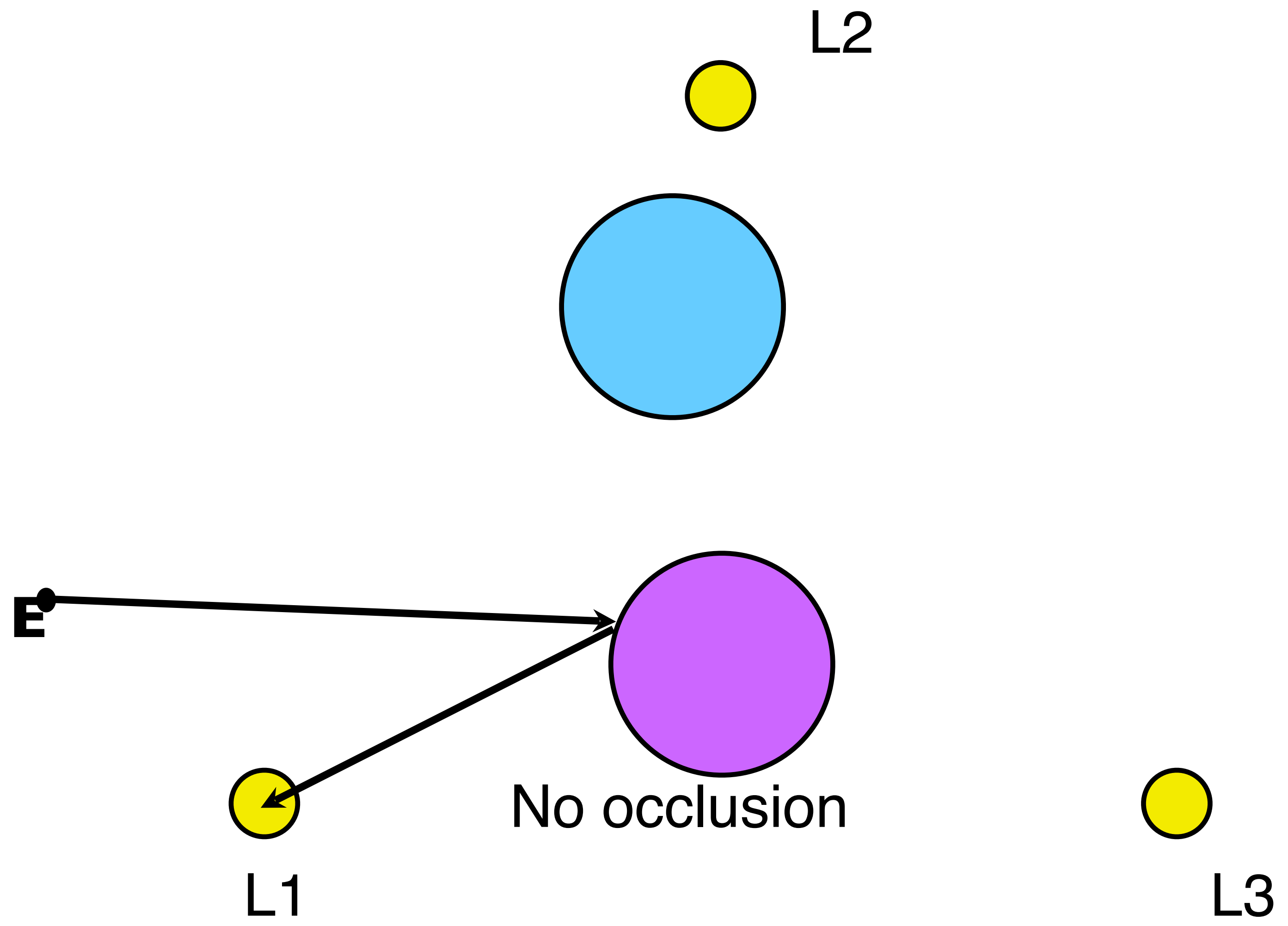
Self-shadows

- We need to take care when the shadow is cast by the hit object itself.
- The shadow feeler will always intersect the hit object at time t=0.
- This intersection is only relevant if the light is on the opposite side of the object.

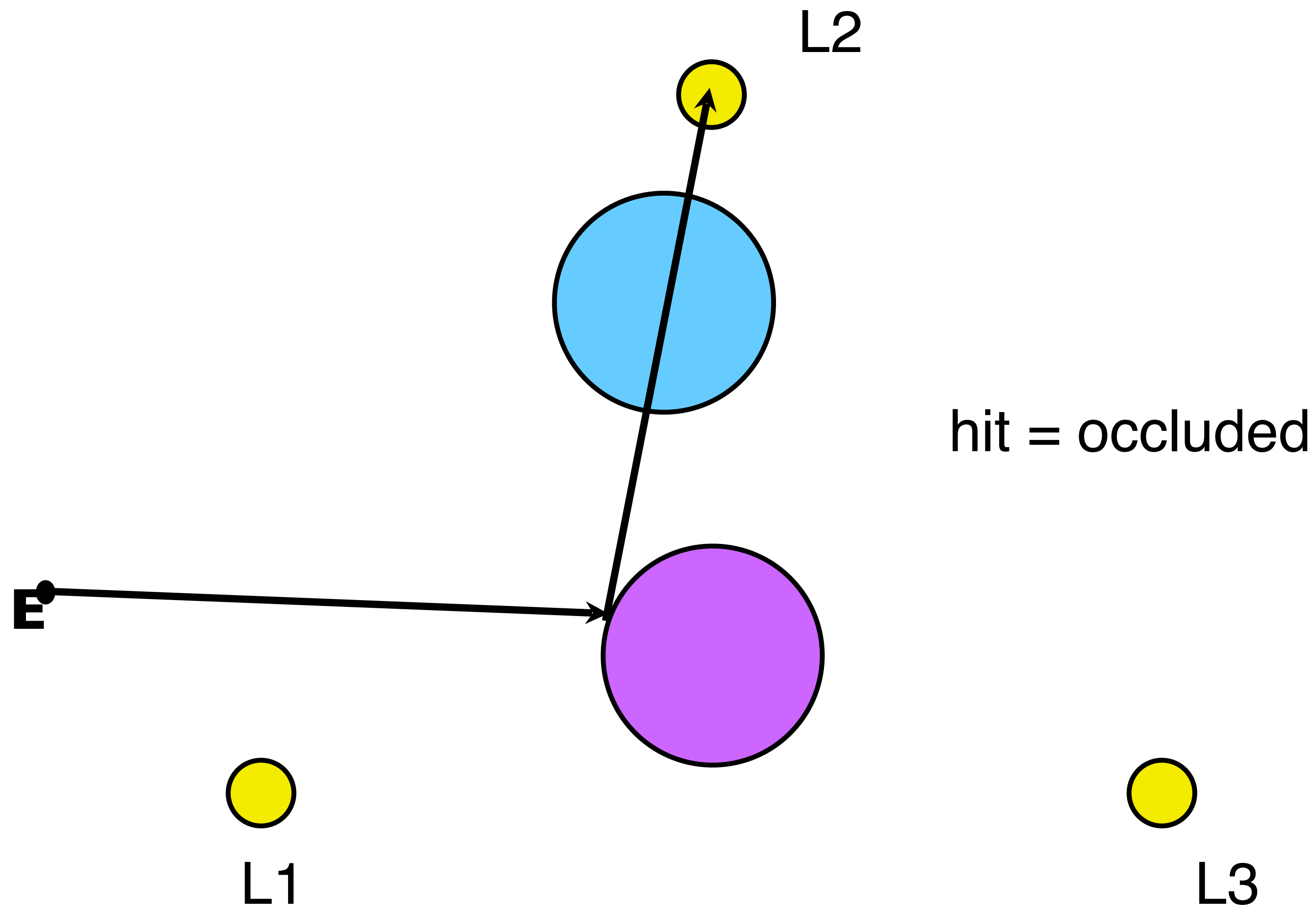
Example



Example



Example



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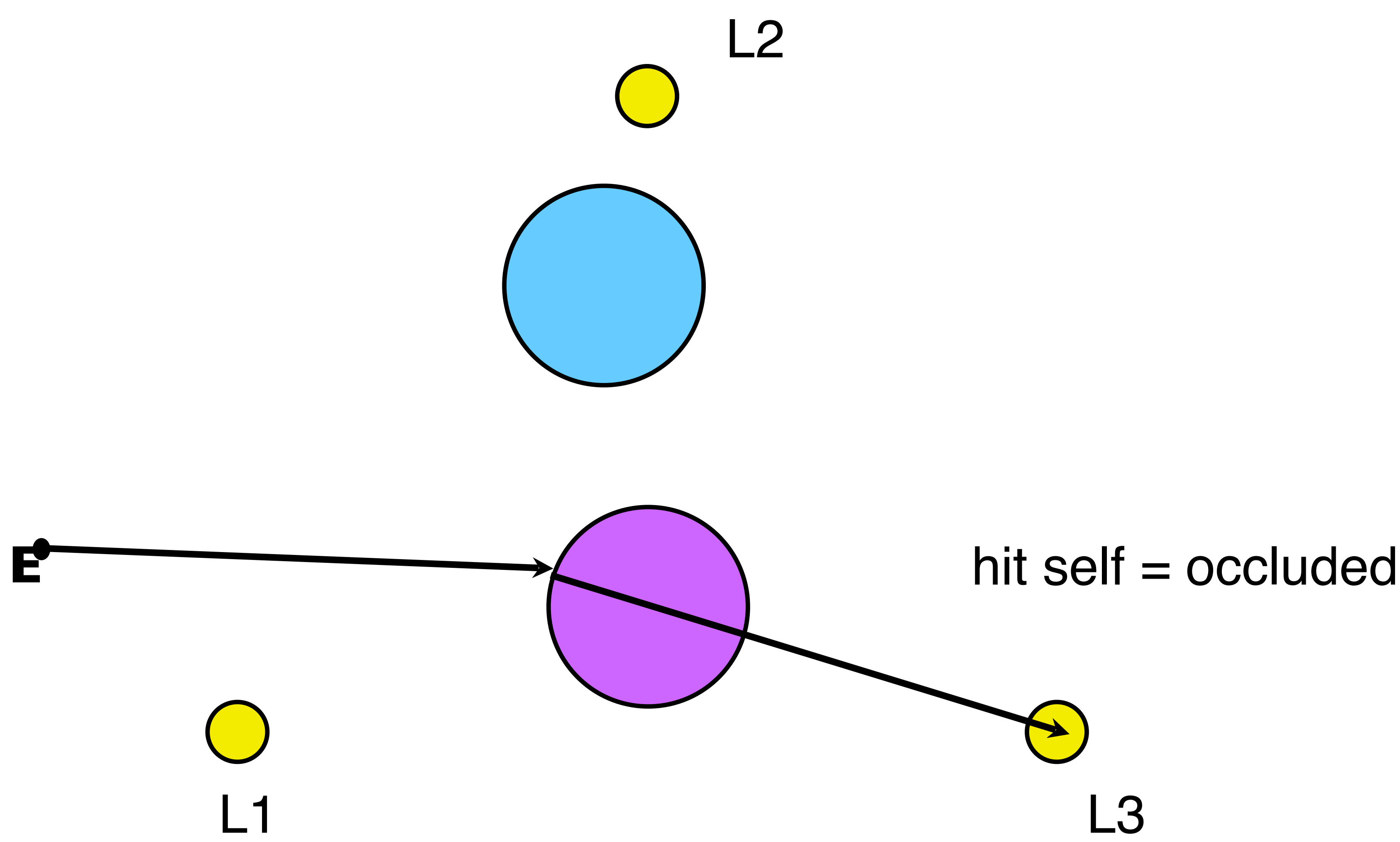

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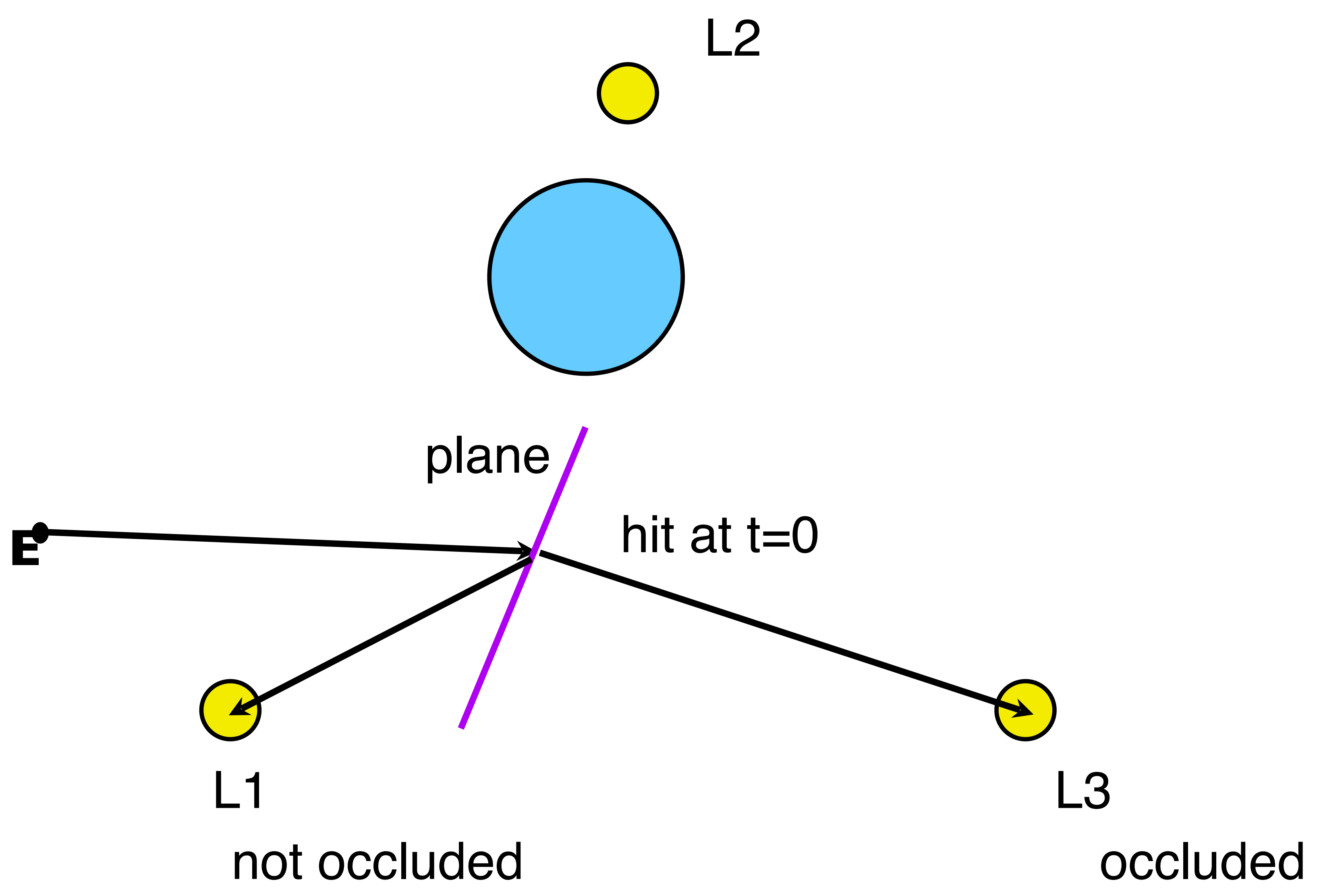
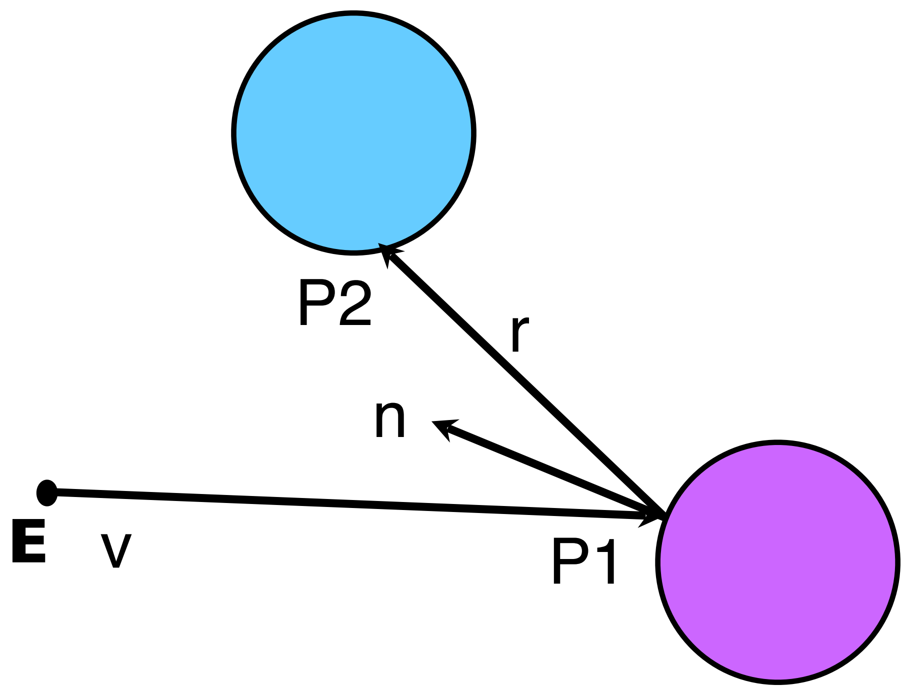


PseudoCode

```
Trace primary ray
if (hit is null)
  set (x,y) to background
else
  set (x,y) = ambient color
  Trace secondary ray to each light
    if not blocked from light
      (x,y) += contribution from light
```

Reflections

- We can now implement realistic reflections by casting further reflected rays.

