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From 4 December 2020

Live sessions:
10 – 13 December 2020

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P-Cloth: Interactive Cloth Simulation on Multi-GPU Systems using Dynamic Matrix Assembly and Pipelined Implicit Integrators

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

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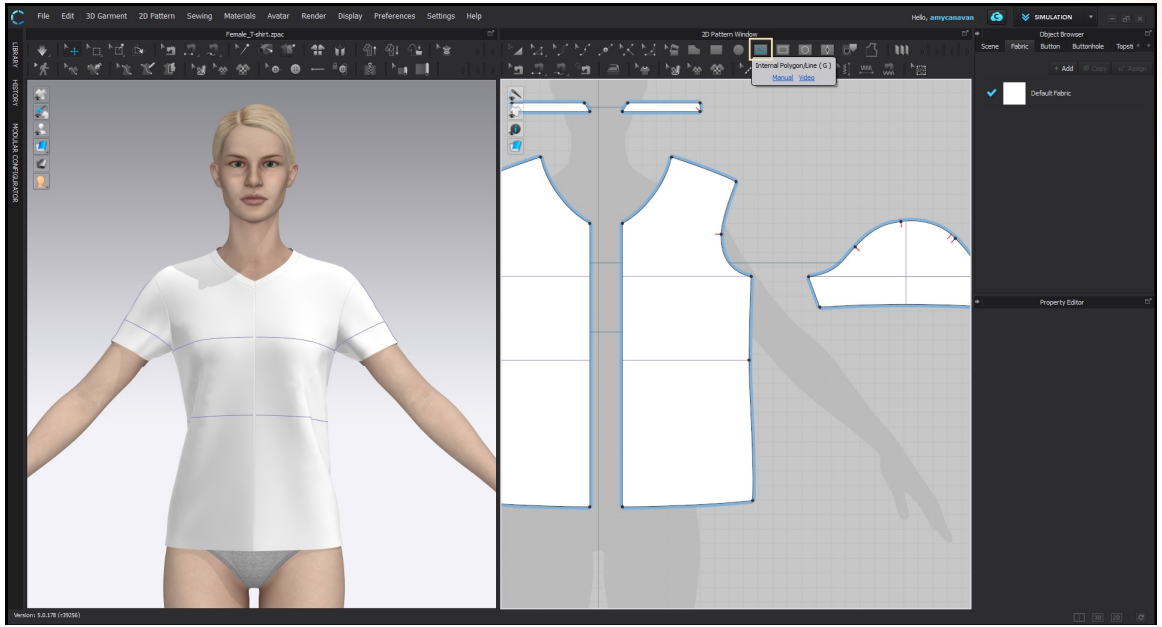
Applications



Garment Design

(CLO, Marvelous Designer)

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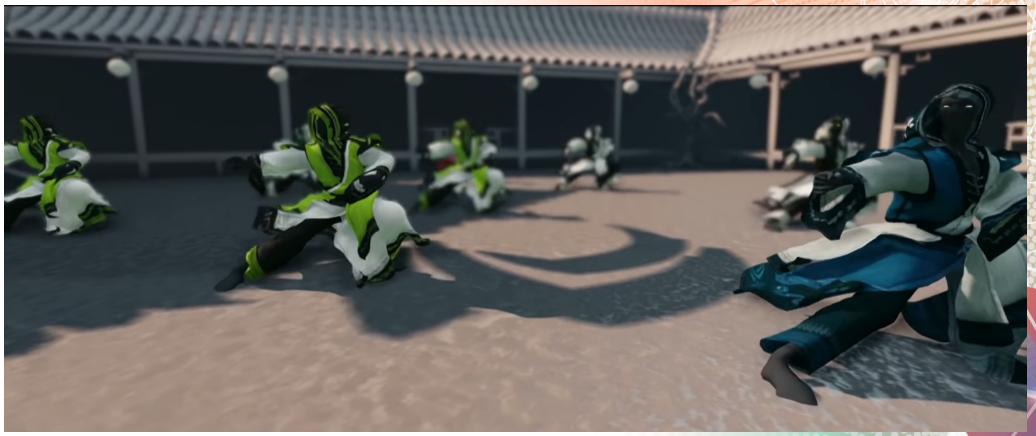
Applications



