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PSCC: Parallel Self-Collision Culling with Spatial Hashing on GPUs

https://min-tang.github.io/home/PSCC/

Min Tang[1,2], Zhongyuan Liu[1], Ruofeng Tong[1], Dinesh Manocha[1,3]

[1]*Zhejiang University*
[2]*Alibaba-Zhejiang University Joint Institute of Frontier Technologies*
[3]*University of Maryland at College Park*

Outline

- Motivation & Challenges
- Related Work
- Main Results
- Algorithms
  - Parallel Self-collision Culling
  - Extended Spatial Hashing
  - Optimized Cloth Simulation Pipeline
- Result & Benchmarks
- Conclusions

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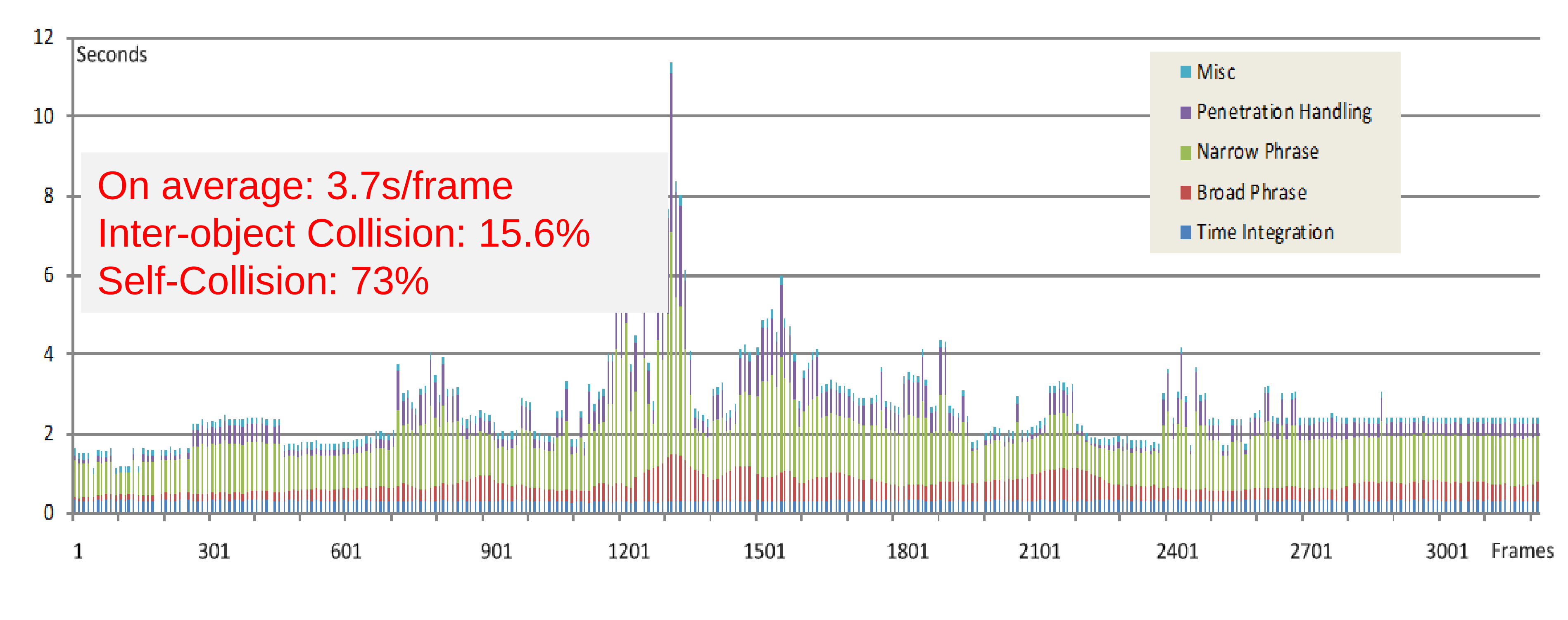
Challenges

- Collision handling remains a major bottleneck in deformable simulation
- Major bottleneck in cloth simulation [Tang et al. 2016]
- Most parallel GPU-base collision detection algorithms do not perform self-collision culling [Tang et al. 2016; Weller et al. 2017]



Challenges

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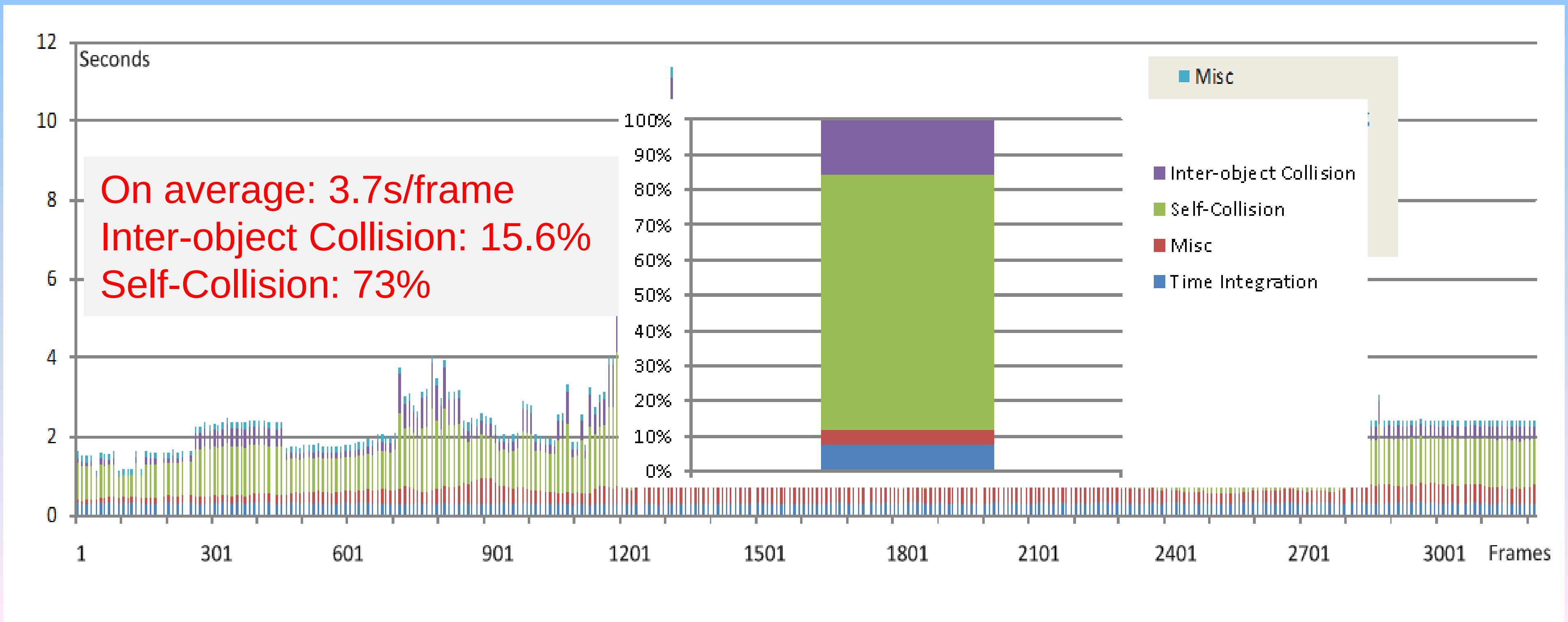

Motivation

- We want to design an optimized collision handling scheme with following capabilities:
  - **Lower memory overhead:** most commodity GPUs have less than 6GB memory (e.g., NVIDIA GeForce GTX 1060)
    - CAMA runs on Tesla K40c with 12G memory [Tang et al. 2016]
  - **Faster collision detection:** A key bottleneck in interactive performance
    - CAMA needs 4-5s/frames for its benchmarks [Tang et al. 2016]
  - **Parallel cloth simulation:** should integrate with parallel, GPU-friendly deformable simulation algorithms

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Related Work

- Self-collision Culling
- Spatial Hashing on GPUs
- Parallel Cloth Simulation on Multi-core / Many-core Processors

Related Work

- Self-collision Culling
  - Normal cone culling [Provot 1997, Schvartzman et al. 2010, Tang et al. 2009, Wang et al. 2017]
  - Energy-based culling [Barbic and James 2010, Zheng and James 2012]
  - Radial-based culling [Wong et al. 2013; Wong and Cheng 2014]
  - Most of them are serial algorithm running on single CPU core

Related Work

- Spatial Hashing on GPU
  - Used for collision detection [Lefebvre and Hoppe 2006]
  - Uniform grids [Pabst et al. 2010] or two-layer grids [Faure et al. 2012]
  - Hierarchical grids [Weller et al. 2017]
  - No self-collision culling
  - Can be used for rigid and deformable simulation

Related Work

- Parallel Cloth Simulation on Multi-core / Many-core Processors
  - Multi-core algorithms [Selle et al. 2009]
  - GPU parallelization for regular-shaped cloth [Tang et al. 2013]
  - CAMA: GPU streaming + Arbitray topology + robust collision handling [Tang et al. 2016]
  - Large memory overhead
  - Takes a few seconds per frame on a Tesla GPU

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Main Results

A GPU-based self-collision culling method; combines normal cone culling and spatial hashing:

1. Parallel self-collision culling based on normal cone test front;
2. Extended spatial-hashing for inter-object collisions and self-collisions;
3. New, optimized collision handling pipeline for cloth simulation.

