Hardware Accelerated Ray Tracing 硬件加速 光线追踪的原理、设计及应用

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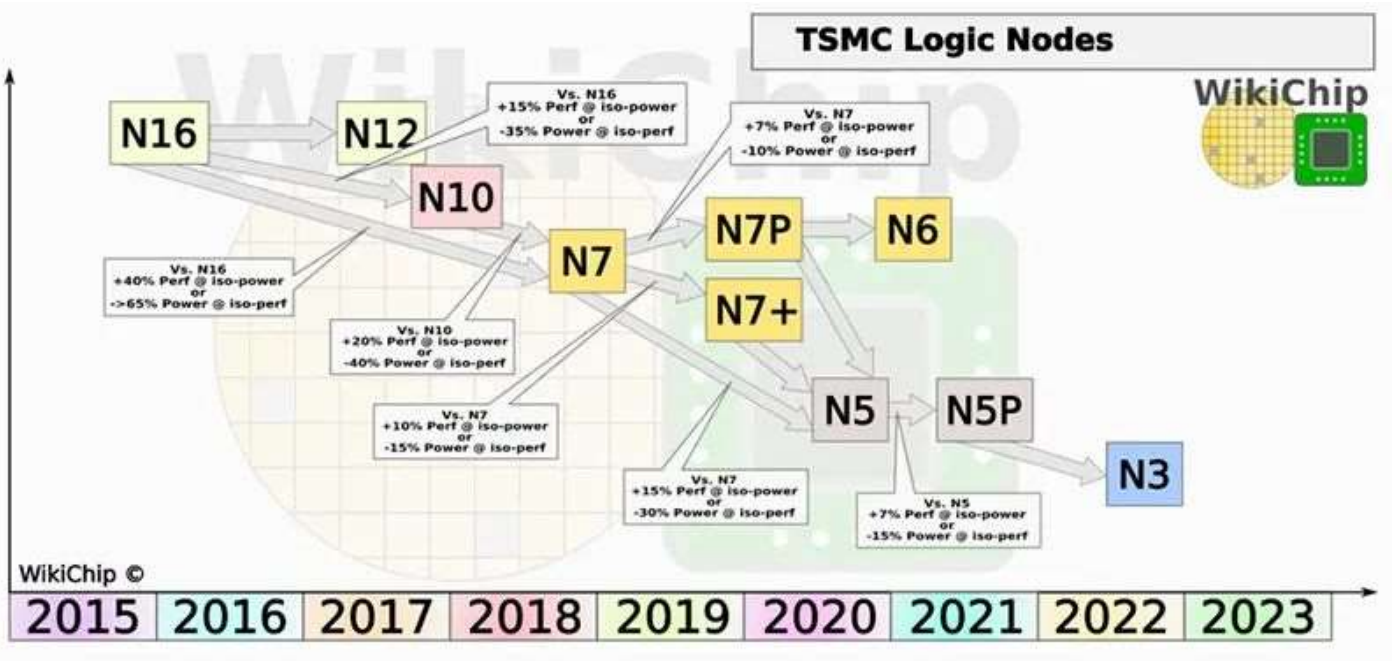
2023/4/17