Video Games

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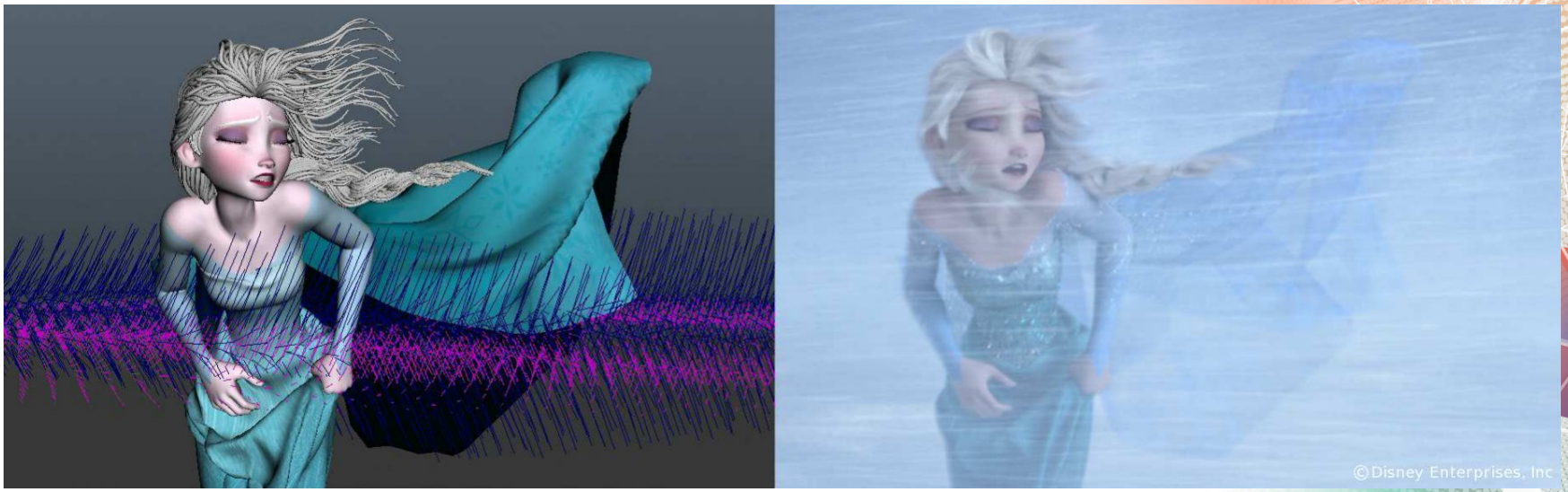
Applications

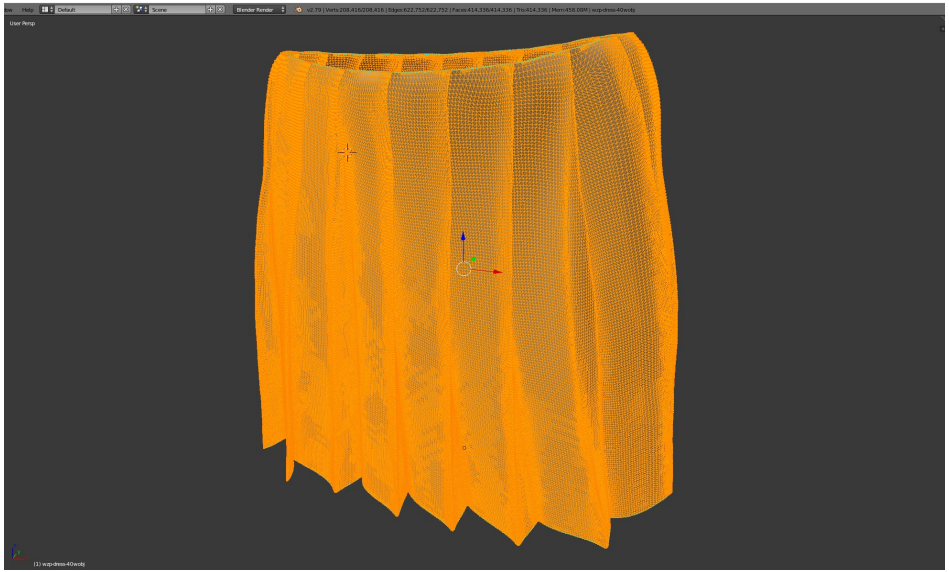


Movies

Challenges

- **Efficiency**

  High fidelity cloth simulation systems use cloth meshes with very high number of vertices.



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Challenges

- **Robustness**

  Self-collisions and inter-object collisions could be extremely complex.

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Challenges

- **Multi-GPU**
  - How to assign data and computations to multiple GPUs ?
  - How to reduce data transfers between multiple GPUs ?