Benefits

1. Lower memory overhead: 5-7X reduction than prior methods

2. Faster GPU-based collision detection between deformable models: 6-8X faster

3. Faster cloth simulation algorithm on GPUs: 4-6X faster

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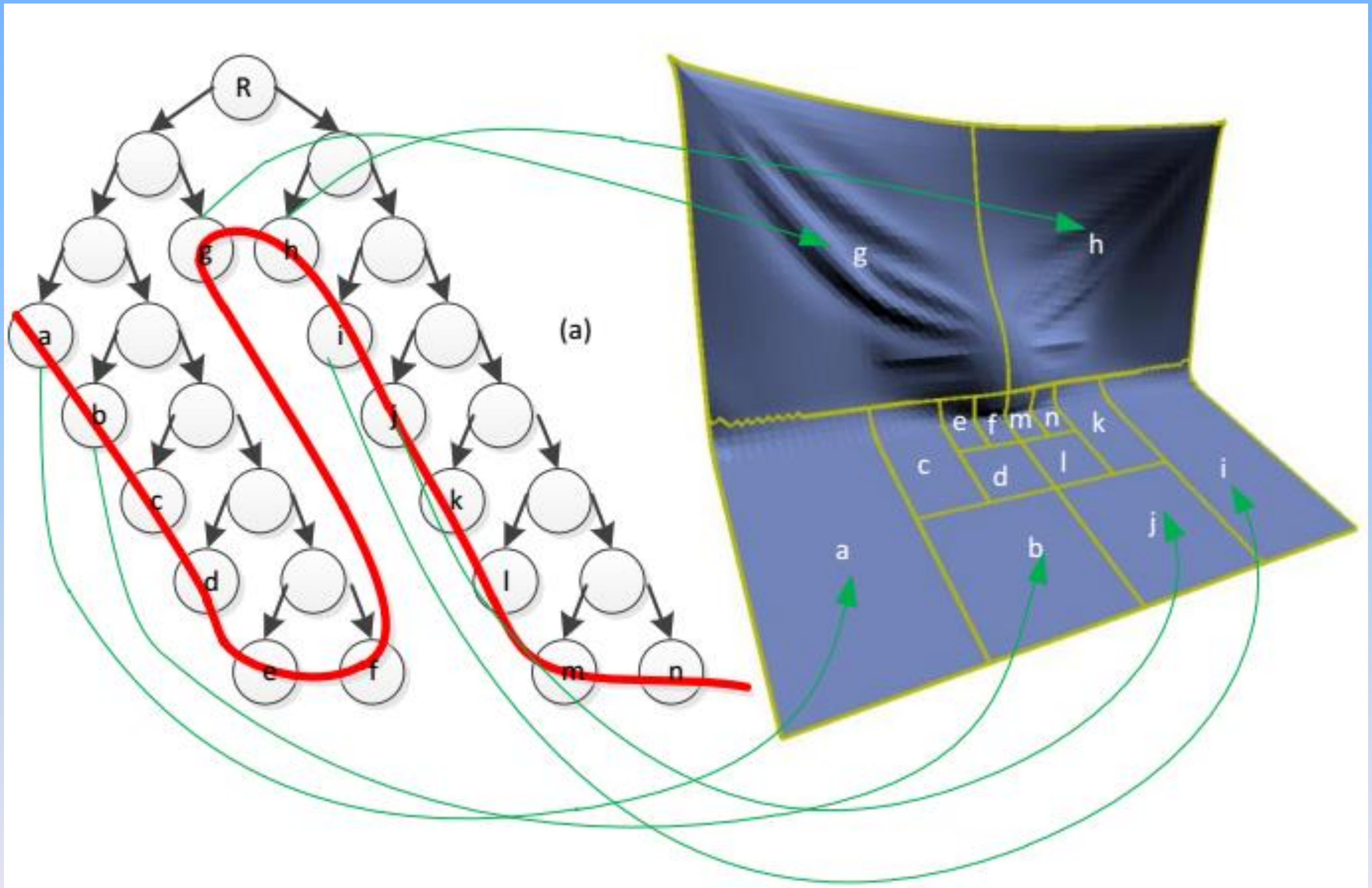
Parallel Normal Cone Culling

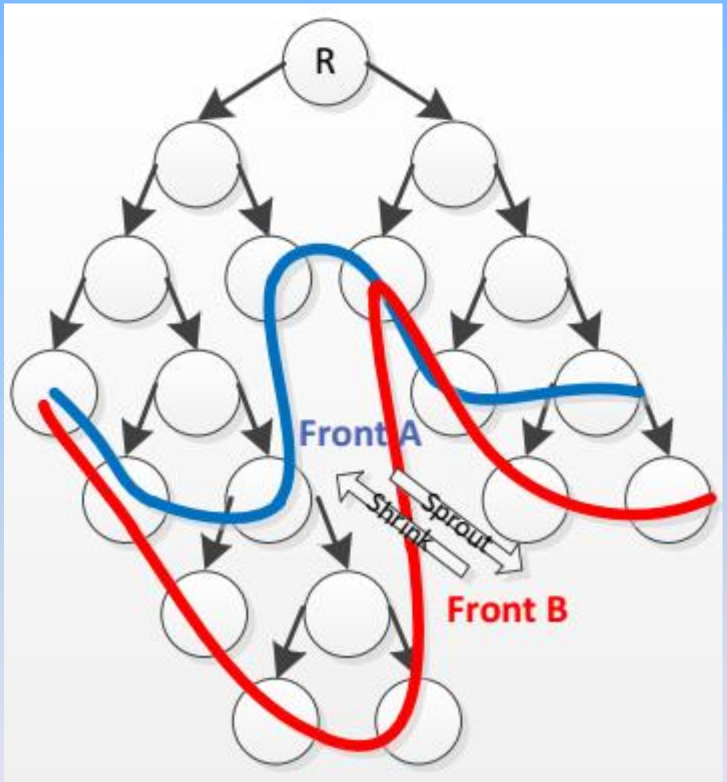
Conventional top-down culling is replaced by parallel culling;

Maintain a Normal Cone Test Front (NCTF).