背景

随着芯片工艺制程的推进，以及芯片设计的进步，
使得硬件加速的光线追踪达到实时效果成为可能。



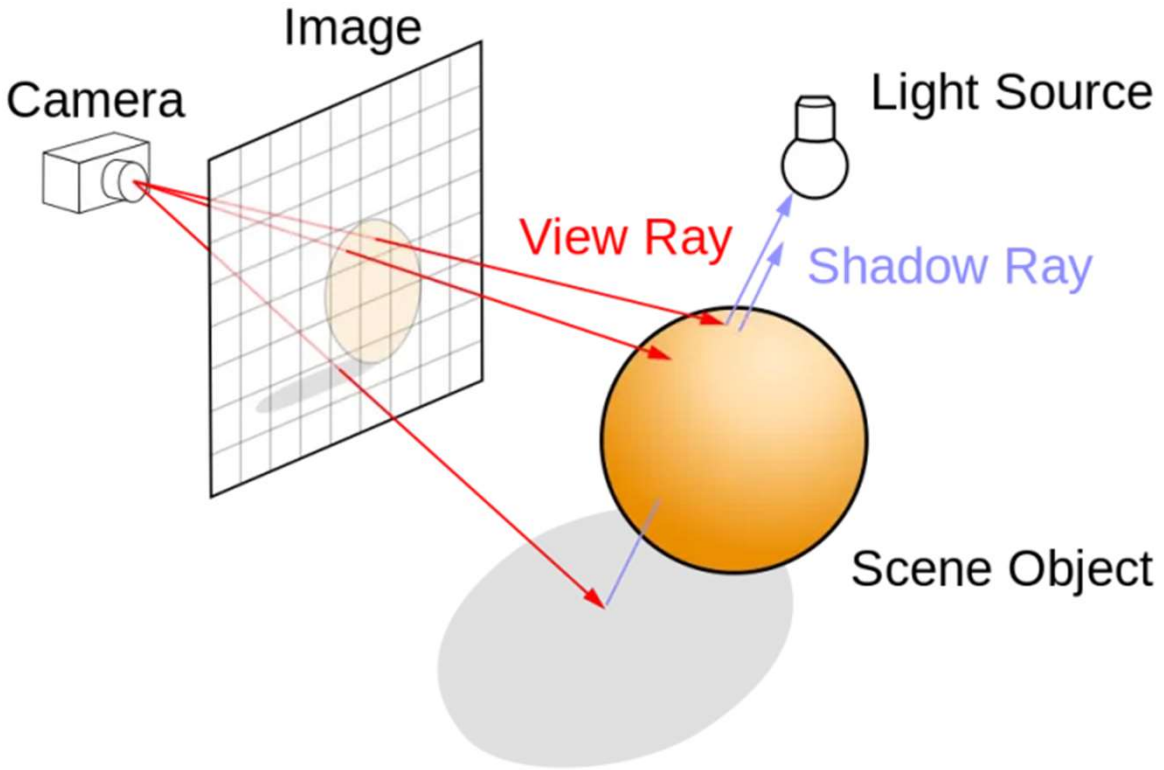
目录

硬件加速光线追踪的

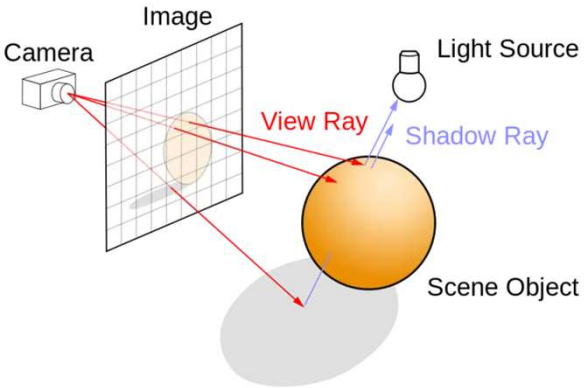
1. 原理
2. 设计
3. 应用

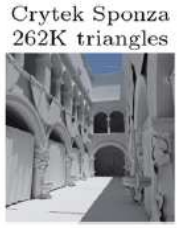
1.原理：什么是光线追踪?

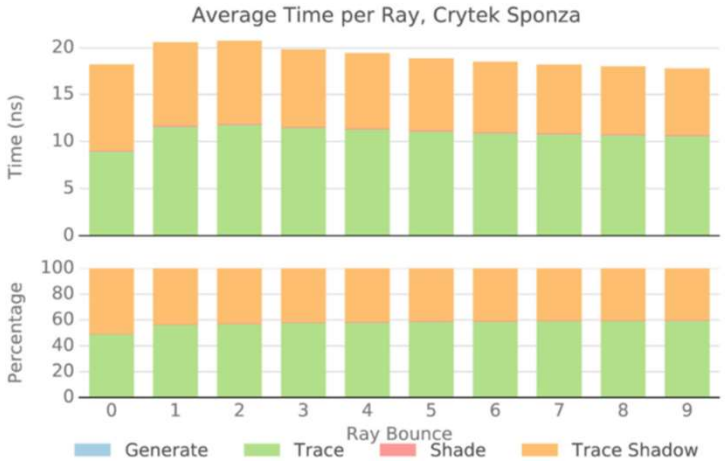
- 光路可逆
- 蒙特卡洛积分

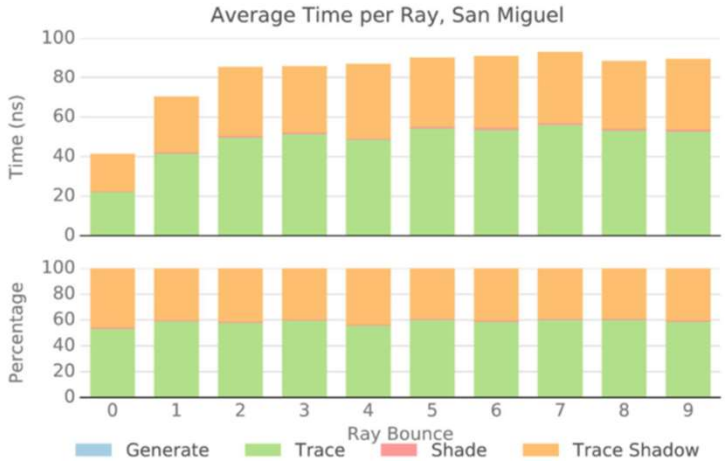


1.原理：什么是硬件加速的光线追踪?







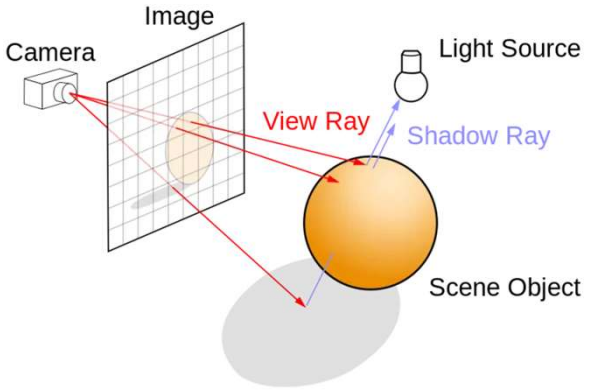


(统计图来自论文: A detailed study of ray tracing performance: render time and energy cost)

绝大部分时间都用于Trace!

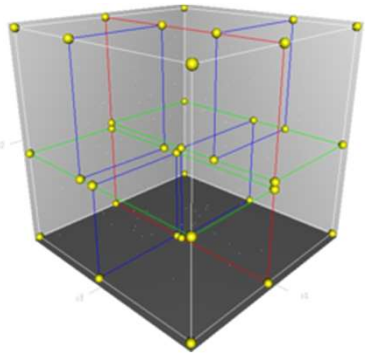
硬件加速光追的本质就是对Trace过程加速

1.原理：如何加速Trace过程?



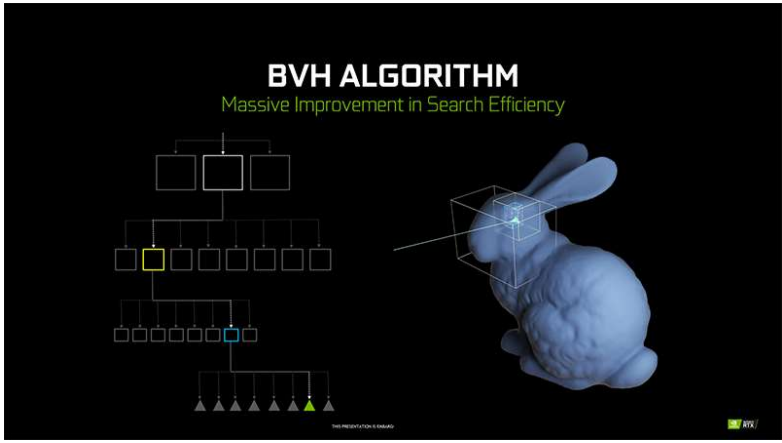
直接遍历需要时间复杂度为O(N)