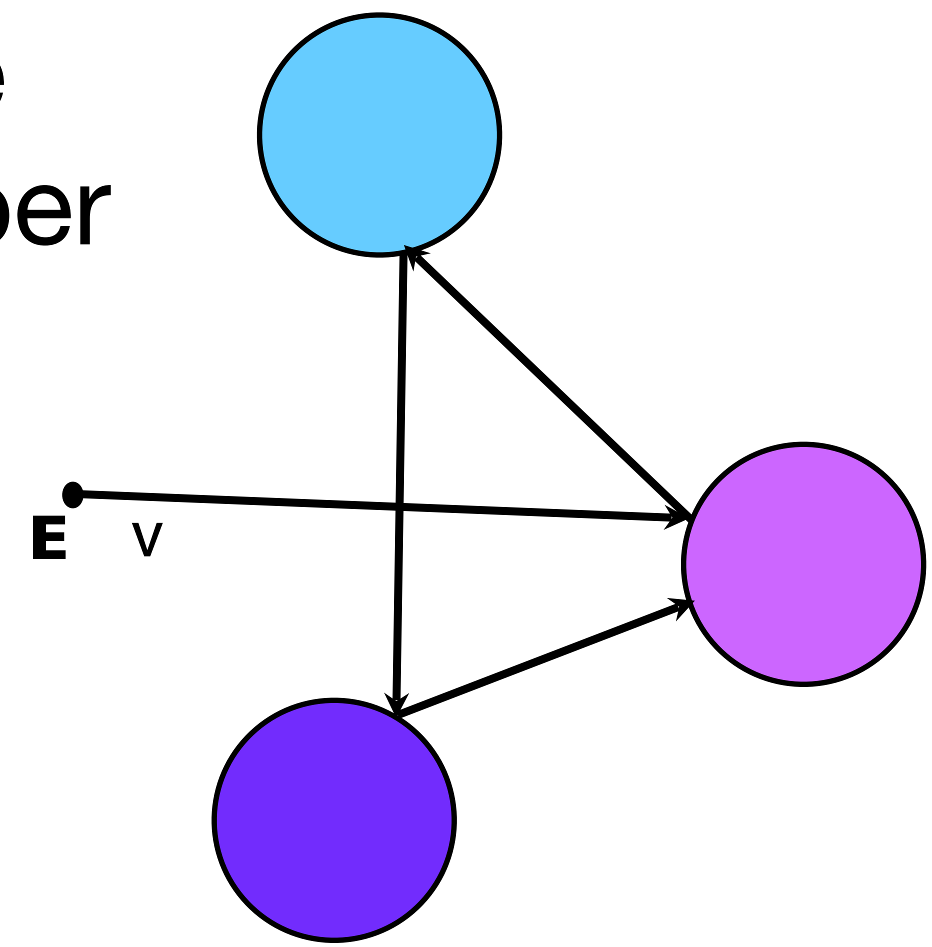


$$\mathbf{r} = \mathbf{v} - 2(\mathbf{v} \cdot \mathbf{n})\mathbf{n}$$

Reflections

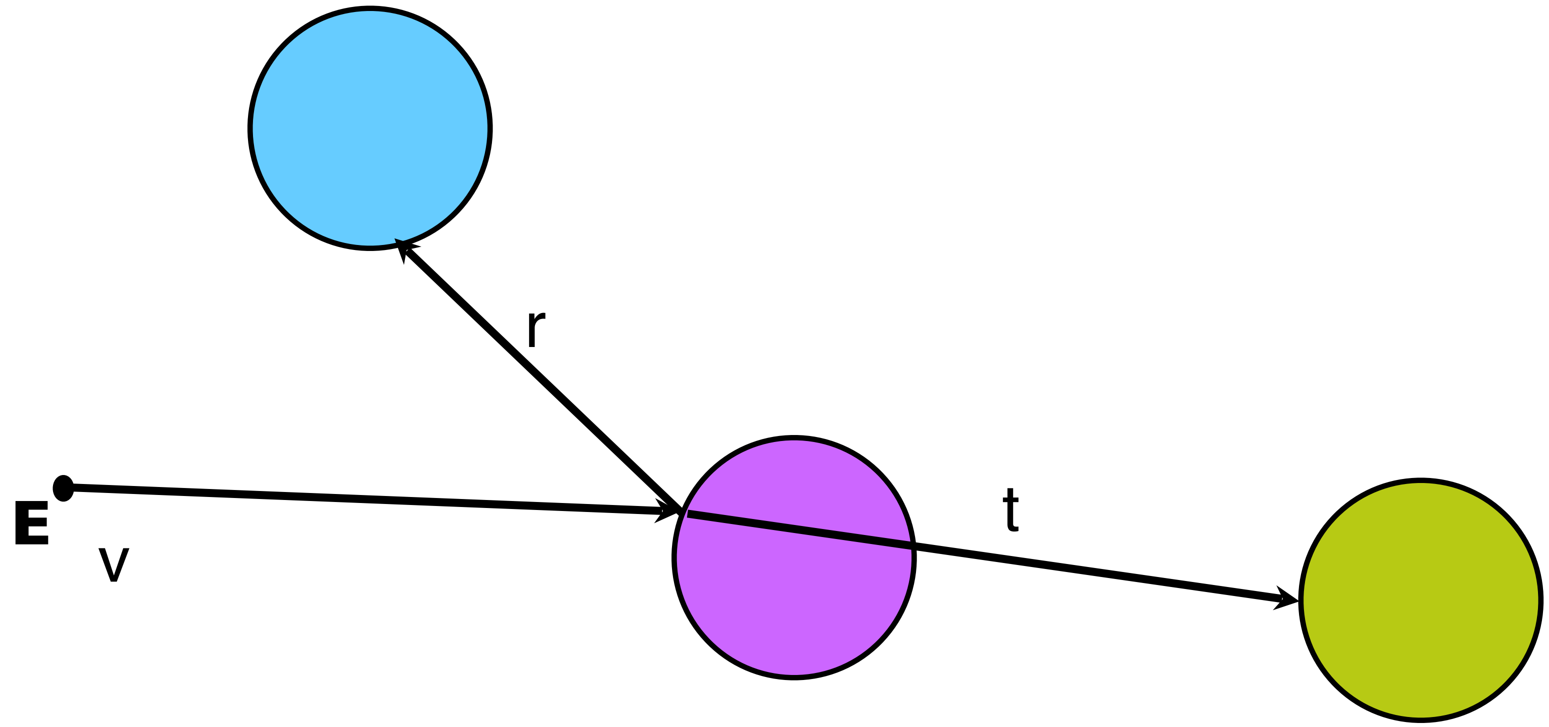
- Reflected rays can in turn be reflected off another object and another.

- We usually write our code to stop after a fixed number of reflections to avoid infinite recursion.



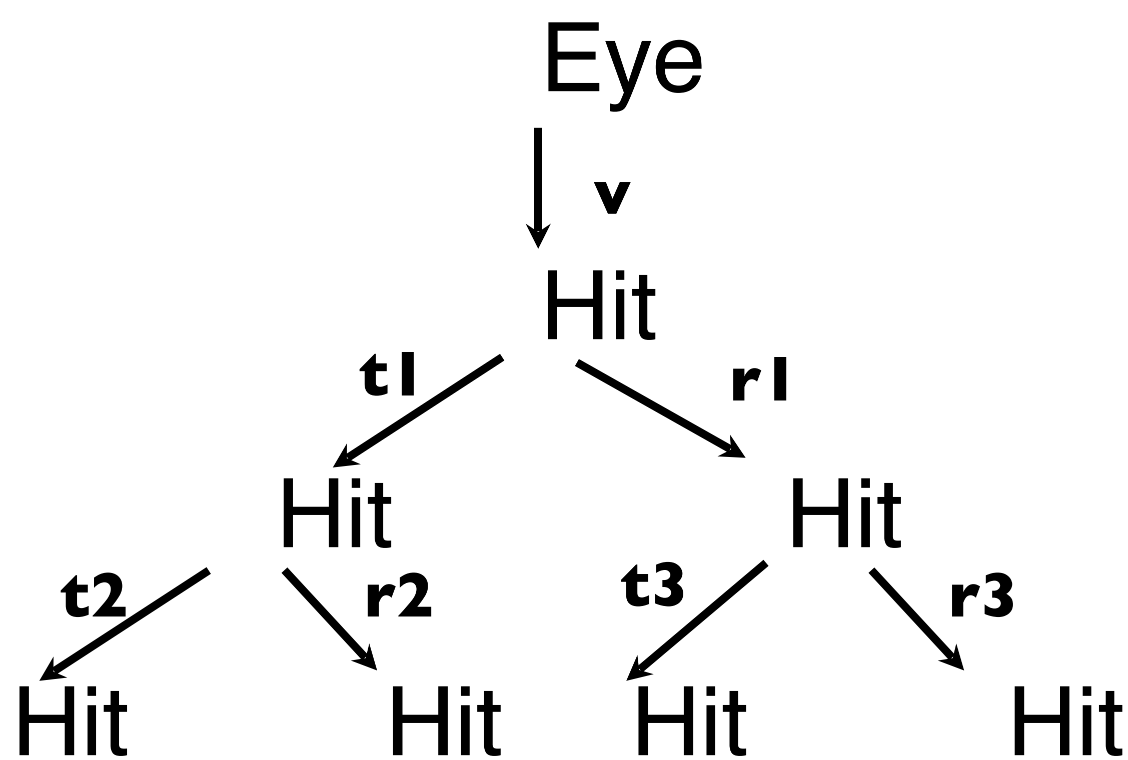
Transparency

- We can also model transparent objects by casting a second ray that continues through the object.



Transparency

- Transparency can also be applied reflexively, yielding a tree of rays.



Illumination

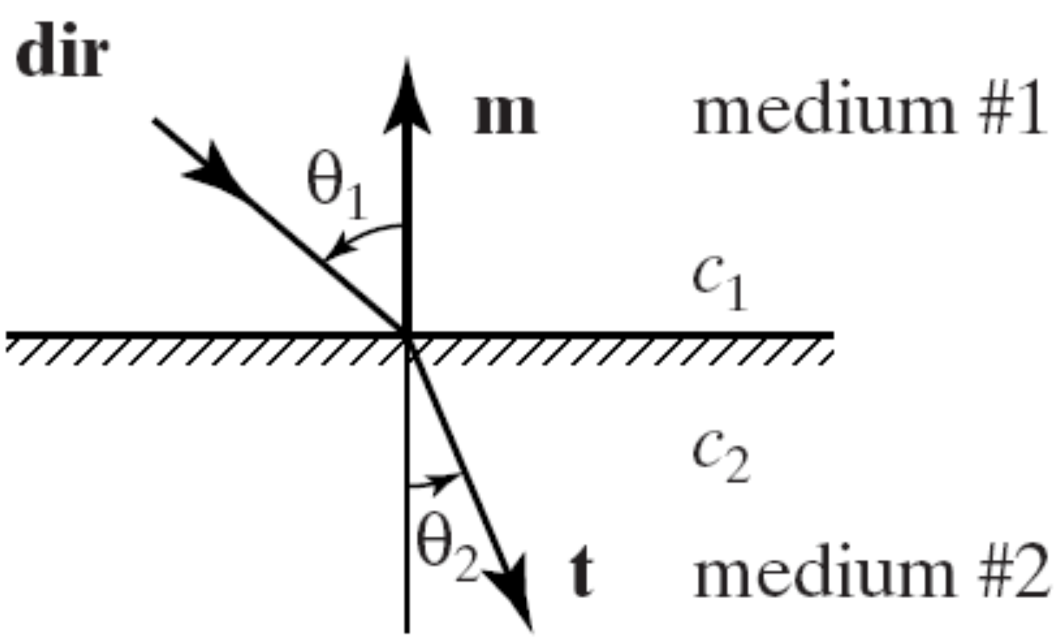
- The illumination equation is extended to include reflected and transmitted components, which are computed recursively:

$$I(P) = I_{amb} + I_{dif} + I_{spe} + \boxed{I(P_{ref}) + I(P_{tra})}$$

- We will need material coefficients to attenuate the reflected and transmitted components appropriately.

Refraction of Light

- When a light ray strikes a transparent object, a portion of the ray penetrates the object. The ray will change direction from **dir** to **t** if the speed of light is different in medium 1 and medium 2. Vector **t** lies in the same plane as **dir** and the normal **m**.



Refraction

- To handle transparency appropriately we need to take into account the refraction of light.
- Light bends as it moves from one medium to another. The change is described by Snell's Law:

$$\frac{\sin\theta_1}{c_1} = \frac{\sin\theta_2}{c_2}$$

- where c1 and c2 are the speeds of light in each medium.

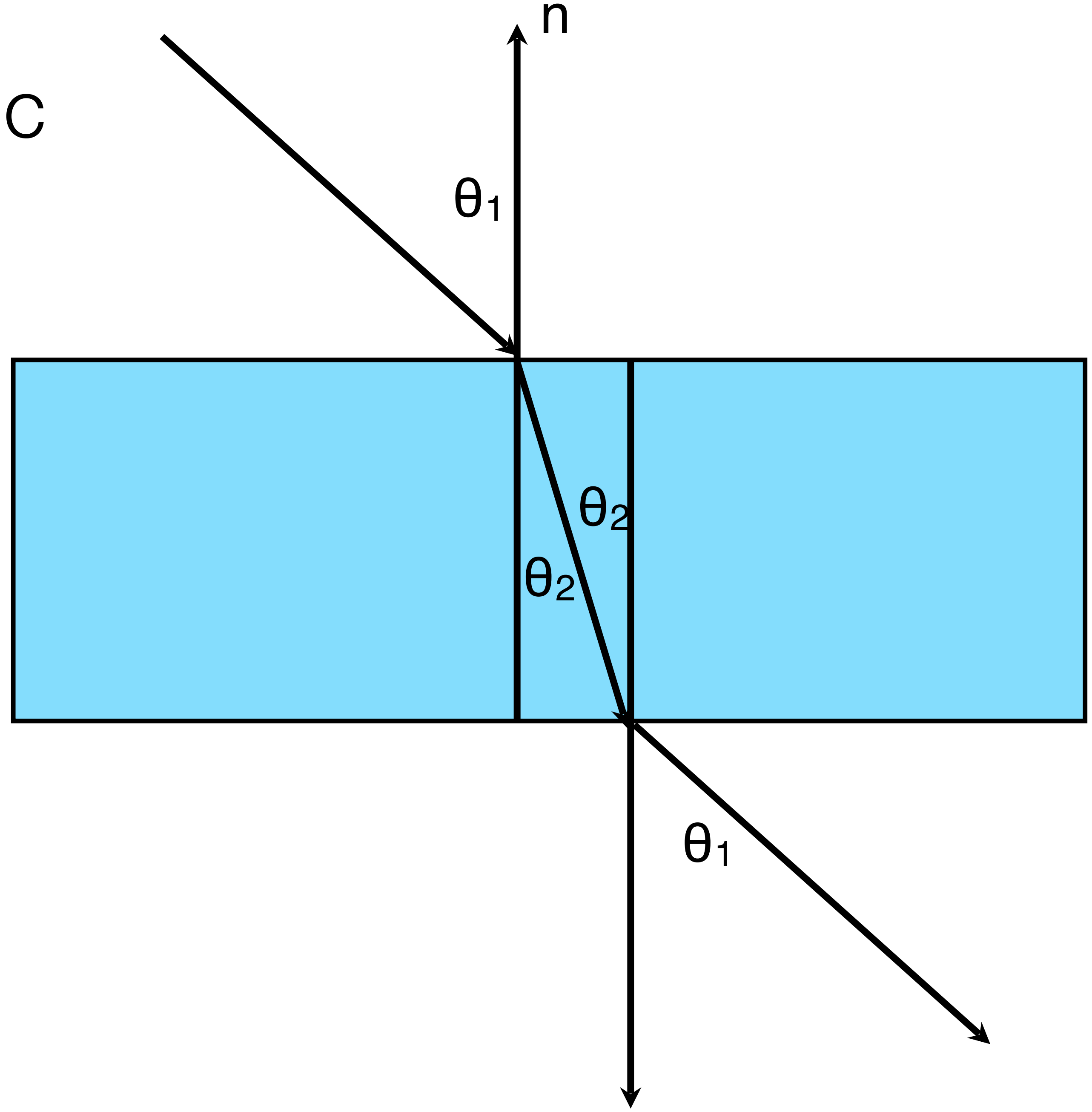
Example Snell's law

Air:

$c_1 = 99.97\%\ c$

Glass:

$c_2 \sim= 55\%\ c$



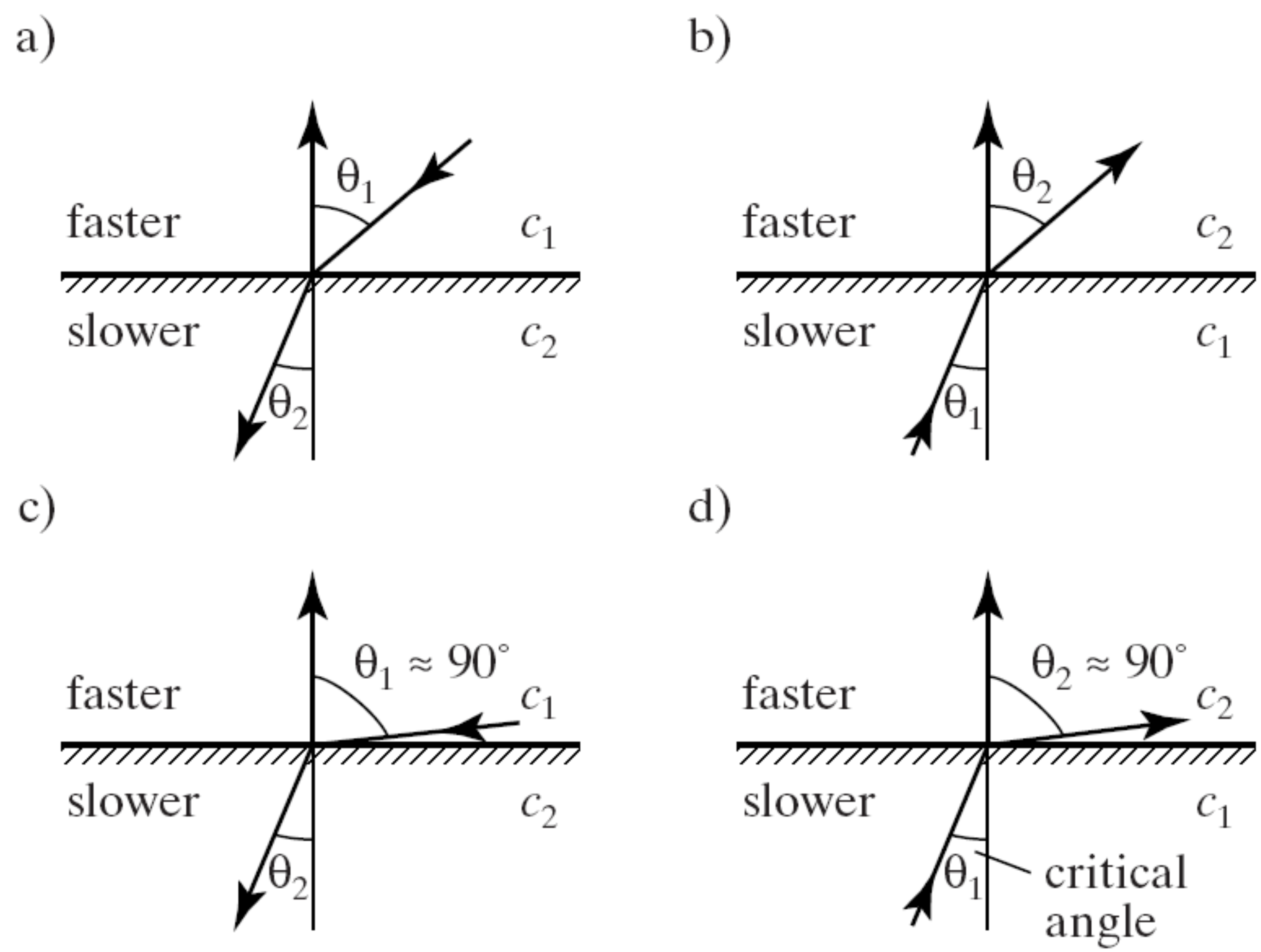
Example

- Suppose medium 2 is some form of glass in which light only travels 55% as fast as in medium 1 which is the air. Suppose the angle of incidence of the light is 60 degrees from the normal. What is the angle of the transmitted light?