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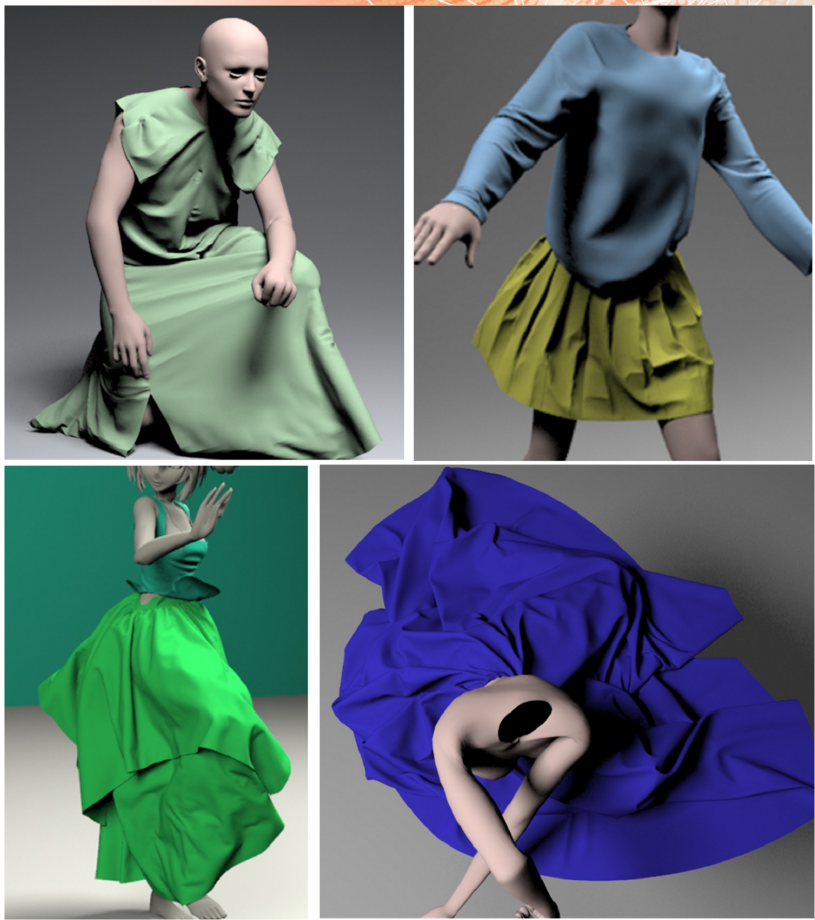
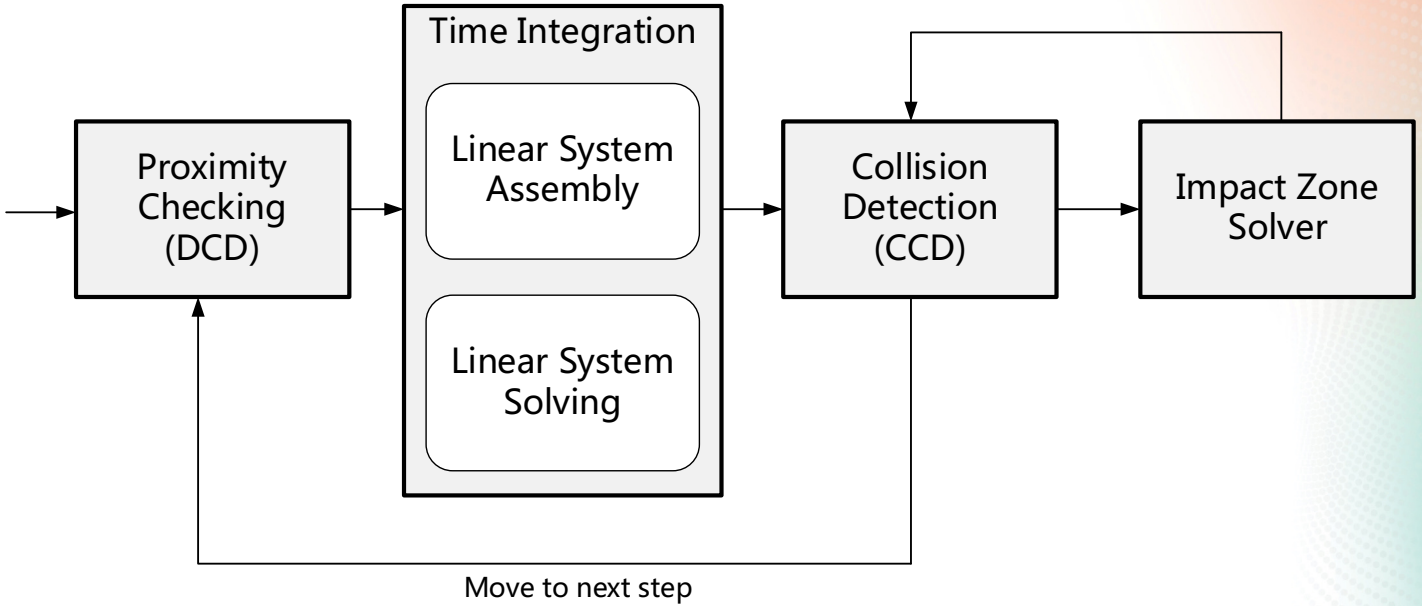
Main Results

- Parallel Multi-GPU cloth simulation
- Scalable parallel algorithms for matrix assembly, sparse linear system solving, and collision handling
- Applicable to cloth meshes with several million triangles on 4/8-GPU systems
- Almost interactive performance on 4 NVIDIA Titan Xp GPUs: 2-5fps
- Up to 8.23X speedups on 8 NVIDIA Titan V GPUs