需要一种空间划分方法，来快速确定光线与片元是否发生相交



1. Kd-tree(k-dimensional tree)：不断使用超平面将空间分为两个子空间。

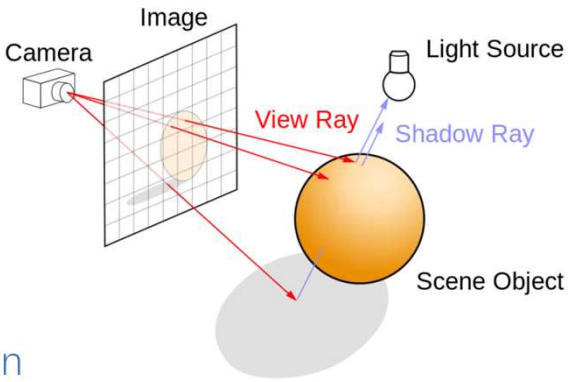
2. BVH(Bounding volume hierarchy):使用嵌套的包围盒将空间细分成更小的子空间。



BVH比起Kd-tree需要更小的内存带宽，更紧凑的遍历状态，成为了光追加速结构的事实标准(Vulkan/DirectX12)

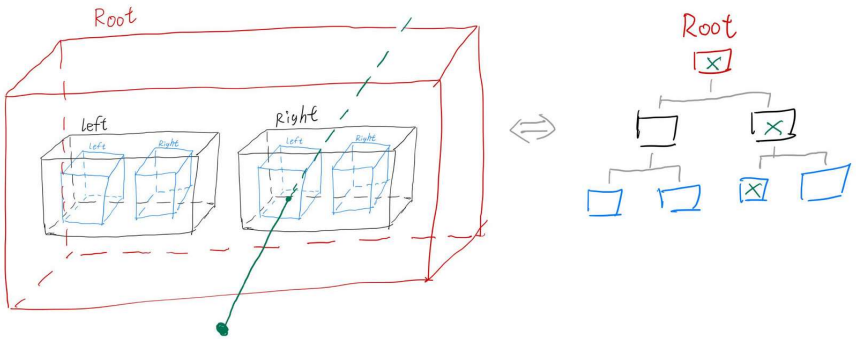
时间复杂度可以降低到O(logN)

1.原理： 如何加速Trace过程?