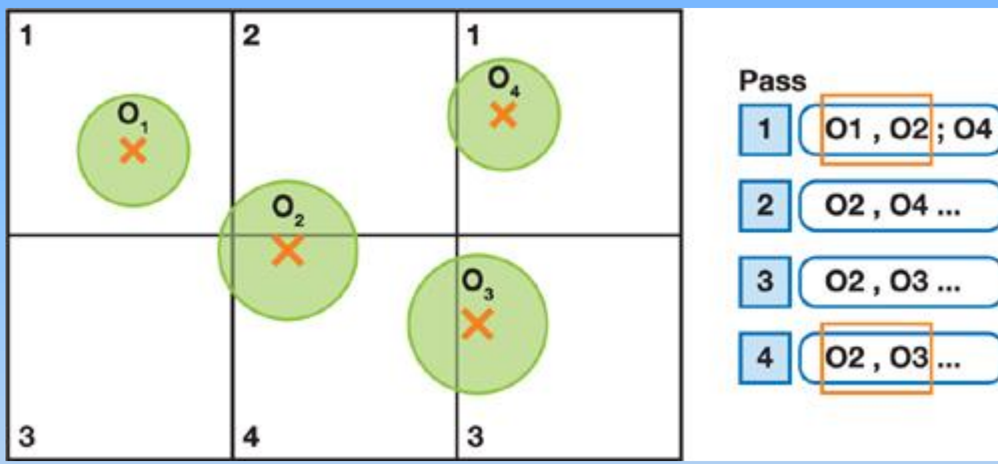


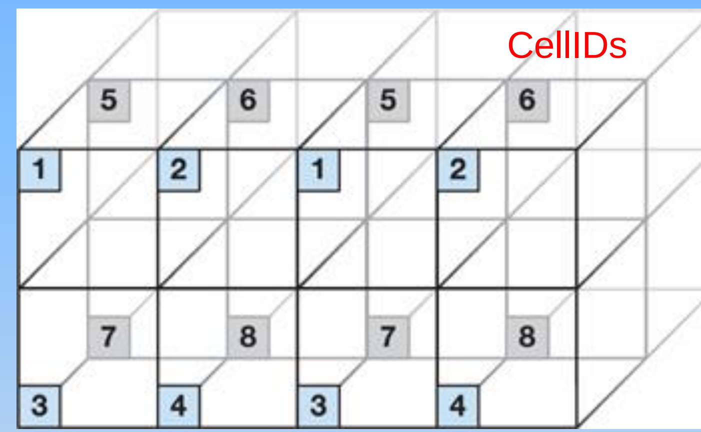
Parallel Normal Cone Culling

Front update using sprouting and shrinking operators



Conventional Spatial Hashing

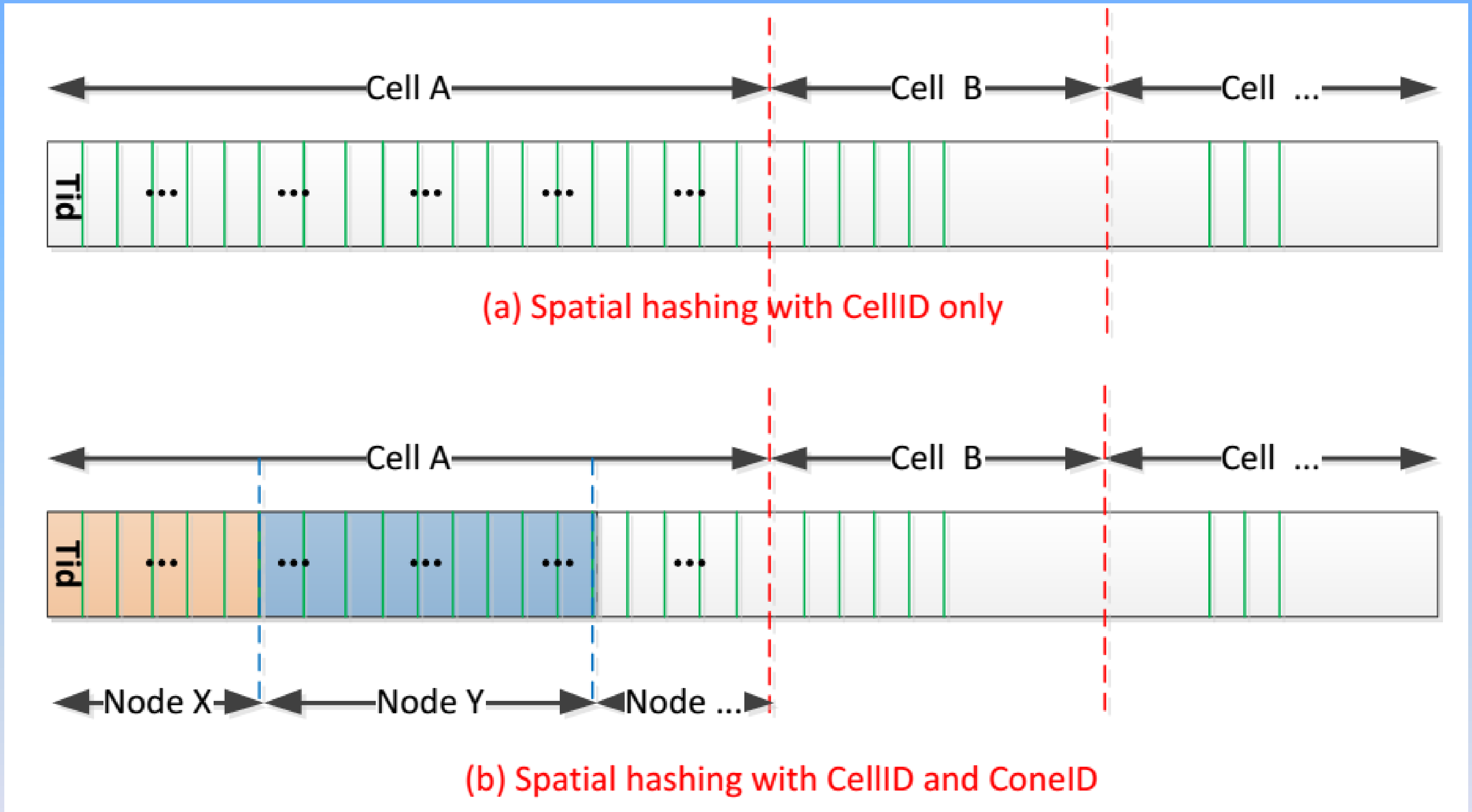




- Distribute all the objects into cells based on a hash function
- Intersection tests for all the objects in the same cell
- No self-collision culling between deformable objects

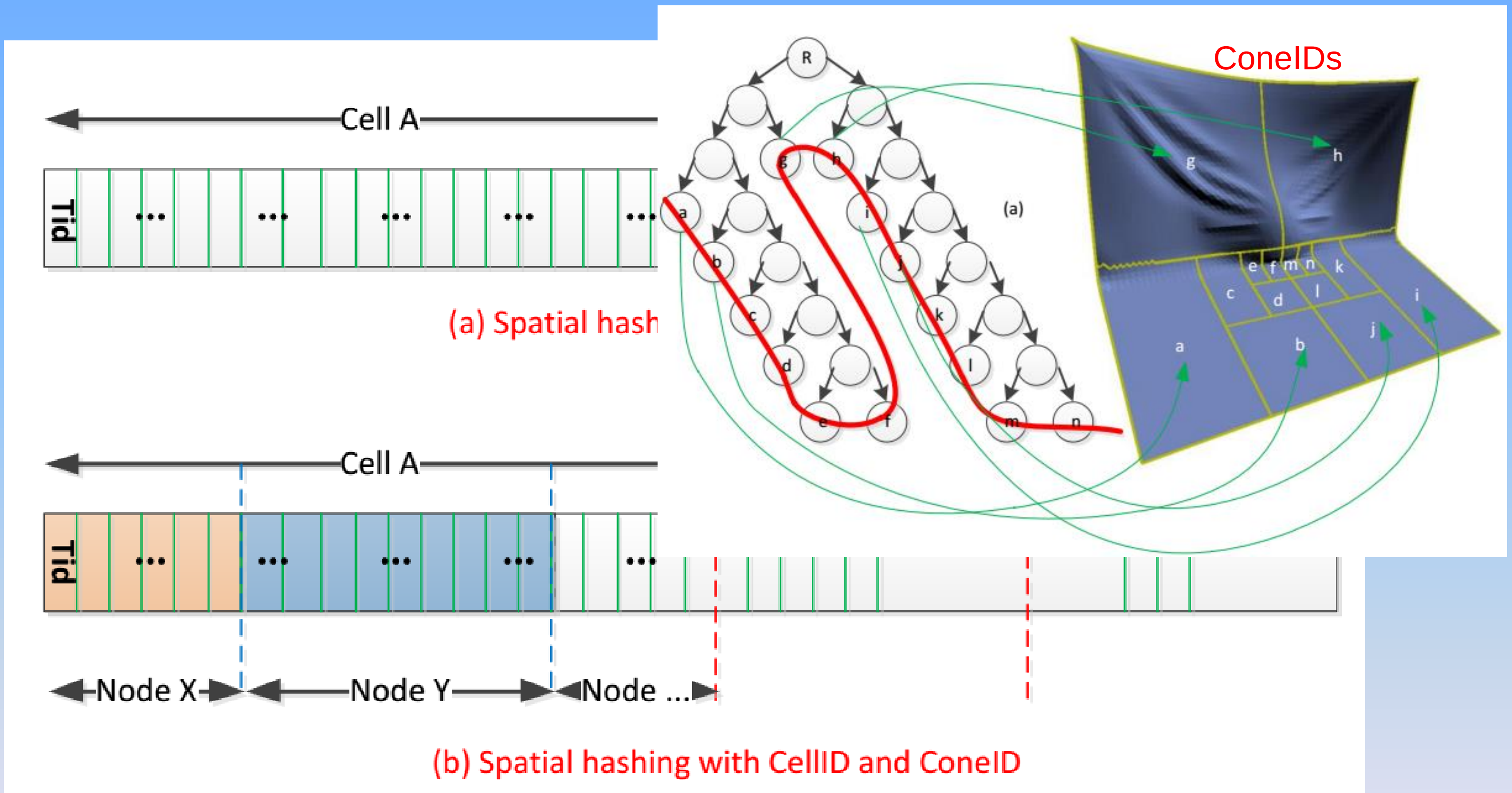
GPU Gems 3: Chapter 32. Broad-Phase Collision Detection with CUDA, *Scott Le Grand, NVIDA.*

Extended Spatial Hashing



To perform both inter-object and intra-object collision culling, CellID (spatial information) and ConeID (normal cone information) are used as hash keys