Background

- **Overview of Cloth Simulation**



Background

- **Time Integration**

$$\mathbf{M}\ddot{\mathbf{u}} = \mathbf{f},$$

$$\mathbf{f}(\mathbf{u}_{t+\Delta t}) = \mathbf{f}(\mathbf{u}_t) + \mathbf{J} \cdot (\mathbf{u}_{t+\Delta t} - \mathbf{u}_t),$$

Considering the formulas:

$$(\mathbf{M} - \Delta t^2 \mathbf{J}) \cdot \Delta \mathbf{v} = \Delta t \mathbf{f}(\mathbf{u}_t + \Delta t \mathbf{v}_t),$$

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Background

- **Collision Detection and Response**
  - Collision Detection

    Broad Phase:

    High-level culling using spatial acceleration data structure

    Narrow Phase:

    Intersection Test
  - Collision Response

    Nonlinear Optimization

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Contributions

- Pipelined SpMV
- Dynamic Matrix Assembly
- Parallel Collision Handling

Pipelined SpMV

- **Recalling CG Solver**

1 **procedure modified-pcg**
2 $\Delta \mathbf{v} = \mathbf{z}$
3 $\delta_0 = \mathbf{filter}(\mathbf{b})^T \mathbf{P}\, \mathbf{filter}(\mathbf{b})$
4 $\mathbf{r} = \mathbf{filter}(\mathbf{b} - \mathbf{A}\Delta\mathbf{v})$
5 $\mathbf{c} = \mathbf{filter}(\mathbf{P}^{-1}\mathbf{r})$
6 $\delta_{new} = \mathbf{r}^T\mathbf{c}$
7 **while** $\delta_{new} > \epsilon^2\delta_0$
8 $\quad \mathbf{q} = \mathbf{filter}(\mathbf{Ac})$
9 $\quad \alpha = \delta_{new}/(\mathbf{c}^T\mathbf{q})$
10 $\quad \Delta\mathbf{v} = \Delta\mathbf{v} + \alpha\mathbf{c}$
11 $\quad \mathbf{r} = \mathbf{r} - \alpha\mathbf{q}$
12 $\quad \mathbf{s} = \mathbf{P}^{-1}\mathbf{r}$
13 $\quad \delta_{old} = \delta_{new}$
14 $\quad \delta_{new} = \mathbf{r}^T\mathbf{s}$
15 $\quad \mathbf{c} = \mathbf{filter}(\mathbf{s} + \frac{\delta_{new}}{\delta_{old}}\mathbf{c})$

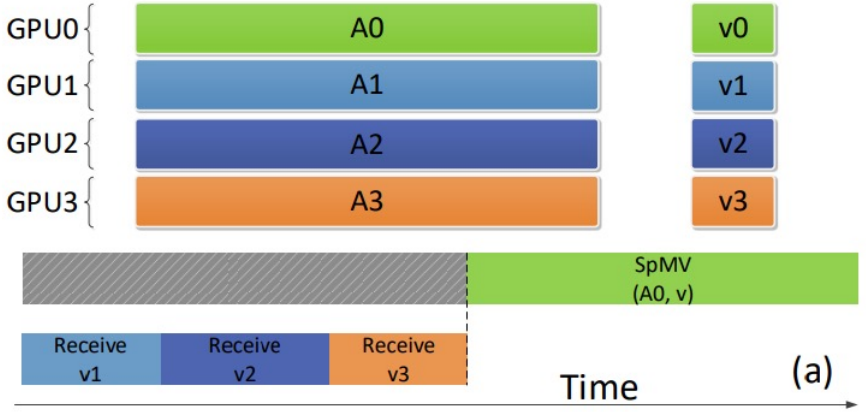
- Vector operations can be easily implemented on multiple GPUs.
- What about matrix-vector multiplication?

[Baraff and Witkin 1998]

Pipelined SpMV

- All-to-all data transfers are expensive
- Significantly reduce GPU loads

$$\mathbf{Av} = \begin{bmatrix} \mathbf{A}_0 \\ \mathbf{A}_1 \\ \vdots \\ \mathbf{A}_{n-1} \end{bmatrix} \begin{bmatrix} \mathbf{v}_0 \\ \mathbf{v}_1 \\ \vdots \\ \mathbf{v}_{n-1} \end{bmatrix} = \begin{bmatrix} \mathbf{A}_0(\mathbf{v}_0, \mathbf{v}_1, \ldots, \mathbf{v}_{n-1}) \\ \mathbf{A}_1(\mathbf{v}_0, \mathbf{v}_1, \ldots, \mathbf{v}_{n-1}) \\ \vdots \\ \mathbf{A}_{n-1}(\mathbf{v}_0, \mathbf{v}_1, \ldots, \mathbf{v}_{n-1}) \end{bmatrix}.$$