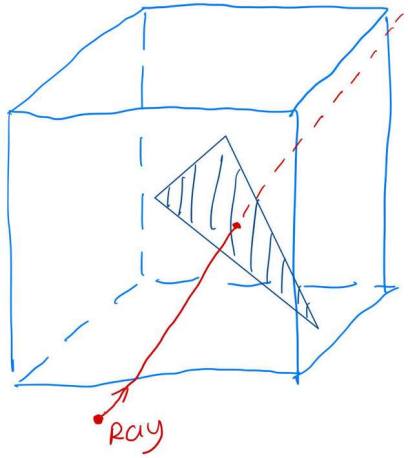


所以可以将Trace过程分解成：

1. Ray Traverse
遍历求交包围盒



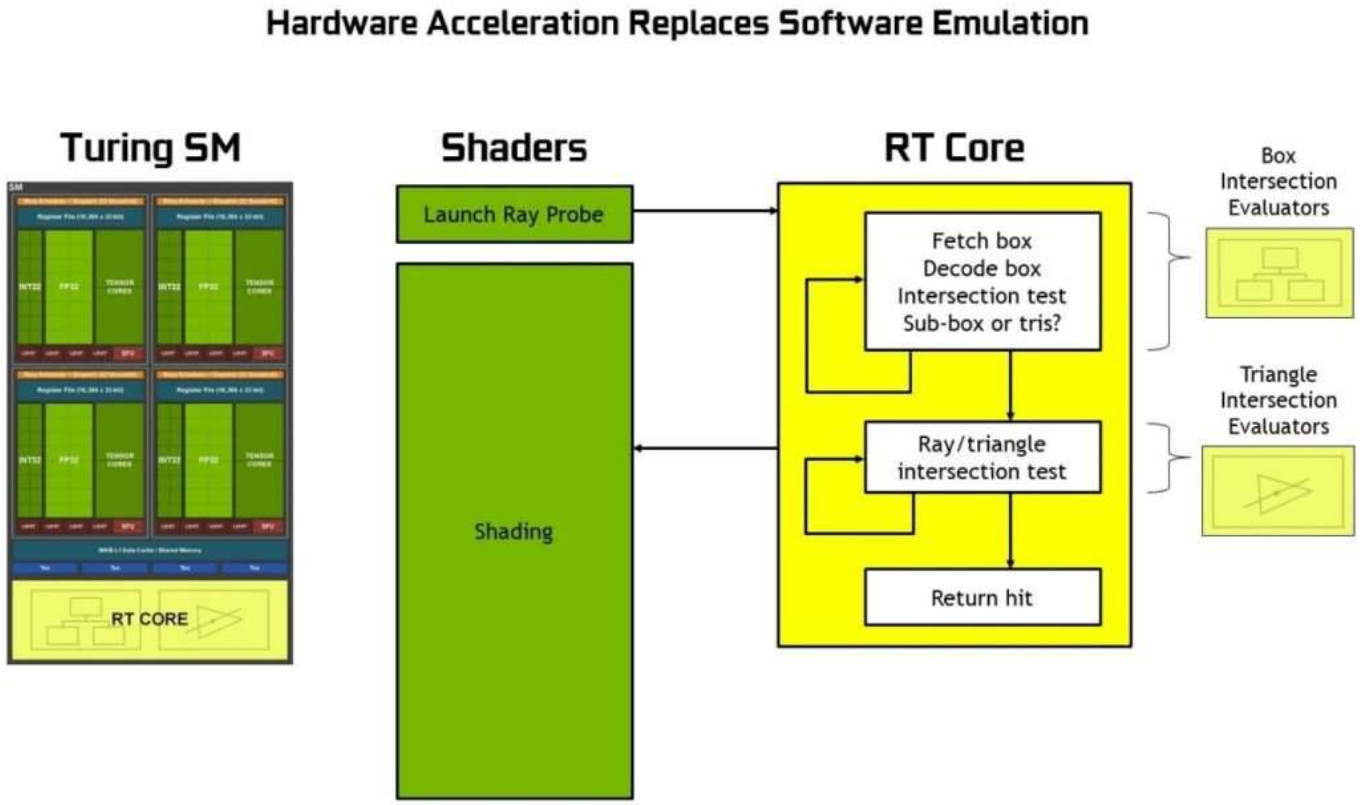
2. Triangle Intersection
对包围盒内的三角形计算其交点



与之相对应的，我们可以分别设计两个专用部件分别对Ray Traverse、 Triangle Intersection 进行加速

2.设计： Nvidia的RT Core

在Nvidia的RTX系列显卡中的光线追踪硬件RT Core也是分别实现了1. Ray Traverse 2. Triangle Intersection



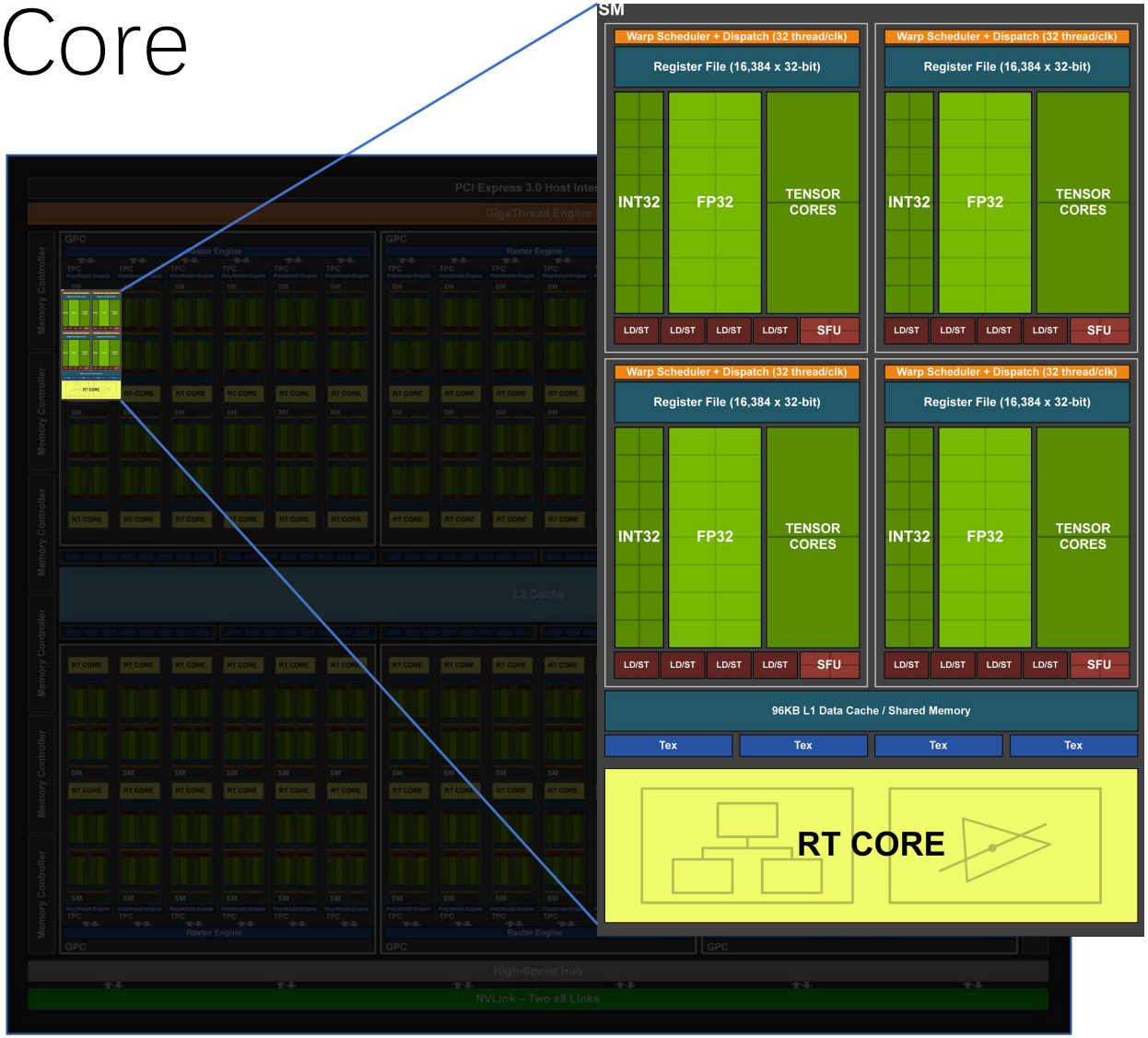
https://developer.nvidia.com/blog/nvidia-turing-architecture-in-depth/

2.设计： Nvidia的RT Core

Turing架构：TU102 GPU

- 6 GPC（图形处理簇）
- 36 TPC（纹理处理簇）
- 72 SM（流多处理器）
- 72 RT核
- 每个GPC有6个TPC，每个TPC有2个SM，每个SM有1个RT核

目前性能表现最好，
但没有提供设计细节



2.设计：硬件加速光追的一种实现

RT Engine: An Efficient Hardware Architecture for Ray Tracing

Run Yan 1 , Libo Huang 1,*, Hui Guo 1 , Yashuai Lü 2, Ling Yang 1 , Nong Xiao 1, Yongwen Wang 1, Li Shen 1 and Mengqiao Lan 1