Extended Spatial Hashing



(a) Spatial hash

(b) Spatial hashing with CellID and ConeID

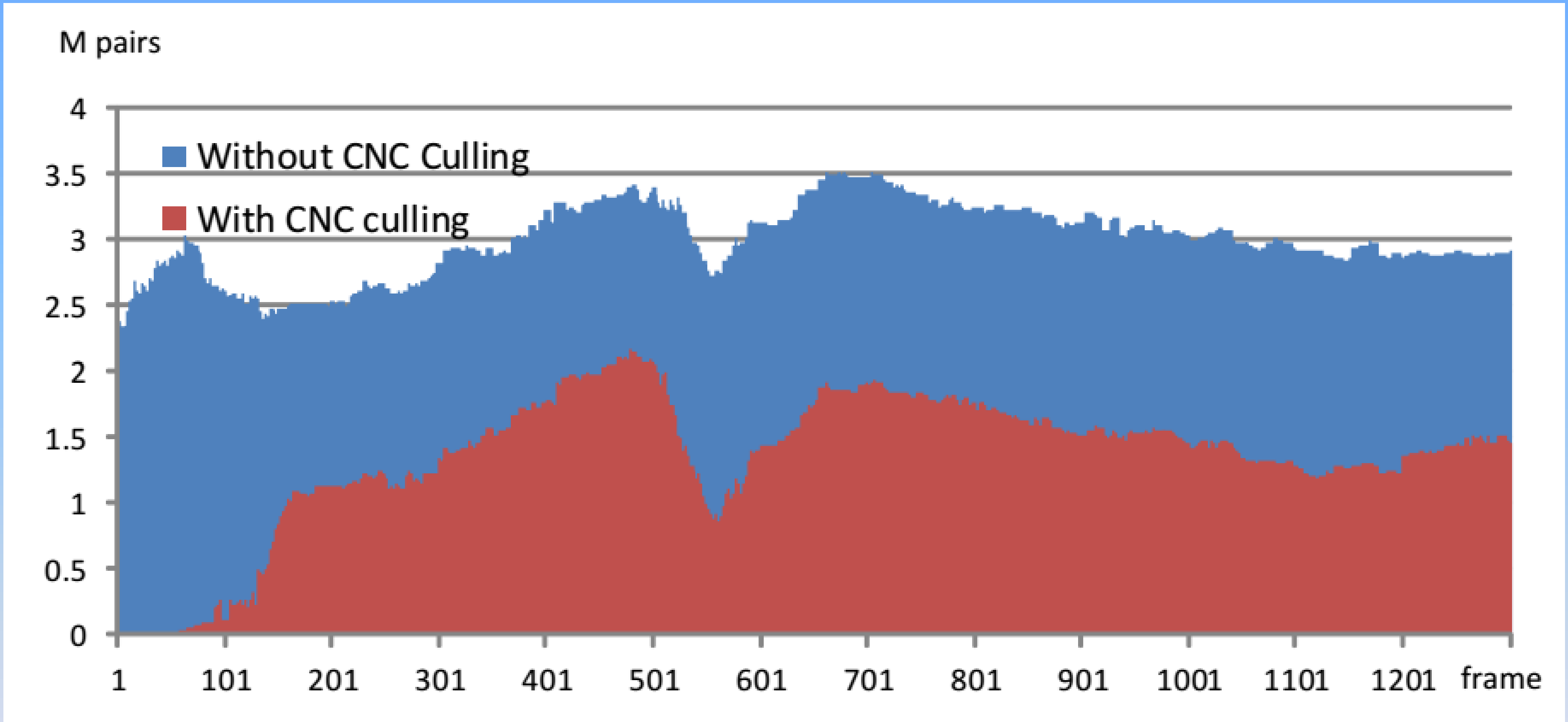
To perform both inter-object and intra-object collision culling, CellID (spatial information) and ConeID (normal cone information) are used as hash keys

Extended Spatial Hashing

Fewer triangle pairs are tested for collisions: due to self-collision culling:

$$
\begin{aligned}
N_{inter} - N'_{inter} &= n_t * (n_t - 1)/2 - \sum_{i \neq j} n_i * n_j \\
&= [(\sum n_i)^2 - \sum n_i - 2 * \sum_{i \neq j} n_i * n_j]/2 \\
&= (\sum n_i^2 - \sum n_i)/2 >= 0
\end{aligned}
$$