Refraction

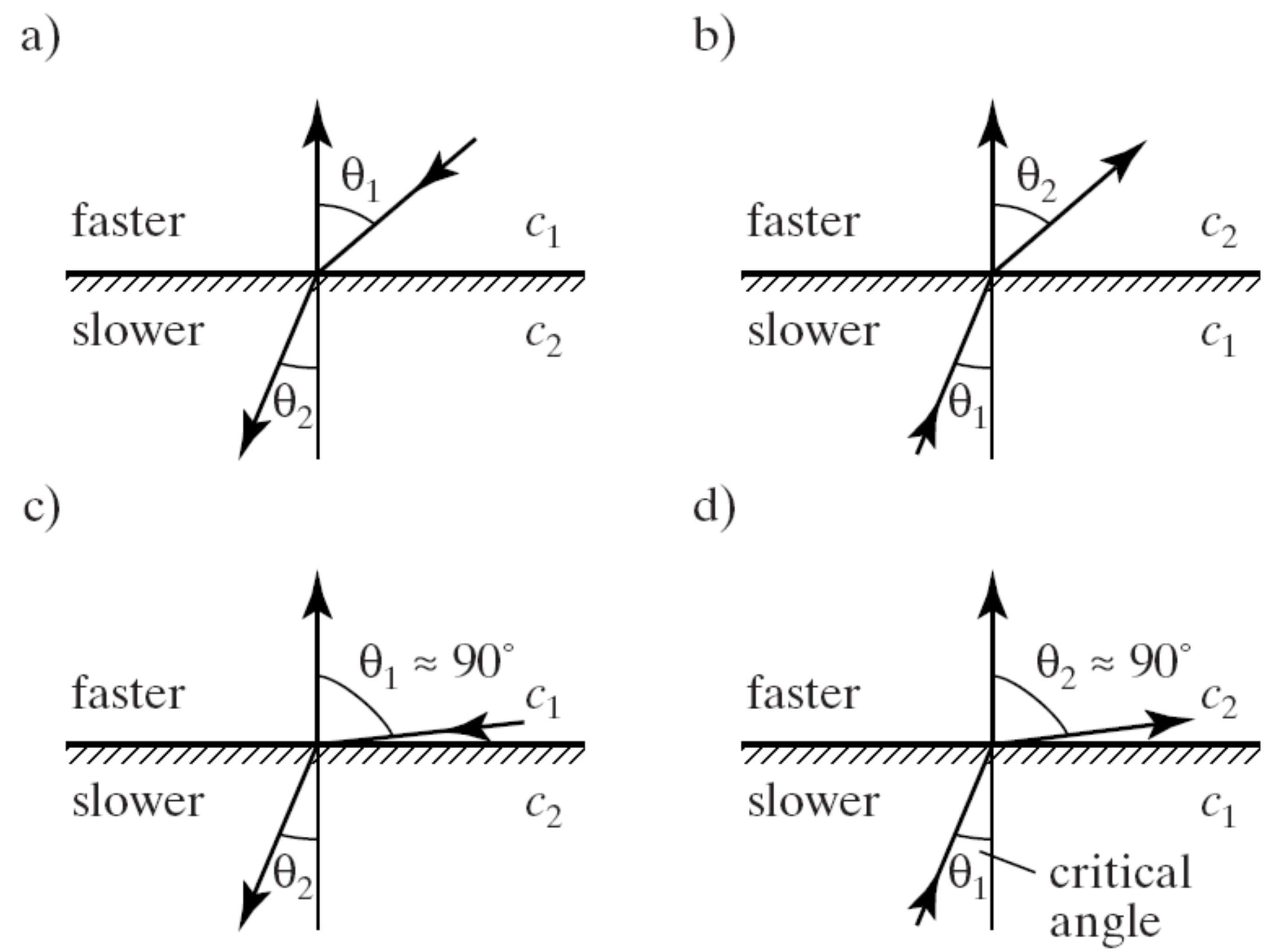
- The figure (a) shows light moving from the faster medium to the slower, and (b) shows light moving from the slower to the faster medium.

- The angles pair together in the same way in both cases; only the names change.



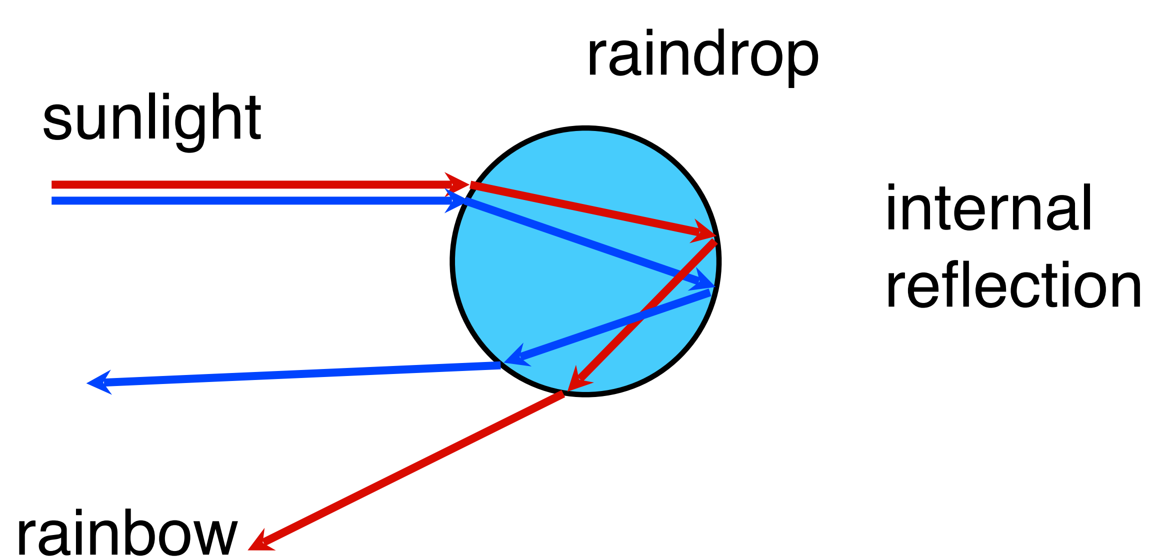
Refraction

- In (c) and (d), the larger angle has become nearly 90^0. The smaller angle is near the **critical angle**: when the smaller angle (of the slower medium) gets large enough, it forces the larger angle to 90^0. A larger value is impossible, so no light is transmitted into the second medium. This is called **total internal reflection**.



Refraction

- Different wavelengths of light move at different speeds (except in a vacuum).
- So for maximum realism, we should calculate different paths for different colours.



Refraction of Light

- Simplest to model transparent objects so that their index of refraction does not depend on wavelength.
- To do otherwise would require tracing separate rays for each of the color components, as they would refract in somewhat different directions.
- This would be expensive computationally, and would still provide only an approximation, because an accurate model of refraction should take into account a large number of colors, not just the three primaries.

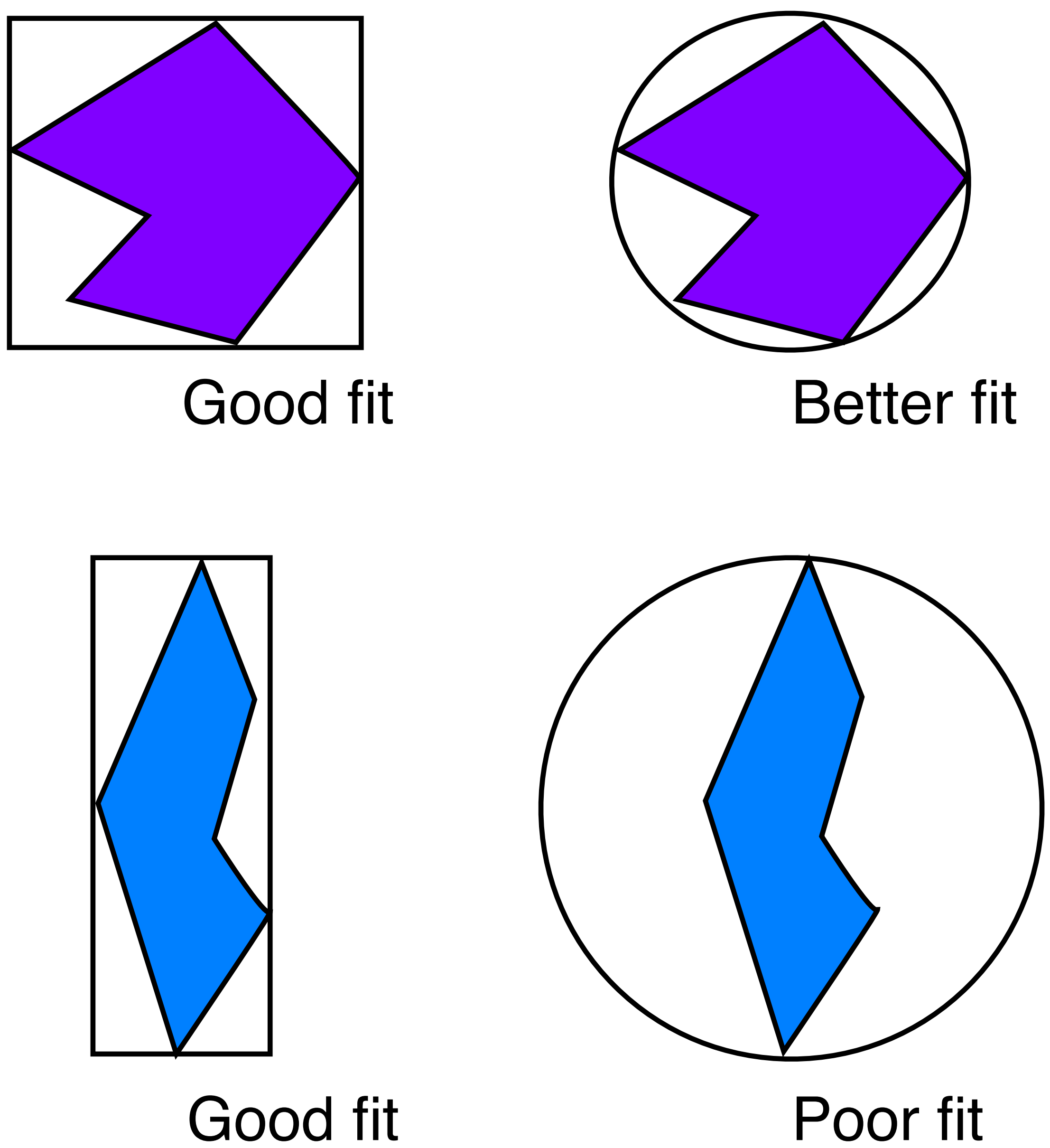
Optimisation

- Testing collisions for more complex shapes (such as meshes) can be very time consuming.
- In a large scene, most rays will not hit the object, so performing multiple expensive collision tests is wasteful.
- We want fast ways to rule out objects which will not be hit.

Extents

- Extents are bounding boxes or spheres which enclose an object.
- Testing against a box or sphere is fast.
- If this test succeeds, then we proceed to test against the object.
- We want tight fitting extents to minimise false positives.

Extents



Computing extents

- To compute a box extent for a mesh we simply take the min and max x, y and z coordinates over all the points.

- To compute a sphere extent we find the centroid of all the vertices by averaging their coordinates. This is the centre of the sphere.

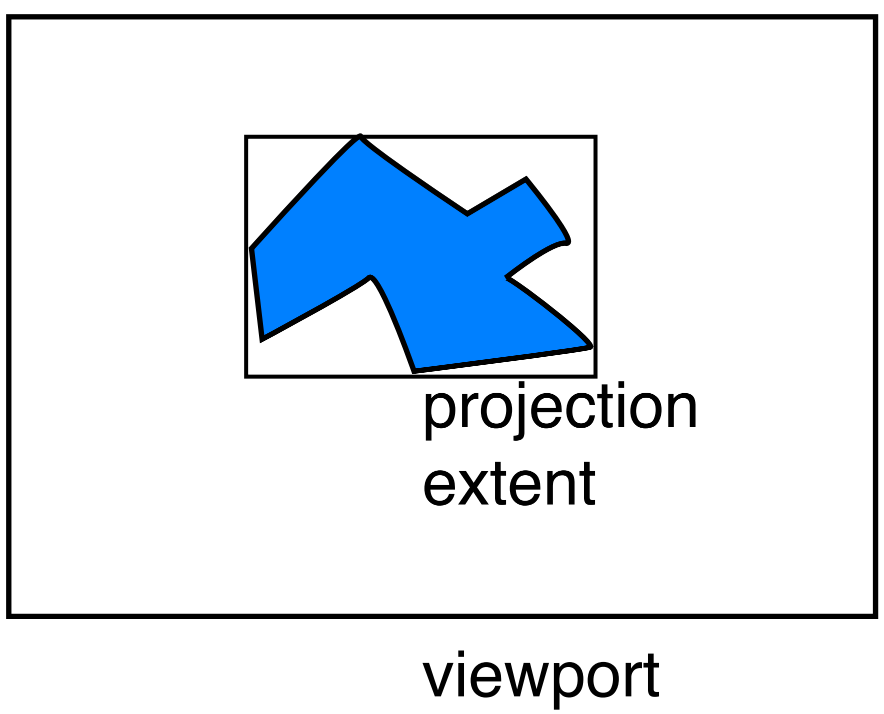
- The radius is the distance to the vertex farthest from this point.

Projection extents

- Alternatively, we can build extents in screen space rather than world space.
- A projection extent of an object is a bounding box which encloses all the pixels which would be in the image of the object (ignoring occlusions).
- Pixels outside this box can ignore the object.
- Doesn’t work for shadow feelers or reflected rays

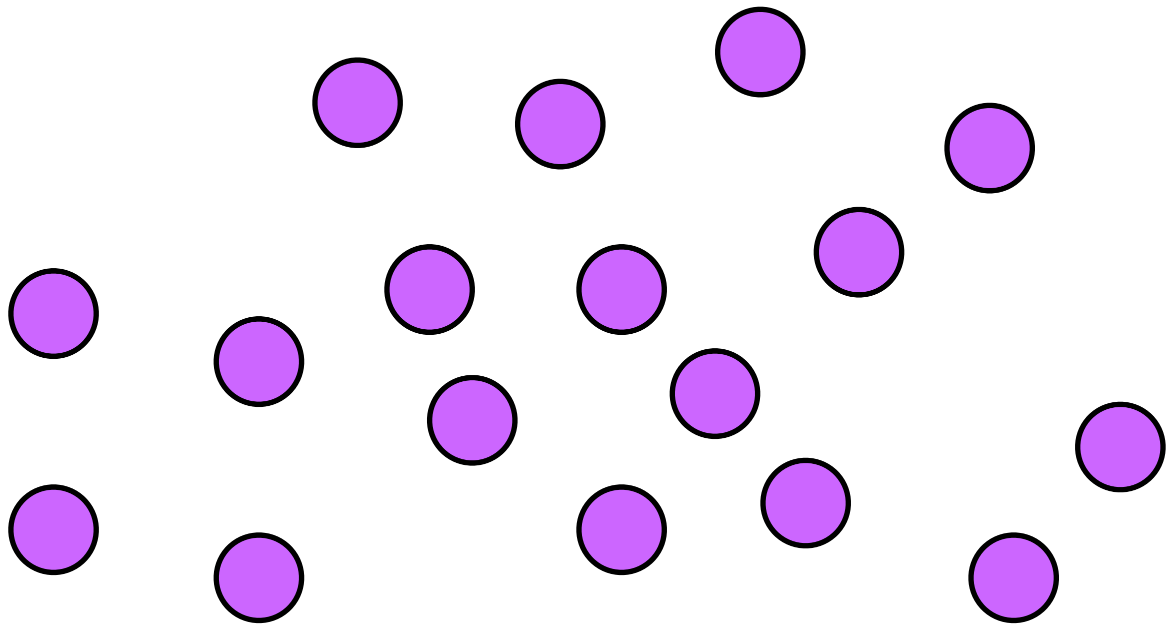
Projection extents

- We can compute a projection extent of a mesh by projecting all the vertices into screen space and finding the min and max x and y values.



Binary Space Partitioning

- Another approach to optimisation is to build a Binary Space Partitioning (BSP) tree dividing the world into cells, where each cell contains a small number of objects.



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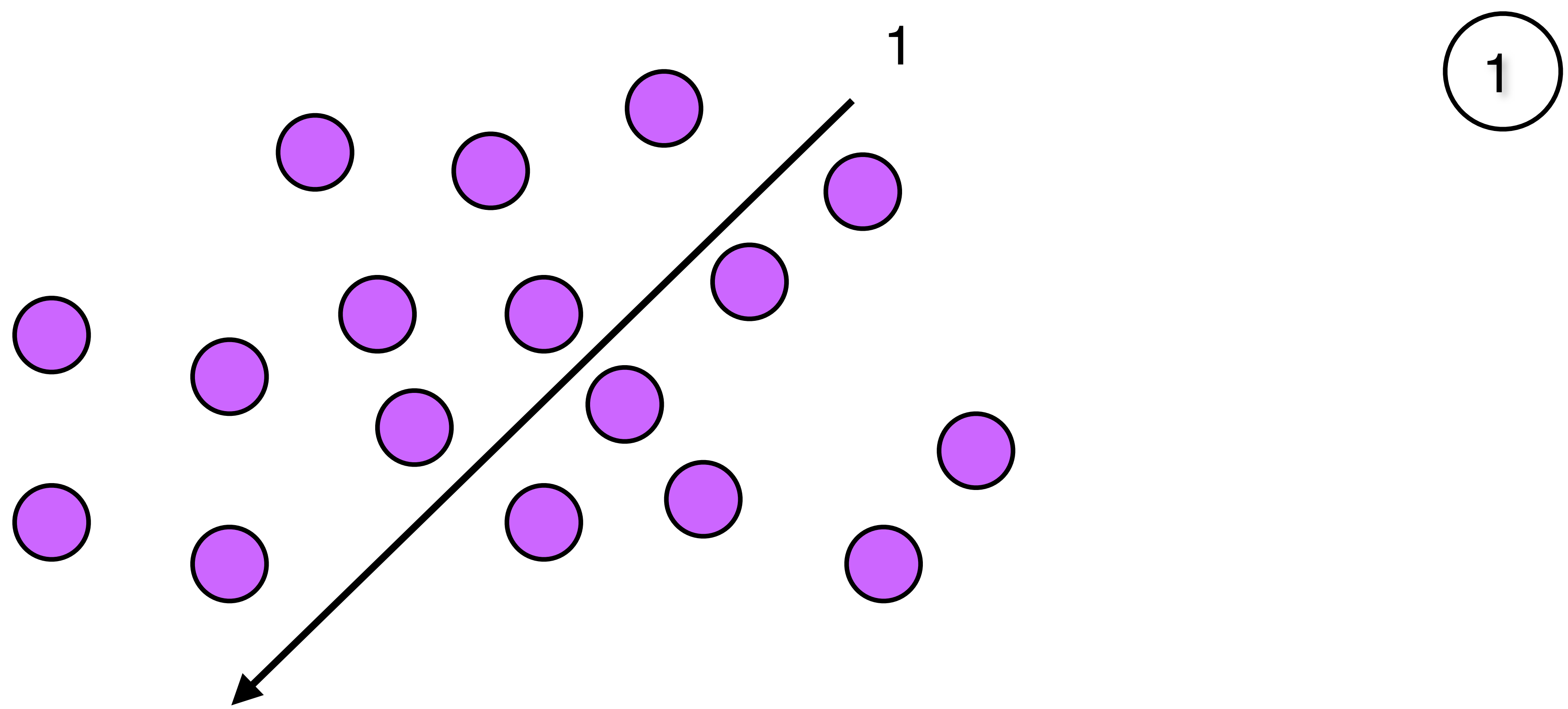

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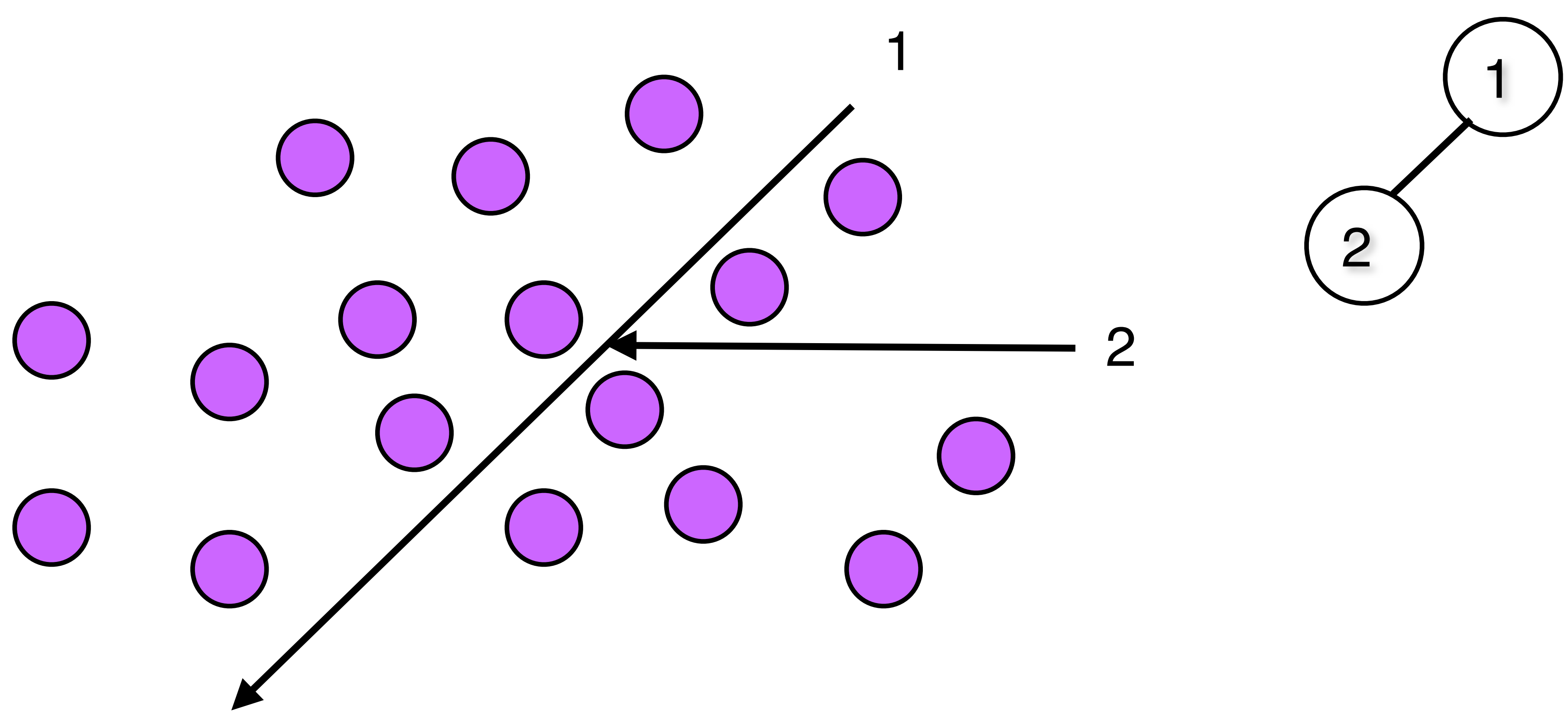