1 School of Computer, National University of Defense Technology, Changsha 410005, China

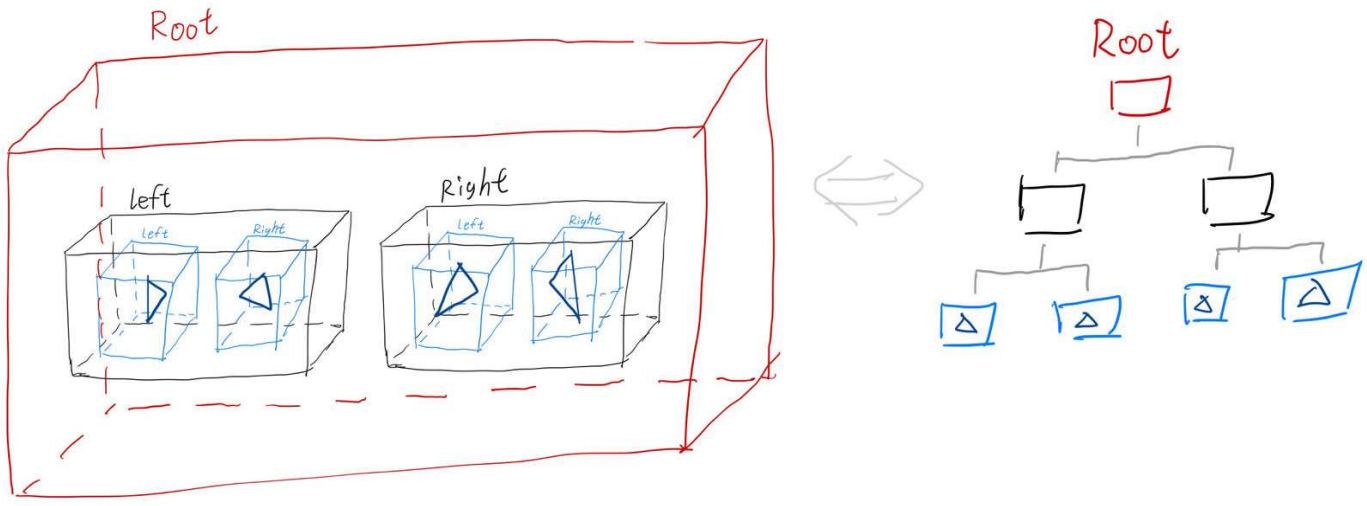
2 Huawei 2012 Labs, Beijing 100089, China

使用硬件描述语言Verilog实现了一个加速光追的专用硬件,主要加速了 Ray Traverse和 Triangle Intersection，在性能与面积比上达到现有设计中的最高。

2.设计： 核心加速数据结构acceleration structure (AS)

使用binary-based BVH作为加速结构AS，每个节点是一个AABB包围盒，其中叶节点内包含实际的三角面片。

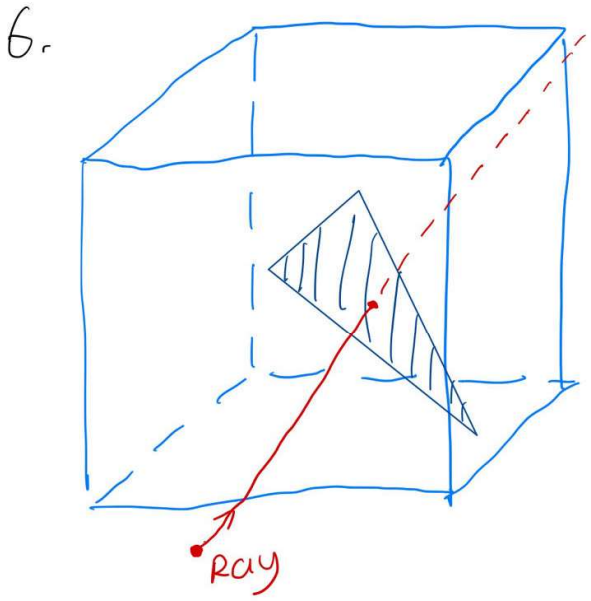
AABB(axis-aligned bounding box):对齐于坐标轴的六面长方体



2.设计：核心加速算法

基于栈的binary-based BVH Traverse算法

- 对内部节点：进行AABB盒的求交并遍历
- 对叶节点：对节点内的三角形求交



Algorithm 1: BVH Ray Tracing Algorithm

```
Input: ray, rootNode of the BVH
Output: intersection results
1  hit ← false
2  curNode ← rootNode
3  Stack ← ϕ
4  while curNode ≠ ϕ do
5      while curNode is a internal node do
6          for each child in curNode do
7              if curRay hits curNode.left and does not hit curNode.right then
8                  Traverse(curRay, curNode.left)
9              if curRay hits curNode.right and does not hit curNode.left then
10                 Traverse(curRay, curNode.right)
11             if curRay hits curNode.right and curNode.left then
12                 if hit_distance_right ≤ hit_distance_left then
13                     Traverse(curRay, curNode.right)
14                     Stack.push(curNode.left)
15                 if hit_distance_right > hit_distance_left then
16                     Traverse(curRay, curNode.left)
17                     Stack.push(curNode.right)
18             if curRay does not hit curNode.right or curNode.left then
19                 curNode = Stack.pop
20     while curNode is a leaf node do
21         for triangles in the node do
22             hitnode← Intersection(ray,traiangle)
23             if hit then
24                 return closest hit
25             break
26         curNode ← Stack.pop()
```