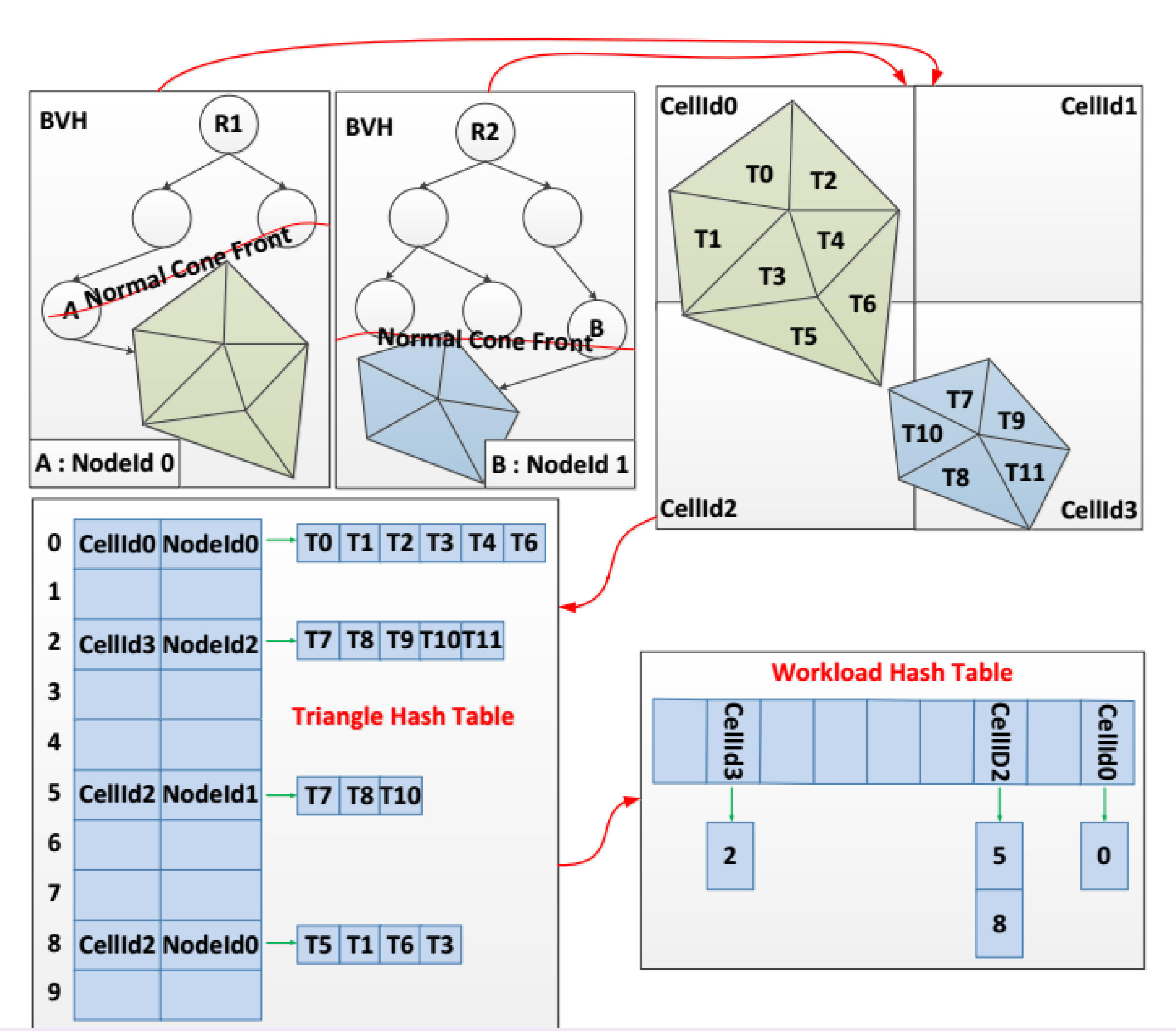
Extended Spatial Hashing



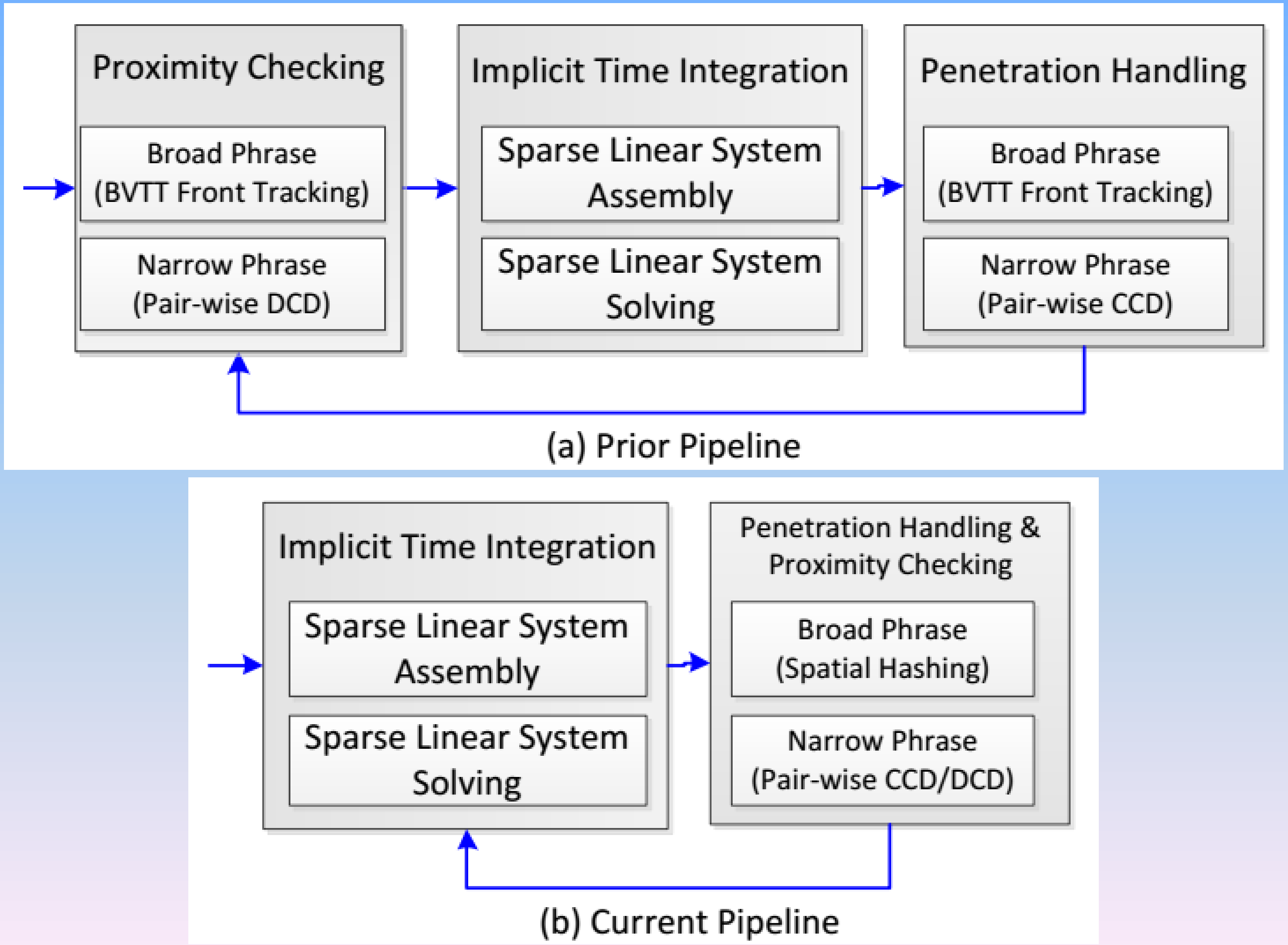
- Triangle pairs from broad phrase culling
- With and without CNC culling
- Fewer false positives with CNC culling

Extended Spatial Hashing

- Building Workload Hash Table on GPU
- GPU-based sparse matrix assembly [Tang et al. 2016]



New Collision Handling Pipeline



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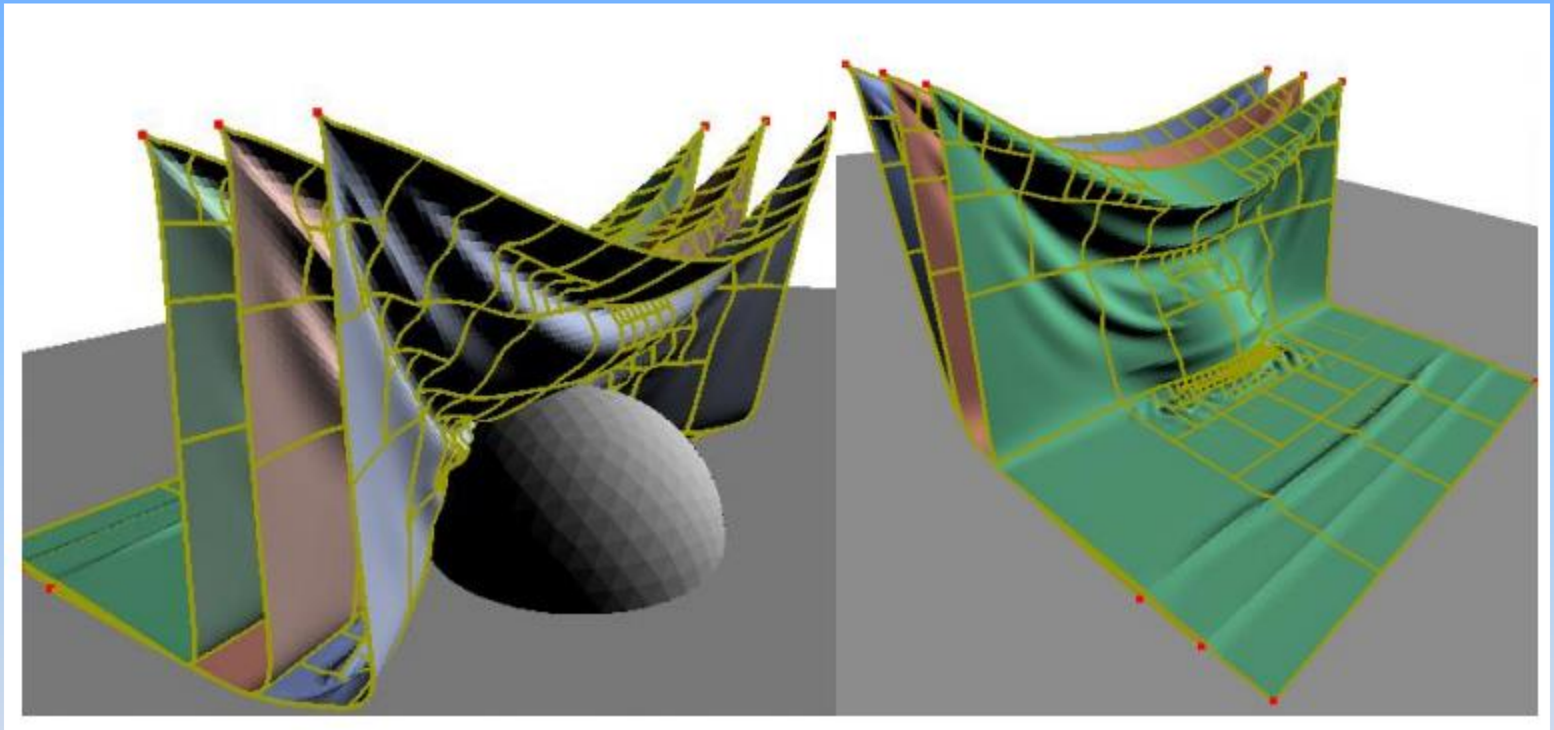

In this benchmark, the number of BV tests and running time of broad phrase culling is reduced by 51.1% and 53.3%, respectively.