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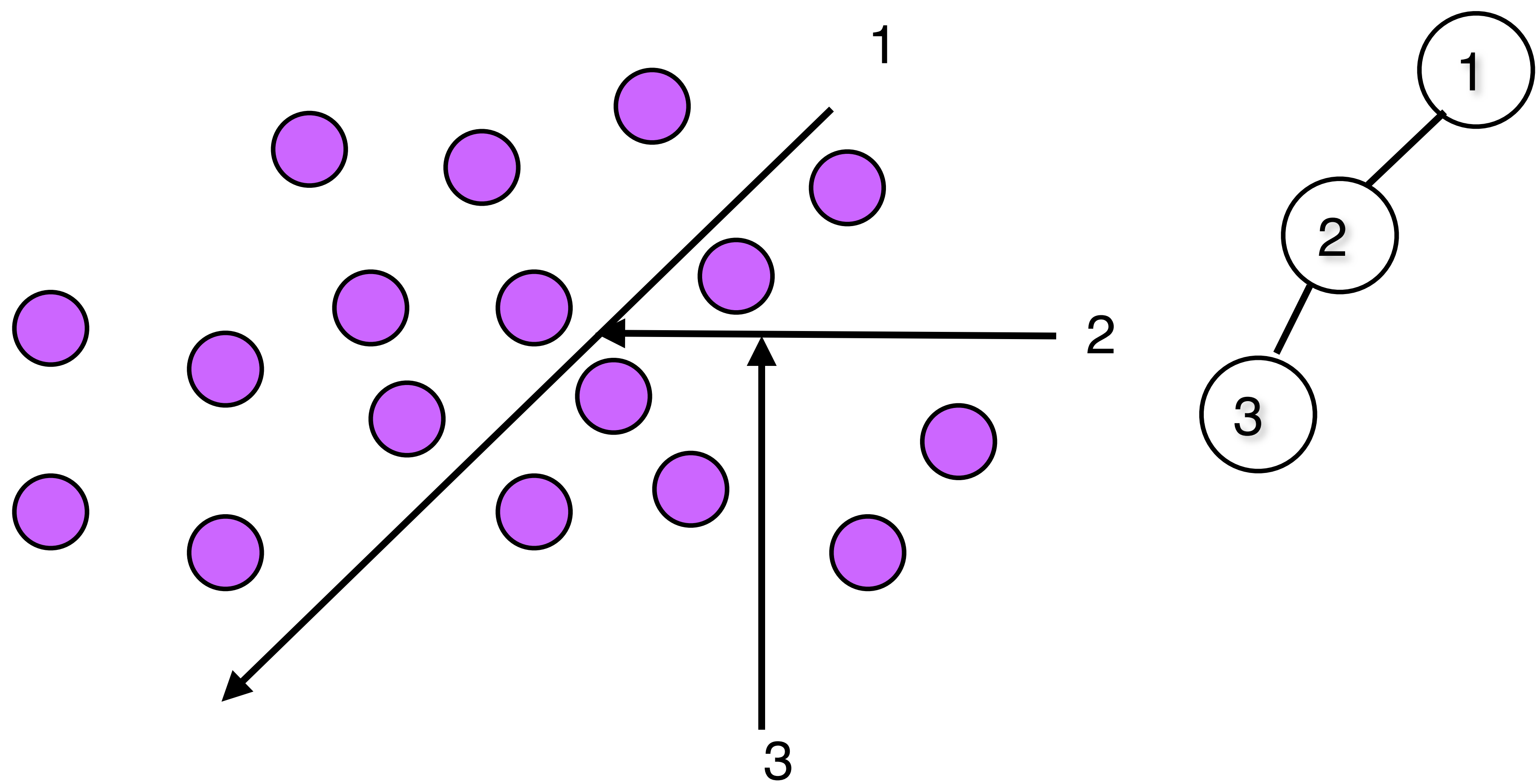

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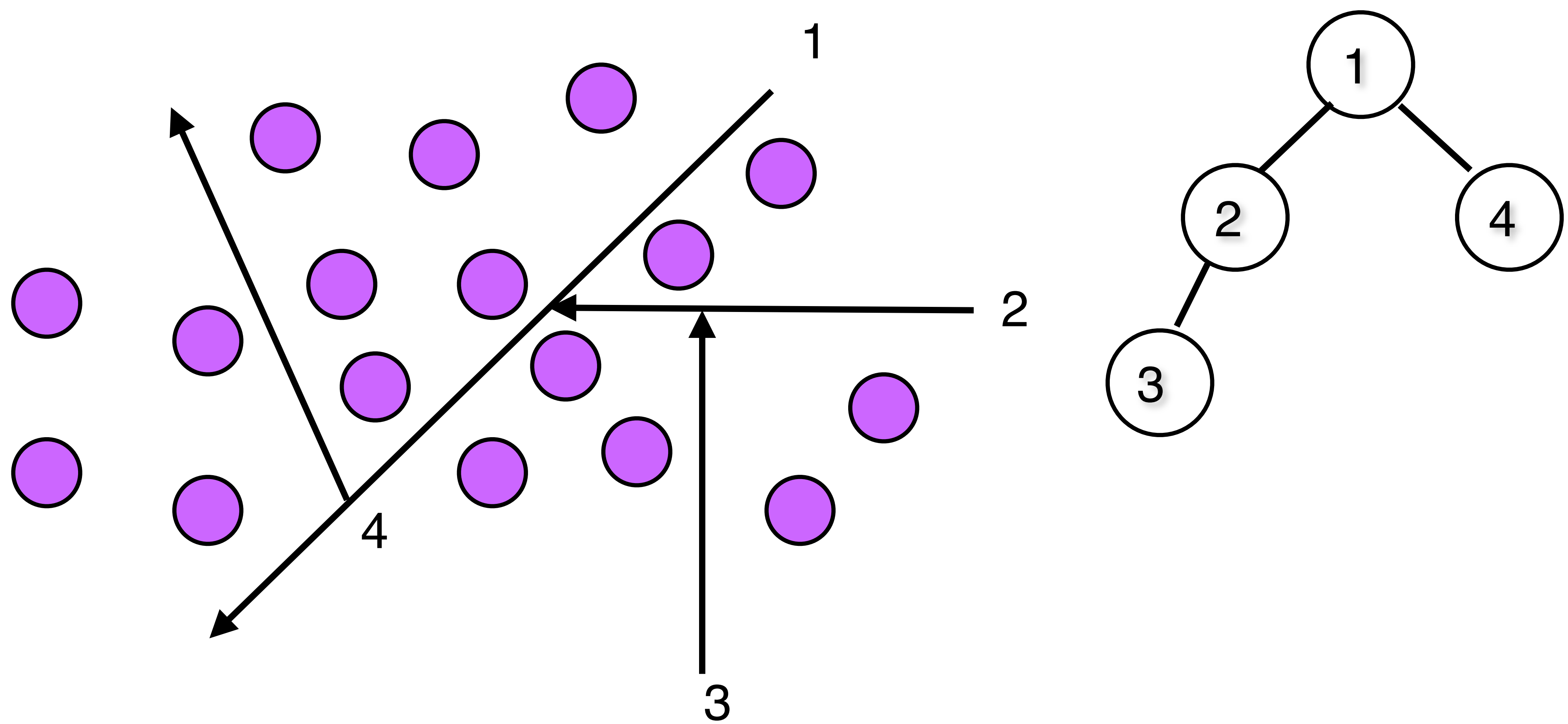

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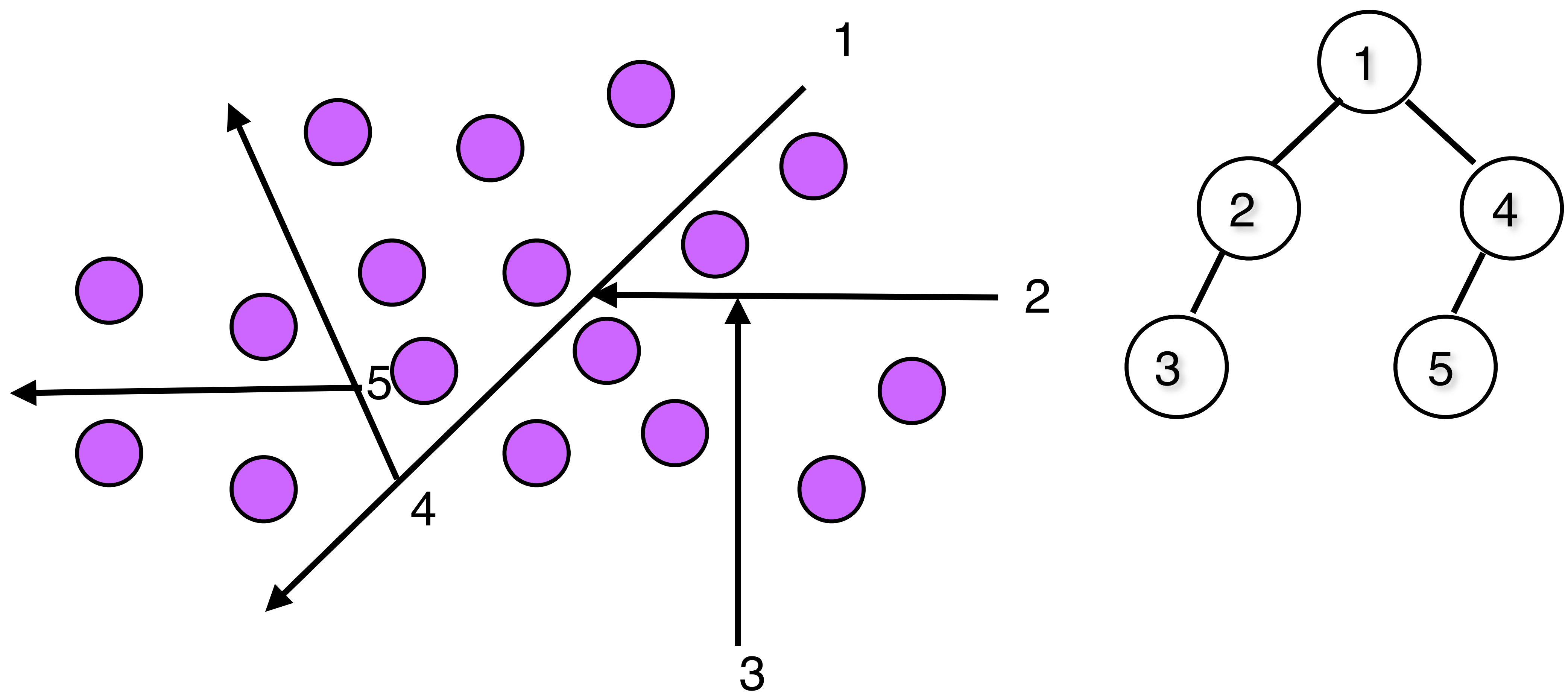

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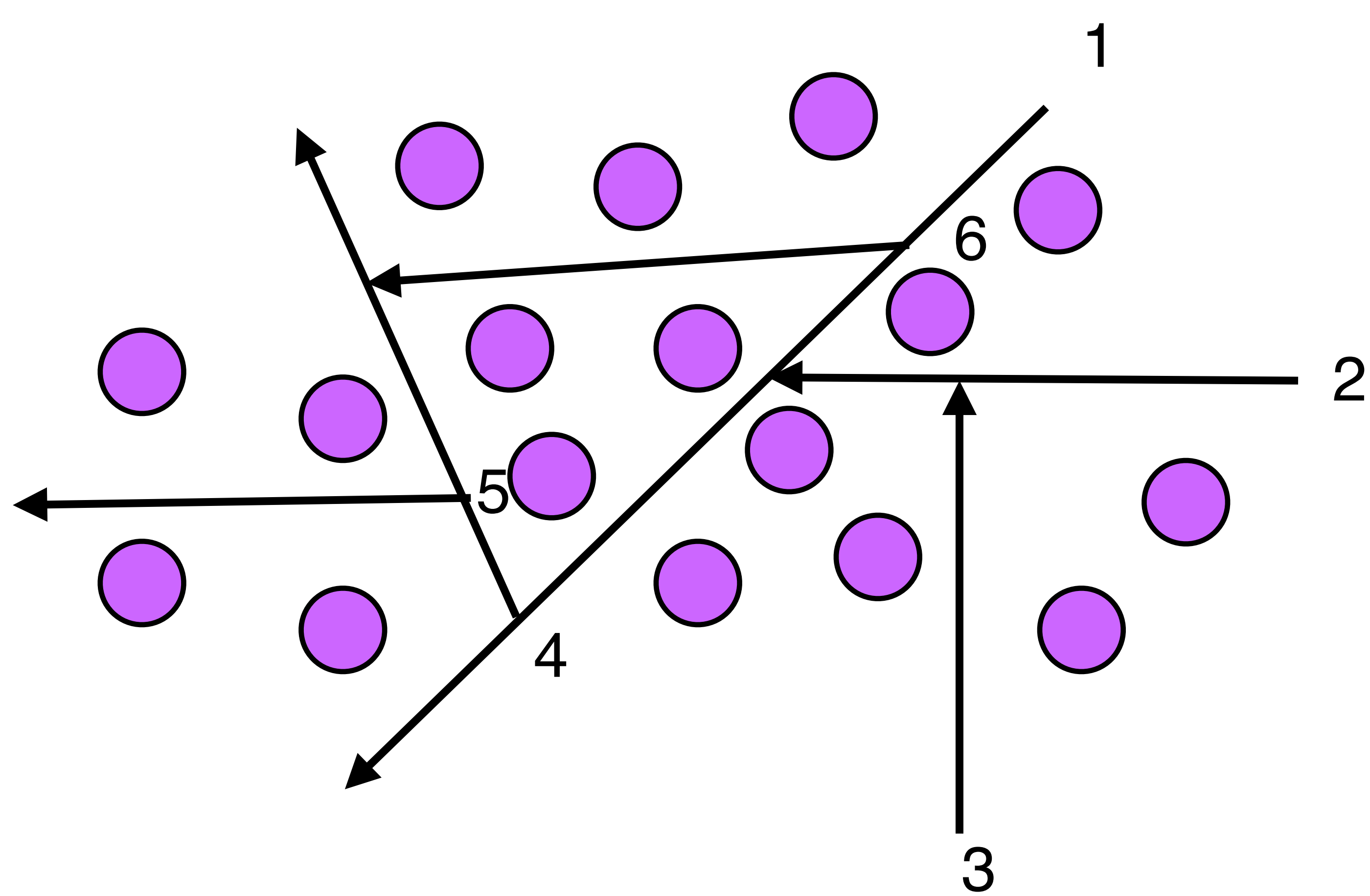

