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Employing GPUs to Accelerate Exact Geometric Predicates for 3D Geospatial Processing

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2nd ACM SIGSPATIAL International Workshop on Spatial Gems (SpatialGems 2020)

This paper’s contribution

- A faster solution to erroneous computations caused by floating point finite precision computations.
- Errors can cause predicates (conditionals) to be evaluated wrong.
- That can cause topological errors.
- Other techniques are either very slow or may fail.
- GPU + interval arithmetic → performance and exactness.

The problem of roundoff errors

- Floating-point errors: computational geometry challenge.
- Generate topological inconsistencies: global impossibilities.
  - intersection point between two lines may not lie in either.

Rationals: one roundoff error solution

- Solution for roundoff errors: exact arithmetic (e.g. GMP rationals), but challenges:
  - Slower than floats (software-based)
  - Apparently little prior art of working (not just proposed) rational number systems on GPUs

Arithmetic filters and Interval arithmetic (IA)

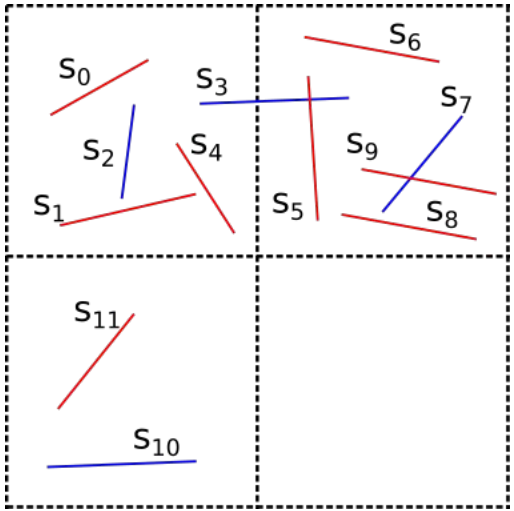
- Technique used in several CG implementations, e.g.: CGAL
- Use exact arithmetic only when **really** necessary
- Basic idea:
  - Computation performed with floats.
  - IA allows us to know if results are reliable.
  - Thus, if reliable → return them.
  - Otherwise (rare), we re-compute using exact arithmetic.

Idea for using exact computation and GPUs

- GPUs:
  - excellent for floating-point arithmetic
  - however, warps of 32 threads should run same instruction stream on adjacent data
- Implement the IA computation on the GPU
- CPU batch offloads evaluation of predicates to GPU.
- Unreliable results are filtered and re-evaluated on the CPU.

Idea for using exact computation and GPUs

- Pre-process data on the CPU (e.g.: index filtering)
- Offload predicates in batch to the GPU
  - Evaluation with FP/IA
- Uncertain results: re-evaluated on the CPU with rationals.