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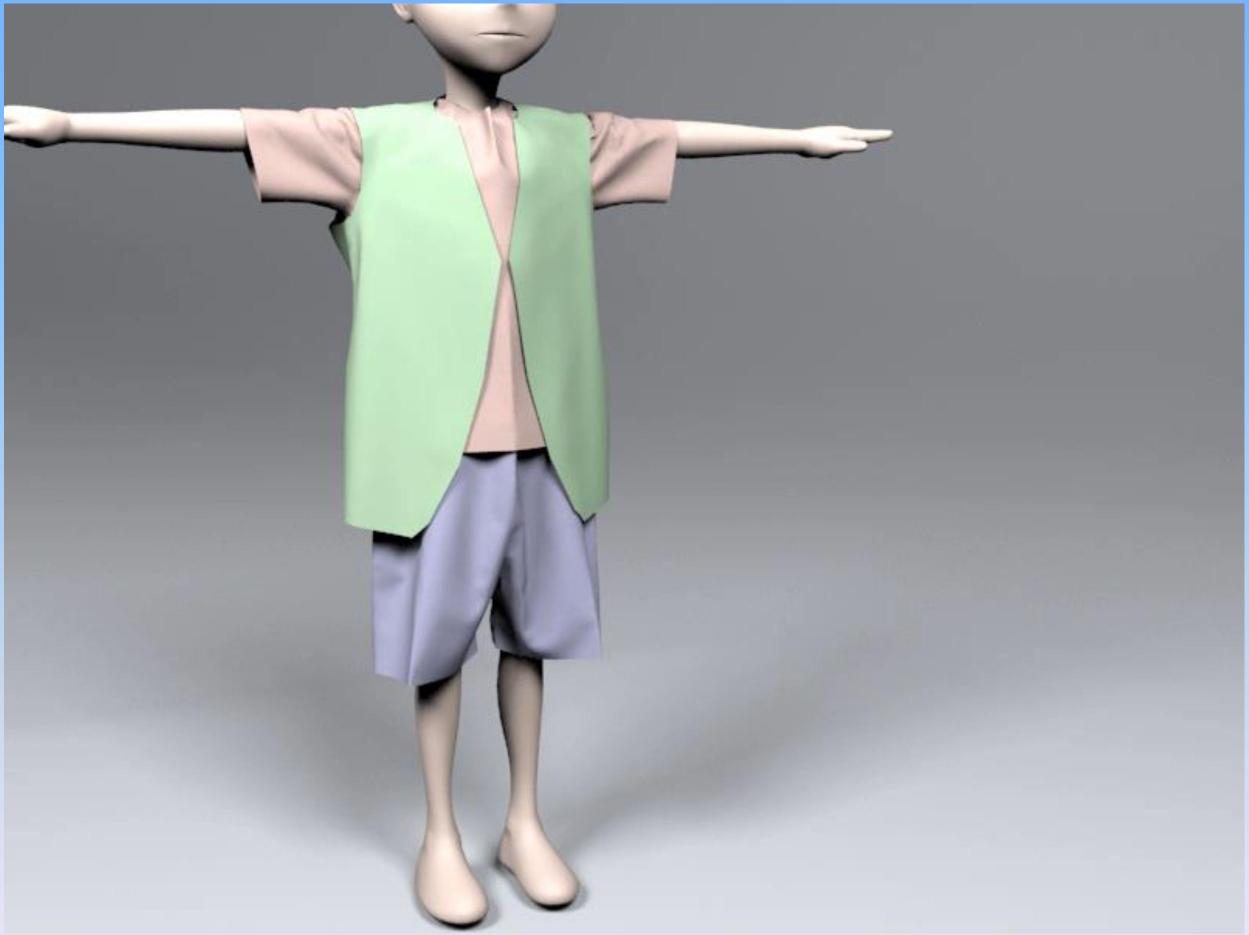
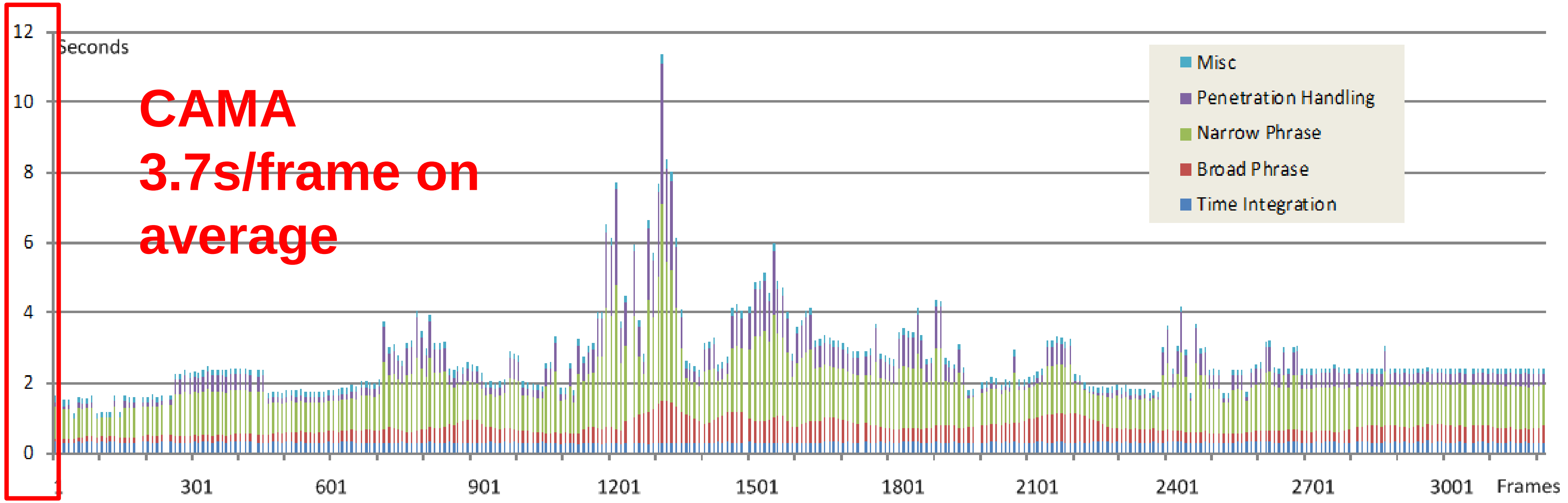
Performance

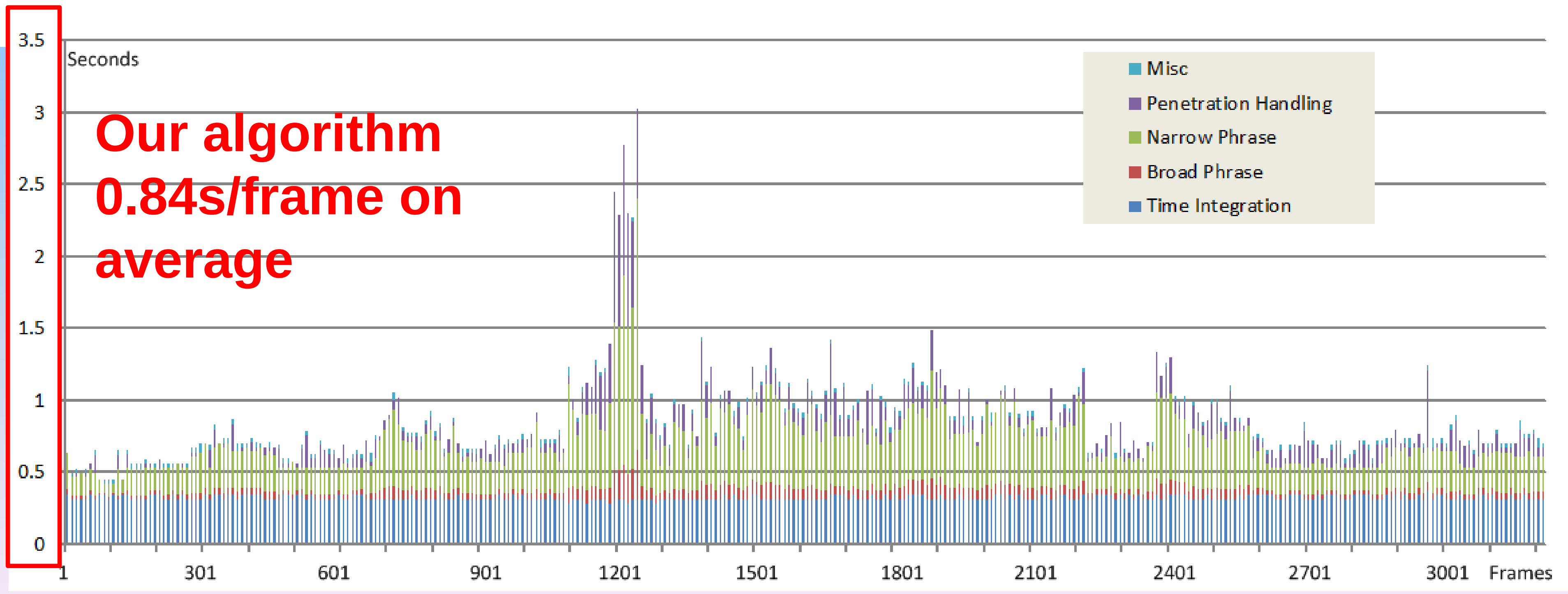
- Evaluated on NVIDIA Tesla K40c, GeForce GTX 1080, and GeForce GTX 1080 Ti;
- Complex benchmarks: 80K-200K triangles
  - High number of inter-object and intra-object collisions & folds
- Less than 1 second per frame for cloth simulation on GTX 1080 and 1080 Ti
- Considerable speedups over prior algorithms

Performance Comparison

- Benchmark Andy
- 127K triangles
- Time step: 1/25s
- NVIDIA GeForce GTX 1080
- Average cloth simulation time: 0.84s/frame
- Played at 24x speed