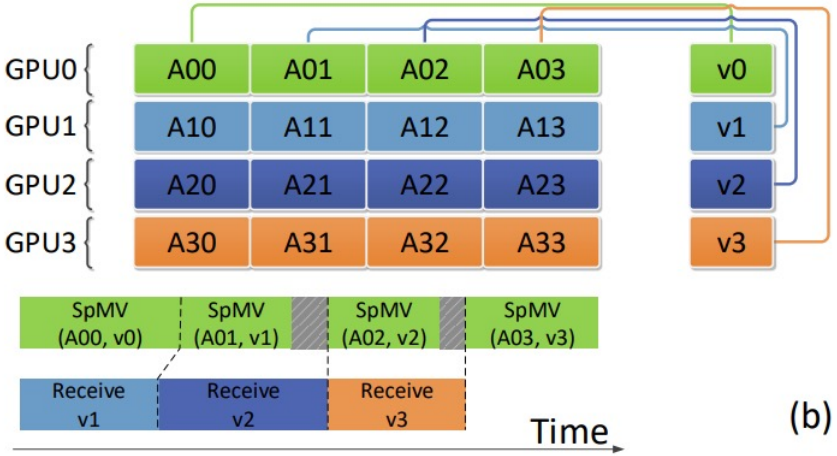


Pipelined SpMV

- **Novel Sparse Matrix-vector (SpMV) Multiplication**
  - Pipeline-based multiplication
  - Inter-leave computation and data transfer

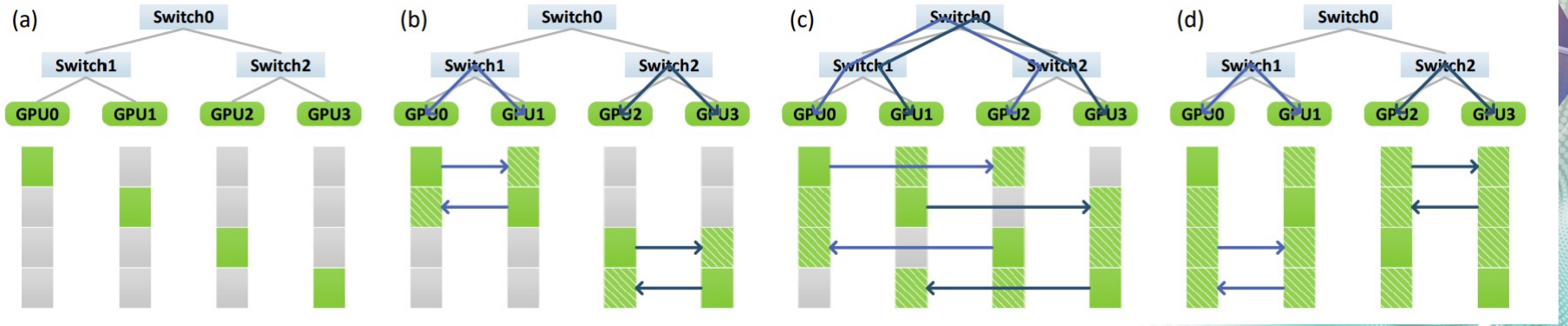
$$\mathbf{Av} = \begin{bmatrix} \mathbf{A}_{00} & \mathbf{A}_{01} & \cdots & \mathbf{A}_{0,n-1} \\ \mathbf{A}_{10} & \mathbf{A}_{11} & \cdots & \mathbf{A}_{1,n-1} \\ \vdots & & \ddots & \vdots \\ \mathbf{A}_{n-1,0} & \mathbf{A}_{n-1,1} & \cdots & \mathbf{A}_{n-1,n-1} \end{bmatrix} \begin{bmatrix} \mathbf{v}_0 \\ \mathbf{v}_1 \\ \vdots \\ \mathbf{v}_{n-1} \end{bmatrix}$$

$$= \begin{bmatrix} \mathbf{A}_{00}\mathbf{v}_0 + \mathbf{A}_{01}\mathbf{v}_1 + \ldots + \mathbf{A}_{0,n-1}\mathbf{v}_{n-1} \\ \mathbf{A}_{10}\mathbf{v}_0 + \mathbf{A}_{11}\mathbf{v}_1 + \ldots + \mathbf{A}_{1,n-1}\mathbf{v}_{n-1} \\ \vdots \\ \mathbf{A}_{n-1,0}\mathbf{v}_0 + \mathbf{A}_{n-1,1}\mathbf{v}_1 + \ldots + \mathbf{A}_{n-1,n-1}\mathbf{v}_{n-1} \end{bmatrix}.$$