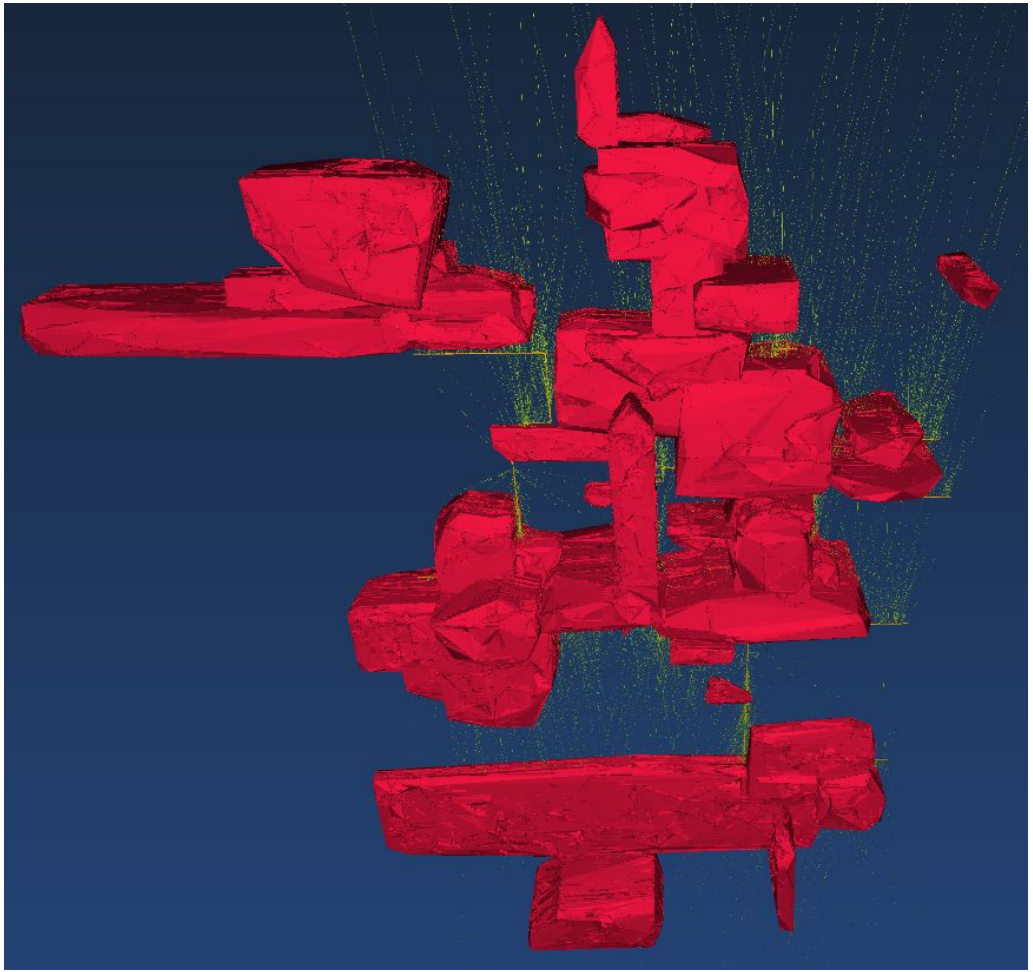


Example of uniform grid index for the 2D red-blue segment intersection

- Only pairs in the same cell may intersect.

Case study

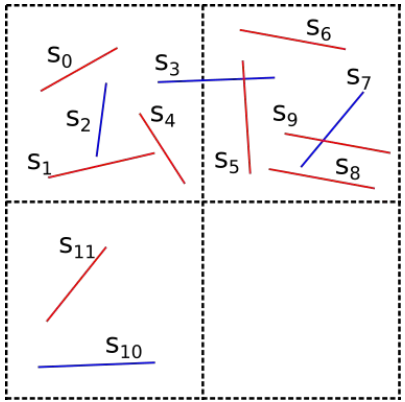
- Presented in a very interesting Sigspatial 2019 paper.
- Detecting pairwise intersections of segments and triangles in 3D.
- Example of application: 3D model of a mining dataset.
  - Segments: sampling drill holes.
  - Triangles: representing minerals polyhedra.



Source: https://github.com/lucasvr/synthetic-mine-maker

Challenges

- First idea:
  - CPU: index generates list of potential intersections.
  - Transfer list of pairs of potentially intersecting triangles to GPU.
  - Transfer back list of intersecting pairs.
- Challenges:
  - Too much work for CPU.
  - Too much data to be transferred between CPU and GPU.

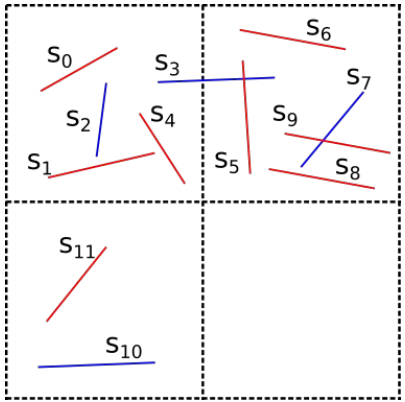


(considering the 2D red-blue intersection problem):

- Index → CPU: creates list with potential intersections: (s0,s2), (s0,s3), (s1,s2), (s1,s3), (s4,s2), (s4,s3), (s6,s3), (s6,s7),....
- **List** copied to GPU
- GPU (processes the list):
  - Thread 0: (s0,s2)
  - Thread 1: (s0,s3)
  - Thread 2: (s1,s2)
  - ...

Challenges

- Second idea:
  - CPU: creates index.
  - GPU: generates potentially intersecting pairs “on-the-fly” and process (one thread per segment or triangle)
  - Transfer back list of intersecting pairs.
- Challenges:
  - Load balancing.

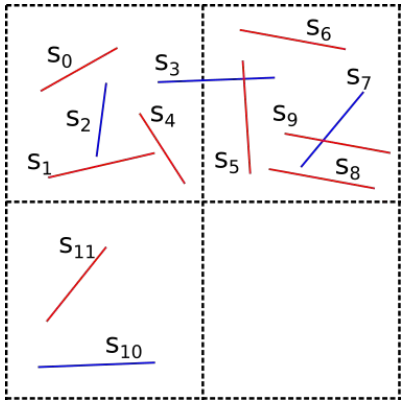


(considering the 2D red-blue intersection problem):

- **Grid** copied to GPU.
- GPU:
  - Thread 0: (s0,s2), (s0,s3)
  - Thread 1: (s1,s2), (s1,s3)
  - ...
  - Thread 7: (s11,s10) (unbalance)
  - ….