1 2 3 4 5 6

2.设计： 硬件总架构图

main contributions：

1. Traverse、Intersection 专用硬件化
2. 多栈设计，可以同时运算多个光线
3. Approximation Method for Reciprocal

Algorithm 1: BVH Ray Tracing Algorithm

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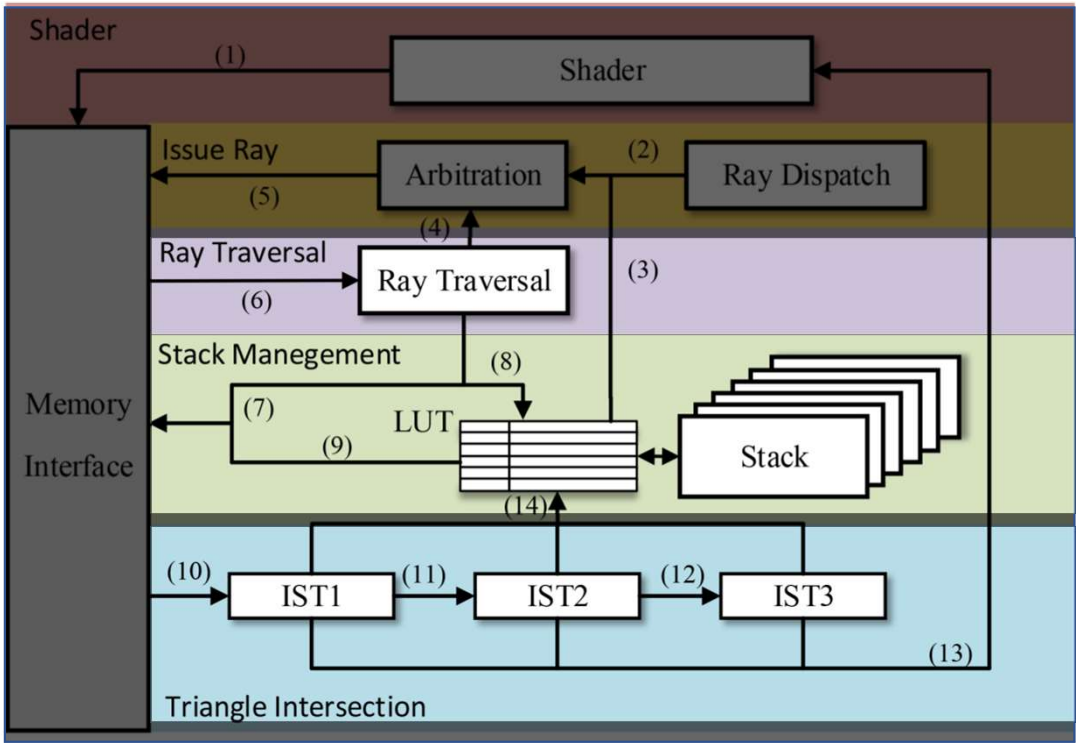


2.设计:Triangle Intersection

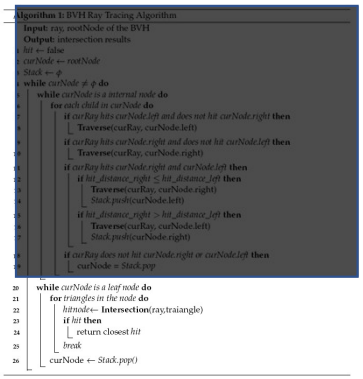
硬件化三角形与光线求交的过程

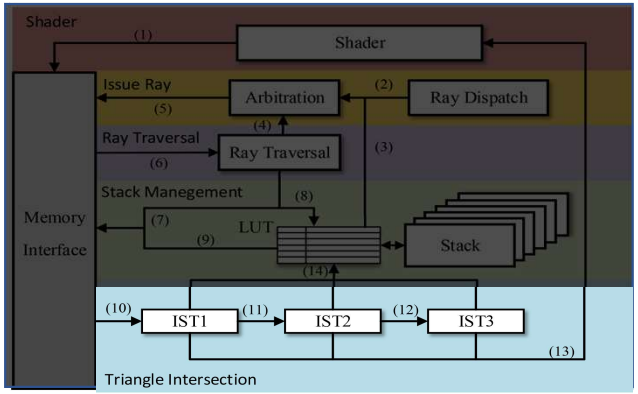
```
20  while curNode is a leaf node do
21      for triangles in the node do
22          hitnode← Intersection(ray,traiangle)
23          if hit then
24              return closest hit
25          break
26      curNode ← Stack.pop()
```

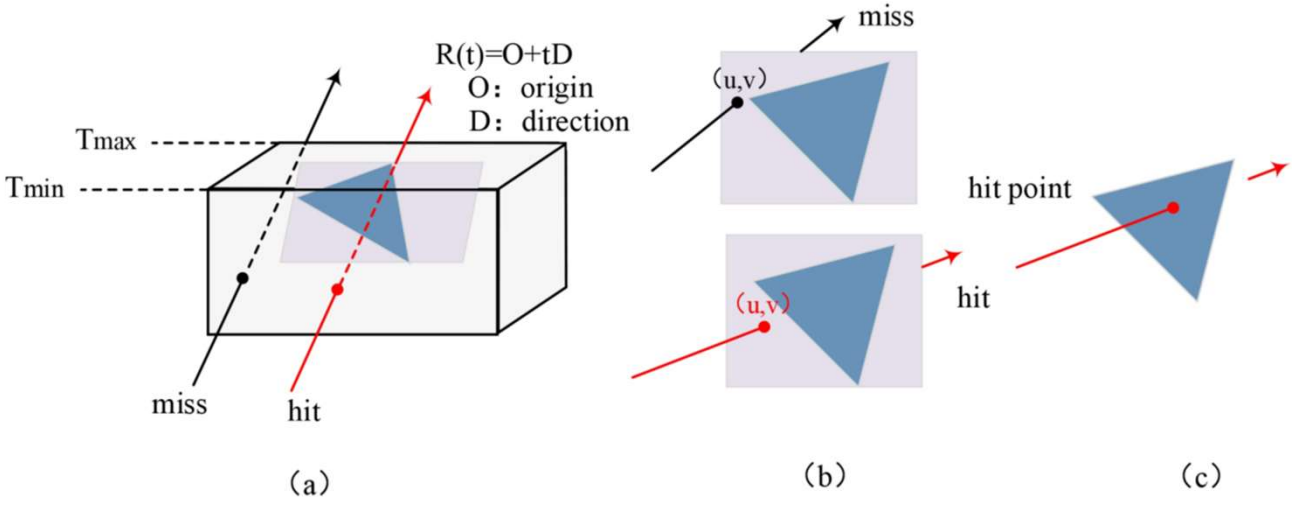
IST1: (a)过程,判断光线与三角形所在的平面是否相交,得到t

IST2: (b)过程,计算交点的关于三角形的重心坐标, 计算u， 判断是否u∈[0,1]

IST3: (c)过程,计算重心坐标v,判断是否v∈[0,1]
向Shader模块返回t,u,v



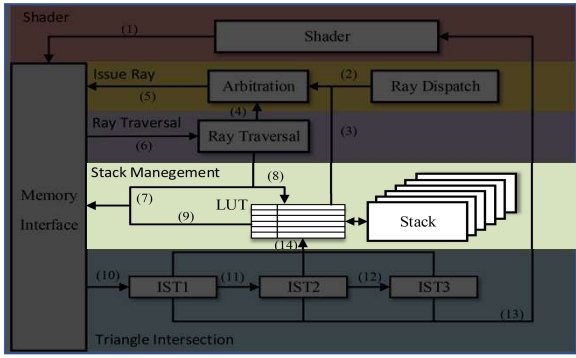




Triangle intersection test.
(**a**) Ray-plane test, (**b**) barycentric test and (**c**) final hit point calculation.