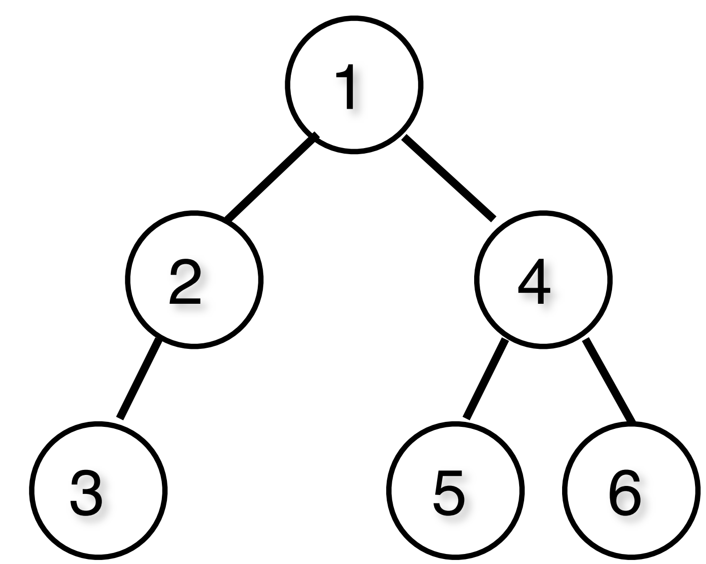

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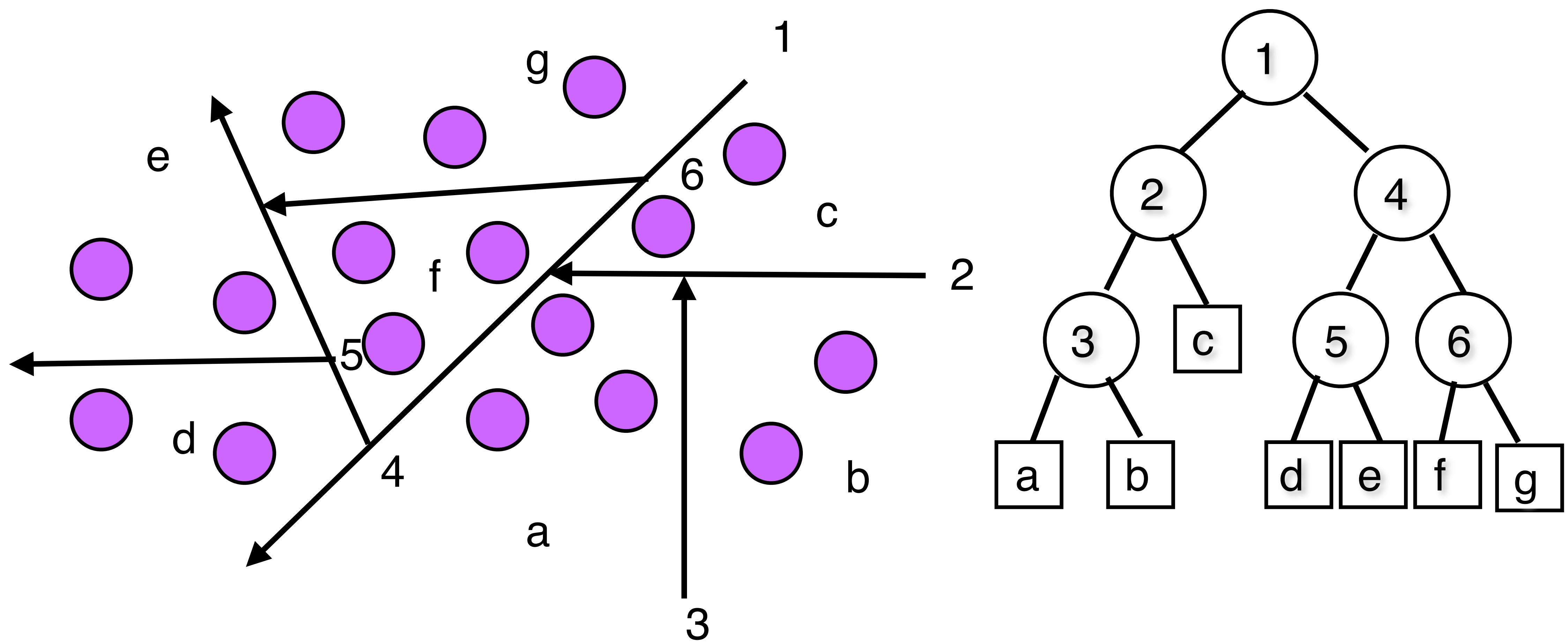
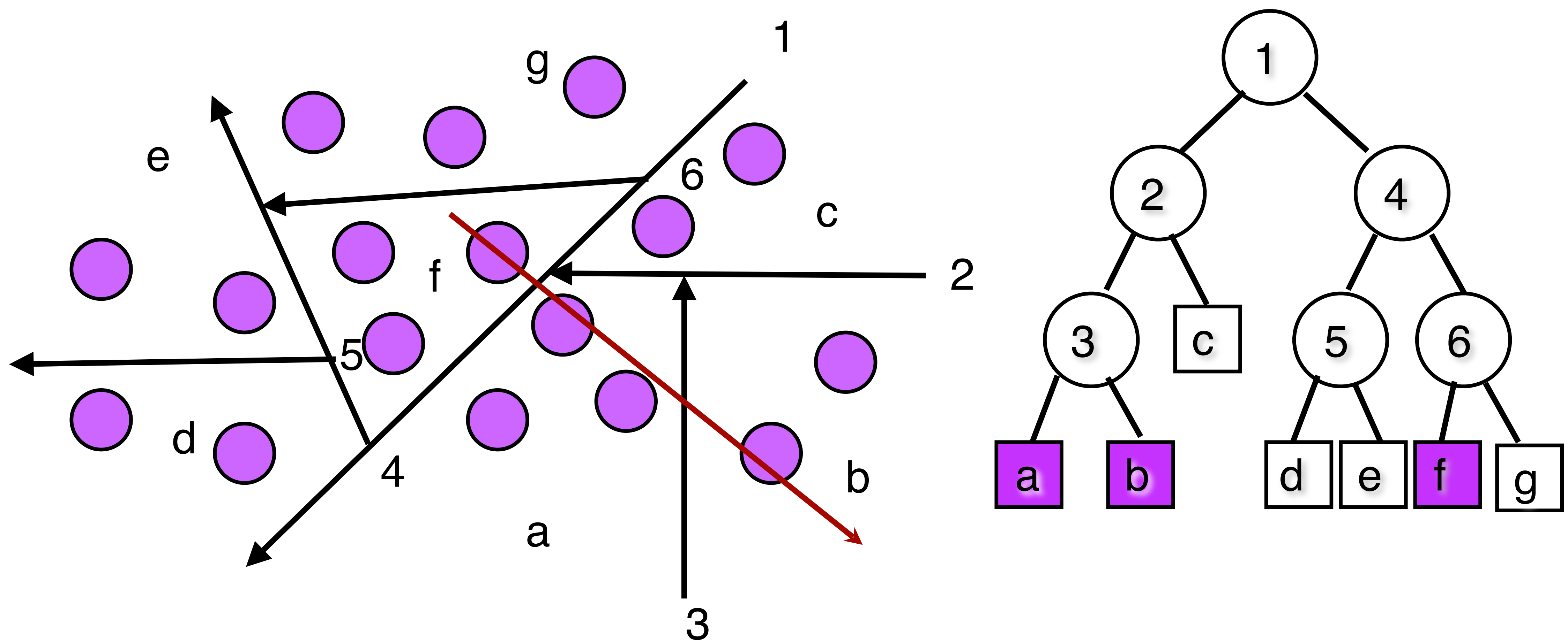


Traversing the tree

- In this case we do not want to traverse the entire tree. We only want to visit the leaves the ray passes through.



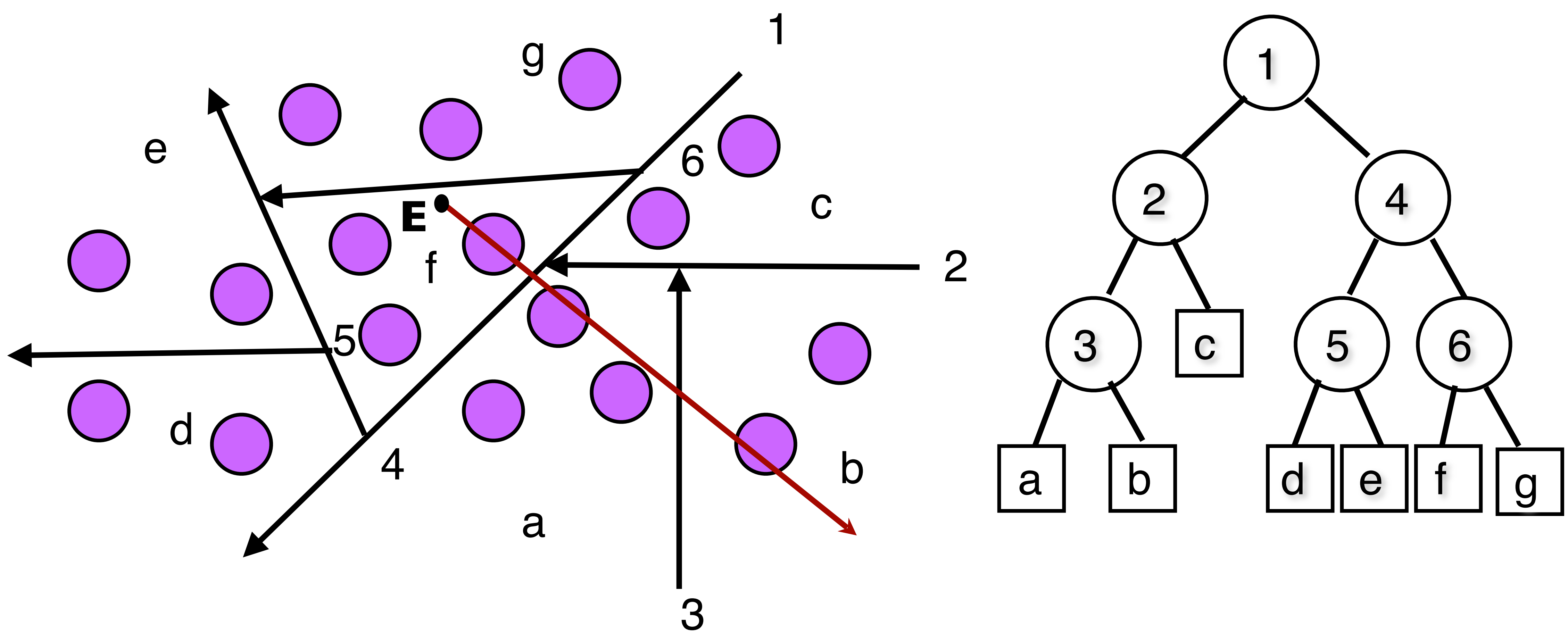
Traversal algorithm

```
visit(E, v, node): (E eye)
  if (node is leaf):
     intersect ray with objs in leaf
  else:
     if (E on left):
         visit(E, v, left)
         other = right;
     else:
         visit(E, v, right)
         other = left
     endif

     if (ray crosses boundary):
         E' = intersect(E, v, boundary)
         visit(E', v, other)
     endif

  endif
```

Traversing the tree



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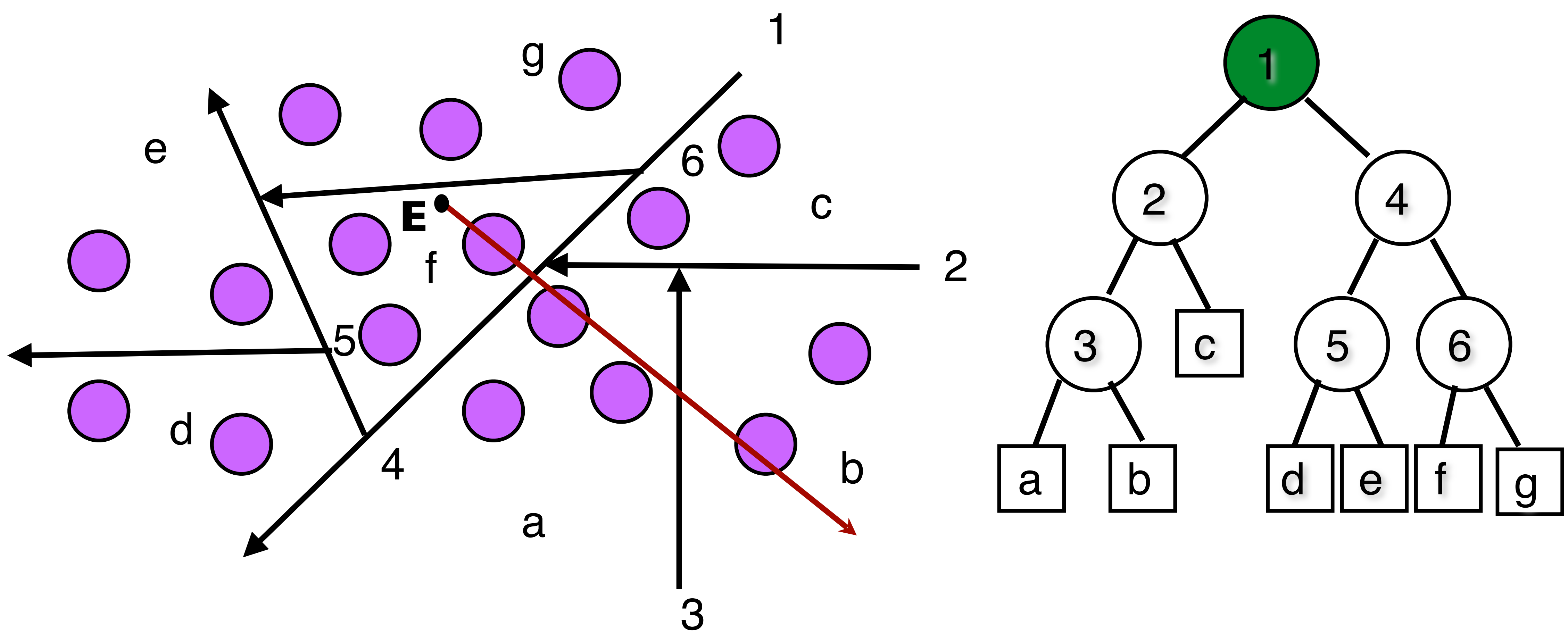

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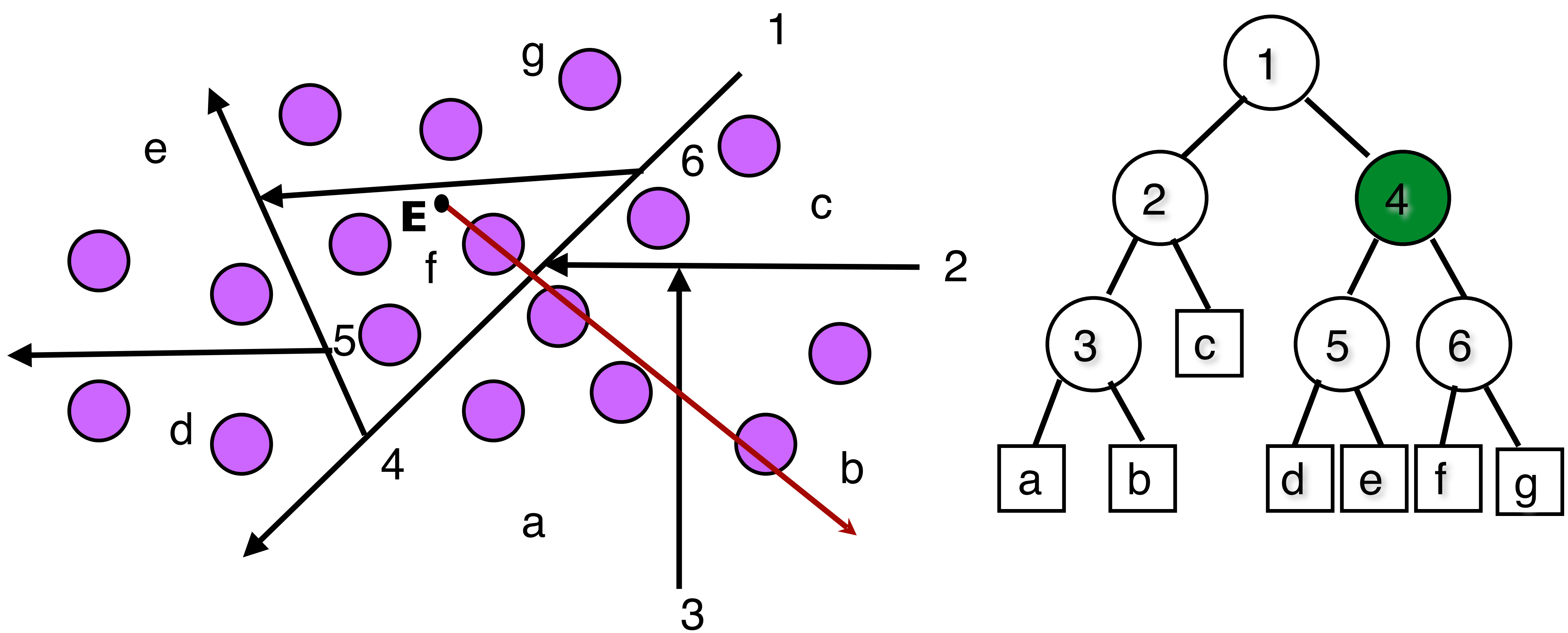

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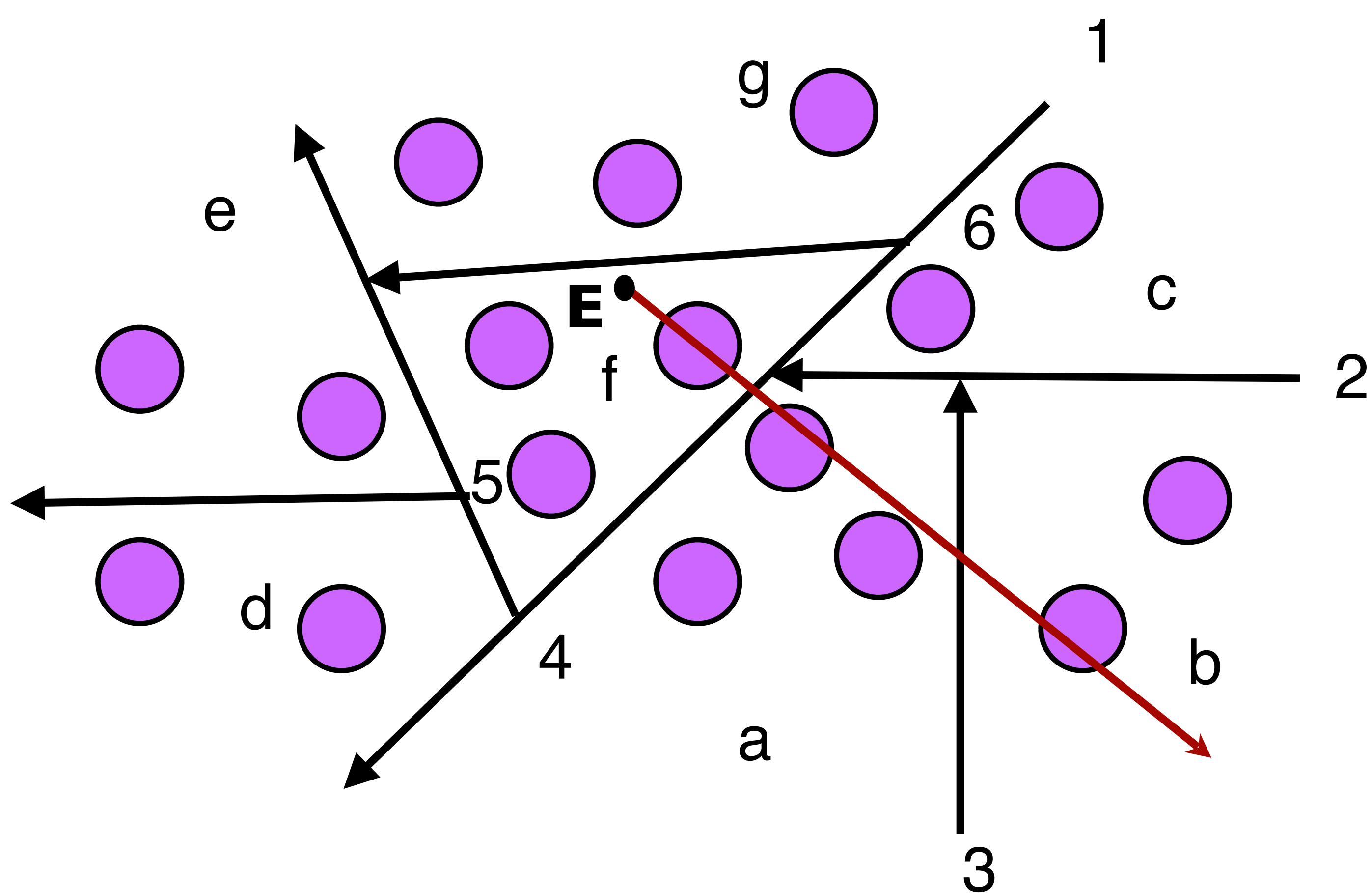