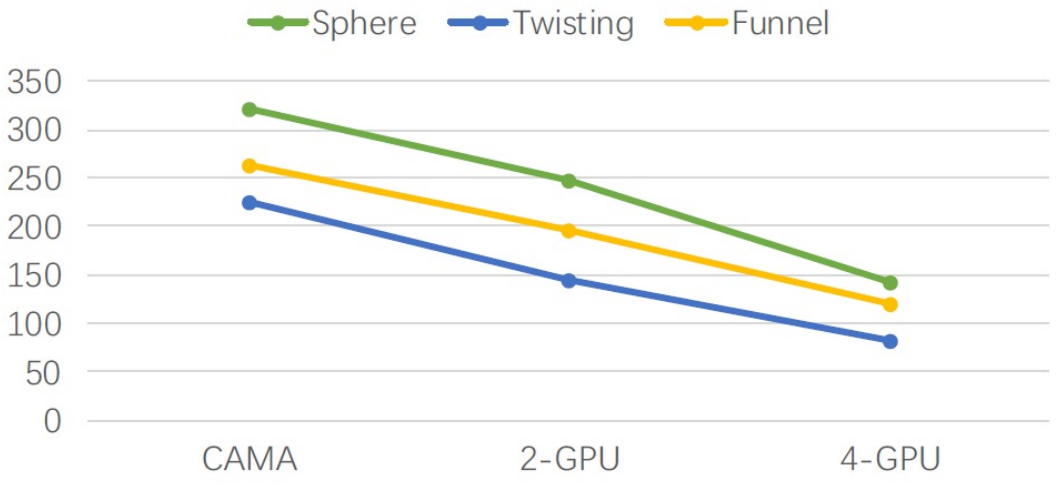
Pipelined SpMV

- **Novel Work Queue Generation Algorithm for Fat-tree Interconnect Topology**
  - Optimize data transfer between multiple GPUs
  - High throughput on complex meshes



Matrix Assembly

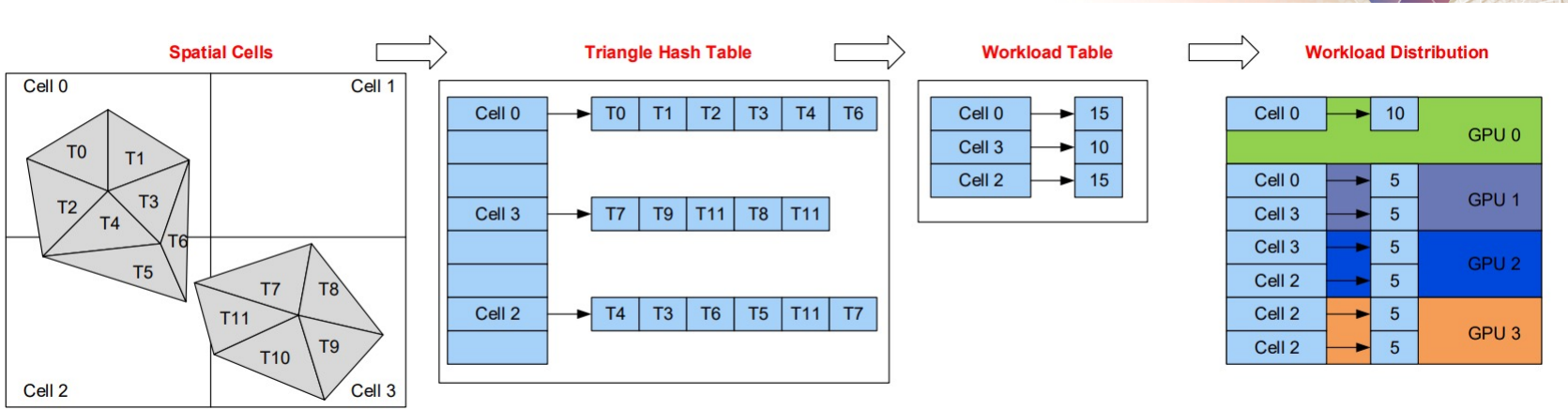
- Compute new contact forces and internal forces at each frame
- Assembly Elements Distribution
- Sparse Matrix Filling
- Use with a preconditioned conjugate gradient (PCG) solver on multiple GPUs



Performance Comparison
with CAMA[Tang et al. 2016]

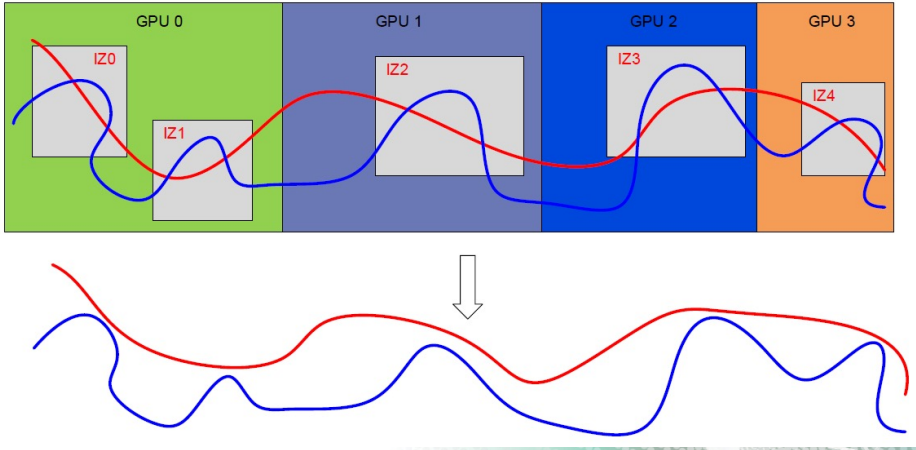
Collision Handling

- **Spatial Hashing**
  - Take hash table into parts and assign them to multiple GPUs