2.设计： 多栈结构

通过LUT（Look Up Table）与多栈设计，同时发射多个光线，
相较单栈设计，提升9.99–20.78x



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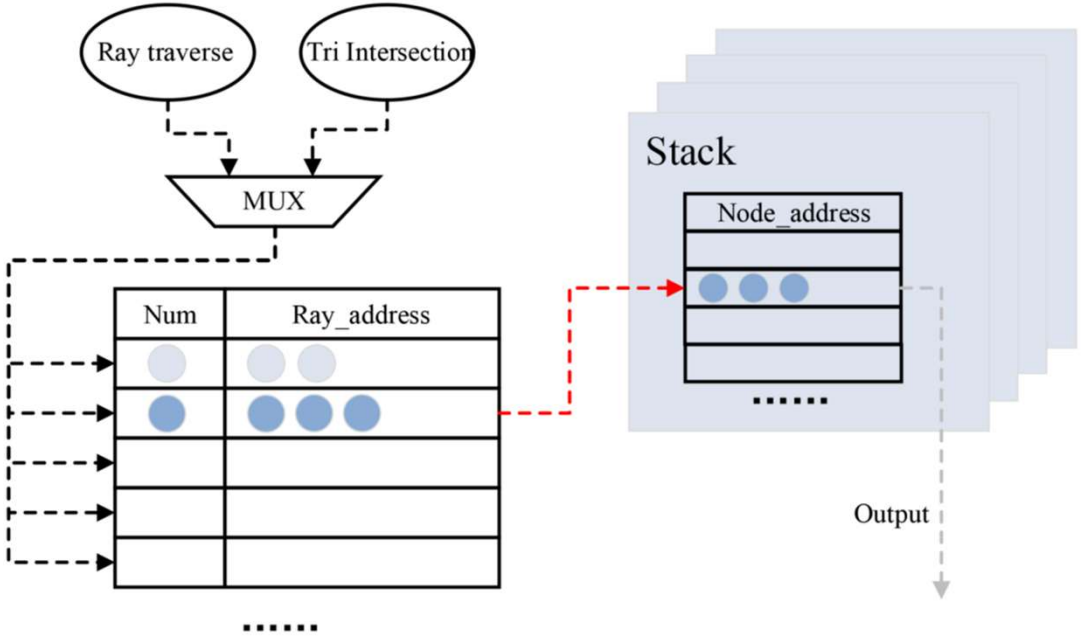


每个光线将自己的内存地址送入LUT，来取得对应stack的索引

2.设计： Approximation Method for Reciprocal

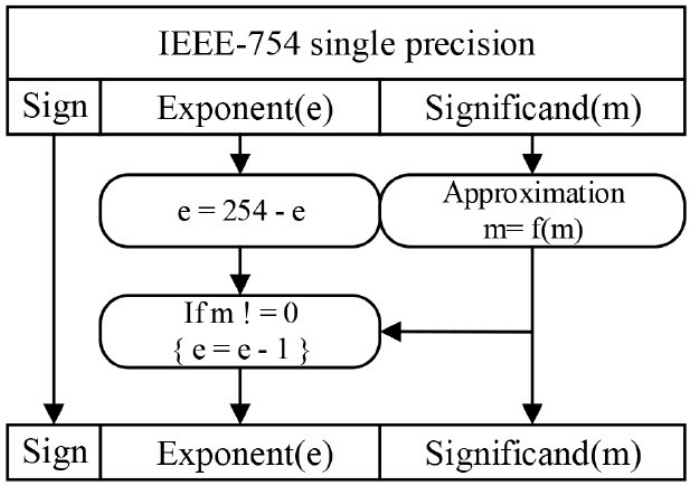
计算光线与三角形的交点的重心坐标需要求一次倒数

该设计使用Parabolic Synthesis与二次插值结合的方法实现浮点数倒数计算

1. 保留Sign位

2.对指数位取反：
(1) 去除偏移：$e' = e - 127$
(2) 取反符号再加偏移：$e'' = 127 - e'$
(3) 组合得到：$e'' = 254 - e$