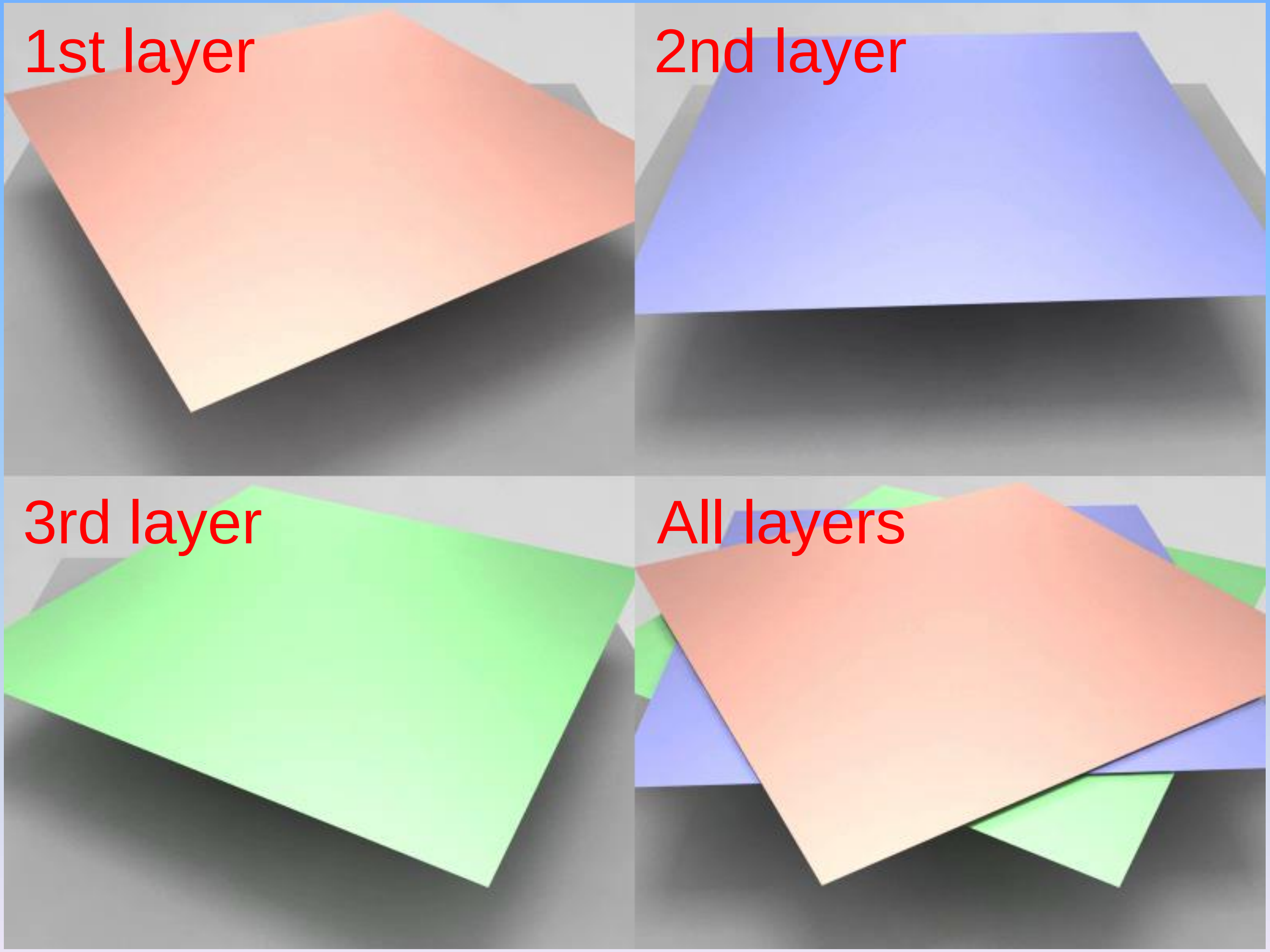



12
10
8
6
4
2
0
Seconds
CAMA
3.7s/frame on average
Misc
Penetration Handling
Narrow Phrase
Broad Phrase
Time Integration
1
301
601
901
1201
1501
1801
2101
2401
2701
3001
Frames


3.5
3
2.5
2
1.5
1
0.5
0
Seconds
Our algorithm
0.84s/frame on average
Misc
Penetration Handling
Narrow Phrase
Broad Phrase
Time Integration
1
301
601
901
1201
1501
1801
2101
2401
2701
3001
Frames

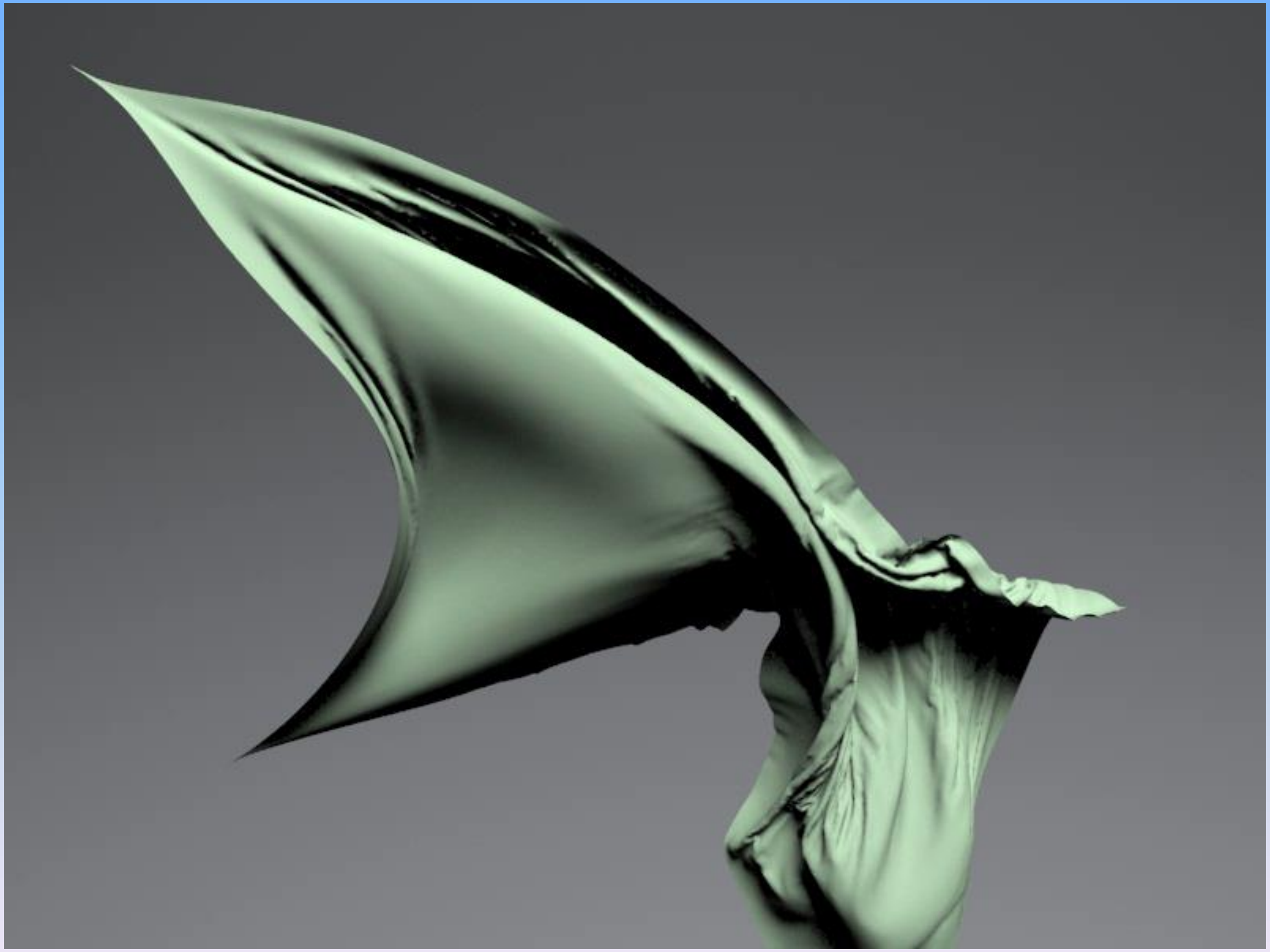
Benchmark: Twisting

- 200K triangles
- Time step: 1/200s
- Multiple layers and contacts
- Average cloth simulation time: 0.97s/frame
- Played at 28x speed