Challenges

- Third idea:
  - CPU: creates index.
  - GPU: generates potentially intersecting pairs “on-the-fly” and process (one thread per pair)
  - Transfer back list of intersecting pairs.
- Challenge: (solved on the paper)
  - How does a thread know which pair to process?



(considering the 2D red-blue intersection problem):

- **Grid** copied to GPU.
- Each thread:
  - Finds out which pair of segment it will process.
    - Thread 0: (s0,s2)
    - Thread 1: (s0,s3)
    - Thread 2: (s1,s2)

Experiments

- AMD Ryzen 5 1600 machine + Geforce GTX 1070Ti GPU (non-professional GPU!).
- Mining dataset (from sigspatial 2019): 1 000 000 triangles and 7846 segments.

Experiments

- Generate list of pairs on the CPU and process on GPU:
  - Too high pre-processing/memory overheads.
  - Good load balancing.

	Sequential	List of pairs	One segment/thread	One triangle/thread	Mult. blocks/cell
Pre-processing	-	0.67	0.00	0.00	0.00
Mem. (CPU to GPU)	-	0.21	0.02	0.01	0.02
Intersection	2.48	0.09	5.96	0.69	0.10
Mem. (GPU to CPU)	-	0.02	0.00	0.00	0.00
Rationals	0.00	0.03	0.00	0.00	0.00
Ensure uniqueness	0.01	0.01	0.02	0.02	0.02
Total	2.50	2.14	6.00	0.72	0.15

Experiments

- Index processed on GPU.
- Each GPU thread processes a segment.
- Segment tested for intersection against all triangles intersecting its bounding-box (index employed on GPU).
- Slow, low occupancy (much less segments than triangles), load unbalance.

	Sequential	List of pairs	One segment/thread	One triangle/thread	Mult. blocks/cell
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Ensure uniqueness	0.01	0.01	0.02	0.02	0.02
Total	2.50	2.14	6.00	0.72	0.15

Experiments

- Index processed on GPU.
- Each GPU thread processes a triangle.
- Triangle tested for intersection against all segments intersecting its bounding-box (index employed on GPU).
- Lower time (better occupancy), but problem with load balancing (some triangles bbox: intersect much more segments than others)

	Sequential	List of pairs	One segment/thread	One triangle/thread	Mult. blocks/cell
Pre-processing	-	0.67	0.00	0.00	0.00
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Total	2.50	2.14	6.00	0.72	0.15

Experiments

- Index processed on GPU.
- Multiple GPU threads per grid (index) block (proportional to number of pairs).
- Proportional → better load balancing/occupancy.
- 17x speedup, 25x speedup for the intersection step.

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Conclusions

- GPU can be employed to accelerate exact computation.
- Good speedups: 17x speedup, 25x speedup for the intersection step.
- Achieve both: performance and quality.
- Future work:
  - Optimize solution using shared memory
  - Map/Mesh intersection using GPUs.
  - Other geometric problems. (e.g. point location)

Reviews

- We thank the reviewers for their time and valuable comments.
- We were asked to make only minor modifications.
- Some sentences were not clear on the paper. We improved them.
- One of the reviewers asked us to present more details about performing other operations with IA (for example, multiplication)
    - Because of space limitations, we included a reference explaining how to perform several operations with IA. (there are also some details at the end of this talk)

Thank you!

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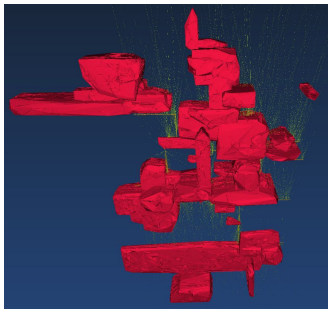
```
1  class CudaInterval {
2  public:
3      __device__ __host__ CudaInterval(const double l, const double u)
4          : lb(l), ub(u) {}
5      ...
6      __device__ CudaInterval operator+(const CudaInterval& v) const {
7          return CudaInterval(__dadd_rd(this->lb, v.lb),
8              __dadd_ru(this->ub, v.ub));
9      }
10     ...
11     __device__ int sign() const {
12         if (this->lb > 0) // lb > 0 implies ub > 0
13             return 1;
14         if (this->ub < 0) // ub < 0 implies lb < 0
15             return -1;
16         if (this->lb == 0 && this->ub == 0)
17             return 0;
18         // If none of the above conditions is satisfied, the sign of the
19         // exact result cannot be inferred from the interval, Thus, a flag
20         // is returned to indicate an interval failure.
21         return 2;
22     }
23     ...
24 private:
25     double lb, ub; // Stores the interval's lower and upper bounds
26 };
```



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