Collision Handling

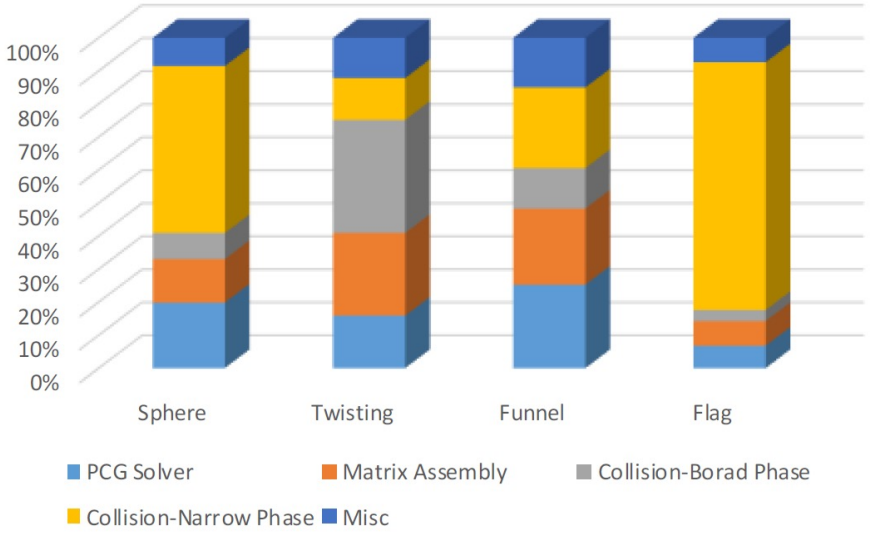
- Parallel algorithms for discrete and continuous collision detection
- Use spatial hashing over multiple GPUs for collision culling
- Scale linearly with number of GPUs
- Reduce memory overhead of each GPU
- First interactive approach for self-collision detection on meshes with 1+M triangles



Parallel Penetration Handling on Multi-GPUs

Results

- P-Cloth: Faster GPU-based simulator for complex meshes
- CUDA 10.0/Ubuntu 16.04
- Handles complex models with 1+ M triangles
- 2-5 fps on 4 NVIDIA Titan Xp GPUs
- Up to 5.1X on 4 NVIDIA Titan Xp GPUs
- Up to 8.23X on 8 NVIDIA Titan V GPUs



Runtime Ratios for Stages

Benchmark: Miku

- 1.33M triangles
- Time step: 1/1000s
- Multiple layers and self-collisions
- Average FPS: 2.59
- 5.4X on 4 GPUs

Benchmark: Miku

- Real-time Playback

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Benchmark: Zoey

- 569K triangles
- Time step: 1/500s
- Multiple layers and self-collisions
- Average FPS: 2.04
- 5.37X on 4 GPUs

Benchmark: Zoey

- Real-time Playback

Benchmark: Kimono

- 1M triangles
- Time step: 1/1000s
- Multiple layers and self-collisions
- Average FPS: 1.11
- 4.73X on 4 GPUs

Benchmark: Flag

- 1.2M triangles
- Time step: 1/250s
- Multiple layers and self-collisions
- Average FPS: 5.45
- 4.66X speedup on 4 GPUs
- 8.23X speedup on 8 GPUs