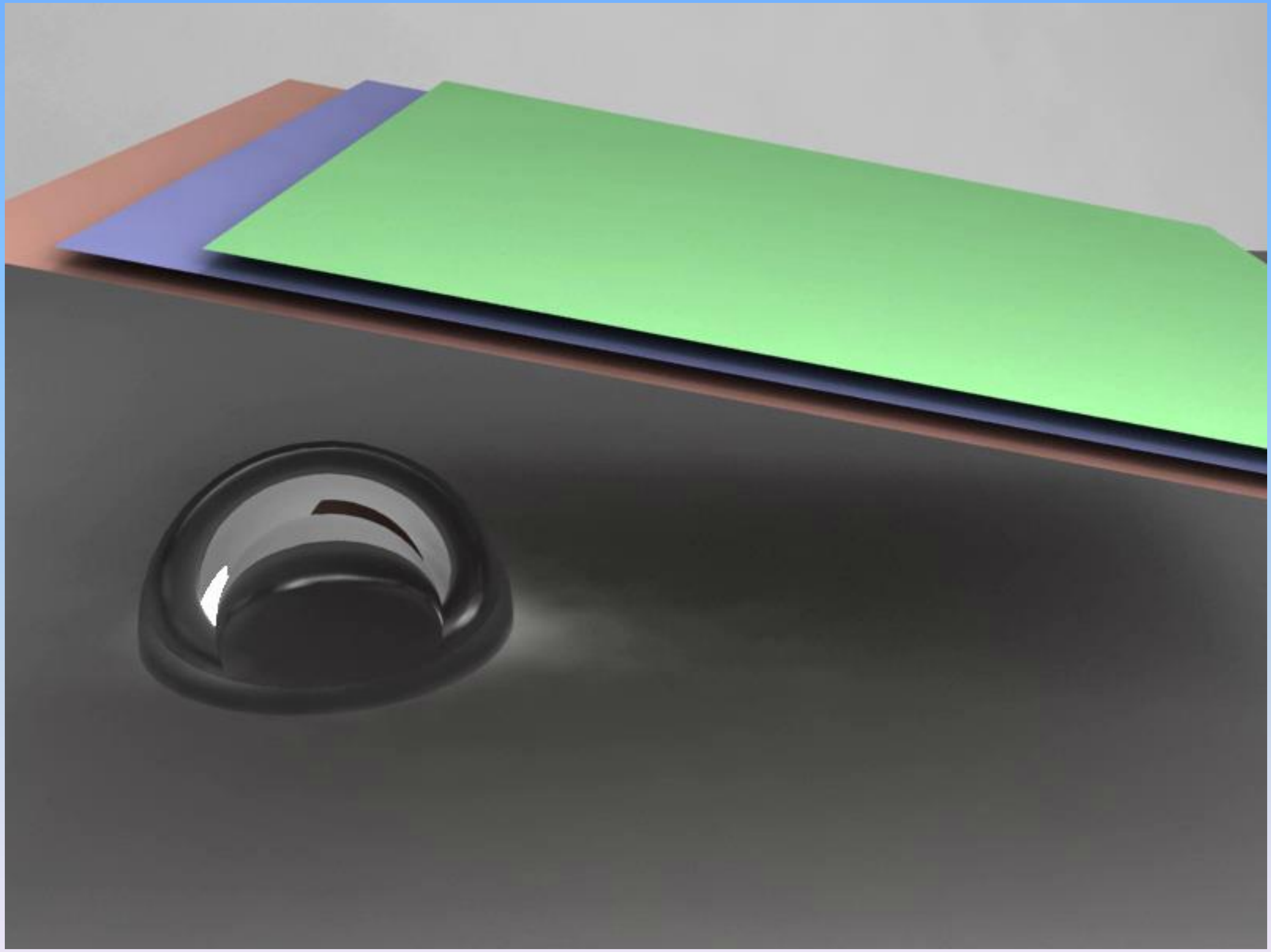
Benchmark: Flag

- 80K triangles
- Time step: 1/100s
- Multiple self-collisions
- Average cloth simulation time: 0.35s/frame
- Played at 10x speed



Benchmark: Sphere

- 200K triangles
- Time step: 1/300s
- Multiple layers and contacts
- Average cloth simulation time: 0.94s/frame
- Played at 26x speed

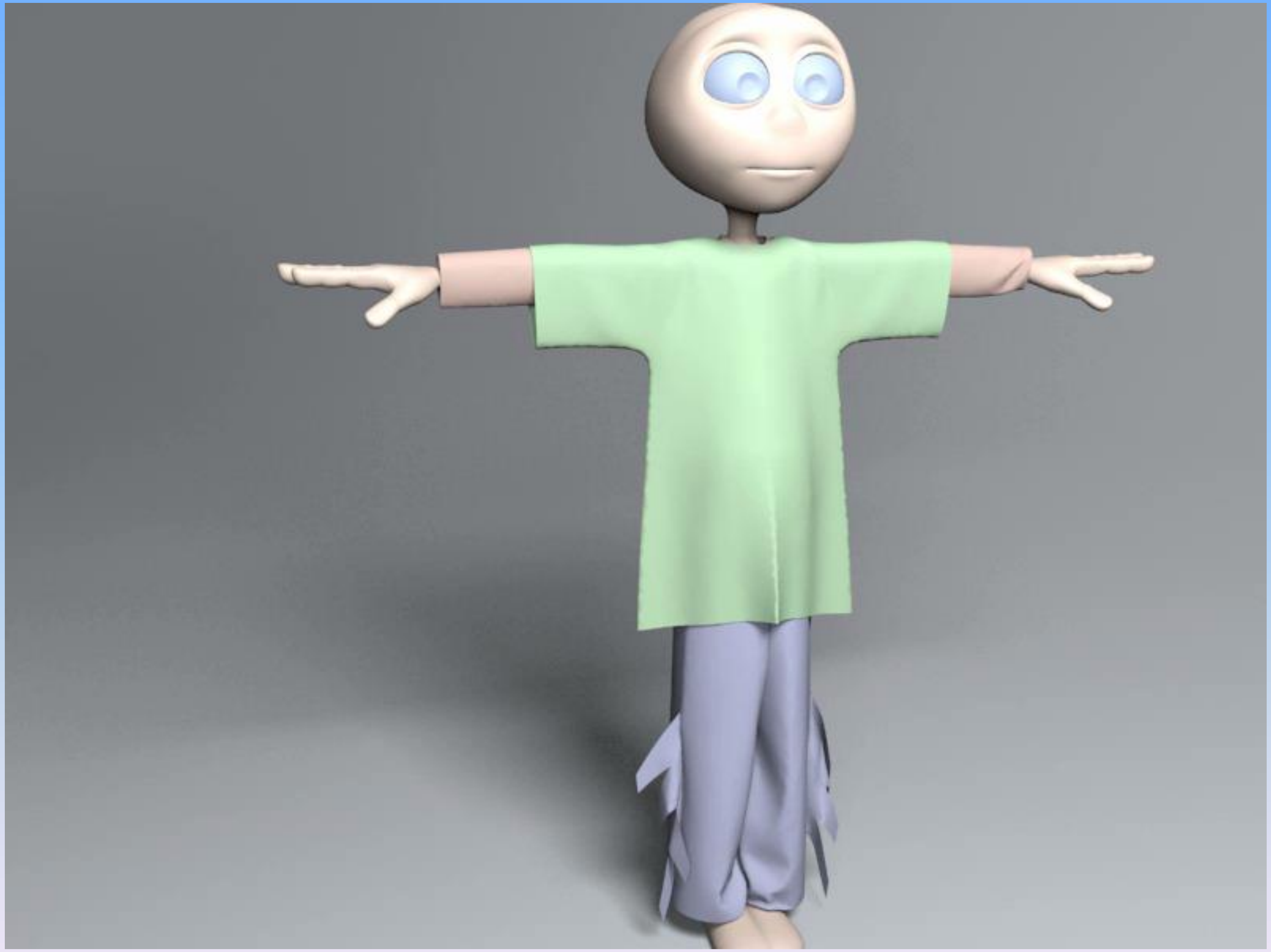


Benchmark: Falling

- 172K triangles
- Time step: 1/30s
- Multiple inter-object and intra-object collisions
- Average cloth simulation time: 0.51s/frame
- Played at 14x speed

Benchmark: Bishop

- 124K triangles
- Time step: 1/30s
- Multiple layers and contacts
- Average cloth simulation time: 0.94s/frame
- Played at 26x speed



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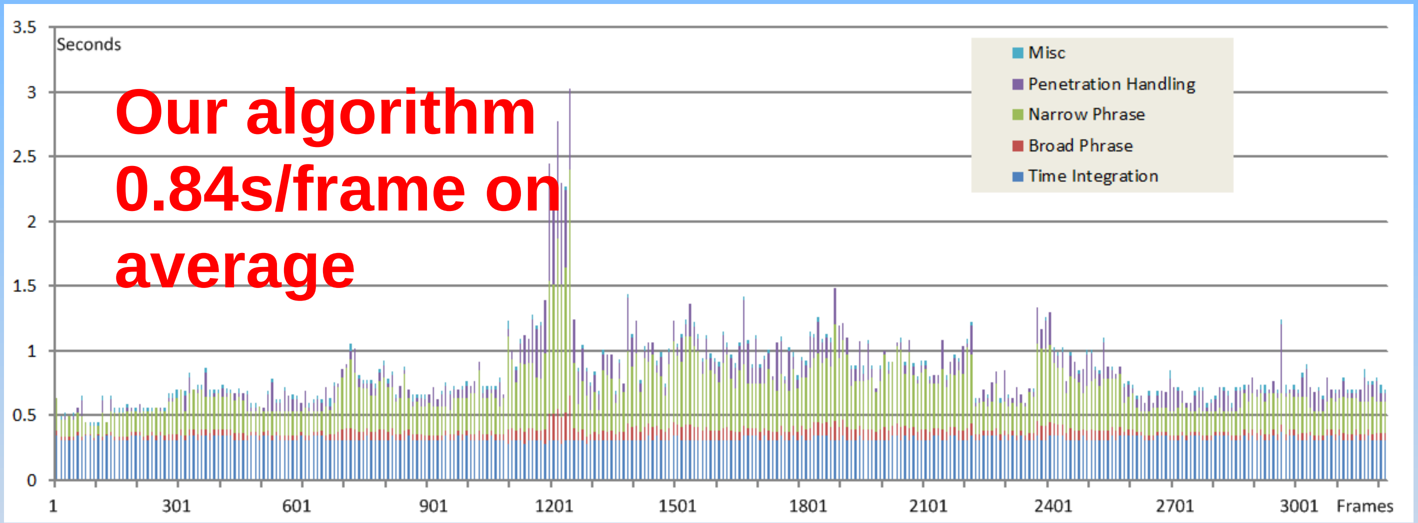
Main Results

- Novel parallel GPU-based self-collision culling algorithm;
- Considerable speedups over prior GPU-based algorithms;
- Almost real-time cloth simulation on complex benchmarks on a commodity GPU

Limitations

- For tangled cloth, collision detection and penetration handling still remain a major efficiency bottleneck;



- For meshes undergoing topological changes, the normal cones and their associated contour edges need to be updated on-the-fly.

Future work

- Faster collision handling
- Distance-field based collision handling
- Integration with cloth design and VR systems

Acknowledgements

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- Providers of all animation data

Q&A

Thanks!