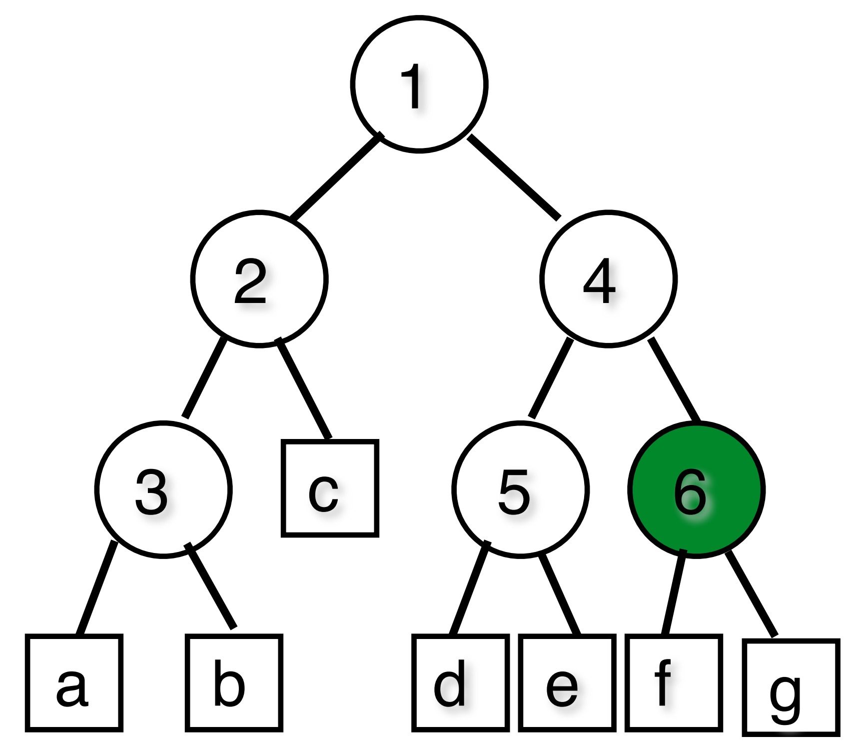

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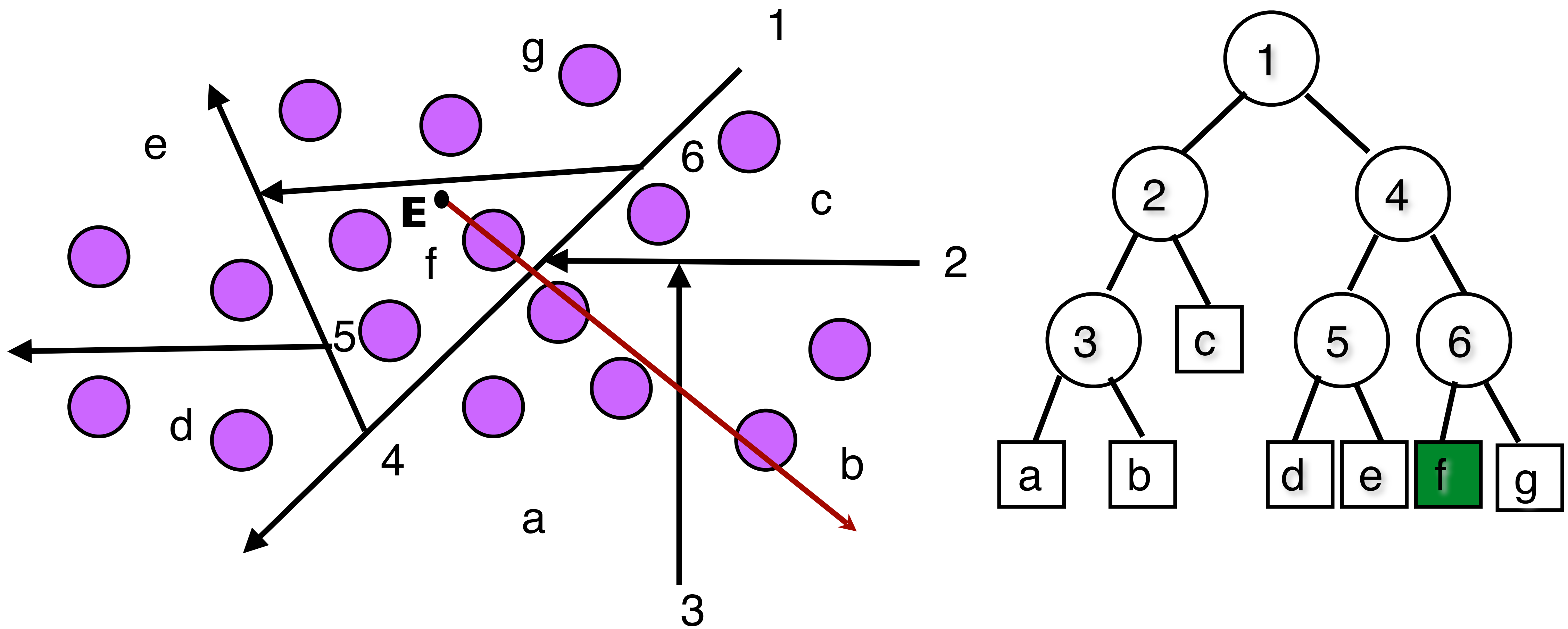

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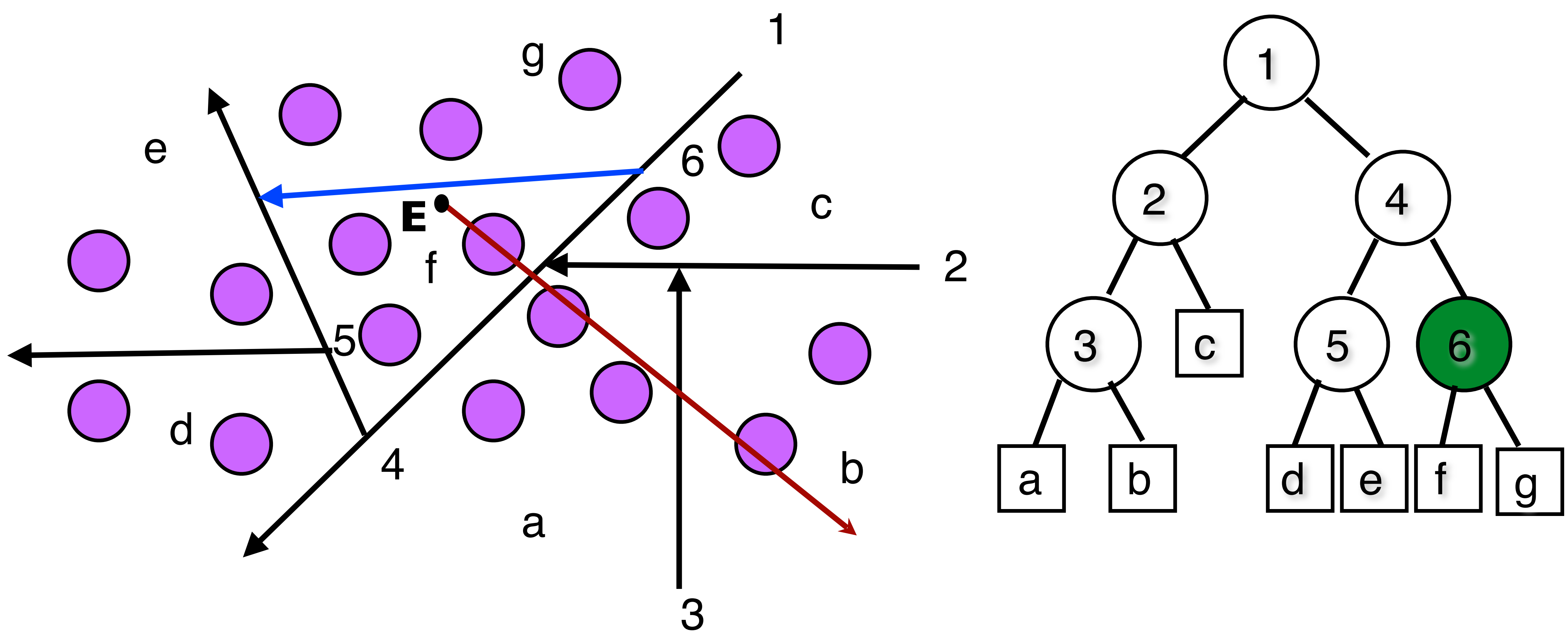

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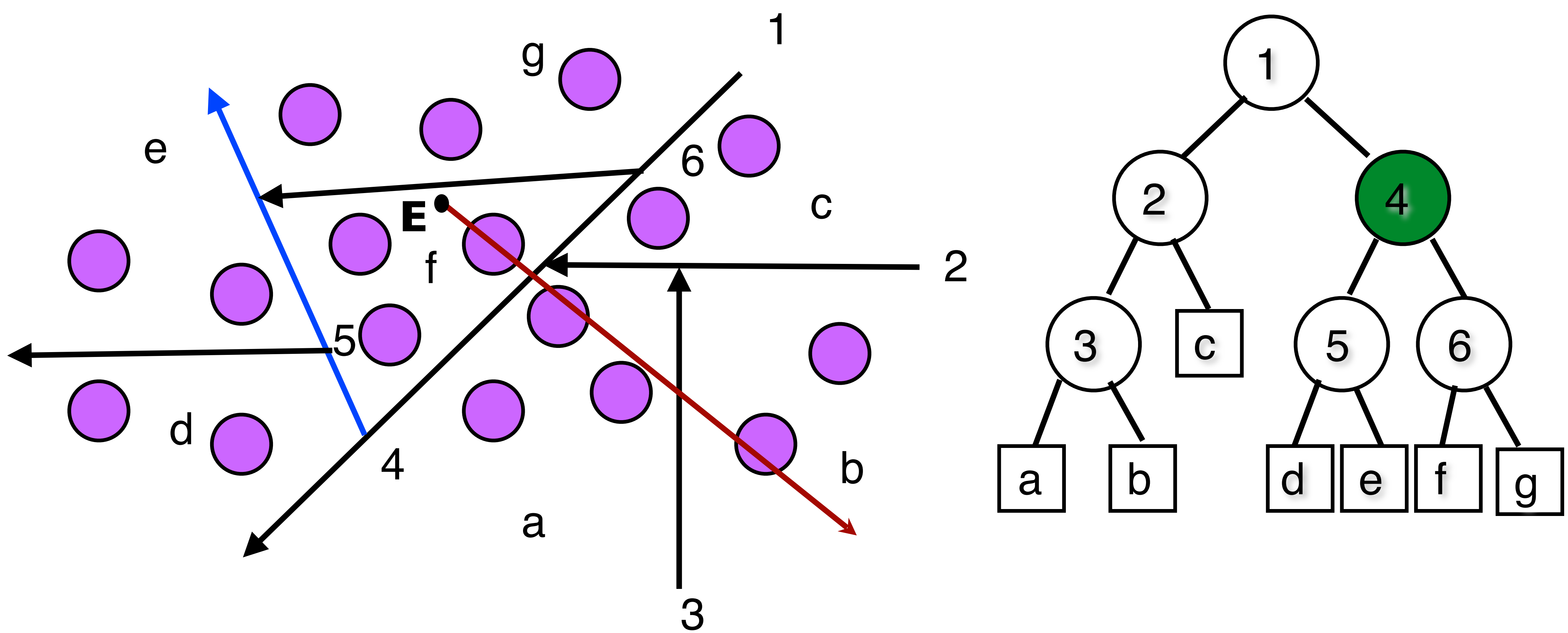

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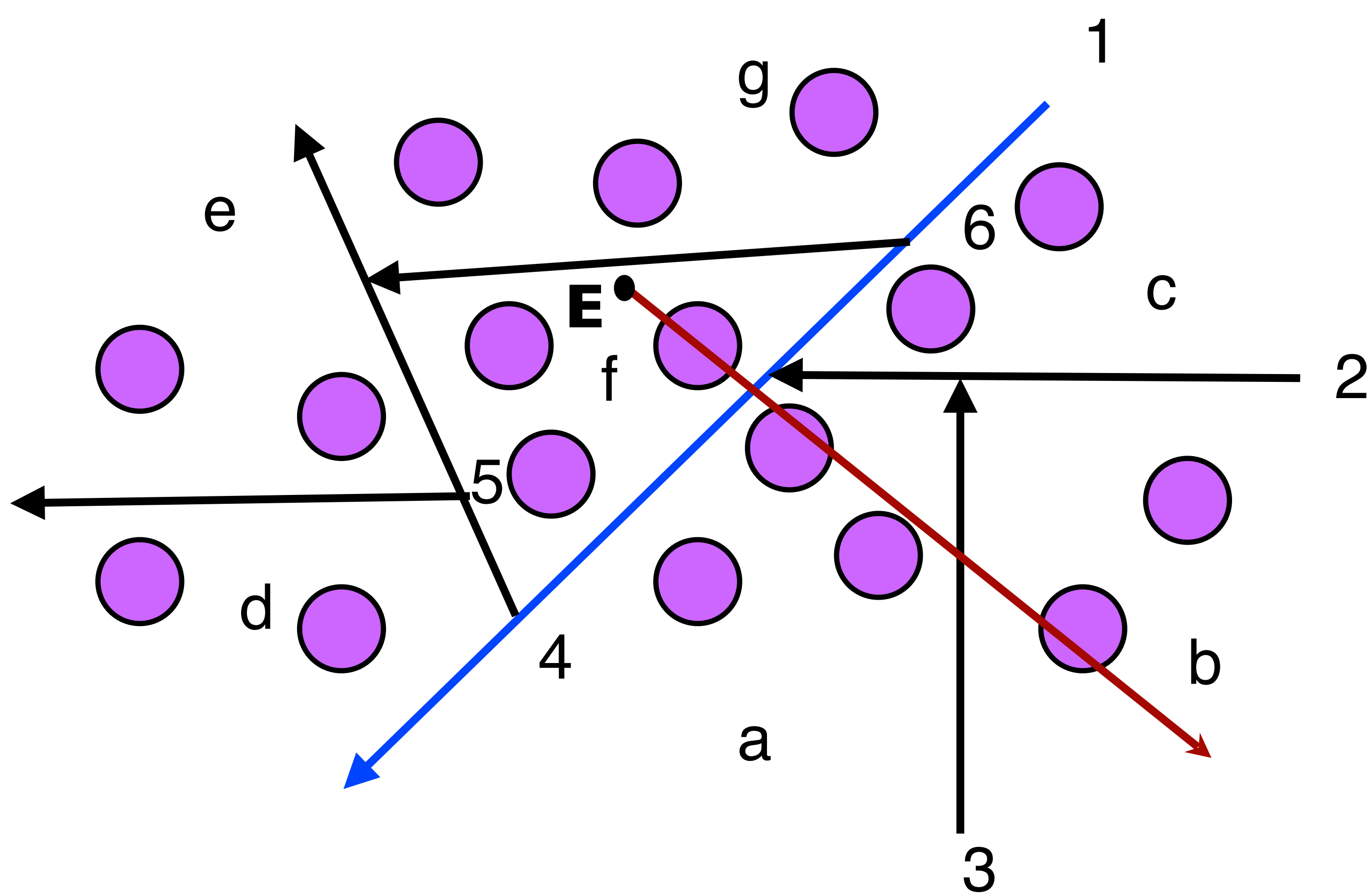

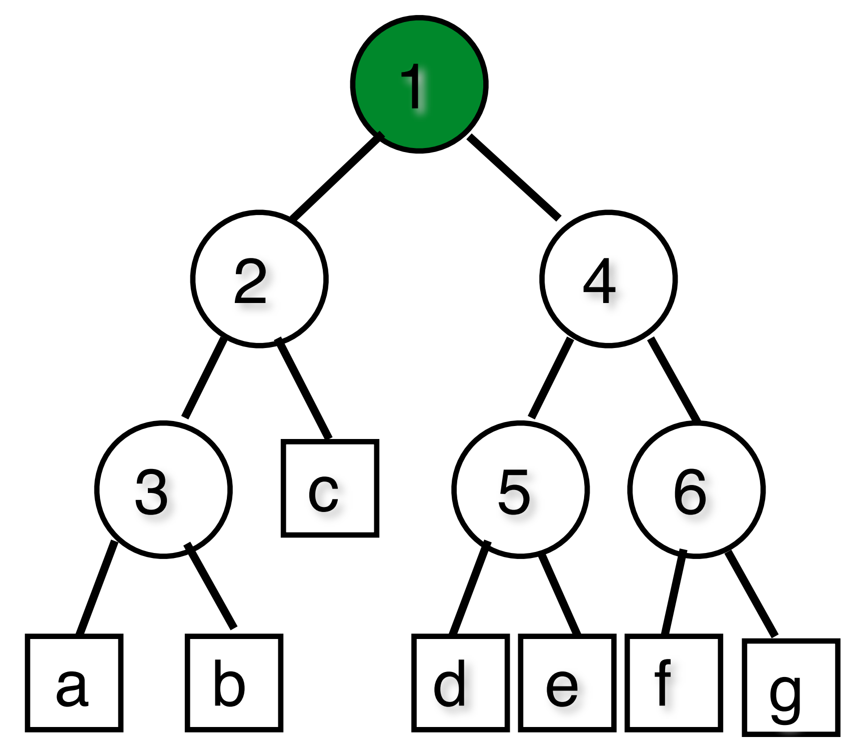

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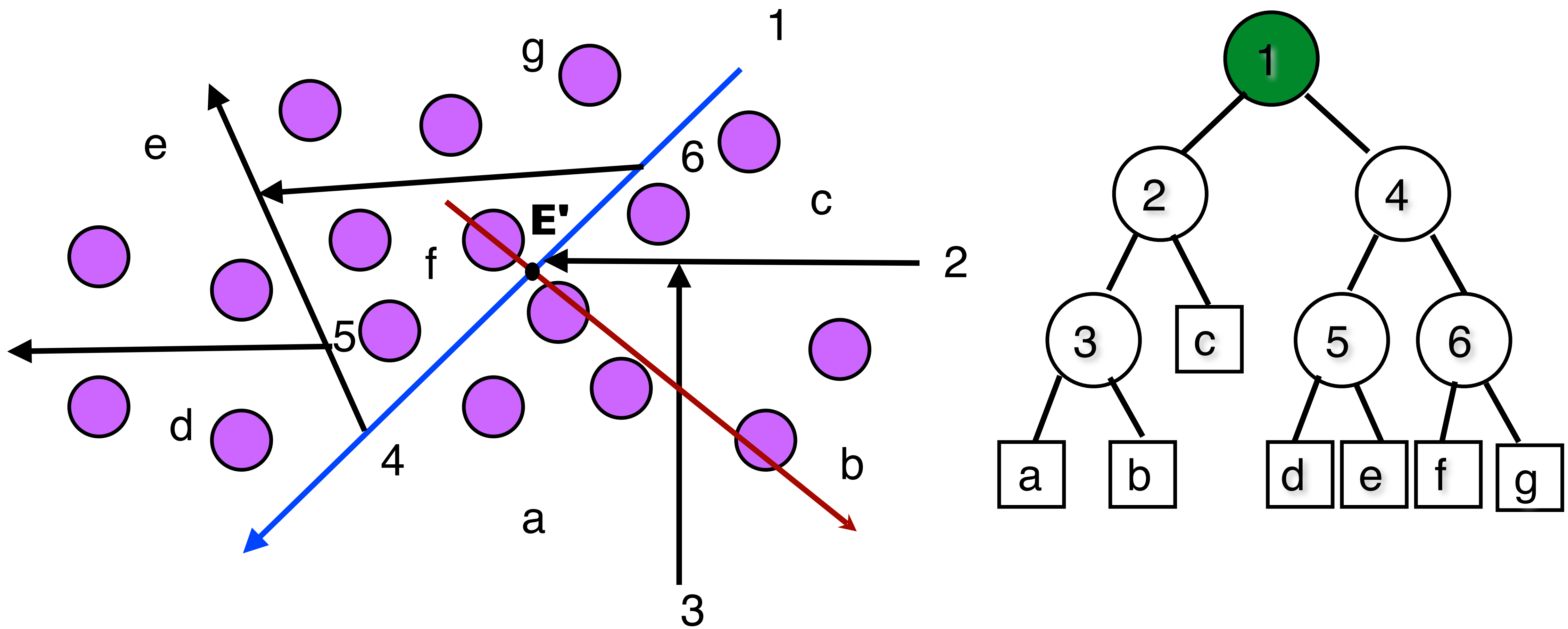

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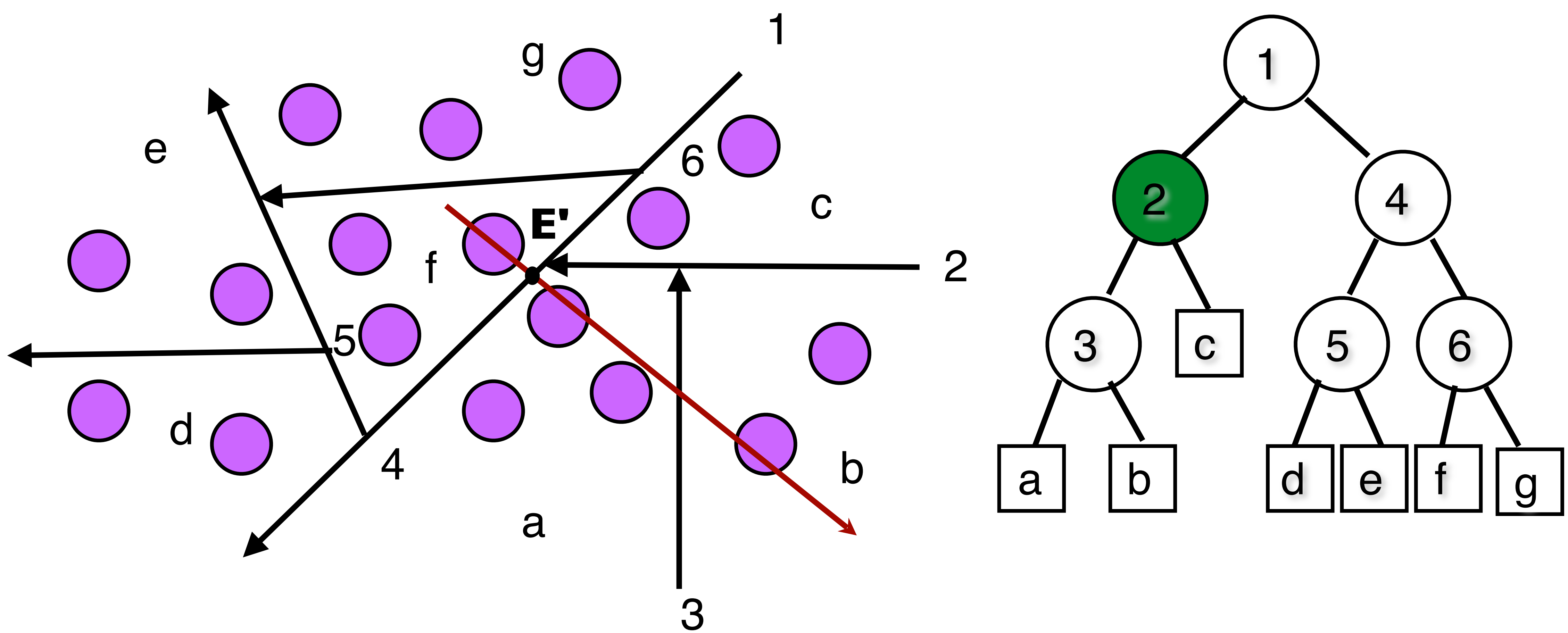