3.对Significant使用Parabolic Synthesis 近似求倒数



Parabolic Synthesis：是一种低开销、低时延的硬件近似方法，
可以近似除法、三角函数、对数、平方根等函数。

并行求解多个子函数，每个函数都是二阶函数，最后通过乘法合成。

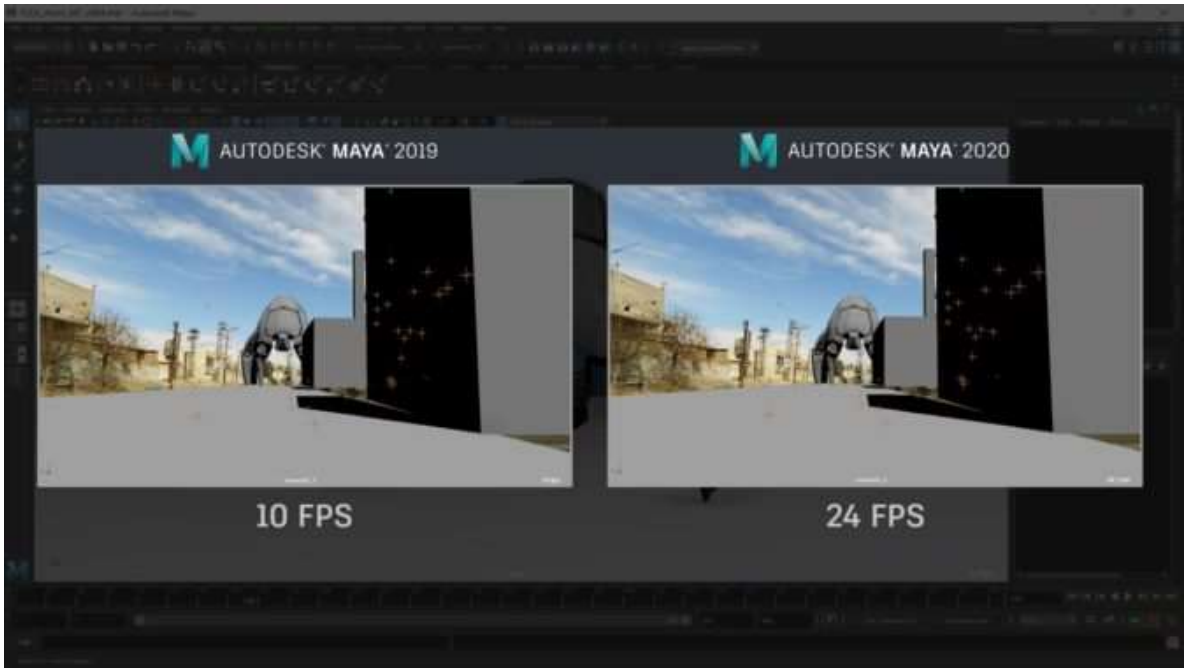
2.设计：结果比较

Table 7. Performance comparison against previous approaches.

	Clock Rate	Acceleration Structure	Performance (MRPS)	Area (mm^2)	Process (nm)	Performance/ Area (MRPS /mm^2)
T&I engine SIGGRAPH'11 [17]	500 MHz	Kd-tree	198	9.04	65	21.90
SGRT SIGGRAPH'13 [18]	500 MHz	BVH	184	7.2	65	25.56
RayCore TOG'14 [19]	500 MHz	Kd-tree	193	18	28	10.72
Two-AABB SIGGRAPH'14 [21]	500 MHz	BVH	297.6	6.82	28	43.63
HART TVCG'15 [20]	500 MHz	BVH	602	7.68	65	78.39
STRaTA CGF'15 [22]	1 GHz	BVH	365.6	57.1	65	6.40
MBVH SIGGRAPH'16 [23]	500 MHz	BVH	88	3.12	45	28.21
Dual Streaming HPG'17 [24]	1 GHz	BVH	345.6	57.1	65	6.05
Mach-RT TVCG'20 [25]	2 GHz	BVH	284.25	52	65	5.47
RT engine	850 MHz	BVH	92.74	0.48	28	193.21

在性能与面积比上达到现有设计中的最高。

3. 应用:加速电影特效制作



AUTODESK

Arnold Maya

https://blogs.nvidia.com/blog/2019/12/10/rtx-autodesk-maya-arnold/

3. 应用:加速求解KNN问题

RTNN: Accelerating Neighbor Search Using Hardware Ray Tracing (PPoPP 2022： 并行计算顶会)

利用Nvidia RTX系列显卡的RT Core 单元的加速BVH求交功能，来对2/3维的KNN（K-Nearest Neighbors） 问题进行求解。

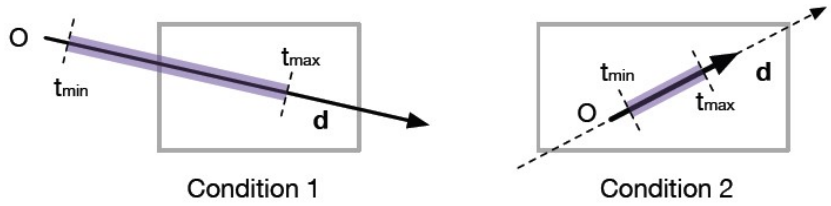
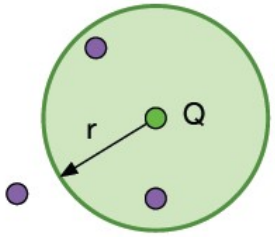
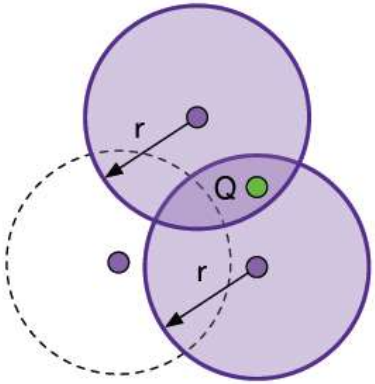


Fig. 2. Two conditions for ray-AABB intersection.



(a) Original neighbor search for query Q.



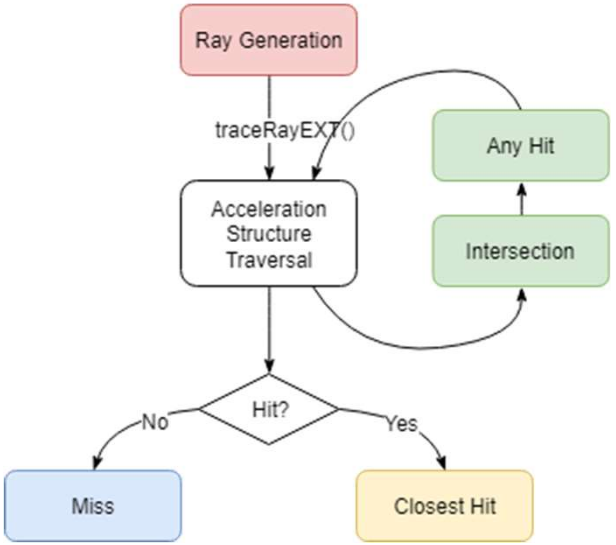
(b) Reversed neighbor search.

位置Q半径R中有几个点？ 等价于 Q位置在几个半径为R的球中

3. 应用:实时光线追踪

渲染器、游戏

实际使用时，使用Vulkan/DX12，
首先使用GPU构建加速结构（BVH），
然后编写5个shader程序即可使用：
Ray Generation、
Any Hit、
Intersection、
Miss和
Closest Hit



演示： NVIDIA Vulkan Ray Tracing Tutorials

参考

- 一篇光线追踪的入门

https://zhuanlan.zhihu.com/p/41269520

- https://github.com/nvpro-samples/vk_raytracing_tutorial_KHR
- 深入GPU硬件架构及运行机制

https://www.cnblogs.com/timlly/p/11471507.html

谢谢！