Comparison on Resolutions

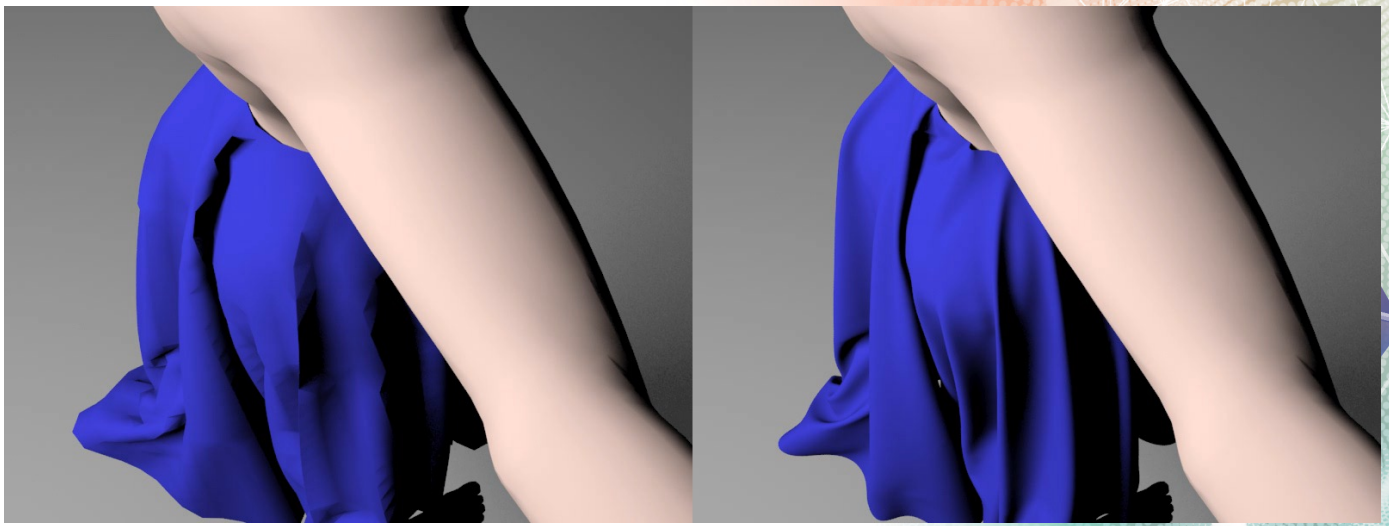
- More wrinkles and folds with higher triangle resolution
- 2.48fps on 4 GPUs with 1.65M triangles

3.1K triangles

1.65M triangles

Comparison on Resolutions

- More wrinkles and folds with higher triangle resolution
- 5.12fps on 4 GPUs with 510K triangles



10.1K triangles

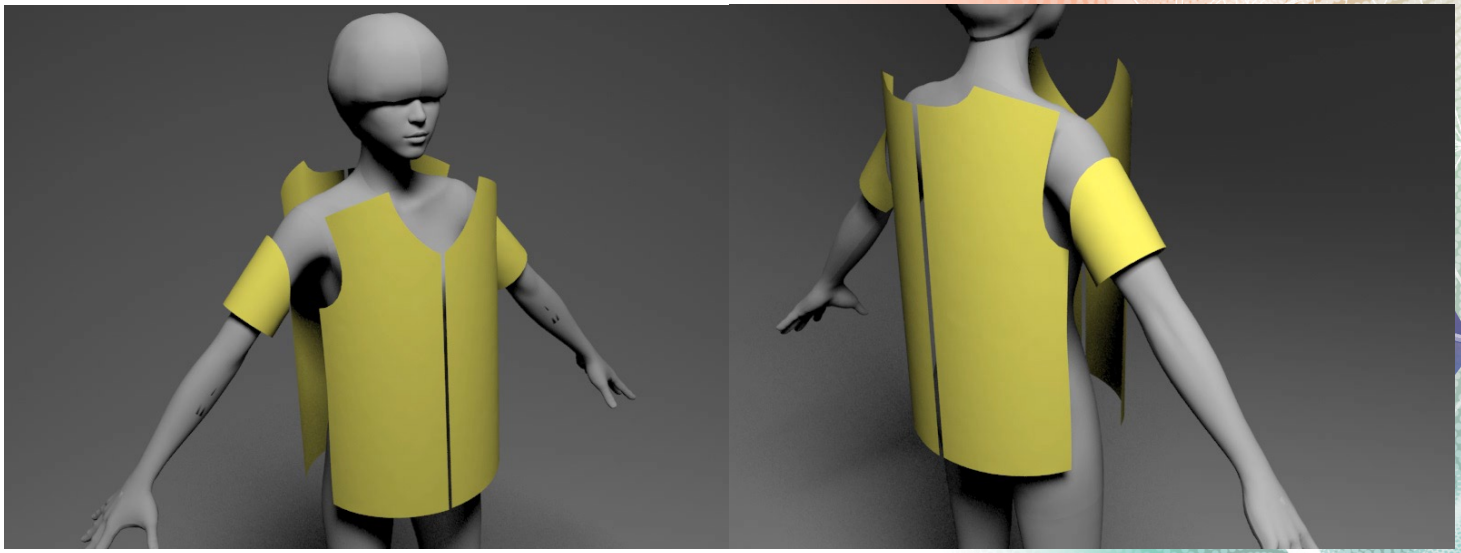
510K triangles

Comparison with I-Cloth

- Similar simulation accuracy
- 5.66X faster on 4 GPUs

Interactive Stitching

- Interactive rate (10+ fps)
- 316K triangles



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Limitations

- Collision detection remains a bottleneck.
- Pipelined SpMV is a general solution for all distributed systems, but work queue and data transfer algorithms are limited to fat-tree topologies.
- Speedup can vary depending on the cloth configuration and data synchronization overhead.
- Robustness is governed by contact force computation and a non-linear impact zone solver for penetration handling.

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Thanks!

Q&A