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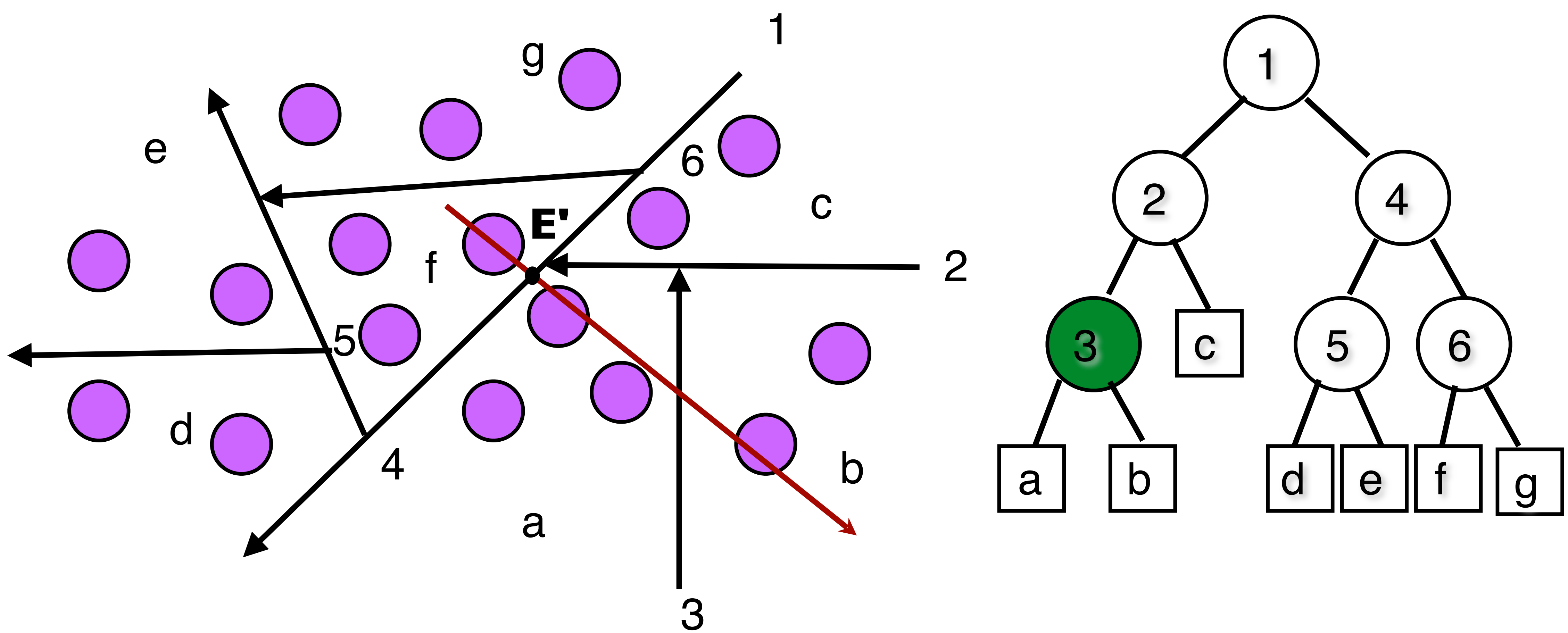

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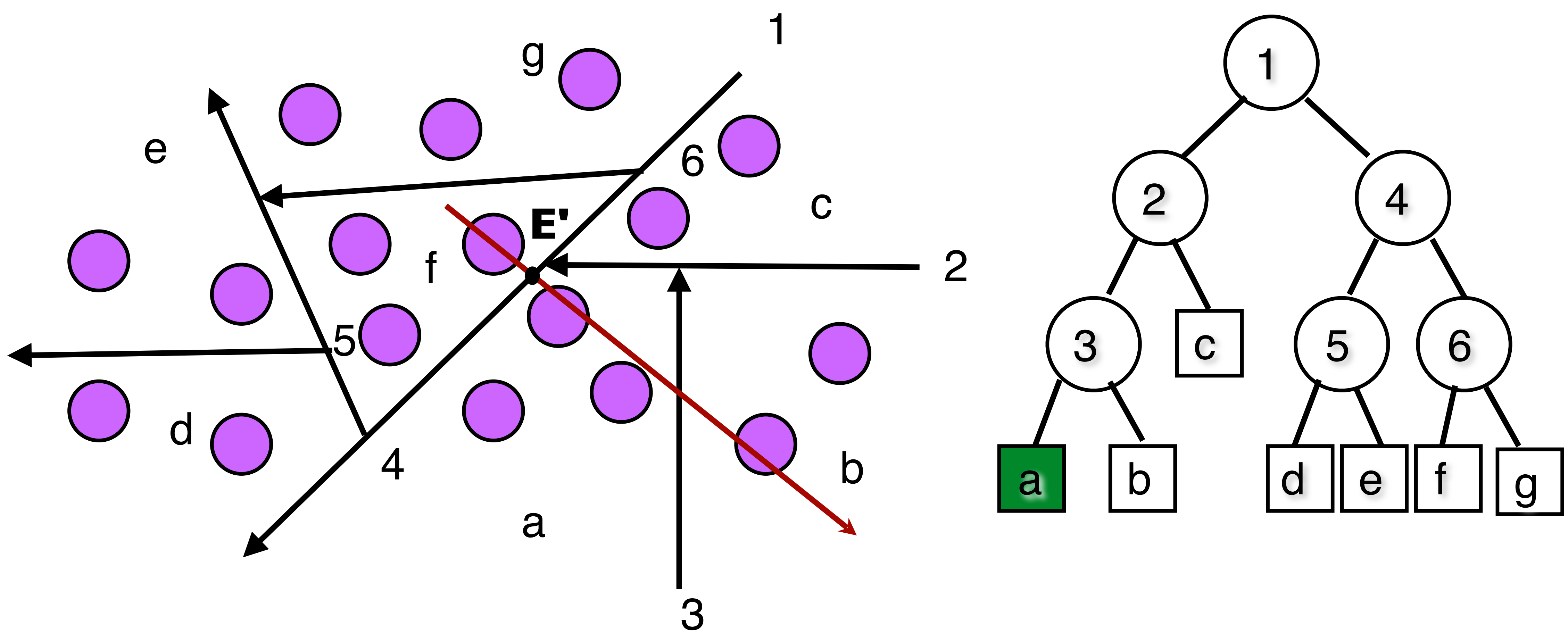

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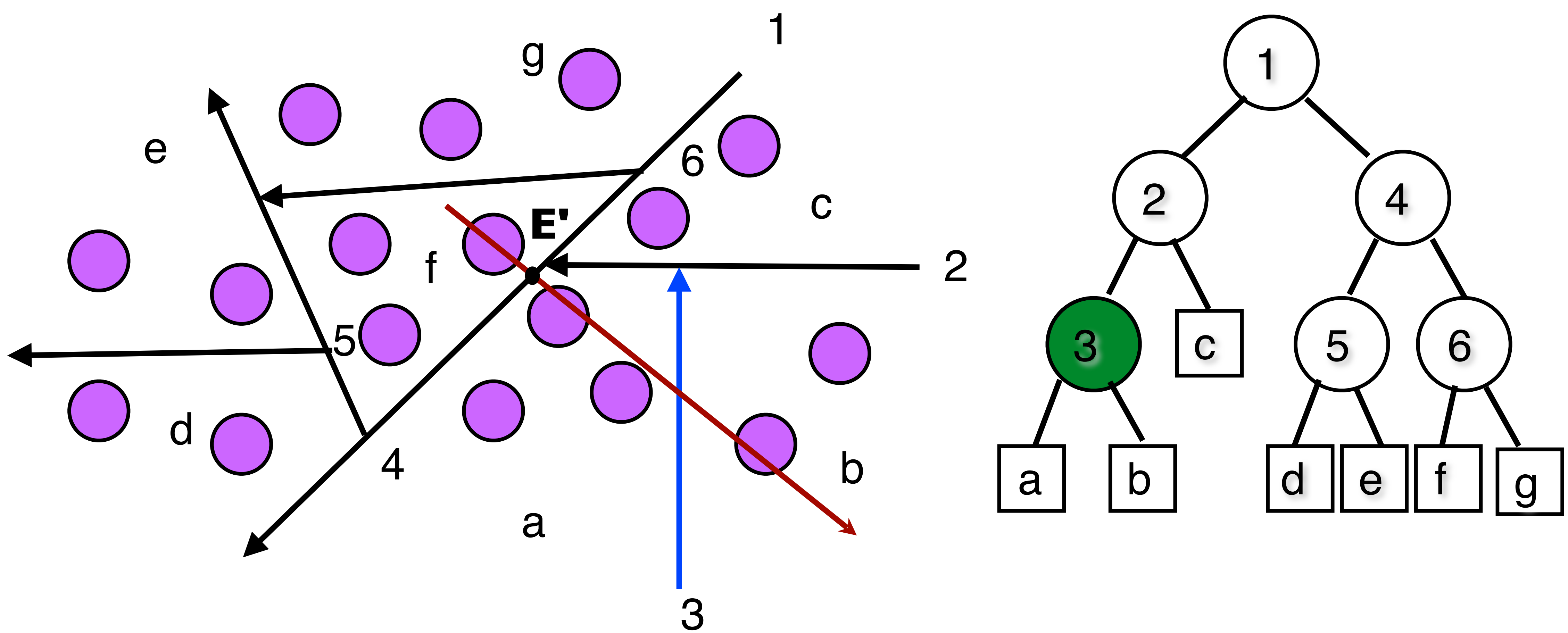

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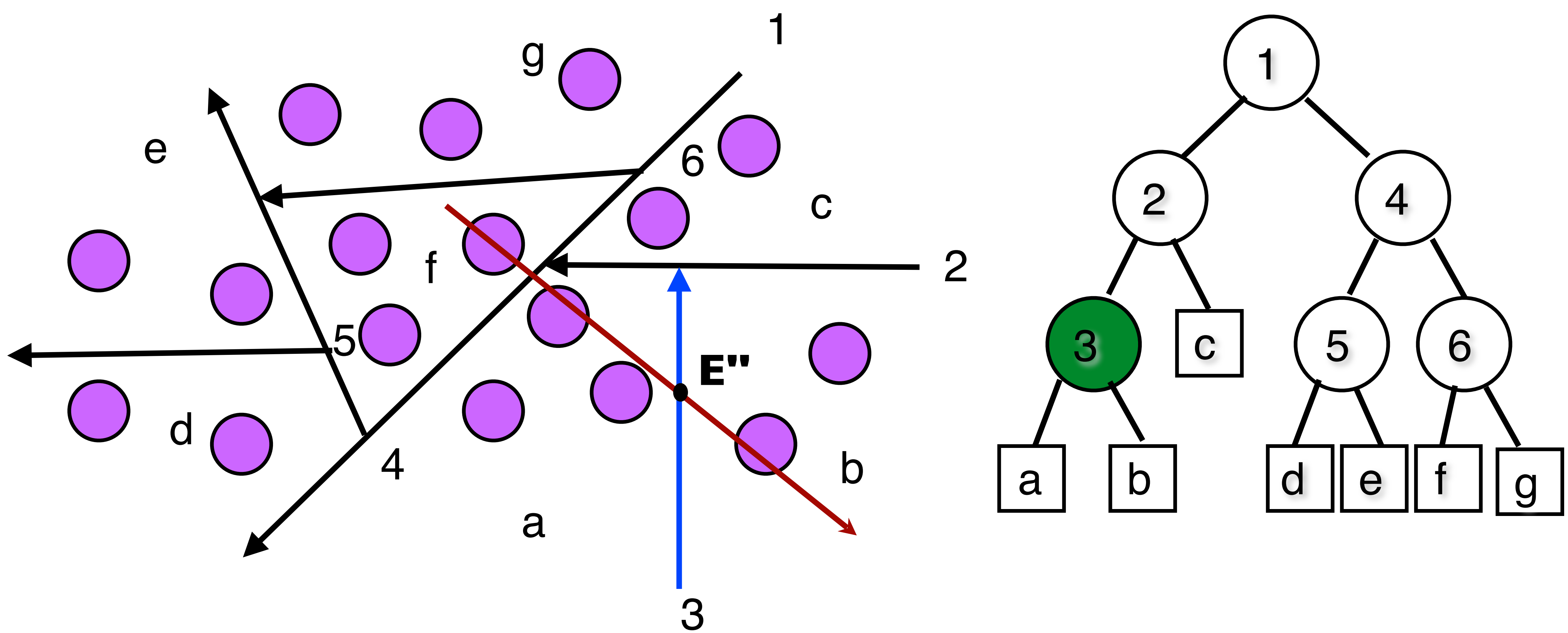

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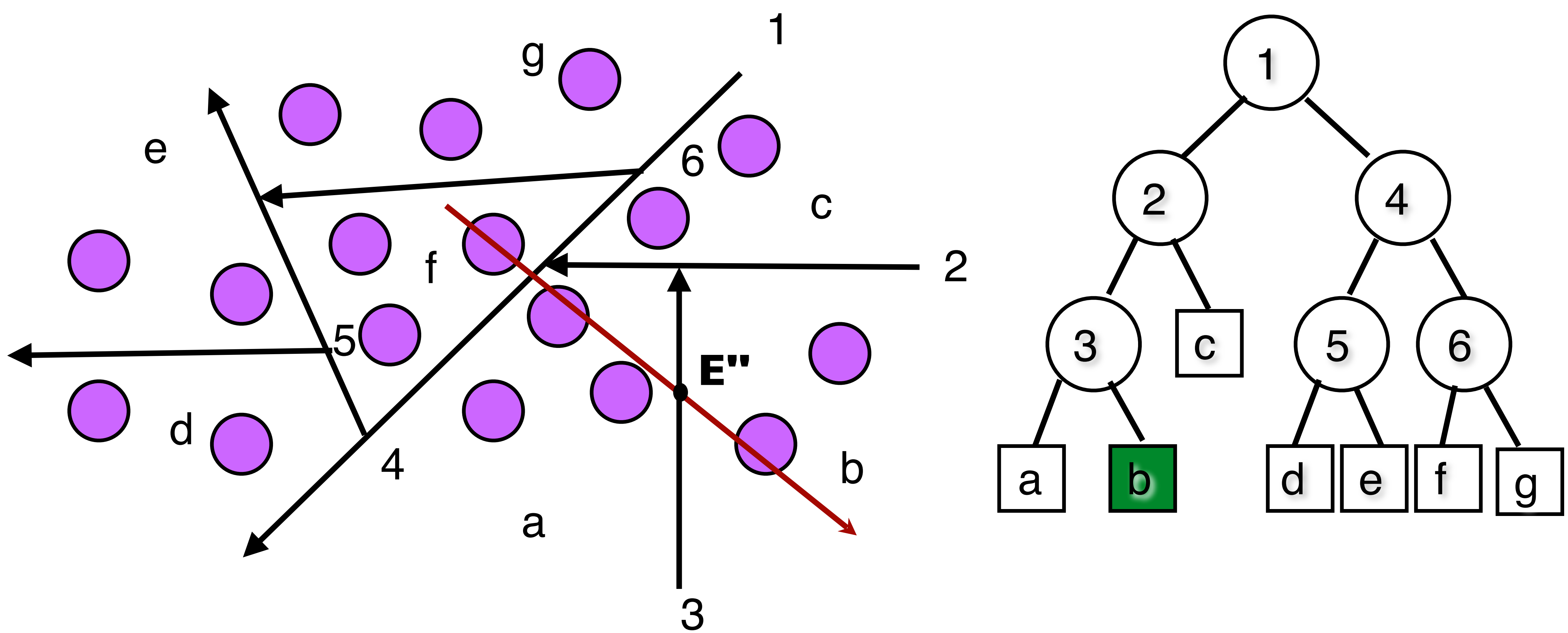

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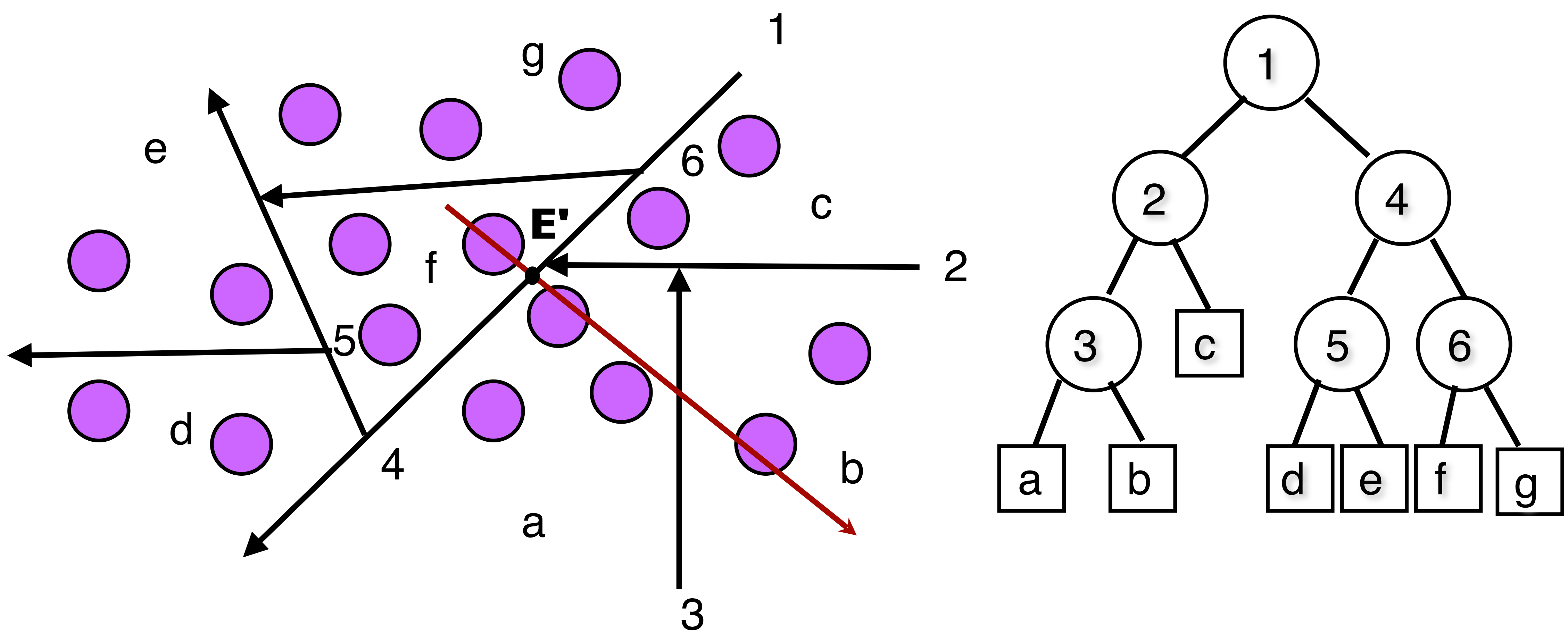


Exercise

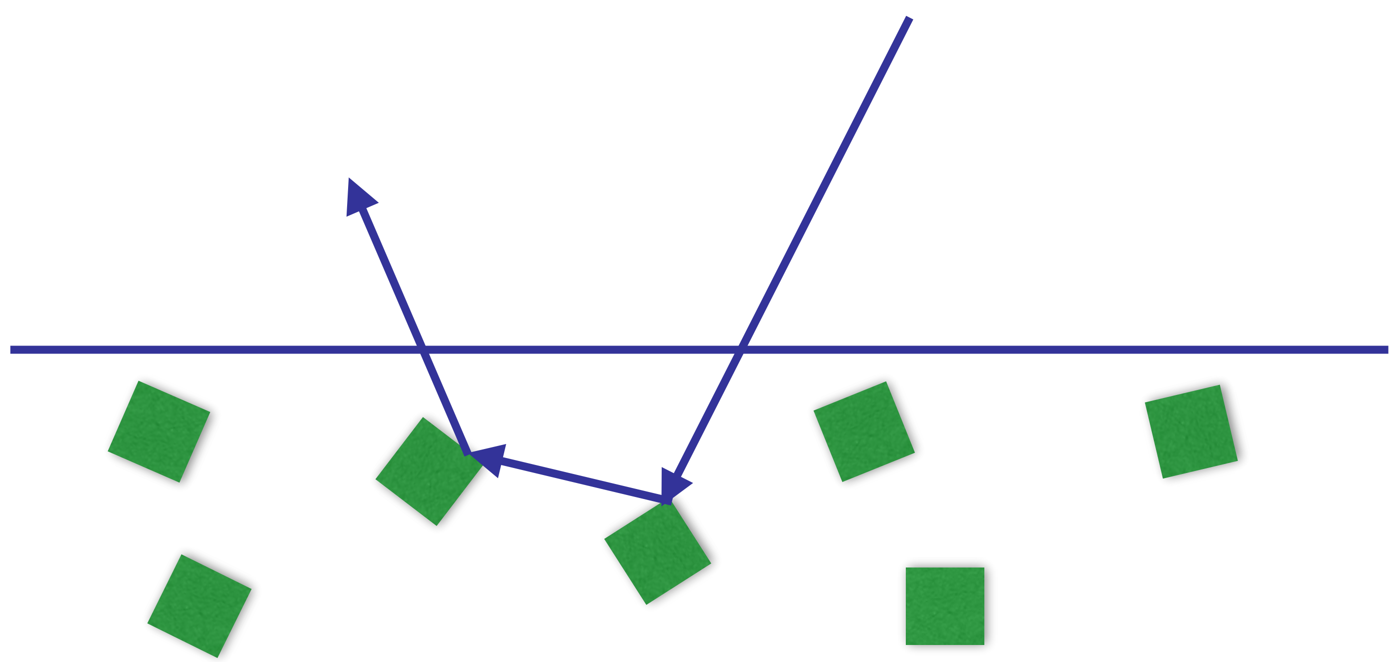
- How does milk look different to white paint?

Exercise

- How does milk look different to white paint?
- Both are opaque.
- Both are essentially pure white.
- Milk is an example of scattering

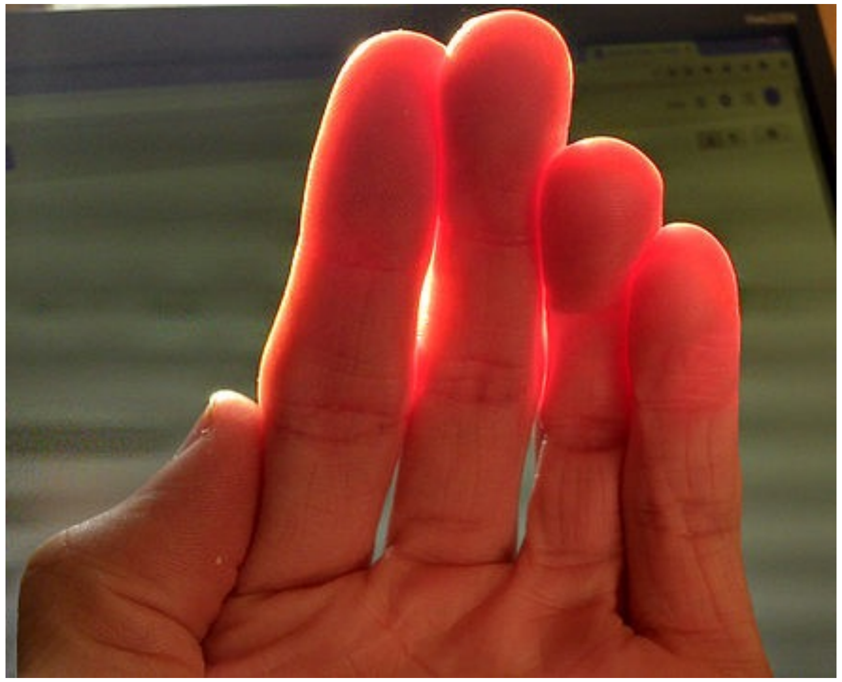
Scattering

- Scattering (or subsurface scattering) is when light refracts into an object that is non-uniform in its density and is reflected out at a different angle and position.



Scattering

- Milk is a substance that has this property.
- As is skin, leaves, and wax.
- Typically, they are hard to render.



Scattering

Scattering

- We don’t really have time to cover this in more depth in this course. Read this if you want to know more (NOT EXAMINABLE).
- http://graphics.ucsd.edu/~henrik/images/subsurf.html

Raytracing Can't Do

- Basic recursive raytracing cannot do:
  - Light bouncing off a shiny surface like a mirror and illuminating a diffuse surface
  - Light bouncing off one diffuse surface to illuminate others
  - Light transmitting then diffusing internally
- Also a problem for rough specular reflection
  - Fuzzy reflections in rough shiny objects

Realtime ray-tracing (RTX)

- Recent Nvidia innovation
- Realtime raytracing supported via specialised hardware
- Programs have to be written to use it, but it fits in quite well with existing graphics pipelines

Realtime ray-tracing (RTX)

- Works by arranging objects in a bounding volume hierarchy (BVH)
- Specialised hardware offers fast traversal of these hierarchies to find ray intersections.

Bounding Volume Hierarchy (BVH)

- Scene is divided into small volumes.
- Child volumes are contained entirely within their parents.
- Sibling volumes may overlap

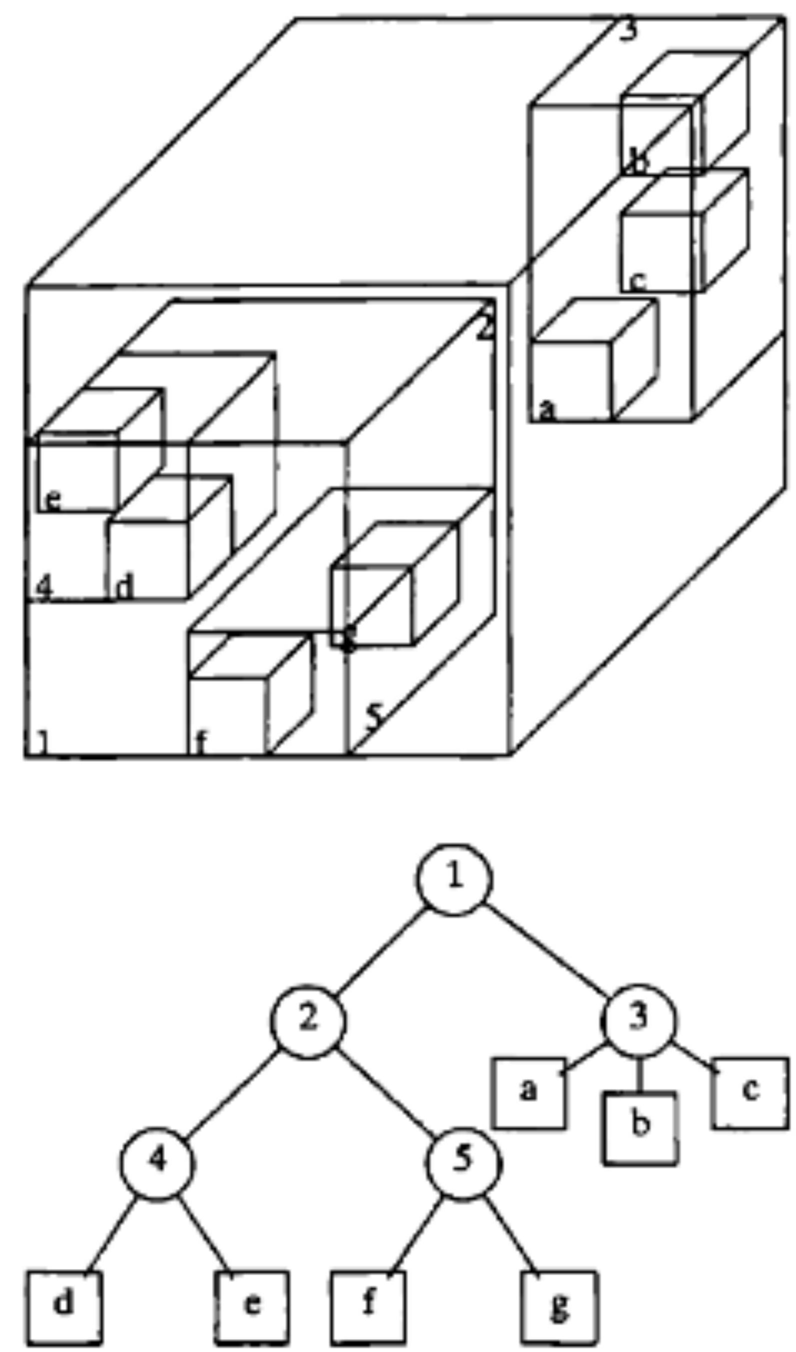


Figure 2.2
Letters a through g represent the objects.
Numbers 1 through 5 represent interior nodes.

Bounding Volume Hierarchy (BVH)

- Parents can have an arbitrary number of children
- The best way to divide up the scene depends on a lot of factors

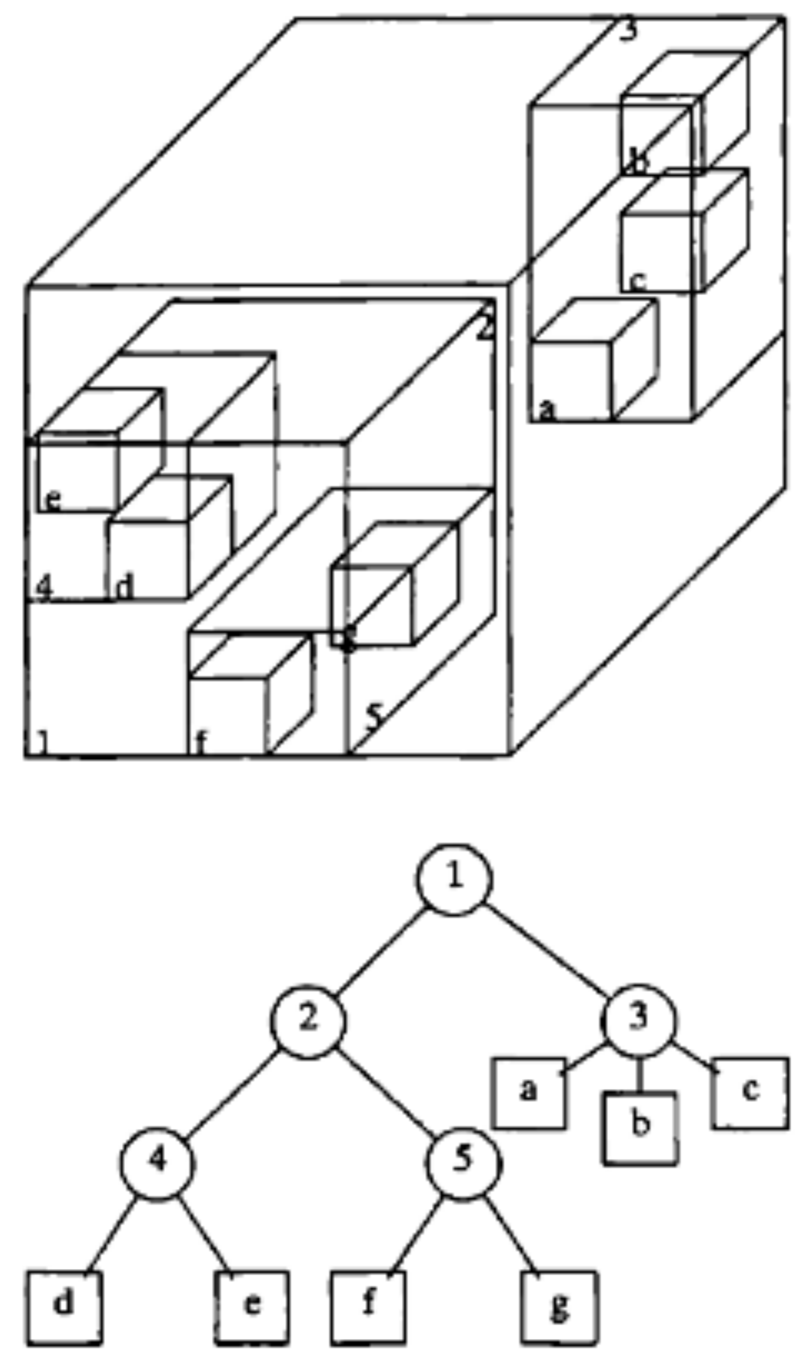


Figure 2.2
Letters a through g represent the objects.
Numbers 1 through 5 represent interior nodes.

Top down construction

- Divide the set of primitives in the scene into two (or more) subsets then recursively subdivide those until all subsets contain only one primitive.
- Easy to implement.
- Usually faster than alternatives.
- Doesn’t always produce the best possible tree.

Bottom up construction

- Treat all primitives in the scene as a set of leaves. Pick two (or more) of them and group them into a node. Repeat till there is only one node in the set.

- Slower than top-down in most cases.

- More difficult to implement.

- Tends to produce better trees.

RTX Examples

- https://www.youtube.com/watch?v=WoQr0k2IA9A
- https://www.youtube.com/watch?v=Ms7d-3Dprio
- https://www.youtube.com/watch?v=1IliQZw_p_E

Volumetric ray tracing

- We can also apply ray tracing to volumetric objects like smoke or fog or fire.
- Such objects are transparent, but have different intensity and transparency throughout the volume.

Volumetric Ray Tracing

- We represent the volume as two functions:

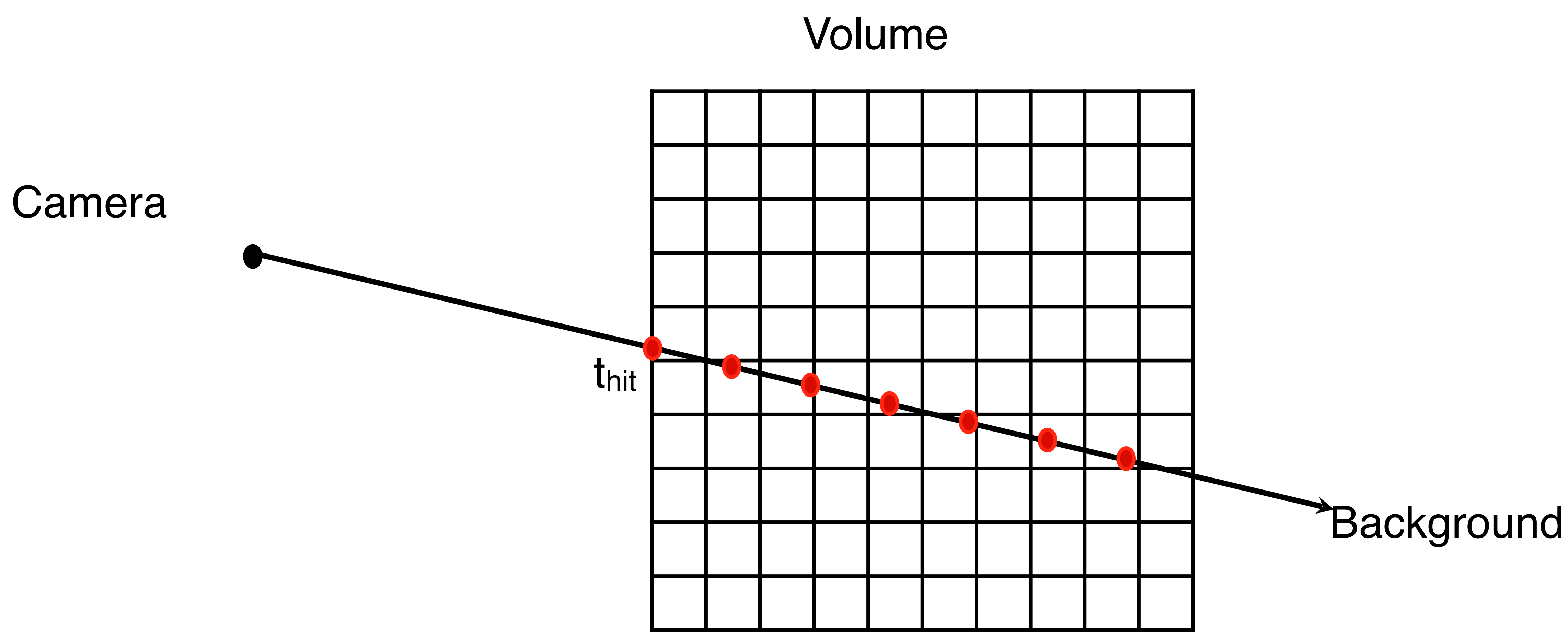
$$
\begin{aligned}
C(P) &= \text{colour at point } P \\
\alpha(P) &= \text{transparency at point } P
\end{aligned}
$$

- Typically these are represented as values in a 3D array. Interpolation is used to find values at intermediate points.

- These functions may in turn be computed based on density, lighting or other physical properties.

Sampling

- We cast a ray from the camera through the volume and take samples at fixed intervals along the ray.



Sampling

- We end up with (N+1) samples:

$$
\begin{aligned}
P_i &= R(t_{hit} + i\Delta t) \\
C_i &= C(P_i) \\
\alpha_i &= \alpha(P_i) \\
C_N &= (r, g, b)_{background} \\
\alpha_N &= 1
\end{aligned}
$$

Alpha compositing

- We now combine these values into a single colour by applying the alpha-blending equation.

$$C_N^N = C_N$$

$$\underbrace{C_N^i}_{\text{Total colour at i}} = \alpha_i \underbrace{C_i}_{\text{Local colour at i}} + (1 - \alpha_i) \underbrace{C_N^{i+1}}_{\text{Total colour at i+1}}$$

Exercise

- Suppose we have a background color of (0,1,0) and a volume with the uniform color of (1,0.5,0.5). A ray cast through that volume takes two samples. The first has an alpha value of 0.2 and the second 0.1. What is the colour of the resulting pixel?

Alpha compositing

- We can write a closed formula for the colour from a to b as:

$$C_b^a = \sum_{i=a}^{b} \alpha_i C_i \prod_{j=a}^{i-1} (1 - \alpha_j)$$

- We can compute this function from front to back, stopping early if the transparency term gets small enough that nothing more can be seen.

In OpenGL

- Volumetric ray tracing (aka ray casting) does not require a full ray tracing engine.
- It can be implemented in OpenGL as a fragment shader applied to a cube with a 3D texture.
- https://www.shadertoy.com/view/XslGRr

Examples

- https://www.shadertoy.com/view/Ms2SD1
- https://www.shadertoy.com/view/4sS3zG
- See http://shadertoy.com/ for more examples.

Sources

- http://en.wikipedia.org/wiki/Volume_ray_casting
- http://graphics.ethz.ch/teaching/former/scivis_07/Notes/Slides/03-raycasting.pdf
- http://http.developer.nvidia.com/GPUGems/gpugems_ch39.html